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DOCTORAL THESIS

Link-Quality based Routing Framework for Wireless Sensor Networks

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Declaration of Authorship

I, Fariborz Entezami, declare that this thesis titled, 'Link-Quality based Routing Framework for Wireless Sensor Networks' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

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Fariborz Entezami

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Abbreviations

2D	Two Dimension Coordinate System
3D	Three Dimension Coordinate System
3DPBARP	Three Dimension Position-Based Adaptive Real-Time Routing Protocol
3DPBRP	Three Dimension Position-Based Routing Protocol
ACK	Acknowledgement
ACTP	moving Average Collection Tree Protocol
AETX	Average Expected Transmission count
ANT	Average Number of Transmissions
AODV	Ad hoc On-Demand Distance Vector
BATD	Bottleneck Aware Routing Metric
BER	Bit Error Rate
CCC	Common Control Channel
CI	Computational Intelligence
CIM	Cumulated Interference Metric
CL-ILD	Cross Layer Interference-Load and Delay aware
CMAC	Cognitive MAC
CORR	Chip Correlation
CPU	Central Processing Unit
CRC	Cyclical Redundancy Checking
CTP	Collection Tree Protocol
DBETX	Distribution Based Expected Transmission Count
DCF	Distribution Coordination Function
DFRP	Directed Flooding Routing Protocol
DIFS	DCF Inter Frame Space
DSR	Dynamic Source Routing

EAB	Expected Available Bandwidth
ED	Energy Detection
EDR	Expected Data Rate
EETT	Exclusive Expected Transmission Time
EETX	Extra Expected Transmission Count
EFPBARP	Three Dimension Position-Based Adaptive Real-Time Routing Protocol
EFRCTP	Energy-eFficient Rainbow Collection Tree Protocol
EFW	Expected Forwarding Counter
ELB	Expected Link Bandwidth
ELD	Expected Link Delivery
ELP	Expected Link Performance
EMTT	Expected Multicast Transmission Time
ENT	Effective Number of Transmission
ERCRP	Energy-efficient Rainbow Collection Routing Protocol
EstdTT	Estimated Transmission Time
ETD	Expected Transmission Delay
ETP	Expected ThroughPut
ETT	Expected Transmission Time
ETX	Expected Transmission Count
ETXMulti	ETX for multimedia
GPS	Global Positioning System
GRP	Geographical Routing Protocols
HC	Hop-Count
iAWARE	interference AWARE routing metric
iBATD	Improved Bottleneck Aware Transmission Delay
IBETX	Interference and Bandwidth adjusted ETX
IDA	Interface Delay Aware
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
iETT	improved ETT
IF	Interference Factor
IMEP	Internet MANET Encapsulation Protocol
IWCETT	Improved Weighted Culminated Estimate Transfer Time

JEFW	Joint Expected Forwarding Counter
LQI	Link-Quality Indication
LQSR	Link-Quality Source Routing
LT	Life Time
MAC	Media Access Control
MCR	Multi Channel Routing
MDP	Markov Decision Process
MDS	MultiDimensional Scaling
MEFW	Maximum Expected Forwarding Counter
mETX	modified ETX
MF	Transmission Failures and Load-Balanced Routing Metric
MIC	Metric of Interference and Channel-switching
MRD	Minimum Root Distance
MR-OLSR	Multi-Radio Optimised Link State Routing
MTD	Minimum Transmission Distance
MTM	Medium Time Metric
MWSN	Mobile Wireless Sensor Network
OLSR	Optimised Link State Routing
PDF	Probability Density Function
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PFR	Parent Forwarding Region
PIT	Point In Triangulation
PLR	Packet-loss Rate
PRR	Packet Reception Rate
PTC	Potential Transmission Count
RCTP	Rainbow Collection Tree Protocol
REL	Routing by Energy and Link-quality indicator
RF	Radio Frequency
RSSI	Received signal strength indication
RTCD	Relatively Increased Contention Degree
RTT	Round Trip Time
SD	Spherical Distance

SERM	Statistical Estimate Routing Metric
SFD	Start of Frame Delimiter
SINR	Signal to Interference and Noise Ratio
SNIR	Signal-to-Noise plus Interference Ratio
SNR	Signal-to-Noise Ratio
TCD	Transmission Contention Degree
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
THL	Time Has Lived
UDP	User Datagram Protocol
VNP	Void Node Problem
WCETT	Weighted Cumulative ETT
WHAT	Weighted Hop, spectrum-Awareness and sTability
WIM	Weighted Integrated Metrics
WMN	Wireless Mesh Networks
WSN	Wireless Sensor Network

Dedicated to my Family

Abstract

Intelligence is the power which makes the owner capable of making a decision defined by reasoning. When traditional solutions and approaches, such as First Principal Modelling or Statistical Modelling, are not feasible or able to effectively address complex real-world problems, then Computational Intelligence with some nature-inspired computational techniques and methodologies is employed.

For transferring data between two non-directly connected devices when some other devices are in between, a set of rules are used by routers which are devices between sender and receiver, to determine the most appropriate paths into which routers should forward data toward the intended destination. This set of rules is called routing protocol. Researchers use some computational intelligence techniques to design network routing protocols.

Wireless Sensor Networks (WSNs) play an important role in today's data communication systems and researchers are expected to proliferate in the field of wireless communication in the near future. The deployment of wireless sensor networks offer several advantages in comparison to traditional infrastructure-based networks, such as fully distributed mobile operation, the easy discovery of joining wireless devices, and instant and low cost network setup. Designing an effective routing protocol is one of the main challenges in the ad-hoc networking paradigm and the utilisation of an adequate link-cost metric is essential.

WSN researchers address issues such as low throughput and high latency in wireless sensor data communication. Routing Protocols in WSNs play a key role in data communication and the main parameter in all routing protocols is data communication link-cost.

This research delivers two surveys on existing routing protocols and link-quality metrics for wireless sensor networks. Most of the routing protocols in this area are considered in different groups. The majority of link-quality metrics in WSNs are studied in different categories. Link-quality and traffic-aware metrics account for most of the metrics, as well as metrics in multi-channel networks and cognitive radio systems, which are also considered in detail. Metrics are reviewed in detail in terms of their performance;

summary and comparison tables of link-quality metrics are provided to enable better comparison and show a brief overview of their appearance to get a clearer picture.

Routing-metrics are important in determining paths and maintaining quality of service in routing protocols. The most efficient metrics need to send packets to maintain link-quality measurement by using the Radi Frequency (RF) module. In this study, a set of statistical analyses is done on some link-quality metrics to select the best metric for energy-aware scenarios. Two prominent link-quality metrics; Received Signal Strength Indication (RSSI) and Link-Quality Indication (LQI), are described in detail. The symmetry of RSSI and LQI in two directions is studied, and relations with the Expected Transmission Count (ETX), RSSI, and LQI as link-quality metrics are analysed. The evaluation in this research is based on a series of WSN test-beds in real scenarios.

Due to implementation of routing protocols in limited power supply devices in WSNs, one novel link-quality metric and also some routing protocols for wireless sensor networks are proposed in this research to obtain better performance in different scenarios. Rainbow Collection Tree Protocol (RCTP) is presented and evaluated as an enhanced version of Collection Tree Protocol (CTP). It uses the Trickle algorithm to optimise overhead cost and the algorithm also makes RCTP quickly adaptable to changes in topology. The Rainbow mechanism is used in RCTP to detect and route around connectivity nodes and avoid routes through dead-end paths.

Energy-efficient Rainbow Collection Tree Routing Protocol (ERCRP) is presented and evaluated as a novel, real-time, position-based and energy-efficient routing protocol in this research. ERCRP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel Parent Forwarding Region (PFR) algorithm. ERCRP as a Geographical Routing Protocol (GRP) reduces the number of forwarding nodes and thus decreases traffic and packet collision in the network.

WSNs are used in three-dimension (3D) scenarios such as sea or land surfaces with different levels of height. Three-Dimension Position-Based Adaptive Real-Time Routing Protocol (3DPBARP) is presented and evaluated as a novel, real-time, position-based and energy-efficient routing protocol for WSNs in this research. 3DPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel PFR algorithm. 3DPBARP as a GRP decreases the number of nodes which participate in packet forwarding and thus shrink the traffic and collision in the network.

Chapter 1

Introduction

1.1 Scope

The scope of this research covers a brief study on Computational Intelligence. Some methods such as Reinforcement Learning and Ant Colony Optimisation are briefly examined in relation to computational intelligence techniques. This research also covers link-quality metrics in routing protocols in Wireless Sensor Networks (WSN)s as a data communication mechanism in wireless devices. The majority of link-quality metrics in WSNs are studied in different categories. Link-quality and traffic-aware metrics account for most of the metrics, and also metrics in multi-channel network and cognitive radio systems are also considered in detail. Routing protocol in Wireless Sensor Networks (WSN)s is another area covered by this research. The routing protocols in WSNs are surveyed and most of the relevant routing protocols are considered.

This research assesses the validity of Expected Transmission count (ETX) as a link-cost metric in real-time test-beds. In the performance evaluation in chapter 3, the ETX performance is studied in different distance scenarios. Fluctuation in ETX values affects routing protocols, leading to wrongly identifying the best path based on current ETX link-cost; therefore, new methods instead of ETX are proposed in this research. The different methods for new link-quality calculation are compared and the best link-cost formula is proposed as a new method. The new proposed metric is called AETX and can be used as a link-cost in routing protocols. AETX reflects the balance required between the consistency of a link-metric value over the time for fixed scenarios and the flexibility required to detect actual changes in link-metric values in dynamic scenarios.

An introduction to topologies supported by the IEEE802.15.4 (It is a standard created and maintained by group of consultants which specifies the physical layer and media access control for low-rate wireless personal area networks), as well as deployment parameters of tree and star topologies are studied in a test-bed environment. Some techniques and measurements are proposed for random deployment of wireless sensors to uncharted areas.

WSN localisation is surveyed in this research. Methods and algorithms to find the location of each sensor without adding any positioning modules is considered.

Two prominent link-quality metrics - Received Signal Strength Indication (RSSI) and Link-Quality Indication (LQI) are described. The symmetry of RSSI and LQI in two directions is studied and relations with ETX, RSSI and LQI as link-quality metrics are analysed. In this research, evaluation is based on a series of WSN test-beds in real scenarios and implementation of novel routing protocols in limited power supply devices in WSNs is covered. There is a presentation and evaluation of Rainbow Collection Tree Protocol (RCTP) as an enhanced version of Collection Tree Protocol (CTP) and Omnet++ [1] is used as a simulator.

Energy-efficient Position-based Adaptive Real-Time Routing protocol (EFPBARP) is presented and evaluated as a novel, real-time, position-based and energy-efficient routing protocol. EFPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel Parent Forwarding Region (PFR) algorithm. EFPBARP as a Geographical Routing Protocol (GRP) reduces the number of forwarding nodes and thus decreases traffic and packet collision in the network.

Three-Dimension Position-based Adaptive Real-Time Routing Protocol (3DPBARP) is presented as a novel, real-time, position-based and energy-efficient routing protocol for WSNs. 3DPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel PFR algorithm.

1.2 WSN Standard Bodies

Industry alliances and Standard Developing Organizations (SDO)s have formed some standard body that made standard in WSN from physical layer up to application levels. Institute of Electrical and Electronics Engineers (IEEE) has IEEE802.15.4 group that works on physical and Media Access Control (MAC) layers. It can operates in the 868 MHz, 915 MHz and 2.4 GHz ISM Band with multi-channel support [2]. Table 1.1 shows spcification of IEEE802.15.4.

TABLE 1.1: IEEE 802.15.4 Specification

Geographical Regions	Europe	America	Wordwide
Frequency Assignment	868-868.6 Mhz	902928 MHz	2.4 2.4835 GHz
Number of Channels	1	10	16
Channel Bandwidth	600 KHz	2 MHz	5 MHz
Symbol Rate	20 ksymbols/s	40 ksymbols/s	62.5 ksymbols/s
Data Rate	20 kbps	40 kbps	250 kbps
Modulation	BPSK	BPSK	Q-QPSK

The Zigbee standard has been maintained by a group of companies that is called the Zigbee Alliance. This is specification of a suit of high level communication protocols that work on top of MAC and Physical (PHY) layers that have been specified in IEEE802.15.4 standards for devices with very low power. Zigbee is a suitable technology to be used in low battery life devices in low data rate applications. Setting up a secure network made this standard a widely deployed in applications for control and monitoring. Zigbee uses Ad hoc On-Demand Distance Vector (AODV) as routing protocol and classifies devices as Full-Function Device (FFD) and Reduced-Funcation Device (RFD) that they could be play roles as Coordinator, Router and End Device. Security could be used in application that has been supported by standard and it uses three keys as Master key, Link Key and Network Key [3].
WirelessHART Is a technology that works on 2.4GHz ndustrial, scientific, and medical (ISM) radio band and formed network as a mesh topology. It operates on top of IEEE802.15.4 and using channel hopping technique for each packet and Time Division Multiple Access (TDMA), Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) to communicate between network devices. WirelessHART uses two routing protocols; Source routing and Graph routing protocols. Graph is a pre-determined routing that defines route path from source toward destination before sending packets. Source Routing is a reactive routing protocol that select path on ad-hoc. WirelessHART use Gateway, Network Manager and security manager as network components. Devices play Repeater, Adapter and Terminal roles. Security is mandatory in this technology and a AES-128 block cipher symmetric keys are used to secure communication to hop-to-hop and end-to-end communication [3].
Instrumentation, System and Automation society (ISA) formed ISA-100 standards for WSNs to enable a single and integrated wireless infrastructure for industrial automation and control applications. It has been designed to operate in network of devices that may another standards work in same area. ISA-100 supports channel hopping to avoid Radio Frequency (RF) interference of devices that works in same frequency and has some capability for future use that make this standard capable to offer additional or enhanced features in future. ISA-100 uses TDMA mechanism and is fully redundant and self-healing and provides end-to-end packet delivery reliability. ISA-100 provide

security for automation industry in form of policy. The policy distributed with security materials such as symmetrical and asymmetrical keys with a limited lifetime and are updated periodically. ISA100.11a is a generation of ISA-100 with focus on security in whole system[3].
Internet Engineering Task Force (IETF) has formed IPv6 over Low Power Wireless PAN (6LoWPAN) group to define a series of standards for Wireless Sensor Network (WSN) is called 6LoWPAN. It supports auto- address configuration, neighbour discovery header comparison and packet fragmentation. It works on top of IEEE802.15.4 PHY and MAC layers and support routing on IP networking layer [4].
Ultra-WideBand (UWB) communication has been defined by U.S. Federal Communications Commission (FCC) in 2002 and then European Commissions (EC) Radio Spectrum Committee approve it in 2006. It operates in a large bandwidth more than 500 MHz. UWB transmits data with short pulses as it is called Impulse Radio (IR). EC identified the frequency band 3.4-5 GHz (with potential to extend to 9 GHz) for using in UWB devices. IEEE 802.15.3a was standard for short range (up to 10 meters) with high data rate in Wireless Personal Area Network (WPAN) was withdrawn as a result of market uncertainty in 2006 [5]. IEEE formed IEEE802.15.6 to develop a communication standard for low power devices to operate on, in or around the human body. It supposed to support applications including medical or consumer electronics and personal devices [6].

1.3 WSN technologies and Applications

Most of WSN technologies operate on IEEE802.15.4 as RF module which covers PHY and MAC layers with maximum 256 kbps data rate. The transmission range is very from 10 m to 10 km depend on RF design. Table 1.2 shows the comparison of different existing communication technologies for WSN.

TABLE 1.2: Communication Technologies for WSNs

Protocol	Governing body	Security	Topology
ZigBee	ZigBee Alliance	global key, 128-bit AES	Star and Mesh
ZigBee Pro	ZigBee Alliance	peer-to-peer key exchange, 128-bit AES	Star and Mesh
ZigBee RF4CE	ZigBee Alliance	peer-to-peer key exchange, 128-bit AES	Star
JenNet-IP	Jennic Proprietary	128-bit AES	Star and Tree
6LoWPAN	IETF	IPsec	Star
ISA100	ANSI/ISA	128-bit AES, Security Manager	Star and Mesh
MiWi	Microchip Proprietary	128-bit AES	star and Mesh
SNAP	Synapse Wireless Proprietary	128-bit AES	Mesh
SynkroRF	Freescale Proprietary	peer-to-peer key exchange, 128-bit AES	Star
WirelessHART	HART Communication Foundation	128-bit AES, Security Manager	Star and Mesh

Service Layer in WSN is dependent on technology platform and could provide Internet of Things (IoT) Sensing, Intelligent Sensing or wireless communication layers. Sensing layer could provide sensing, actuating, identifying, interacting and communication [7]. WSN applications could be in industries, Social IoT Social Internet of Things (SIoT), healthcare, infrastructure, security and surveillance. WSN industrial applications are able to improve the business transactions with efficiency of real-time information and provide online monitoring and control critical environments.SIoT is described as a world where things around us can be intelligently networked and could be sensed, monitored and controlled by human. SIoT makes human able to monitor and control his/her life environment. Healthcare applications are important area of WSN. A number of medical devices are used to sense and monitor medical parameters such as body temperature, blood glucose level and pressure. Wearable Body Sensor Networks (WBSN)s is a set of WSN devices and sensors to monitor patient activities and medical parameters continuously. WSN infrastructure applications are used in smart cities, smart home, Smart Grid (SG) and environment monitoring. It makes a network of wireless devices to communicate actuated data and control commands and operate as integrated network. WSN security and surveillance applications are provide a secure connection between wireless devices with resistance to hacking and unauthorised access. They operate in critical area to monitor and control in a very sensitive manner[7]. WSN is used in industrial environment for controlling and monitoring purpose. Smart Grid (SG) use WSN for remote monitoring of wind and solar farms, power quality monitoring and also equipment fault diagnostics. WSN could monitor overheat transmission line and conductors. It could report back to the centre the fault detection and location and also animals and vegetation control in control areas. In consumer side of SG, WSN could report Wireless Automatic Meter Readings (WAMR)s or Residential energy-management (REM). WSN cooperates in building automation, Demand-side load management and automated panels management [4]. Table 1.3 shows wireless technologies in different technologies.

TABLE 1.3: Wireless Technology comparison

Wireless Technologies	802.15.4 ZigBee	WiFi 802.11b	Bluetooth 802.15.1
Application	Monitoring-Control	Web,Email, Video	Wireless Conectivity
System Resources	4HB-32KB	1MB+	250KB+
Battery Life (days)	100-1000+	.5 - 5	1-7
Network Size	Unlimited	32	7
Maximum Data Rate (kbps)	20-250	11,000+	720
Transmission Range (meters)	1-100+	1-100	1-10+
Advantages	Reliability, Power, Cost	Speed, Flexibility	Cost, Convenience

1.4 Motivation for the research

WSNs are formed by small devices in which energy consumption is a key to system design and life-time running. Any protocol used has to be energy-aware. Collection Tree Protocol (CTP) is a lightweight, simple and efficient routing protocol and is also a best-effort, reliable and many-to-one routing protocol. This simple and effective routing protocol is the foundation for sensor applications that work on top of the network layer. For almost a decade CTP has suffered from poor performance with delivery ratio of 2-68%. [8–11]. Adding some simple mechanisms can improve CTP performance and make it more efficient. In this research, considering different metrics and finding a stable version of Expected Transmission Count (ETX) was a motivation to improve CTP. Implementing Average Expected Transmission count (AETX) as a new link-quality metric in CTP, improving the mechanism of parent selection and also using the Rainbow mechanism make Rainbow Collection Tree Protocol (RCTP) a new version of CTP that demonstrates better performance in comparison with traditional CTP.
Energy usage in a transponder is based on the range of the RF coverage, as the energy consumed in transponder is proportional to the square of RF-range radius. Any reduction in RF transmission range can save significant energy in a wireless transponder. Energy-efficient Rainbow Collection Routing Protocol (ERCRP) is a lightweight, simple, reliable, efficient, best-effort and many-to-one routing protocol. Decreasing the number of nodes that receive unrelated signals in ERCRP decreases the number of retransmissions and can save energy in the whole system.
WSNs are used in three-dimension (3D) scenarios such as sea or lands with different heights. Three Dimension Position-Based Routing Protocol (3DPBRP) is a Three Dimension Coordinate System (3D) and position-based version of CTP as a lightweight, simple reliable, efficient, best-effort and many-to-one routing protocol. Using the CTP concept in a 3D routing protocol is one of the main motivations for this research.Adding energy consuming efficiency in current routing protocols is another motivation.

1.5 Research Objectives

1.5.1 WSN Routing Protocols

Routing protocol play an important role in data communication. A wireless sensor network (WSN) is usually deployed in scenarios where efficient and energy-aware routing protocols are desired. This research presents a survey on routing protocols in WSNs. In

Chapter 2, routing protocols for wireless sensor networks are studied in different categories. Network Structures, communication model schemes, technology based schemes and reliable routing schemes are categorised and routing protocols in each category are considered.

1.5.2 Metrics in Routing Protocols

Research in the fields of wireless communication especially in Wireless Sensor Networks (WSN)s that plays an important role in data communication is expected to grow significantly in the near future. The deployment of wireless ad-hoc networks in comparison to traditional infrastructure-based networks offers several advantages such as fully distributed mobile operation, easy discovery of joining wireless devices, and instant and low-cost network setup. Designing an effective routing protocol is one of the main challenges in the ad-hoc networking paradigm and utilisation of an adequate link-cost metric is essential.

WSN researchers address issues such as low throughput and high latency in wireless sensor data communication. Routing Protocols in WSNs have a key role in data communication and the main parameter in all routing protocols is data-communication link-cost. In this research, the majority of link-quality metrics in WSNs are studied in different categories. Link-quality and traffic-aware metrics account for most metrics; however, metrics in multi-channel network and cognitive radio systems are also considered in detail. Metric performance is reviewed in detail, and summary and comparison tables of link-quality metrics are provided for a better comparison and for a brief visualisation of the metrics.

1.5.3 AETX a Novel Routing Protocol Metric

In this research, the validity of Expected Transmission count (ETX) as a link-cost metric is studied in a real-time test-bed environment. In the performance evaluation in chapter 3, ETX performance is observed in different distance scenarios. Subsequently, the main observation shows that ETX values are not steady over the observation time and fluctuate in fixed scenarios. Fluctuation in ETX values affects routing protocols by wrongly identifying the best path based on current ETX link-cost; therefore, new methods instead of ETX are proposed in this research. The new proposed metric called AETX, can be used as a link-cost in routing protocols. AETX reflects the balance required between the consistency of a link-metric value over time for fixed scenarios and the flexibility required to detect actual changes in link-metric values in dynamic scenarios.

1.5.4 Localisation methods in WSN

WSNs are expected to be used for remote monitoring, home automation and industrial control. One of the goals of WSNs is to minimise running costs and therefore Star and Tree topologies are designed to save energy as they do not require any routing table to send packets to a destination. Introduction to topologies supported by the IEEE802.15.4 and deployment parameters of Tree and Star topologies are studied in a test-bed environment in chapter 3. Some techniques and measurements are proposed for random deployment of wireless sensors into the field.
Location of sensors is one piece of critical information that merges with other information collected from sensors and together make a proper vision from the point that sensors were installed. Finding the location of wireless sensors automatically is needed in some scenarios for updating databases in the case of location-aware sensitive data or making change in sensor network topology. Localisation in WSN is a challenging and interesting area for research that is studied in chapter 3.
Finding the exact location of wireless sensors needs an extra device such as a Global Position System (GPS) module to find WSN location accurately and simultaneously. Wireless sensors are tiny devices with limited functionality and with a limited source of memory and energy. These devices are in sleep mode most of the time and energy consumption is a major issue in the most WSN scenarios. Finding a balance between huge position calculation and energy consumption and other resources is a big challenge. In chapter 3, localisation in WSNs is studied and the methods and algorithm to find the location of each sensor without adding any positioning modules are considered.

1.5.5 Statistical Analysis of Link-quality Metrics

Routing protocol plays an important role in wireless sensor's data communication and radio-frequency (RF) modules consume the majority of total energy consumption. Routing metrics are important in determining paths and maintaining the quality of service in routing protocols. The most efficient metrics need to send packets to maintain link-quality measurement using the RF module. In chapter 4, two prominent link-quality metrics; Received Signal Strength Indication (RSSI) and Link-Quality Indication (LQI) are described. The symmetry of RSSI and LQI in two-directions are studied, and relations with the ETX, RSSI, and LQI as link-quality metrics are analysed. The evaluation in this research is based on a series of WSN test-beds in real scenarios. The collected data from the test-beds show symmetry in RSSI in both directions as well as a significant correlation between RSSI and distance. This makes RSSI a suitable link-quality metric for routing protocols in devices that operate in limited-resource scenarios.

1.5.6 Energy-efficient Routing Protocols

Due to implementation of routing protocols in limited power supply devices in WSNs, Chapter 5 presents and evaluates Rainbow Collection Tree Protocol (RCTP) as an enhanced version of Collection Tree Protocol (CTP). The basic foundation of CTP is link-quality identification and it uses ETX as radio link-quality estimation between nodes. RCTP uses Average Expected Transmission count (AETX) as link-quality metric that is shown it is more stable than ETX. It also uses a new mechanism in parent selection to make it more accurate in term of forming a tree topology. The Rainbow mechanism is used in RCTP to detect and route around connectivity nodes and avoid routes through dead-end paths. The Omnet++ [1] is used as a simulator.
Chapter 5 also presents and evaluates an Energy-efficient Position-based Adaptive Real-Time Routing protocol (EFPBARP) as a novel, real-time, position-based and energy-efficient routing protocol. EFPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel Parent Forwarding Region (PFR) algorithm. EFPBARP as a Geographical Routing Protocol (GRP) reduces the number of forwarding nodes and thus decreases traffic and packet collision in the network. A series of performance evaluations through Matlab and Omnet++ simulations show significant improvements in network performance parameters and total energy consumption over CTP and Directed Flooding Routing Protocol (DFRP).

1.5.7 Proposed Routing Protocols for 3D scenarios

WSNs are used in three-dimension (3D) scenarios such as sea or lands with different level of height. Chapter 5 presents and evaluates Three-Dimension Position-based Adaptive Real-Time Routing Protocol (3DPBARP) as a novel, real-time, position-based and energy-efficient routing protocol for WSNs. 3DPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel PFR algorithm. 3DPBARP as a GRP reduces the number of forwarding nodes and thus decreases the network traffic and collision. A series of performance evaluations through Matlab and

Omnet++ simulations show significant improvements in network performance parameters and total energy consumption over 3D Position-based Routing Protocol (3DPBRP) and DFRP.

1.6 Research Contribution to Knowledge

A number of peer-reviewed publications in high quality conferences and journals are produced as results of this research. The publications are based on research described in this thesis and they are listed in Appendix A. The research achievement as result of this research thesis can be summarized as follows:

- Mobility impact on 6LoWPAN based Wireless Sensor Network [12].

- An enhanced routing metric for wireless networks based on real-time testbed [13].

- Survey on measurement localisation techniques on wireless sensor networks [14].

- CTP-A: An enhanced version of collection tree protocol [15].

- Deploying Parameters of Wireless Sensor Networks in Test-bed Environment [16].

- An Analytic study on Link-quality metrics: RSSI, LQI and ETX in Wireless Sensor Network [17].

- Statistical Analysis on Wireless Sensor Network Link-Quality Metrics [18].

- An Analysis of Routing Protocol Metrics in Wireless Mesh Networks [19].

- RCTP: An Enhanced Routing protocol based on Collection Tree Protocol [20].

- Energy-efficient Rainbow Collection Routing Protocol for Wireless Sensor Networks [21].

- Three-Dimension Position-based Adaptive Real-Time Routing Protocol for Wireless Sensor Networks [22].

- An Energy-efficient Position-based Adaptive Real-Time Routing Protocol for WSNs [23].

1.7 Structure of Thesis

The Structure of this thesis has followd as:
Chapter 2 presents the literature review on WSNs' routing protocols. Intelligence algorithms are considered regarding routing protocol and then the routing protocols for WSN are considered in different categories. Link-quality metrics are studied in this chapter in three categories; link-quality and traffic-aware metrics and also metrics for multi-channel networks. In the last section of this chapter, the localisation methods are studied with providing a glance of the studied methods.
In chapter 3, AETX as a novel routing protocol metric is proposed and investigation process and evaluation methods are described in the first section. In the second section, Deployment parameters of WSNs are studied. In this study, Star and Tree networks are evaluated based on a set of real test-bed scenarios.
Chapter 4 shows study on statistical analysis of WSN's link-quality metrics. In this section RSSI, LQI and ETX are considered and statistical results to show any relation between these three metrics and also with nodes distance are studied.
Chapter 5 presents the proposed routing protocols. RCTP, ERCRP and 3DPBARP are presented with evaluation methods and results.
Chapter 6 provides thesis conclusion and future work. The publications that are based on this research are listed in Appendix A. Appendix B presents a survey on WSN routing protocols in different categories.

Chapter 2

Literature Review

A decision maker needs to use the power of intelligence to reach a rational conclusion. Computational Intelligence (CI) is used to find solutions for complex real-world problems by inspiring the employment of nature-based computational techniques and procedures. In this chapter, intelligent algorithms and their relation to routing protocols are studied and some techniques are briefly considered which are utilised in routing-protocol model strategy.

WSNs, as part of wireless data communication, employ effective routing protocol to send data to the destination in an optimised manner. In this chapter, the routing protocols in WSNs are surveyed and the majority of routing protocols in this area are included.

WSNs are a big part of todays data communication puzzle. Researchers make a concerted effort to discover all behaviour of this system in the real environment. The deployment of wireless ad-hoc networks has several advantages such as fully distributed mobile operation, easy discovery of joining wireless devices, instant and low-cost network setup. Routing protocol is key in ad-hoc network data communication. Designing an effective routing protocol and utilisation of an adequate link-cost metric are the main challenges in this area. In this chapter, the majority of link-quality metrics in WMNs are studied in different categories.

2.1 Intelligent Algorithms and Routing Protocols

When the traditional solution and approaches such as First Principal Modelling or Statistical Modelling are not feasible or effective to address complex real-world problems, CI is employed to solve them [24]. Nature uses biological techniques and also provides many counter examples of biological systems that function practically and which can be used to solve complex real-world problems [24]. CI is used in Artificial Neural Networks, Evolutionary Computing, Fuzzy Logic, Swarm Intelligence Artificial Immune Systems, Image Processing, Data Mining, Natural Language Processing and many other applications [25][26][27]. Scientists who study network topology and routing protocols use CI techniques such as Artificial Neutral Networks, Fuzzy Logic and Swarm Intelligence to solve problems [24][28][29].

2.1.1 Reinforcement Learning

Reinforcement Learning is part of Machine Learning and is inspired by an area in psychology that combines theory, methodology and philosophy. Reinforcement Learning is used in applications such as Game Theory, Control-Theory, Information Theory, Operation Research, Simulation-based Operations, Swarm Intelligence, Multi-agent Systems, Statistics and Generic Algorithms [24][30][31]. In Machine Learning, problems are typically formulated as a Markov Chain Process such as many Reinforcement Learning algorithms and this is called Dynamic Programming. Dynamic Programming is a technique for solving a complex problem by breaking them into simple problems. Solving all sub problems results in a solution for the main and complex problem [32][33]. Reinforcement Learning forms a model with these elements: a set of environment states, a set of actions, rules between states, rules to measure immediate reward in each transition, and finally rules of observation by agent. Reinforcement Learning runs randomly in different states and calculates the awards obtained in each state and compares these with the target until the problem is solved [34].

2.1.2 Ant Colony Optimisation

Ant Colony Optimisation (ACO) is an area of CI used in artificial systems. ACO is inspired from behaviour of real ants in their colonies. Ant Colony Optimisation is used to solve discrete optimisation problems [24][35]. Ant Colony Optimisation system was introduced for the first time by Marco Dorigo in 1992. Marco Dorigo called it the Ant System in his PhD thesis. In 1992, the Ant Colony Optimisation metaheuristic was published by Dorigo Di Caro and Gambardella [24]. When ants wander randomly, they find food and then leave the food source to walk back to the colony. On the return, the ants leave pheromones (markers) to show the path toward the source of the food to the other ants in the colony. Any ant that comes across the food-source path will follow it because of the pheromones. As more ants use the path, the pheromones become stronger and when the food source is depleted and the path is no longer visited by ants, the pheromones slowly decay [36]. ACO is a dynamic and self-managed system and works very well in graphs with dynamic topologies. ACO is used in the travelling-salesman problem, computer networks and in artificial intelligence. Ant Colony Optimisation is used in most routing protocol in computer science and networking such as CTP. Each node in the network is responsible to send data to a centre (call Sink) and it should find the best path to the Sink among several possible routes [37].

2.1.3 Fuzzy Logic

Fuzzy Logic has been studied since the 1920s and the term of Fuzzy Logic was introduced in 1965 by Lotfi A. Zadeh [38][24]. Fuzzy Logic considers many logic values to measure a phenomenon rather than take a fixed and exact value. Binary Logic takes true or false values, although in Fuzzy Logic a truth-value can take a range between 0 and 1. Partial truth is a concept in Fuzzy Logic where the truth-value can take a range of completely true and completely false. Fuzzy Logic has been used in control-theory applications such as the high-speed train in Sendai, Japan, recognition of hand writing in Sony Pocket Computers, flight aid for helicopters, improving fuel consumption in automobiles and many other applications [39][40]. Fuzzy Logic is used in most computer programming wherein a decision should be taken. It is used in routing protocols, especially in energy-efficient routing protocols whereby each node in the selected path has to obey the minimum energy-consumption rule in the system [41][42].

2.1.4 Genetic Algorithm

Genetic Algorithm is a section of Artificial Intelligence which is a search heuristic that is the result of simulating the process of making a decision in nature and subsequently used in applications in chemistry, manufacturing, bioinformatics, computational science, engineering, phylogenetic, economics, mathematics, physics and other science fields. The heuristic or metaheuristic is used to provide an optimised solution or finding the best solution through candidate solutions. Genetic Algorithm from another perspective is part of Evolutionary Algorithm (EA) [24]. Evolutionary Algorithm provides optimum solutions using methods and technics, which are used by natural evolution such as selection, inheritance and mutation. Genetic Algorithm is applied on a population. Population in Artificial Intelligence is candidate solutions and the population can be called individuals, phenotypes or creatures. The possible candidates are considered to find better solutions. Each candidate has some properties that can be altered or mutated during the process [24]. Evolution in Genetic Algorithm starts with a randomly generated creature in an iterative process. The creature in each iteration is called a generation and each generation is evaluated based on a fitness. Fitness is a value of the objective function that is used to solve the optimisation problem. The new generation creature is used in the next algorithm iteration. The algorithm terminates when the fitness value reaches a satisfactory level or reach to the maximum number of generations which is limited by resources. Generic Algorithm is used throughout computer science, especially in object-oriented system design. In routing protocol, especially in cluster-based versions, each node in a cluster inherits from the head of the cluster some properties such as cluster ID [24].

2.2 Routing Protocols in WSNs

The main duty of a WSN as a distributed computing network is to collect data from a large amount of nodes. They have the capacity of sensing the environment, processing data and also short-range communication. WSN applications collect data from wireless sensors and a proper routing protocol can help them to achieve scalability and improve system performance.

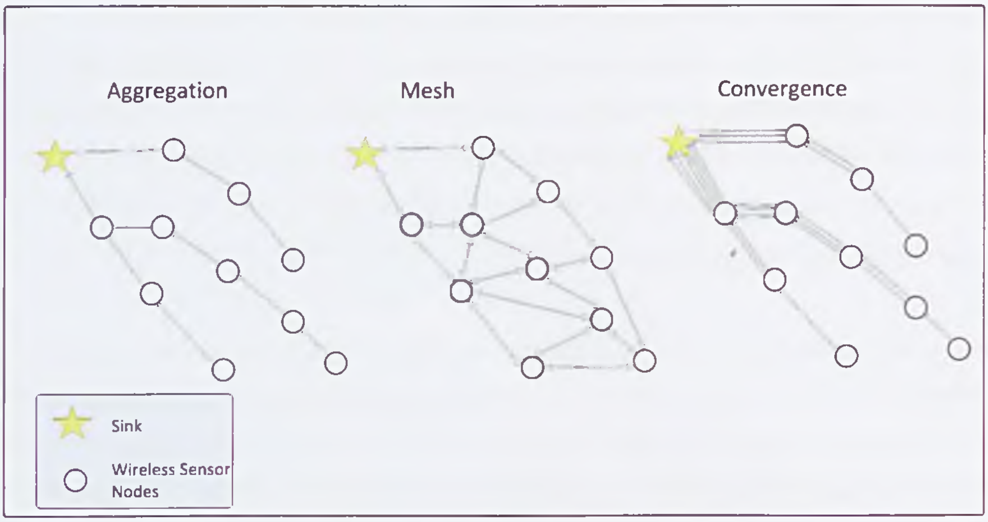

FIGURE 2.1: WSN Patterns

Figure 2.1 shows data flow diagrams in three routing schemes: aggregation, mesh and convergence. In the aggregation scheme, the sensor nodes send their data to their parents. The parents merge the received data with collected data and then send to its parent and then finally all data is delivered to the Sink. In the mesh scheme, all wireless nodes have two-way communication with all their neighbours and communication can occur as a mesh network. The Sink can communicate with each sensor node and reverse. In the convergence scheme, all nodes send their data to their parents and the parents retransmit any received messages to their parent until they are arrived in the Sink.

In this research, routing protocols in WSNs are considered in four categories: Network structure, communication model, technology based and reliable routing-protocol schemes [43].

2.2.1 Network Structure

Network Structure is a category that considers routing protocols based on node uniformity. In this category, routing protocols are studied based on the formation of the network topology based on type of nodes. In some routing protocols, a uniform type of nodes is used. These form the topology and all nodes in the topology have the same task. In some routing protocols, two or more types of nodes form the network topology and node tasks are related to node type. Routing protocols in network structure schemes are considered in two categories: Flat Network and Hierarchical model schemes. Flat routing protocols can be categorised as table-driven or demand-driven schemes. In a table-driven scheme, each node sends data to the destination based on destination table that keeps it up-to-date. In a demand-driven scheme or source-initiated, a destination node floods the network with its demand and then the source sends data back based on the asked demand.

2.2.1.1 Flat Routing Protocols

Wireless Routing Protocol (WRP) [44] is a proactive or table-driven routing protocol that uses the distributed Bellman-Ford algorithm. It uses a set of tables to maintain an up-to-date network viewpoint to make it capable to make a decision based on accurate information [44][43]. WRP benefits from the avoidance of loops and fast route convergence in the case of link failure; it has limited scalability with limited mobility support. It uses shortest path as a routing metric and uses table exchange for maintaining topology. It is categorised as a low robust routing protocol. WRP is not suitable for highly dynamic and large-scale scenarios of wireless sensor networks and this is its drawback [24].

Topology Dissemination Based on Reverse-Path Forwarding Protocol (TBRPF) [45][46] is a pro-active routing protocol that sends updates when the state of the topology changes from the previous state. TBRPF uses smaller routing update messages than other routing protocols [45][46][43]. TBRPF benefits from sending less frequent periodic topology updates compared with other routing protocols in this category. It has limited scalability with good mobility support. It uses the shortest path as the routing metric and uses

HELLO message for maintaining topology. It is categorised as a good robust routing protocol. TBRPF is not a suitable routing protocol for networks with low mobility [24]. Temporarily Ordered Routing Algorithm (TORA) [47, 48] is a reactive, highly adaptive, loop-free and distributed routing protocol based on link reversal. The main concept of TORA is to limit control-message dissemination in highly dynamic mobile computing scenarios. TORA benefits from minimising communication overhead and also supports multiple routes. It has good scalability with good mobility support. It uses shortest path as a routing metric and uses Internet MANET Encapsulation Protocol (IMEP) control message for maintaining topology. It is categorised as a low robust routing protocol and TORA cannot be incorporated into multicast scenarios [24][47, 48][43].

Gossiping [49] is reactive routing protocol that uses gossiping instead of broadcasting. In broadcasting, one node sends its unique information to all neighbours; however, in Gossiping each node sends the incoming information to a randomly selected neighbour. Gossiping benefits from using less communication overhead. It has good scalability with good mobility support. It uses random selection to choose the path to a destination and does not use any message for maintaining topology. It is categorised as a good robust routing protocol. Gossiping suffers from long delivery times for messages to all nodes in the network [24][49][43].

Flooding [50] is a traditional, reactive and simple routing protocol for WSNs. Each node retransmits any received message to all nodes except the node that the message came from. Flooding is a robust routing protocol that provides source-to-destination delivery guarantee; however, it generates an enormous amount of traffic within the network [50][43]. Flooding benefits from a simple and robust routing technique for WSNs. It has good support of scalability and mobility. It uses shortest path as the routing metric and does not use any message for maintaining topology. It is categorised as a good robust routing protocol. Flooding suffers from generating enormous amount of traffic within a given network and it may broadcast the same message several times as there is no mechanism to control duplicated messages for broadcasting [24].

Rumour Routing (RR) [51] is a reactive routing protocol that allows queries to be delivered to the nodes that sense the event. It is a tuneable routing protocol based on application requirements that are balanced between network overhead and data-packet reliability [51][43]. RR benefits from handling node failure gracefully and keeping a record of routes with node failure. It has good scalability with low mobility support. It uses shortest path as the routing metric and use HELLO messages for maintaining topology. It is categorised as a good robust routing protocol. RR suffers in that it may deliver duplicate messages to the same node [24].

Energy-aware Temporarily Ordered Routing Algorithm (E-TORA) [52] is a reactive and energy-aware version of TORA. The original TORA selects the best route with the least hops based on network topology [52][43]. E-TORA benefits from minimising energy consumption and creating a balance between nodes in the network. It has good scalability with good mobility support. It uses the best route as the routing metric and uses IMEP control messages for maintaining topology. It is categorised as a low robust routing protocol. E-TORA suffers when it is incorporated with multicast routing [24].

Zone Routing Protocol (ZRP) [53] is a hybrid routing protocol and benefits from the advantages of proactive and reactive routing protocols. It finds loop-free routes to the destination by dividing the topology into zones. These zones use proactive techniques for locating local neighbours in the zone and dramatically reduce overhead costs [53][43]. ZRP benefits from using low routing traffic. It has good scalability with good mobility support. It uses the best route as the routing metric and uses HELLO messages for maintaining topology. It is categorised as a good robust routing protocol. ZRP suffers from excessive delays in some complex scenarios [24].

2.2.1.2 Hierarchical Routing Protocols

These types of routing protocols are more energy-aware than flat routing protocols and are suitable for coverage of a large area without degrading the quality of services. They are more stable with capability of scalability. The topology structure is organised in clusters. In each cluster, one node with more capacity in residual energy, processing or radio module plays the role of cluster head. The cluster head coordinates activities within the cluster and communication between clusters. The clusters perform data aggregation and fusion tasks. Hierarchical protocols consume less energy and the network has more life-time than with flat routing protocols. High delivery ratio and scalability are characteristics of these routing protocols. The main disadvantages of this kind of routing protocol are that nodes are depleted around the base-station or cluster head faster than other nodes in the network and there is also non-connectivity of the part of network based on a single point of failure in the topology [43].

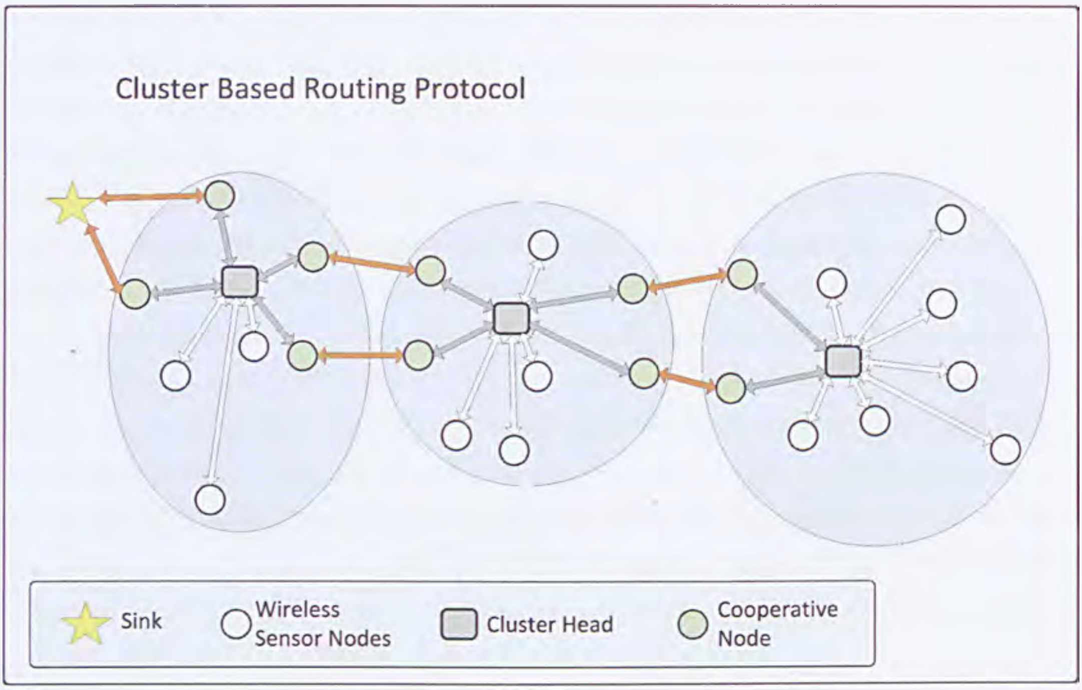

FIGURE 2.2: Cluster Based Routing Protocol

Figure 2.2 shows Cluster Based Routing Protocol and how nodes communicate until the packets are sent to the destination or Sink.

Low-Energy Adaptive Clustering Hierarchy (LEACH) routing protocol was introduced by Heinzelman, et al [54] and was the first hierarchical, self-organised and adaptive clustering routing protocol [54][43]. The advantage of LEACH is its low-energy consumption level; it is distributed and has a good rate in scalability by using a fixed base-station and uses shortest path as a routing metric. It is not applicable to operation in large areas and creates more overhead by using dynamic clustering.

Energy-Leach (E-LEACH) [55] is an energy-aware version of LEACH. The algorithm is similar to LEACH except the mechanism of CH's election is different after the first round. In the first round, the Cluster Head (CH) is chosen based on a probability function such as LEACH; however, in the next rounds the remaining energy level of each node accounts for choosing to become a CH. The nodes with a higher level of remaining energy have more chance to become a CH than nodes with low battery charge.

Low-energy Adaptive Clustering Hierarchy Centralised (LEACH-C) [55] is a centralised version of LEACH. Base-station (BS) plays the role of a centralised cluster information centre in this algorithm and initially BS receives information regarding node location, their neighbours and energy levels of nodes in the network. The advantage of LEACH-C is that it uses less energy to transmit message than LEACH and has a good rate in scalability with a fixed base-station. It uses the best route as the routing metric and also has a good rate of robustness; however, it generates more overhead [55][43].

Two-Level Hierarchy LEACH (TL-LEACH) [56] is designed to send data to the base-station in one hop. CH plays the role of hops in this protocol and the network is formed with two levels of cluster head, which are called primary and secondary. There is a reduction in energy consumption regarding data that is sent through a two-level structure to the Base-station.
Multi-hop LEACH (M-LEACH) [43] uses others CH as relay in the network and data is sent to the Base-station through multi-hop networks which are CHs. This solves the problem of distant CHs; however, it consumes more energy to transfer data through a far distance.
Vice LEACH (V-LEACH) [43] is a version of LEACH that defines some Vice-CH. Vice-CH would be a CH in the case that a current CH dies and then it takes its role. It solves the disconnection of cluster nodes regarding disappearing CH.
U-LEACH [57] is a combination of I-LEACH and PEGASIS. It benefits energy-aware CH selection from I-LEACH and multi-hop transmission from PEGASIS. Master CH (MCH) sends the gathered data to the base-station and the clustering of nodes and electing the CH is based on a probabilistic approach such as LEACH.
Power-Efficient Gathering in Sensor Information System (PEGASIS) is an enhanced version of routing protocol in WSN that was proposed after LEACH. It is a chain-based protocol that saves more energy in the system and increases network life-time because each node only needs to communicate to its closest neighbour. Then, nodes receiving data are responsible to make the replay to the base-station and this works such as a chain-based protocol [43]. The advantages of PEGASIS are most of the nodes reduce the transmission radio range to save more energy and it has a good scalability rate with a fixed base-station. It uses greedy-route selection to choose the best routing path and has a good rate of robustness. However it does not consider the location of the base-station and also the residual energy level for nodes that become a cluster head is not taken into account [43].
Hierarchical PEGASIS was proposed by [58] to reduce packet-delivery delay by avoiding collision between nodes that use the same spatial transmission. To avoid collision between close nodes, simultaneous data-transmission is considered and only nodes with a separate spatial data-transmission range are allowed to have simultaneous data-transmission[58][43].
Threshold-Sensitive Energy Efficient Sensor Network Protocol (TEEN) [59] and Adaptive TEEN (APTEEN) [60] are two hierarchical routing protocols for wireless sensor networks. TEEN is designed for time-critical scenarios and although the nodes sense attributes continuously, they transmit data only on a few occasions. Wireless nodes sense the object uninterruptedly and nodes receive two parameters regarding the objects. Each object that the wireless nodes have to sense has two thresholds, hard threshold and soft threshold. If the object measurement passes the hard threshold or its changes are more

than the soft threshold, this then triggers the node to turn on the radio module and transmit the data. The hard and soft thresholds are sent to nodes by the CH. The disadvantage of TEEN is if the update packet regarding hard and soft thresholds has not transmitted properly or if the node does not receive it, the data received in centre is then not as accurate as it should be [60][43].

APTEEN is a hybrid routing protocol that uses proactive and reactive attributes. It sends some properties to each node by CH. The parameters are: the physical parameters which nodes have to sense, Hard Threshold (HT) and Soft Threshold (ST); the TDMA schedule to let the nodes communicate with CH; and, Count Time (CT) (the maximum time period that nodes have to send data to the centre) [59][60][43]. The advantages of APTEEN are: its capability to handle sudden changes in sensing attributes; it has a good rate in scalability in a fixed base-station and choose the best route in routing; and, it has a good rate of robustness attribute. It is not an energy-aware protocol and creates more overhead to handle large networks [43].

CHIRON is a hierarchical chain-based and energy-efficient routing protocols for WSNs. CHIRON splits the sensing area into smaller areas to make several short chain-based paths to reduce packet delivery delay and also increases the redundant path to BS. It can save more energy and extend network life-time. Nodes in CHIRON are self-organised and dynamically form the network [61].

Small Minimum Energy Communication Network (MECN) [62] is an energy-aware routing protocol for WSNs. It computes the energy level of each sub network and chooses the best relay zone for each node based on neighbours′ regions. The best neighbour′s region is selected based on the transmission of data through the zone with less energy consumption compared with other regions. The regions with fewer nodes use less energy to relay data than regions with more number of nodes.

Small MECN (SMECN) [63] is a version of MECN which considers obstacles between two nodes. In MECN, all pairs have a communication link and obstacles do not come into account while it is assumed the network is fully connected.

Self-Organizing Protocol (SOP) was proposed by Subramanian et. al [64]. It is a proper routing protocol that can structure and support heterogeneous wireless sensors in stationary and mobile cases. In this protocol, some stationary wireless nodes work as routers and form the backbone of the network. Energy consumption for broadcasting a message in SOP is less than SPIN. The disadvantage of SOP is that when the network finds some hole in the topology, it increases the probability of reorganising the network as a cost-effective task and increases energy consumption in the system [64].

Virtual Grid Architecture (VGA) routing is an energy-aware routing protocol that benefits from data aggregation and in terms of network processing increases network life-time [65]. The process has two phases, clustering and routing-aggregated data. VGA is a proper routing protocol in terms of achieving energy efficiency and maximising the life-time of a network. It has a good rate in term of scalability in fixed scenarios for nodes and base-station. It uses greedy-route selection in routing to choose the best path and has a good rate to be a robust routing protocol [43].

Two-Tier Data Dissemination (TTDD) proposed by [66] as a capable routing protocol to deliver data to multiple mobile base-stations. In TTDD, sensing nodes are fixed and location-aware in this protocol although base-stations or Sinks are mobile. Regarding of data collection, all sensor nodes in the area sense the event and there is a predefined node that is responsible to prepare data and then transmit it to the base-station. TTDD can be used in scenarios wherein fixed nodes are distributed in the field and there are multiple mobile Sinks to collect messages. It has a low rate in scalability and uses greedy-route selection in routing messages and has good rate of robustness routing. The drawback is all source nodes must have the essential capacity to build a virtual grid topology of dissemination nodes to make it capable to send message to mobile Sinks. [43].

WB-TEEN [67] uses distributed clustering and a time-driven model that was proposed to cover the weakness of an unequal number of nodes in different clusters in TEEN. Conceptually, it is the improved version of LEACH and TEEN. WB-TEEN forms the clusters with an equal number of nodes in each cluster. Each CH has two parameters, the number of nodes in a cluster and a degree. CH decides to accept or reject a new member based on the numbers already joined to the cluster and the degree of the cluster.

WNM-TEEN [67] is an improved version of WB-TEEN that keeps all capability of WB-TEEN and also highlights multi-hop routing in the cluster by using performance-quality metrics. A performance-quality metric takes energy consumption of the process, number of live nodes, number of data-transmission rounds and network life-time into account to find the best route.

Base-station Controlled Dynamic Clustering Protocol (BCDCP) [68] is a centralised routing protocol that formed clusters in a balanced fashion. The base-station receives status information of all nodes in a topology before forming the clusters. BCDCP benefits from being a low-energy consumption routing protocol and has limited scalability with no mobility support. It chooses the best route in routing protocol and has a limited rate to be a robust routing protocol. It also has a drawback in that performance decreases in scenarios in which the field areas of sensing become small [43].

Hierarchical Power Aware Routing (HPAR) [69] is categorised as an energy-aware routing protocol in wireless sensor networks. It splits network into group of sensors that are called zones. The zones are formed by grouping nodes which are geographically close. HPAR benefits from the advantage of taking transmission power into account as well as the residual energy level of nodes in the path. It also maintains a large number of nodes in zones; however, has low scalability and does not support mobility. It uses the shortest path with a view to total energy consumption as the routing metric. It is categorised as a robust routing protocol; however, its drawback is the requirement to create more overhead to find power consumption in the paths [43].

Sleep/Wake Scheduling Protocol (SWSP) [70] is an energy-aware routing protocol that saves energy by switching off the radio module when not in use and turns it on only before transmitting or receiving a message. The sending and receiving time periods are scheduled by neighbouring nodes. Synchronisation is a big challenge in this protocol as both nodes which want to exchange the message should wake up at the same time otherwise the communication fail. SWSP significantly increases network life-time and it is a suitable routing protocol for low-energy power systems. It has a satisfactory level in term of scalability; however, with no supporting mobility in base-stations or even in nodes. It selects the best route in routing metric and has a limited robustness rate. Its drawbacks are in the synchronisation mechanism and scheduling and these challenges affect the overall performance of the system [43].

Grid Based Data Dissemination (GBDD) [71] is an energy-aware routing protocol for wireless sensor networks. In TTDD, nodes start to initiate the structure of a cluster; however, in GBDD the Sink constructs the network and defines the clusters in the grid by sending and receiving the first messages. GBDD is a routing protocol that guarantees the sending of data from source to the sink continuously and has a good rate in scalability with supporting limited mobility. It uses the closest corner node in the case of an existing valid grid in term of routing metrics and has a good rate of robustness. Its drawback is that it consumes more energy when the frequency of data gathering increases [43].

Extending Life-time of Cluster Head (ELCH) [72] is a hybrid routing protocol by combining cluster architecture and multi-hop routing that uses low-energy and increases the life-time of the network. In ELCH, wireless nodes elect the CH by using a voting system. ELCH operates in two phases; in the first phase or setup phase, clusters are formed and CH is selected based on an election. ELCH can achieve minimum energy consumption in terms of data-transmission and benefits from balancing energy efficiency in the whole network. It has limited capability in term of scalability in fixed base-station scenarios. It uses paths with maximum residual energy nodes as a routing metric and has good rate of robustness [43].

Novel Hierarchical Routing Protocol Algorithm (NHRPA) [73] is a routing protocol for WSNs that takes into account network parameters such as distance of node to the base-station, the node distribution density the residual level of node energy. NHRPA benefits from low power consumption and has a good level of scalability in fixed base-station scenarios. It selects the best path in routing metrics and has good rate of robustness. Its drawback is packet-delivery latency in the whole system [43].

Scaling Hierarchical Power Efficient Routing (SHPER) [74] was proposed for scenarios with a powerful base-station and a set of homogeneous wireless sensors nodes. The nodes are randomly distributed in a certain area. The base-station is normally out of sensing area and uses an unlimited power source it has enough power to transmit with high power. SHPER benefits from balanced energy distribution in the whole network and has good scalability with a fixed base-station. It selects the best path in routing metrics and has a good rate of robustness. Its drawback is that it does not support mobility [43].

Distributed Hierarchical Agglomerative Clustering (DHAC)[75] is a routing protocol for WSN wherein the main concept is that each node forming a cluster need only have a neighbour node; with one neighbour's acknowledgment, one node can form a cluster. DHAC benefits from longer network life-time and has a good rate of scalability. It selects the best path in routing metrics and has a limited rate of robustness. Its drawback is that it suffers from low performance in scenarios when traffic increases to a high level [43].

In summary, there are more types of hierarchical routing for wireless sensor networks such as [76–80]. To provide a view of hierarchical routing protocols, some are more scalable than others such as LEACH, PEGASIS, TEEN, VGA, SWRP, GBDD, NHRPA, SHIPER and DHAC. Regarding the use of greedy routing with the aim of reducing energy consumption in the system, protocols such as PEGASIS, VGA, GBDD, ELCH and TIDD operate with better performance. Some routing protocols operate with more robustness such as LEACH, PEGASIS, TEEN, VGA, SWRP, GBDD, NHRPA, SHPER and DHAC [43].

2.2.2 Communication Model Scheme

The Communication Model Scheme refers to a group of communication-based routing protocols which form a network based on data query and in some scenarios data processing passes to some sensing nodes or intermediate nodes. This category is divided into three sub-categories: query-based, coherent data processing based and negotiation-based routing protocols.

2.2.2.1 Query-based Routing Protocol

Query-based routing protocols work based on data queries that are broadcast by destination nodes. The sensing task is the first task in query-based routing protocols in that the data query disseminates through the entire network. The node that has collected data is matched with the query, the requested data is sent back to the destination node that initiated the query. The query can be in natural language, programming code or high-level query-based languages. For instance, a node may send a query to nodes in the network and ask, *"Is the temperature more than 50 in region A?"* and all nodes have a table that can translate the query to a data structure and respond or retransmit the query [43].

Directed Diffusion (DD) [81] is a query-based routing protocol in which all nodes are query based and can respond to a series of predefined queries. DD has shown that it selects best paths and has the capability of saving and processing queries in the network in terms of using less energy.

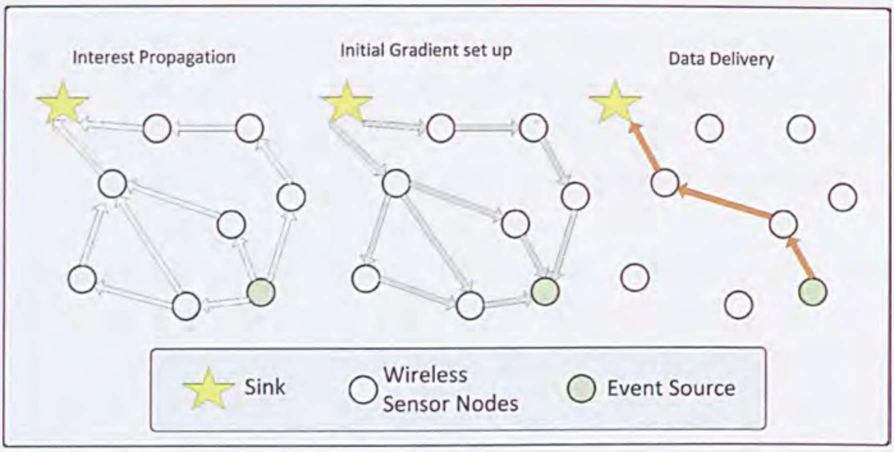

FIGURE 2.3: Directed Diffusion Routing Protocol

Figure 2.3 shows different phases in DD routing protocol. DD operates based on four tasks: Naming, Interests and Gradients, Data Propagation and Reinforcement. The Naming task declares the name of event or other attributes such as data type, maximum or minimum thresholds, and the interval of data-transmission. They are formed as a list of attributes and values in Naming. DD benefits from extending network life-time and it has a good scalability rate with limited mobility support. It uses the best path for routing metrics and is categorised as a low robustness protocol. The weakness of DD is it cannot be used for continuous online data monitoring or event-driven applications [43].

COUGAR [82] is a query-based routing protocol for WSN. It is based on the concept of the data in the network nodes forming a huge distributed database. It uses declarative queries to distribute the processing task between nodes from network layer up to application layer. COUGAR performs with energy efficiency in scenarios with huge data generation. It supports limited scalability in fixed scenarios. It uses the best path for routing metrics and is categorised as a low robustness protocol. The weakness of COUGAR is its overhead and also the complexity of synchronisation in the network [43].

ACtive QUery forwarding In sensoR nEtworks (ACQUIRE) [83] is a query-based routing protocol similar to COUGAR and it considers the network as a huge distributed

database. In ACQUIRE, a complex query splits into several sub queries that can handle by nodes. ACQUIRE is an ideal routing protocol for one-shot and complex query-based scenarios wherein a query can be responded to by sub-query responses. It supports limited scalability with limited mobility. It uses shortest path for routing metrics and is categorised as a low robustness routing protocol. The weakness of ACQUIRE is its overhead, which can be compared with flooding [43].
In summary, DD and COUGAR select the path based on less energy consumption and can only support limited mobility. DD is more scalable than COUGAR. ACQUIRE selects the path based on short path to the destination to save more energy and it is less scalable than DD and COUGAR. Some other protocols can categorised as query-based routing protocols such as RR, SPIN-PP, SPIN-EC, SPIN-BN and SPIN-RL[43].

2.2.2.2 Coherent and Non-Coherent Data Processing-Based Routing Protocols

WSN as distributed data network in some scenarios is required to pass some data processing tasks to nodes to distribute the processing load and balance it within the network. [84] has proposed a routing mechanism for processing data in nodes. The mechanism can be categorised into two routing protocol groups; Coherent and Non-Coherent Data Processing-based Routing [85].
Coherent Data Processing based routings are energy-aware routing protocols for WSN which allow running minimum processing task by sensor nodes such as time stamping and checking duplicated message. The nodes run the tasks with minimum processing effort and then the message is forwarded to the aggregators [43]. Non-Coherent Data Processing based routings allow nodes to process data. Sensor nodes process the collected data locally and then forward them to other nodes for further process. Aggregator is the next node which runs the further process when receiving message from sensor nodes. The processing data takes place in three phases. Phase one is target detection, data collection and processing. In this phase, node detects the target and collects relative and predefined data and then process it based on dedicated task. Phase two is membership, in this phase node chooses and declares its membership and participates in a group task function and declares its task in this corporation to all its neighbours. Phase three is Central-node election that the central node which does more refine processing task in the final processing stage selects between eligible candidates [85].
Single Winner Algorithm (SWE)[86] is a routing protocol that selects an aggregator node as Central Node (CE). CE takes responsibility to do the complex processing tasks. CE is elected based on a comparison mechanism. In this election mechanism, the reserved energy level and computational capacity of nodes and many other properties take into

account to find the best node in the network to run the complex data processing tasks [86].

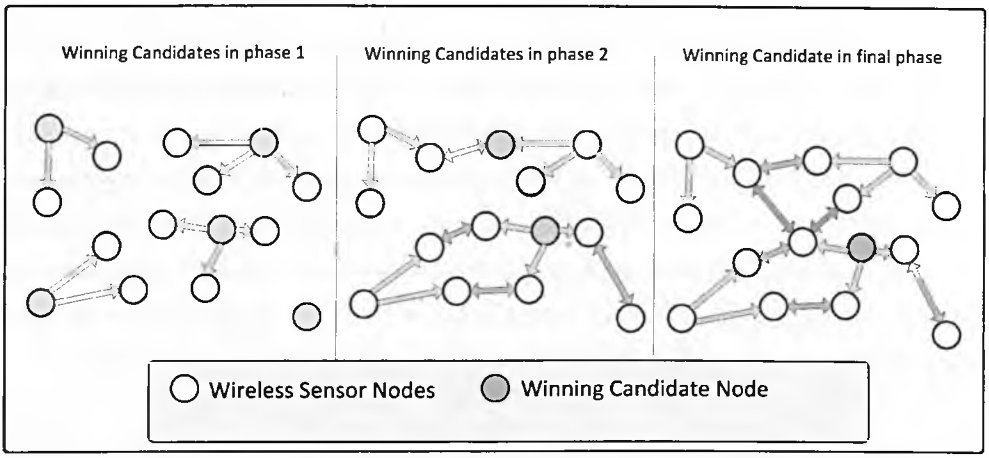

FIGURE 2.4: SWE Routing Protocol - Election Mechanism

Figure 2.4 shows different phases of election mechanism in SWE. It shows how winning candidate is selected from small group of nodes toward whole network. SWE is a routing protocol that builds a minimum-hop spanning tree with reasonable level in scalability with no mobility support. It uses shortest path for routing metrics and categorised as a low robustness routing protocol. The weakness of SWE is its complexity in maintaining the network [43].

Multiple Winner Algorithm (MWE) [86] is a proposed routing protocol that in reality it is an extended version of SWE. SWE defines all nodes as source node and a node as a centre node (CN) and all nodes are allowed to send data to the centre node. This process in SWE uses energy and MWE proposed a mechanism that can save more energy and makes a balance in residual energy in the network. MWE is a routing protocol that each node discovers the best path to each source's node based on minimum energy consumption in each path. It supports low scalability with no mobility and uses shortest path for routing metrics. It is categorised as a low robustness routing protocol. The weakness of MWE is its long message delivery delay and it is not a scalable routing protocol [43].

In Summary SWE and MWE are two routing protocols in this category. SWE is more scalable than MWE and MWE is a more sophisticated routing protocol that computes the paths to source node for each node based on minimum energy consumption.

2.2.2.3 Negotiation-based Routing Protocols

Negotiation-based Routing Protocol uses data centric routing mechanism that is also called Sensor Protocol for Information via Negotiation (SPIN).
SPIN [87] is a Negotiation-based Routing Protocol that designed based on data-centric routing mechanism. SPIN was proposed based on two concepts; first, operates with high performance and low-energy consumption and sensor nodes share data with each other regarding the data they have and the data they have to obtain. Second, nodes are responsible to monitor the energy level in the network to maintain the operability and extending the life-time in the system.

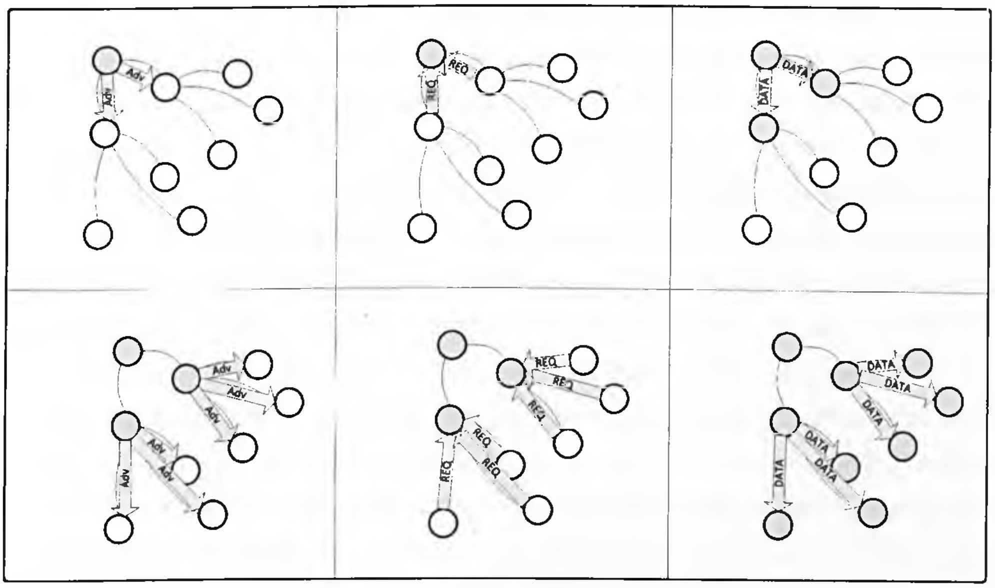

FIGURE 2.5: SPIN Routing Protocol

Figure 2.5 shows different phases in SPIN routing protocol. It shows how the nodes receive and send ADV, REQ and Data-packets in the network. The drawback of SPIN is there is no guarantee for data delivered to all nodes specially if the sensor node and interested node are far or the node between these two is not interested on the data [88].
SPIN for Point to Point Communication (SPIN-PP) [89] is from SPIN family routing protocol that focuses on one-to-one communication technique instead of one-to-many. SPIN-PP is a routing protocol that benefits from simplicity with minimal setup cost and also avoiding implosion. It is in good scalability rate and support mobility. It uses the direct connection to its neighbours in routing protocol and it does not use any routing metrics. It is categorised as a robustness routing protocol. The weakness of SPIN-PP is it does not guarantee the data delivery and consumes unnecessary energy [43].
SPIN with Energy Conservation (SPIN-EC) is an energy-aware version of SPIN-PP that

takes the energy level into account when the node decides to send REQ message. SPIN-EC operates such as SPIN-PP in three stages for advertising, requesting and sending data. When the energy level in node is higher than threshold then SPIN-EC works such as SPIN-PP. When the energy level comes lower than threshold then the nodes does not send any REQ message even when it interests on data [89]. SPIN-EC is a routing protocol that benefits to be used in the energy-aware scenarios. It reduces participation to the data-transmission if the energy level comes lower than threshold. It is scalable and it supports mobility and uses direct connection to its neighbours in routing procedures. It does not use any routing metrics and it categorised as a robustness routing protocol. The weakness of SPIN-EC is it does not support receiving ADV and REQ messages when the energy level of node is less than threshold [43].

SPIN for Broadcast Networks (SPIN-BC) [89] in a broadcast version of SPIN that use broadcast mechanism to send ADV message through the network that uses a shared channel for communication. In SPIN-BC, sensor node sends an ADV message in a broadcast manner and all nodes in radio coverage range receive the ADV message. SPIN-BC is a routing protocol that performs better than SPIN-PP as using broadcast mechanism. It is in good level of scalability and supports mobility and uses direct connection to its neighbours in routing protocol. It does not use any routing metrics and categorised as a robust routing protocol. The weakness of SPIN-BC is it does not respond to REQ message instantly and it should passes a certain period of time to respond [43].

SPIN with Reliability (SPIN-RL) [89] is a reliable version of SPIN-BC that each node keeps records of ADVs from each node and also REQ messages and traces each ADV message to receive at least one REQ message. If within certain period of time, the DATA message has not been received, then the node sends a REQ message again to be sure REQ message was delivered. SPIN-RL traces the ADV and sending data with avoiding to send redundant data; however, if it senses that REQ message has not been delivered, it sends it again to guarantee reliability. It is in a good rate in scalability and support mobility. It uses direct connection to its neighbours in routing protocol and it does not use any routing metrics. It categorised as good robustness rate. The weakness of SPIN-RL is it is time consuming and increases delay in end-to-end packet delivery time period [43].

In summary, SPIN-PP, SPIN-EC, SPIN-BC and SPIN-RL are energy-aware routing protocols with mobility support. These protocols send message if the node has data to send and they minimize energy consumption in the system. The SPIN protocols are scalable and can maintain the network regardless of the size and its performance is not related to the size of the network. Finally they are categorised as robust routing protocols [43].

2.2.3 Technology Based Scheme

Technology Based Scheme is a category of routing protocols which using technologies such Global Positioning System (GPS) to aid protocol to find the best path to the destination in an optimised manner. In this category location based routing protocols and mobile agent based routing protocols are studied.

2.2.3.1 Location Based Routing Protocols

In position-based or location aided routing protocols, it assumes that all nodes in the network know their location and also know about other nodes' location. This kind of routing protocols benefits from influence of physical distance and nodes' distribution into the field in network performance. Location based routing protocols based on two assumed concepts; first, each node knows about its neighbour position. Second, the source node before sending the data to the destination would be informed about position of the destination node. They use HELLO message to exchange neighbours' positions. They are not using a routing table and use positions to send data toward destination through direct neighbours. The drawback of this kind of routing protocols is the performance depends on distribution of nodes and the amount of traffic to exchange.

Distance Routing Effect Algorithm for Mobility (DREAM) [90] is a proactive routing protocol that all nodes keep a table of nodes in the network with their positions. This protocol was designed to fully support mobility and wireless node called Mobile Node (MN). DREAM benefits from efficient data-packet transmission and has limited scalability with good mobility support. It uses minimum power consumption in path as the routing metric and uses control message to maintain the topology. It is categorised as limited robust routing protocol. DREAM has a drawback as it wastes the network bandwidth [43].

Geographic and Energy-aware Routing (GEAR) [91] is a position-based and also energy-aware routing protocol that uses greedy algorithms to forward the message. GEAR uses position and energy level information of neighbours to find the best route to a destination. GEAR benefits from balancing energy level in the network to increase network life-time. It has limited scalability with limited mobility support. It uses the best path as the routing metric and uses HELLO message to maintain the neighbour exchange table and is categorised as a robust routing protocol. Its drawback is it needs to exchange the neighbour's tables periodically and uses bandwidth [43].

Graph EMbedding for routing (GEM)[92] is a position-based routing protocol for wireless sensor network that uses a Unique Identification Number (UIN) for each node in the network. A node in a routing path forwards the message based on the next UIN neighbour that is predefined by the sender. GEM benefits from running with efficient message delivery based on having only neighbours' table and have a good scalability rate with limited mobility support. It uses the shortest path as the routing metric and does not use periodic message to maintain the topology and is categorised as a robust routing protocol. Its drawback is the nodes with close distance to the base-station are overloaded and drain their energy earlier than others[43].

Implicit Geographic Forwarding (IGF)[93] is a state-free, location based and energy-aware routing protocol that uses distance and energy level to select next-hop as a valid receiver in radio transmission rang without having knowledge of nodes in the network. It uses an integrated Network/MAC solution to select the best forwarding node in the neighbours. IGF benefits from robust performance and distributing the workload within the network and has limited scalability with good mobility support. It uses the best route as the routing metric and does not use periodic message to maintain the topology. It is categorised as a robust routing protocol. Its drawback is the performance is depend on local neighbour table that has to be up-to-date [43].

Scalable Energy-efficient Location Aided Routing (SELAR)[94] is a position-based and energy-aware routing protocol for WSNs. It uses the location and also the energy level of neighbours to select the next-hop node. SELAR benefits from selecting the node with higher energy level and it provides uniform energy level dissipation. It supports limited scalability with no mobility support. It uses maximum energy level in neighbours as the routing metric and uses control message to maintain the topology. It is categorised as a robust routing protocol. The disadvantage of SELAR is it does not show good performance in case of nodes' mobility [43].

Greedy Distributed Spanning Tree Routing (GDSTR) [95] is a geographical routing algorithm that routes messages through shortest path by generating less overhead than CLDP. GDSTR benefits from finding the shortest routes and generates low traffic to maintain the topology. It supports limited scalability with no mobility support. It uses shortest path as the routing metric and uses HELLO message to maintain the topology. It is categorised as a robust routing protocol. The disadvantage of GDSTR is its overhead traffic in the network [43].

Minimum Energy Relay Routing (MERR) [96] is a position-based and energy-aware routing protocol. The basic concept of MERR is energy consumption in radio transmission module in energy consumption has the square relation to the distance between transponder and receiver. MERR benefits from providing energy consumption distributed in the network and sensor nodes uniformly consume their energy. It supports limited scalability with low mobility support. It uses minimum energy consumption in the path as the routing metric and does not use control message to maintain the topology. It is categorised as a robust routing protocol. The disadvantage of MERR is it uses more energy in case the nodes are close to each other [43].

On-demand Geographic Forwarding (OGF) [97] is a purely on demand, energy-efficient and position-based routing protocol for delivering data in the large scales in static scenarios within unreliable sensors. OGF is a cross layer algorithm that uses an explicit contention scheme to find the next-hop node in a distributed wireless sensor network. OGF benefits from a superior performance in terms of scalability, energy consumption and void handling. It supports scalability with limited mobility support. It uses the best route as the routing metric and does not use any control message to maintain the topology. It is categorised as a robust routing protocol. Its drawback is its performance depends on up-to-date local neighbour table.

Partial-partition Avoiding Geographical Routing-Mobile (PAGER-M)[98] is a geographical routing protocol for mobile sensor nodes that supports frequently mobility. The protocol uses the information of nodes and base-station to initiate a cost function that is similar to Euclidean length of shortest path. PAGER-M benefits from a superior high delivery ratio, low routing overhead and low-energy consumption. It supports scalability with mobility support. It uses the shortest path and greedy algorithm as the routing metric and uses HELLO message to maintain the topology. It is categorised as a robust routing protocol [43].

Hybrid Geographic Routing (HGR) [99] is a geographical, hybrid and energy-aware routing protocol for wireless sensor network. The geographical routing protocols use distance-based or direction-based strategies to select the next-hop between neighbours. HGR benefits from using combination of distance and direction scheme to select the next-hop in a flexible manner. It supports scalability with mobility. It uses the paths with minimising the total power consumption and does not use control message to maintain the topology. It is categorised as a robust routing protocol. Its drawback is it does not guarantee end-to-end packet delivery time [43].

Dynamic Hybrid Geographic Routing (DHGR) [99] is a dynamic version of HGR that supports quality of service by using more parameters from application layer. In DHGR, packet delivery's decision takes place locally and uses a parameter alpha to adjust decision to reach to QoS level. DHGR benefits from using combination of distance and direction scheme to select the next-hop in a flexible manner and also guarantee the QoS level in application level. It supports scalability and mobility. It uses the paths with minimising the total power consumption and does not use control message to maintain the topology. It is categorised as a robust routing protocol.

In summary, DREAM, IGF, PAGER-M. HGR and DHGR uses lower energy consumption during the operation and also support nodes mobility. GEM and GDSTR uses shortest path for sending data-packet to minimize energy consumption. GEM, IGF, PAGER-M, HGR and DHGR avoid using periodic maintaining network message to minimize energy consumption in the system. GEM, OGF, PAGER-M, HGR and DHGR are more scalable than others protocols in this category. TTDD, COUGAR. ACQUIRE can be categorised in this section; however, they are considered in other categories.

2.2.3.2 Mobile Agent Protocol

Mobile Agent Protocol (MAP) [100] is used for high-level interference and surveillance applications in WSNs where bandwidth and power consumption are the main concerns. MAP employs migrating code to provide re-tasking, local processing, collaborative signal and data processing. MAP adds more flexibility to WSN and makes it capable to operate the conventional tasks based on a client-server computing model. The main attribute of MAP is reducing significant amount of bandwidth by moving the data processing from base-station or a central Sink to sensor area where the main portion of energy consumption in the WSNs is in transmission of raw data. MAP provides a higher degree of re-tasking flexibility and collaborative information processing. MPS not only can work as single processing units; however, also it can form a distributed collection of components that can collaborate to achieve a given task. The core components of MAP are Architecture that can be flat or hierarchical, Agent Corporation that can be single agent or multiple agents, Itinerary planning that can be Static, Dynamic or Hybrid and finally Middleware system that can be fined or coarse grained [43].
The first generation of MAP is Single agent based Itinerary Planning (SIP) that cannot provide good performance in large scale network regarding long delay and unbalanced load distribution. Multi-agent based Itinerary Planning (MIP) [101] is a multi-agent based that cover drawbacks of SIP. MIP benefits from using less energy in large number of nodes scenarios and has limited scalability with good mobility support. It uses minimum power consumption in path in the routing metric and does not use any control message to maintain the topology. It is categorised as a robust routing protocol. MIP has a drawback as it has high delay in end-to-end packet delivery time [43].
Itinerary Energy Minimum for First-source-selection (IEMF) [102] considers data aggregation and energy efficiency in itinerary selection. Itinerary Energy Minimum Algorithm (IEMA) is iterative version of IEMF, during each iteration; IEMA selects the best node based on IEMF as the next source to visit between other source nodes. There is a trade-off between energy efficiency and computational complexity based on application requirements. IEMF and IEMA benefit from optimizing the remaining itinerary to a certain degree and have limited scalability with good mobility support. It uses minimum power consumption in path as the routing metric and does not use control message to maintain the topology. It is categorised as a robust routing protocol. IEMF and IEMA has a drawback as they are not scalable when a large number of source nodes to be visited [43].
Reliable Routing Scheme is a category of routing protocols that using techniques such as multi-path Routing or Quality-of-Service QoS parameters to guarantee packet delivery within certain properties. In this category, two sub-categories as multi-path routing and QoS-based routing are considered.

2.2.3.3 Multi-path Routing Protocols

Multi-path Routing Protocols as it is obvious from the title, they use several paths to send data toward the Sink or destination instead of trusting only one path. The protocols benefit from balancing load in whole network and show more resilient to node failures [103]. The routing protocol in this categories have advantage of lower routing overhead and also lower delay and avoiding congestion in comparison with single-path routing protocols.

Routing On-demand Acyclic Multipath (ROAM) [104] is a distance-vector routing protocol that uses concept of feasible distance to maintain routes and avoids loop in the network. ROAM maintains the network topology by asking nodes to send an update to their neighbours whenever the distance was changed based on a certain threshold. ROAM benefits from avoiding sending packets to unreachable destinations that prevents routers to send unnecessary search packets. It has limited scalability with limited mobility support. It uses any path in routing messages and uses HELLO message to maintain the topology. It is categorised as a limited robust routing protocol. ROAM makes significant amount of overhead as sending HELLO messages to maintain the active nodes [43].

Label-based Multipath Routing (LMR) [105] is a routing protocol for WSNs that broadcasts a message to find the possible alternative path in form of a control message. The recent used paths that deliver the messages are labelled and then this label is used for finding the backup path in case of the best path is not achievable any more. LMR uses localisation information and flooding to discover the topology and reserves several segments to protect current paths. LMR benefits from decreasing network overhead by using label information and also discovers the backup paths. It has good scalability with good mobility support. It uses any path in routing messages and does not use any message to maintain the topology and is categorised as a robust routing protocol. Disadvantage of LMR is it creates overhead for finding possible alternative paths [43].

GRAdient Broadcast (GRAB) [106] is a routing protocol that was proposed for scenarios that need a robust data delivery guarantee within unreliable nodes and weak communication links. GRAB broadcasts advertisement message that contents cost of each node into the whole network. GRAB benefits from the collective efforts of multi path through multiple nodes to deliver data and not trusting only one route with specific nodes. It has a good scalability rate with mobility support. It uses the paths which satisfy the QoS requirements. It uses HELLO message to maintain the topology. It is categorised as a robust routing protocol. GRAB makes a significant amount of over-head for sending redundant data [43].

Hierarchy-Based Multipath Routing Protocol (HMRP) [107] uses a Candidate Information Table (CIT) to keep topology up-to-date. Each node including Sink, broadcasts a layer construction packet and then nodes try to keep own CIT table up-to-date. Each nodes needs to know only the next parent node when decide to send a data-packet. HMRP benefits from scalability, simplicity and increasing system life-time. It is a scalable with low mobility support. It uses any path to rout messages and does not use any message to maintain the topology. It is categorised as limited robust routing protocol. HMRP makes significant over-head for sending construction packet once when the topology starts to form in initiation stage [43].

Cluster-Based Multi-Path Routing (CBMPR) [108] is a hierarchical routing protocol that benefits from both cluster based and multi-path attributes regarding delivering packets with high efficiency. CBMPR uses clustering to find independent multi path toward destination. CBMPR benefits from simplicity and low interference. It has good scalability with low mobility support. It uses the best path in routing messages and uses HELLO messages to maintain the topology. It is categorised as a limited robust routing protocol. CBMPR may suffer from path joining problems [43].

Directional Geographical Routing (DGR)[109] was proposed for delivering real-time video streaming packets through the bandwidth and energy limited networks. DGR delivers packets from a small number of distributed video sensor nodes to a Sink with forwarded error correction (FEC) coding. An active Video sensor Node (VN) broadcasts the video data-packets to its directed neighbours. DGR is a suitable routing protocol for real-time video streaming. It has high level of scalability with no mobility support. It uses paths with different initial direct neighbour in routing messages and does not use any message to maintain the topology. It is categorised as a high robustness routing protocol [43].

Directional Controlled Fusion (DFC) [110] is a multi-path, load balancing and also data fusion routing protocol for WSNs. DFC uses number of multi-path in the topology to achieve specific QoS requirements in various applications. DFC uses multi-path in message delivery to achieve application requirements. It has properties of high scalability with high mobility support. It uses the best path in routing messages and does not use any message to maintain the topology. It is categorised as a robust routing protocol. DFC selects only one source node as reference source per round and it is its disadvantage regarding high risk of failure point [43].

Routing Protocol for Low power and Lossy Networks (RPL) [111] is an IPv6 routing protocol for WSNs that was proposed by ROLL (Routing working group in IETF). Directed Acyclic Graph (DAG) is a directed graph that all nodes in the path are terminated to one or more root nodes and they are loop-free. RPL is a low-energy consumption routing protocol. It has good scalability rate with good mobility support. It uses shortest path in routing messages and uses DIO message to maintain the topology and is categorised as a robust routing protocol. RPL weakness is it only supports unicast traffic [43].

2.2.3.4 QoS-Based Routing Protocol

QoS-Based Routing Protocol balances between energy consumption in the network and QoS requirements at the application level [112, 113]. The network may need to achieve certain QoS metrics such as delay, energy level, bandwidth, etc. In best-effort routing protocols, increasing the throughput and decreasing end-to-end delay are the main concerns. Most of the proposed mechanisms for QoS-based routing for multimedia data in wired based networks are not applicable in wireless communication due to the nature of the media or limited energy sources in the nodes.
Sequential Assignment Routing (SRA)[114] is a QoS-based routing protocol that takes into account application level requirements when taking a decision to deliver a packet. Parameters such as energy resources, QoS on each path and packet properties are taken into account when SAR decides to send a packet. SAR benefits from low power consumption while maintaining multipath to the destination. It has limited scalability with no mobility support. It uses path with minimum average weighted QoS metric, uses HELLO message to maintain the topology and is categorised as a low robust routing protocol. SAR creates overhead in maintaining tables and states at each node and it may need a large memory capacity if the number of nodes goes high [43].
SPEED[115] Protocol is a QoS routing protocol that provides end-to-end, real-time packet delivery guarantee. It also provides congestion avoidance when the network experiences the congestion. Stateless Geographic Non-Deterministic forwarding (SNFG) is the routing module in SPEED. SPEED benefits from good performance in terms of end-to-end delay. It has limited scalability with no mobility support. It uses a path which is geographical stateless, uses HELLO messages to maintain the topology and is categorszed as a low robustness routing protocol. SPEED cannot perform well in heavy congestion scenarios [43].
Multi-Path and Multi-SPEED (MMSPEED) [116] is QoS-based routing protocol designed for probabilistic QoS guarantee in wireless sensor applications. The guarantee can be in two domains, time domain and reliability domain. In time domain, it guarantees end-to-end delay and in reliability domain, it guarantees various reliability requirements by probabilistic multipath forwarding. MMSPEED benefits are QoS guarantees in terms of reliability and end-to-end delay. It has limited scalability with no mobility support. It uses a path that is geographical stateless, uses HELLO messages to maintain topology and is categorised as a low robustness routing protocol. MMSPEED cannot meet the end-to-end delay requirement in a high loaded network [43].
Multimedia Geographic Routing (MGR) [117] is an energy-aware routing protocol for Mobile Multimedia Sensor Networks (MMSN)s where in Mobile Multimedia sensor Node (MMN) is exploited to enhance the capacity for event description. MGR benefits from

minimising energy consumption and guaranteeing end-to-end delay. It is a scalable protocol with good mobility support. It uses the path with minimum delay in routing messages and does not use any message to maintain the topology. It is categorised as a low robustness routing protocol [43].

2.2.3.5 Energy-Aware Routing Protocol

Energy-Aware routing Protocols find the best path through destination based on consuming less energy and using the intermediate nodes which have at least a certain level of energy. Reliable Energy Aware Routing (REAR) has been proposed by Shin et al. [118]to employ multi-path routing mechanism. In REAR, source broadcasts the destination to find out the multi-path and energy-level in each path then it selects the paths with higher energy level to send the packet. Nodes in the selected paths operate as relay nodes. It could extend the network life time but it suffers from unguaranteed end-to-end delay[4]. LQER has been proposed by Chen et al. [119] as a quality estimation routing protocol to performs with better link connectivity and decreasing retransmission cost. It increases the network life time and perform with more reliability and energy efficiency. It makes a connected graph from existing topology before performing the routing operation. LQER could not provide end-to-end packet delivery as a QoS parameter[4].

2.3 Routing Protocol's Link-quality Metrics

Wireless mesh networks consist of wireless nodes in an area where nodes can only communicate directly with others that are within its transmission range. Nodes which need to send information to other nodes outside of their radio frequency coverage uses intermediate nodes to act as routers to receive the information and forward it to other nodes to traverse the network towards the destination [120]. The routing protocol that is used by the network plays a key role in perceived performance and a major part of each routing protocol is the link-metric [121]. The metrics that are used in wired networks cannot be extended to wireless networks because wireless links often have more packets lost than wired networks [122]. Additionally, wireless nodes use the electromagnetic spectrum as its sole medium and all neighbours can cause interference to the communication channel, thus affecting throughput performance when compared with wired networks [122].
Hop-count is the traditional and most popular link-metric in Wireless Mesh Networks (WMN)s. It is simple to calculate; however, link-quality is not taken into account and because that it is not accurate enough to estimate the path cost as the cost is equal to only the total number of routers through the path [123]. To improve metrics in routing

protocols, more parameters such as interface bandwidth or path delay are considered in the calculation to choose the best path and estimate link-quality more accurately. These kinds of routing metrics are categorised as link-quality metrics and examples are ETX[124], Expected Transmission Time (ETT)[125], or Effective Number of Transmission (ENT)[123].

Radio communication is often unpredictable and the properties of a radio channel between two nodes are not constant. Background noise, obstacles, channel fading and interference are some examples that often cause channel qualities to vary with time [123]. Authors in [126] show that the influence of wireless channel characteristics significantly impact performance more than node mobility in a practical environment. They also found that transmission interference behaviour is highly dependent upon wireless link-loss rates [124, 127]. Interference can be *intra-path* interference, where transmissions on different links in a path interfere with one another or *inter-path* interference, which is the result of transmission interference on links in different paths. In Load-dependent metrics [128], the best route is selected based on link-quality and the estimation of traffic load on nodes which participate in the route, while link-quality metrics choose routes based only on the quality of links through the route [128].

Interference in wireless links in an unlicensed spectrum can be *controlled* or *uncontrolled*[129]. When a wireless node uses a channel, the nature of wireless broadcast produces interference to the entire neighbourhood of the nodes that are within signal coverage area. This interference is called *controlled interference*. *Uncontrolled interference* is the result of other equipment that operates in the same frequency band; however, it does not utilise the protocols used in the wireless network. *Uncontrolled interference* can result from a range of devices that operate in the same frequency such as Bluetooth devices or microwave ovens which work in 2.4 GHz [129].

The two main differences make *traffic-aware* routing metrics exhibit better performance than *link-quality based* ones. Firstly, links with higher bit rates have more efficiency than links with lower bit rates. Conversely, nodes that have congested links wherein collisions are prominent have lower performance than other nodes where the wireless medium is under-utilised. Some newly proposed metrics such as Expected Link Performance (ELP)[128], Distribution Based Expected Transmission Count (DBETX)[124] and Expected Available Bandwidth (EAB)[130] have better performance in finding best paths than link-quality metrics. They consider link-quality and also monitor the network for inter- and intra-path interference to recognise busy links and bottlenecks in the network and avoid using them in sending packets to destinations [131].

To increase wireless capacity in the network, two approaches can be selected. Firstly, increasing the data rate in wireless channel that uses a fixed amount of spectrum by improving modulation, modifying antenna and MAC protocols to increase bits/sec/Hz. The second approach involves in each node using a different frequency to communicate with other nodes; thus nodes in same communication area can communicate simultaneously at the same time by utilising different frequencies [129]. For increasing network capacity and reducing interference, multi-radio interfaces were utilised in WMNs by assigning different channels to network access points to support multi transmitting simultaneously in the neighbouring region. In addition, they take advantage of channel diversity for load interference balancing within access points. Real-time monitoring can also be used as a performance enabler to achieve lower end-to-end delay [132]. Metric of Interference and Channel-switching (MIC)[125], Weighted Cumulative ETT (WCETT)[133] and Weighted Hop, spectrum-Awareness and sTability (WHAT)[134] are some metrics that support multi-radio channels in WMNs.

2.3.1 Traditional Routing Metric

Hop-count is the most popular and the IETF standard metric. It is simple to compute by devices that have low resources in Central Processing Unit (CPU), memory or energy level such as Wireless Sensors. This metric avoids any computational burden on devices in calculating the best route to the destination. The path weight is equal to the total number of routers through it. The most traditional routing protocols such as AODV, Dynamic Source Routing (DSR) and Optimised Link State Routing (OLSR) use hop-count to select the best path that does not show best performance in Ad hoc WMN[135]. packet-loss ratio, transmission rate or interference when calculating link-cost are not taken into account [121, 133]. Hop-count is more attractive when computing link-quality is costly such as in networks with high mobility [121]. The hop-count routing metric inherently quantizes the state of a communication link between two nodes as up or down. The other link-quality parameters are not taken into account [123].

2.3.2 Link-quality metrics

Link-quality metrics evaluate the quality of each link in the path and also the cost of each link based on parameters such as bandwidth, packet latency and packet-loss rate. Hop-count as a traditional metric does not consider wireless link-quality. Thus, when using the hop-count metric, a link with high capacity of bandwidth, low packet latency and less interference has equal cost to a link with low bandwidth, high packet latency and high interference levels. The hop-count metric forces the routing protocol to choose the path with fewer hops without considering link-quality of each path, this results of avoiding using a path with a higher number of hops, even though a path may be available with higher hop-count; however, improved total performance along the path.

Expected Transmission Count (ETX)

ETX[124] is calculated based on packet-loss rate that is collected from the MAC layer and is the predicted value of data-transmissions that deliver a packet successfully over a wireless link. ETX is a metric that is calculated by each node for each link. The calculation is based on the probability that packets are successfully transmitted between sender and receiver in a bidirectional manner. Forward delivery ratio or d_f is the probability that a packet is received successfully at the receiver end. The probability that a packet is received successfully at the sender end is called reverse delivery ratio or d_r. Reverse delivery ratio is calculated based on reception of Acknowledgement (ACK) packets that the receiver sends to the sender in order to acknowledge that a packet was successfully received. The probability that a packet is sent to the receiver and a receiver acknowledgment is received by the sender is $d_f * d_r$. ETX is defined as the expected number of transmission for a successful transmission of a packet in one hop as shown in equation

$$p = 1 - (d_f \times d_r) \tag{2.1}$$

$$ETX = \frac{1}{1-p} = \frac{1}{d_f \times d_r} \tag{2.2}$$

ETX sends a small packet with the size of 134 bytes every second and calculates the delivery ratio based on a large window that is typically 10 seconds to dampen variation in the delivery ratio due to interference [128, 136]. D_f and d_r are totally independent and they are affected by forwarding and returning channel specification respectively. ETX combines these two parameters and could be representative of both forwarding and returning channel specifications as one parameter. ETX is the second well known and common metric that is used in many routing protocols. Its calculation is not heavy and it can even be used in low-energy devices such as wireless sensor networks. ETX creates more overhead than hop-count; however, the increase in overhead can be negligible when the associated increase in throughput is considered [121].

ETX calculation is based on small packets and it is possible to degrade the link performance if the packets are significantly large and this is one of the weaknesses of ETX[128]. The main limitation in ETX is not taking into account the asymmetry of traffic on a wireless link. ETX is designed for a single radio with a single channel environment. Also link interference is not taken into account when computing the calculation of this metric.

ETX is suitable for short routes with fewer hops and is not suitable for longer paths because longer paths have multiple links that can transmit concurrently. When reusing

the channel, the actual path cost is lower than the sum of the transmission counts of all links in the path [122]. For this reason ETX does not work properly in longer paths and this makes ETX a more conservative estimate for path cost for paths with more than three to four hops [122].
Authors in [127] show that paths with same sum of ETXs can achieve very different data output rates as the transmission rate in different links is not taken into account [133]. The sum also does not consider the mechanism on MAC back off, and it is not a multi-radio channel support metric [127]. ETX also does not have a mechanism to detect interference that can become a bottleneck in the network [133].

Potential Transmission Count (PTC)
Potential Transmission Count (PTC) was introduced as a metric that is based on the total number of packets transmission and retransmission require in a link to send a packet successfully. PTC is calculated as the inverse of the probability of successful transmission as shown in equation (2.3). It is based on link-layer ACKs in the IEEE802.11 [126].

$$PTC = \frac{1}{d_f * d_r} \tag{2.3}$$

Equation (2.3) shows the calculation of PTC[126]. It has exactly the same pattern as ETX and it was not a novel metric as ETX had been published previously.

Average Expected Transmission count (AETX)
Authors in [13] showed that ETX fluctuation with time affects routing protocol performance and proposed the AETX metric. AETX is based on the last three average of ETX and makes this metric more stable with better performance in the case of topological variations over the channel in the period of channel monitoring. Equation (2.4) shows calculation of AETX[13, 18].

$$AETX = \Big(\sum_{i=n-1}^{n-3} ETX(i) \Big) / 3 \tag{2.4}$$

ETX for multimedia (ETXMulti)
Multimedia traffic accounted for more than 50% of all communication traffic in 2012

and there is a prediction that it will increase to 80% in 2022 [137]. ETX for multimedia (ETXMulti)'s authors in [137] have presented a new routing metric based on ETX to ensure that it finds the best path for multimedia traffic. Real-time multimedia applications do not use Transmission Control Protocol (TCP) for communication and instead use User Datagram Protocol (UDP), which does not use ACK in its mechanism. ETX is based on the probability of successful transmission both ways. UDP protocol only uses one-way communication and ACK is not sent back to sender in the UDP mechanism. ETXMulti was designed for the UDP protocol and takes into account the probability for forwarding packets.

$$ETXMulti = \frac{1}{d_f} \tag{2.5}$$

Equation (2.5) shows ETXMulti calculation where *df* denotes the probability that a packet successfully reaches the next neighbour node [137]. ETXMulti is similar to ETX and has all the same pros and cons.

ETX-Embedded

ETX-Embedded [138] was proposed based on the combination of network topological structure and channel quality. The geographic routing is an ideal approach for routing protocols to find the best path in an end-to-end manner. In geographic routing, it is assumed that a packet can be moved closer to the destination in the network topology if it is moved geographically closer to its destination in physical space [138]. This assumption is correct when the wireless network nodes are distributed uniformly and use wireless channels with perfect transmission status. Sometimes, the geographical routing may lead a packet to a local minimum or low-quality route [138]. ETX-Embedded accurately considers network topology as well as channel quality and make it feasible to run on small nodes such as wireless sensors [138].

ETX-Embedded improves end-to-end routing performance by embedding a wireless network into an Euclidean space, where the virtual distance of each node equal to the ETX or probability that packets are successfully transmitted between sender and receiver [138].

$$\delta(X_i, X_j) = min_{l_i \in L} ETX(l_i) \tag{2.6}$$

Equation (2.6) shows the ETX-Embedded where L is the set of routing paths between nodes X_i, X_j and l_i is the link between nodes X_i and X_j [138]. In a greedily forwarding algorithm, the packet is forwarded to the next hop from the neighbour nodes in which the ETX node summary to the destination is minimised. Assuming we need to send packets from node X_j to X_k and node X_i is an intermediate node from a set of N neighbour nodes, then the intermediate node is chosen by equation (2.7)[138].

$$X_j = arg\ \ min_{X_j \in N}(\delta(X_i, X_j) + \delta(X_j, X_k)) \tag{2.7}$$

To embed a wireless network into a low-dimensional Euclidean space with Multi-Dimentional Scaling (MDS)[139], there is a need to have the measurement of ETX distances between all pairwise nodes in the network. Instead of measuring ETX as a distance between each pair, a set of beacon messages broadcast by a set of reference points is used. Each beacon message is sent with a transmission counter initialised by zero. This transmission counter increases by each transmission or retransmission. Each node finds the smallest transmission count through all received beacon messages and the node can forward its ETX distance to the sampling beacon. In this method, all the beacons are embedded based on measurements between any beacon's pair in the low dimensional space and other nodes can be added according to their relative ETX-distance to the beacons. The accuracy in embedding depends on a sufficient number of beacons that are uniformly distributed such that sampling beacons are fully representative of a network spatial characteristics [138]. ETX-Embedded is an optimal end-to-end routing metrics that causes small overhead and it is a suitable metric for resource-constrained devices in complicated environments.

Statistical Estimate Routing Metric (SERM)

Statistical Estimate Routing Metric (SERM)[140] was published as an ETX-based metric with the aim of working on limited-energy devices with reliable transmission such as wireless sensor networks. SERM is based on the statistical mean of packet reception ratio and also the correlation coefficient of moment estimator [140]. Authors in [140] show $\hat{\rho}(P_{ij}, P_{ji})$ as moment estimator of correlation coefficient for link between nodes i and j, and they show that smaller values of $\hat{\rho}(P_{ij}, P_{ji})$ indicates poor stability of link P_{ij}, P_{ji} and this link is considered not to be used. The equation (2.8) shows the calculation formula of moment estimator of the correlation coefficient [140].

$$\hat{\rho}(P_{ij}, P_{ji}) = \frac{S_{ij}}{(S_i \times S_j)} \tag{2.8}$$

${S_i}^2$ and ${S_j}^2$ are the variance of packet reception ratio for node i and j respectively and S_{ij} is the covariance for the two nodes.

$$S_i^2 = \frac{1}{n}\sum_{K=1}^{n}(P_{Kij} - \bar{P_{ij}}) \tag{2.9}$$

$$S_j{}^2 = \frac{1}{n}\sum_{K=1}^{n}(P_{Kji} - \bar{P_{ji}}) \tag{2.10}$$

$$S_{ij} = \frac{1}{n}\sum_{K=1}^{n}(P_{Kij} - \bar{P_{ij}})(P_{Kji} - \bar{P_{ji}}) \tag{2.11}$$

Equations (2.9), (2.10) and (2.11) show how to calculate SERM where $\bar{P_{ij}}, \bar{P_{ji}}$ are the statistical mean of packet reception ratio for node i and j after n cycles and $S_i{}^2, S_j{}^2$ are the variances of packet reception ratio for two nodes. S_{ij} is variance covariance for the two nodes [140]. SERM is a suitable metric for an environment with instability and also non-symmetry in the links. It was shown that in such environments, SERM performs better than hop-count and ETX[140]. SERM does not need heavy calculation and it is applicable to energy-limited devices.

Expected Forwarding Counter (EFW)

Nodes in WMNs have a tendency to be selfish in order to increase their network utilisation by prioritising their own traffic and dropping selected packets from neighbouring nodes/routers. To cope with this problem, authors in [141] proposed a novel routing metric called EFW. It is a metric with a combination of ETX and forwarding behaviour. To address the selfish behaviour of nodes, the proposed Expected Forwarding Counter (EFW) metric considers the forwarding reliability of relaying nodes in its path calculation. $P_{d.ij}$ denotes the dropping probability of node j and the forwarding probability is calculated $(1 - P_{d.ij})$.

$$EFW = \frac{1}{P_{fwd.ij}} = \frac{1}{(1 - P_{ij}) \times (1 - P_{ji})} \times \frac{1}{(1 - P_{d,ij})} \tag{2.12}$$

Equation (2.12) shows how to calculate EFW where P_{ij}, P_{ji} are packet reception ratios for node i and j in both directions [141]. To calculate EFW, the network topology in a directed graph mode should be kept in memory. However, this results in increased resource consumption and more computational analysis in wireless nodes. It is possible that the forwarding probabilities of two wireless nodes may differ. (i.e. for nodes i , j $P_{fwd,ij} \neq P_{fwd.ji}$); therefore, selecting path for forward and reverse transmission may differ and these affect network performance [141]. To cover these points, two further refinements, Maximum Expected Forwarding Counter (MEFW) and Joint Expected Forwarding Counter (JEFW) are introduced in equations (2.13) and (2.14) that avoid using a link by considering the worst and the joint-dropping behaviour [141].

$$MEFW_{ij} = \frac{1}{(1 - P_{ij}) \times (1 - P_{ji})} \times \frac{1}{(1 - Max(P_{d,ij}, P_{d,ji}))} \tag{2.13}$$

$$JEFW_{ij} = \frac{1}{(1-P_{ij}) \times (1-P_{ji})} \times \frac{1}{(1-P_{d,ij}) \times (1-P_{d,ji})} \tag{2.14}$$

Where P_{ij}, P_{ji} are packet reception ratios for node i and j in both directions and $P_{d,ij}$ is the dropping probability of node j and the forwarding probability is calculated $(1-P_{d,ij})$. MEFW takes into account the maximum dropping probabilities and JEFW considers the cumulative effect of selfish behaviour by multiplying the forwarding probabilities of two nodes [141]. EFW with two alternative refinements (MEFW, JEFW) as a cross-layer routing metric was examined and the results show that it is a suitable routing metric to selects the most reliable path based on the quality of the wireless link. It also considers the forwarding behaviour to increase network throughput and also fairness.

Modified ETX (mETX)

The most popular ETX-based metric is modified ETX (mETX)[123]. It considers significant changes in communication channels during a time period. It considers how time-varying channels affect throughput, and by considering a variety of parameters in the communication channel and taking them into the optimised routing metrics, it can improve communication performance in wireless networks [123]. mETX is based on two parameters, average error probability and the variance of the error probability [123]. $\frac{1}{P_{c,k}}$ is the instantaneous number of transmissions that signifies the number of transmissions for successful reception based on probability of an error-free packet $P_{c,k}$.
It is assumed that $P_{B,t}$ is probability of bits transmitted at time t which are not detected by the intended receiver. t_k is the starting time for transmission of the k^{th} packet and $\eta_{B,t}$ defines as $-log(1-P_{B,t})$ and S is period of observation and by basic algerbra we could show Equations (2.15).

$$P_{B,t} \leq \eta_{B,t} \leq P_{B,t} + \frac{(P_{B,t})^2}{1-(P_{B,t})^2} \tag{2.15}$$

$$P_{B,t} \cong \eta_{B,t} \tag{2.16}$$

Equation (2.16) shows that for all t Thus, $P_{B,t}$ equal to $\eta_{B,t}$ for reasonably small values of $P_{B,t}$.

$$\frac{1}{P_{c,k}} = exp(\sum_{t=t_k}^{t_k+S-1} \eta_{B,t}) \tag{2.17}$$

$$\sum_{k} = \sum_{t=t_k}^{t_k+S-1} \eta_{B,t} \tag{2.18}$$

by assuming Equations (2.17)-(2.18) that show the calculation of $\mu\sum, \sigma_{\Sigma}{}^2$ which are mean and variance of $\sum_k$ respectively and are error probabilities, we can write mETX as equation (2.19) [123].

$$mETX = exp(\mu\Sigma + \frac{1}{2}{\sigma_\Sigma}^2) \tag{2.19}$$

Equation (2.19) shows how to calculate mETXand it is obvious that it is increased by increasing $\mu\Sigma$, which is the average level of the bit error rate probability over a period of time. The variant of the packet delivery is monitored by ${\sigma_\Sigma}^2$ [123].
mETX does not take intra-flow interference into consideration and it is an optimised metric for energy conservative networks such as a wireless sensor. [123] showed that by using mETX, the average packet-loss rate achieved up to 50% better performance than ETX[123].

Effective Number of Transmission (ENT)

ENT[123] is based on the calculation of packet-loss such as ETX and mETX and it considers the visibility of packet-loss for upper-layer protocols such as TCP and also the maximum transmission limits in higher layers. ENT takes M as the maximum limitation of retransmission for the upper-layer in the metric calculation. ENT is an advanced version of mETX. Based on mETX calculation and equations 16-19, the ENT calculation can be given in equation (2.20)[123].

$$\begin{aligned} P(\frac{1}{P_{c,k}} \geq M) &= p(\sum_{t=t_k}^{t_k+S-1} \eta_{B,t} \geq LogM) \\ &\cong exp(-\frac{1}{2}(\frac{LogM - \mu_\Sigma}{\sigma_\Sigma})^2) \end{aligned} \tag{2.20}$$

Where $P_{c,k}$ is probability of an error-free packet, t_k is the starting time for transmission of the k^{th} packet and $\eta_{B,t}$ defines as $-log(1 - P_{B,t})$. S is period of observation and $\mu\sum, {\sigma_\Sigma}^2$ are mean and variance of $\sum_k$ respectively, and are error probabilities. ENT assigns cost of ∞ to the links that have $log(ENT) > log(M)$. ENT is aware of probe size and considers the standard deviation to observe data-transmission variation along with average link-quality; however, intra-flow interference is not taken into account [123].

Expected Transmission Time (ETT)

The motivation behind ETT[125] was to improve ETX by bringing the parameters of transmission rate and packet size into path calculation. The cost of a link is calculated based on MAC layer duration for a successful transmission.

$$ETT = ETX \times \frac{S}{B} \tag{2.21}$$

Equation (2.21) shows calculation of ETT where S is the packet size, B is transmission rate of the link and ETX as it was previously described. The cost of the path is calculated by the summation of the ETTs of the links on the path [125]. ETT just such as ETX is isotonic; another drawback to ETT is that it does not calculate inter-flow and intra-flow interferences and does not have any mechanism to encounter interference that can become a bottleneck in the network [133][125].
ETT is suitable for short routes with fewer hops in the network. It is not suitable for longer paths as longer paths can have multiple links that can transmit concurrently because they are not in same contention domain. In the case of reusing the spatial, the actual path cost is lower than the sum of the transmission counts of all links in the path [125].

Medium Time Metric (MTM)

The traditional routing metric such as hop-count is used in single rate networks; however, Medium Time Metric (MTM)[142] was designed for use in multiple transmission rates networks. MTM can be calculated on below:

$$MTM(_{ij}, p) = \sum_{\forall e \in \pi_{ij}} \tau(e, p) \tag{2.22}$$

Equation (2.22) shows the calculation of MTM where $\tau(e, p)$ is the time required to transit a packet p over edge e. $\tau(e, p)$ takes into account the overhead that include contention, headers and multiple frame exchanges. π_{ij} is path for packet p. MTM finds paths with the minimum total transmission time and it simultaneously optimises the usage of the medium by maximising end-to-end path capacity [142]. MTM increases path capacity by minimising medium time consumption. Maximising residual capacity available to other flows minimizes medium time consumption. MTM avoids to prone to oscillating by tracking path capacity. Path capacity is opposed the path utilisation and using it increases path elasticity in case of mobility [142].

$$\tau(e, p) = \frac{overhead(e) + \frac{size(p)}{rate(e)}}{reliability(e)} \tag{2.23}$$

Equation (2.23) shows calculation of $\tau(e, p)$ where $overhead(e)$ is the average of overhead per packet including control frames, contention back off and fixed headers. $reliability(e)$ is the fraction of successfully received packets. $rate(e)$ is the selected transmission rate and $size(p)$ is the size of the data payload [142]. In multi-rate networks, long distance link can experience low effective throughput and low reliability as a result of low/weak signal level. MTM has the capability to avoid the use of long distance link, hence it can experience relatively higher throughput and more reliability [142].

Expected Multicast Transmission Time (EMTT)

Expected Multicast Transmission Time (EMTT) was published as a high throughput and reliable multicast metric in multi-rate wireless mesh network. EMTT takes into account the reliability in MAC layer retransmission, transmission rate diversity, link-quality awareness and wireless broadcast services [143]. The end-to-end Packet Delivery Ratio (PDR) is considered in the EMTT calculation for every transmission rate from the sender to the receiver in the next hop. EMTT uses Markov Decision Process (MDP) theory as a model to rate adaptation process, calculate EMTT metric and to determine the optimal rate adaptation policy [143].

Rate adaptation is the first phase of calculating EMTT. In this phase, link-layer acknowledgement mechanism enables the sender to reduce its transmission rate when none of the next hop nodes have received the multicast packets. This is achieved by applying an adaptation scheme based on transmission rate information received [143]. $\Pi_{i,s}$ denotes the best transmission rate for node i in state of S that is subset of next hop receivers R_i of node i. This phase defines a policy to guide the sender to choose the best transmission rate when the process is in a particular state and then in next phase the optimal policy of rate adaptation in different state can be determined in EMTT calculation.

EMTT uses MDP for modelling the sequential decision in rate adaptation process. For each forwarding node in multicast session, it is modelled as a stationary infinite-horizon MDP[143]. The list of actions that each nodes can choose from when making decisions on each MDP states forms a policy. The goal of the MDP is to find the optimum policy to meet the other specifications in the model. The specification of MDP can be termed as a revenue, then MDP optimisation criterion would be maximising the expected total revenue or if it termed as a cost, then it would be minimising the expected total cost [143].

The EMTT of node i at state S, which is the state when none of the nodes has received multicast packets can be calculated as:

$$EMTT_{i,s} = Min_k(C_{k,s} + \sum_{S' \in S} P_{S,K,S'} EMTT_{i,s}) \tag{2.24}$$

$$C_{K,S} = \frac{L}{r_k} \tag{2.25}$$

Equations (2.24)-(2.25) show how to calculate EMTT where L denotes the multicast packet size and r_k denotes the transmission rate in k^{th} transmission, $P_{S,k,S'}$ denotes the probability of k^{th} transmission. EMTT as a multi-rate support metric considers MAC-layer retransmission-based reliability and also link-quality that can effectively reduce the end-to-end latency by increasing packet delivery ratio [143].

Estimated Transmission Time (EstdTT)

[136] used Estimated Transmission Time (EstdTT) for the SrcRR [136] which was a new routing protocol for 802.11 mesh networks. They used an extended version of ETX by predicting the best 802.11 transmission bit rate. The goal of EstdTT was to predict the time that each packet uses the channel and make it busy. The sum of the EstdTT of each link represents the total cost of the route. SrcRR as a routing protocol sends a set of broadcast probes in each node based on all 802.11 bit rates and then predicts the best possible throughput in each link to node's neighbours. EstdTT is calculated based on the highest possible throughput and the delivery probability of ACKs in both directions [136].

$$EstTT = \frac{1}{P(ack) \times r_t} \tag{2.26}$$

$$r_t = max(r_1, r_2, r_{5.5}, r_{11}) \tag{2.27}$$

Equations (2.26) and (2.27) show the calculation of EstdTT where $P(ack)$ is the probability of delivery of ACKs on probe losses in both direction and r_t is the estimated throughput at bit rate of megabit per second. SrcRR sends an average of five probe packets in every 10 seconds in 802.11b standard. One small probe packet at the communication rate of 1 Mbps and one 1500 bytes packet at each 802.11b bit rates (1,2,5.5,11 Mbps) are sent. Each probe packets are sent at independent random intervals in 10 seconds period [136]. EstdTT is very similar to ETT and the only difference is that packet size is not taken into account. The Pros and Cons are similar to ETT.

Weighted Integrated Metrics (WIM)

Weighted Integrated Metrics (WIM)[144] was proposed as a dynamic and generic routing metrics which can be used in a wide range of routing protocols for finding reliable paths with consistent throughput. Authors in [144] claim that this metric performs well in highly unstable wireless networks [144]. WIM employs 4 different metrics and monitors the situation of these metrics in the network. The best values of each 4 metrics are calculated in equation (2.28) and then the margins of each metrics are calculated by equation (2.29).

$$BEST - Value_{ETX|RTT|HC|LT} = \frac{\sum_1^N (ETX|RTT|HC|LT)_i}{N} \tag{2.28}$$

$$MARGIN_{ETX|RTT|HC|LT} = \frac{(BEST-Value_{ETX|RTT|HC|LT})-(ETX|RTT|HC|LT)}{BEST-Value_{ETX|RTT|HC|LT}} \tag{2.29}$$

$$\begin{aligned} BUILD = {} & MARGIN_{ETX} + MARGIN_{RTT} \\ & + MARGIN_{HC} + MARGIN_{LT} \end{aligned} \tag{2.30}$$

Equations (2.29)-(2.30)show how to calculate $BUILD$ where N is the number of entries in the routing table, $BEST-Value$ is calculated for each 4 metrics (ETX, Round-Trip Propagation Time (RTT), Hop-Count (HC) and Life Time (LT)) separately and then replaced the $BEST-value$ to the routing table. For instance, to calculate the $MARGIN$ for RTT, the $BEST-Value$ for RTT is calculated based on RTT values in the routing table. $BUILD$ value shows the best route by calculating $BEST-Value$ and $MARGIN$ of a particular metric. The $MARGIN$ shows how better or worse the metric of a selected route is with regards to the $BEST$ value in the routing table [144]. In another word, WIM uses four metrics and gives each metric the same weight. $BEST-value$ is the average of each metric and $MARGIN$ of each metric is the normalized one to make them four absolute numbers without having any unit then they can be added in $BUILD$. By comparing $BUILD$ in routing table with the new reported one from the discovery route, routing protocol decide to use the new route or use the previous one that was stored in routing table.

Resource-aware Link Quality (RLQ)

Resource-aware Link Quality (RLQ) has been proposed by Gungoe et al. [145] to evaluating the varying wireless channel conditions and operates in heterogeneous environment. This metric considers communication link quality statistics and also the residual energy level of wireless nodes in the path [4].

Summary of Link-Quality Metrics

TABLE 2.1: Link-quality metrics comparison

Metrics Characteristics	ETX	PTC	AETX	ETXMulti	ETX-Emb	SERM	EFW	mETX	ENT	ETT	MTM	EMTT	EstdTT	WIM
Calculation Complexity	2	2	2	2	3	4	3	4	4	3	3	5	3	4
Packet-loss Probability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Link Interface Specification										✓	✓	✓	✓	✓
Bandwidth Aware										✓	✓	✓	✓	
Proble Size									✓	✓	✓	✓	✓	
MAC-Layer Retransmission Value	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Multi-Rate Links Support										✓	✓	✓	✓	
Longer Path Support					✓						✓			
Using MAC-Layer Information	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Selfishment Recognition Facility							✓							
Using Packet-loss Statistic Analysis					✓	✓		✓	✓					
Transmission Delay Aware										✓	✓			✓
Asymmetry Aware in Link														✓

Table 2.1 shows the comparison of different link-quality metrics. The different parameters considered in this table are described below: (*i*) *Calculation Complexity* is the amount of calculation needs for running each metrics. It is from 1 (simple) to 5 (complex) and it is estimated for each metric. (*ii*) *Probability of packet-loss* shows that the metric observes the communication link-quality based on successful communication rate in each link. (*iii*) *Link interface specification* shows which metrics take the characteristic of network interface into account. (*iv*) *Bandwidth aware* shows the metrics which consider the bandwidth of communication channels. (*v*) *Probe size* shows the metrics that take into account the probe size. (*vi*) *Mac-Layer retransmission value* shows the metric that uses the number of retransmission of packets in MAC layer in calculations. (*vii*) *Multi-Rate support* shows the metrics that support network with multi-rate transmission over the channels. (*viii*) *Longer Path Support* shows the metrics that have better performance in running in networks with longer paths. (*ix*) *Using MAC-layer information* shows the metrics that use MAC layer data as a cross layer metrics for collecting information to calculate the metric. (*x*) *Selfishment Recognition Facility* shows the metrics that can consider the nodes that drop others packets and try to increase priority of its own packets to deliver in network. (*xi*) *Packet-loss statistical analysis* shows the metrics that use statistical parameters such as average or variance of packet-loss in each node to select the best path to the destination. (*xii*) *Transmission Delay Aware* considers the metrics that calculate the packet travel time and delay in packet delivery to find the best path. (*xiii*) *Asymmetry in links* shows the metrics that consider link-quality of both side of a link, sending and receiving links separately.

In summary, ETX is the most popular metric after HC that is simplest routing protocol metric and is used when the details of link-quality are not available or it changes too much such as scenarios with nodes mobility. ETX is used in most routing protocols. ETX shows instability in real environment that AETX is the stable version of

ETX. ETXMulti is ETX version for multimedia or in another word it designed for UDP packets. ETX-Embedded is more accurate version of ETX and suits for devices with limited resources such as wireless sensors. SERM is another metric that suits to limited resources' devices as it does not need heavy calculation and has showed that works with better performance than HC and ETX in instability and non-symmetry environments. mETX is another metric that is optimised for WSN and observes channel changes during the time by considering the probability of packet error. EFW covers selfishness nodes issue in networks. ENT uses links with packet lost less than a maximum that was defined in upper-layer. ETT is a light weighted metric that estimates end-to-end delay in the whole path. EstdTT predict the best transmission bit rate and it is similar to ETT. MTM is a metric for multiple transmission rates networks. EMTT is also metric for multi rate networks with focusing on high throughput. WIM compares four metrics (ETX, RTT, HC, LT) and select the best one.

2.3.3 Traffic-aware Metrics

More accurate cost of each link depends on the quality of the link and also other factors such as traffic on communication channels. This traffic can be regarded as the amount of data which passes through this link or other traffic which passes through other links; however, that interference makes neighbouring channels unusable. In this section, metrics that take into account link-quality specification and also traffic on channels are considered.

Distribution Based Expected Transmission count (DBETX)

DBETX[124] is a metric where calculation is based on physical layer measurements, channel information such as level of noise and other local information such as the selected modulation scheme.

DBETX has three goals [124]; firstly, it is to monitor the variations on wireless channel, secondly, it reflects the maximum MAC layer retransmission limit and thirdly, it selects links with lower loss probability [124]. Based on these link measurements, nodes are able to estimate the Probability Density Function (PDF) of the experimented Signal-to-Noise plus Interference Ratio (SNIR). DBETX also has the ability to derive the number of required transmission. It takes the maximum number of MAC-layer retransmission into account and does not choose lossy links as it tries to find routes with lower end-to-end loss rate. DBETX is based on two parameters: Average Number of Transmissions (ANT) and the average availability per used link (defined as $1 - P_{outMAC}$).

$$DBETX(l) = E[ANT](l) \times \frac{1}{1 - P_{out_{MAC}}(l)} \tag{2.31}$$

$$P_{limit} = \frac{1}{MaxRetry} \tag{2.32}$$

$$ANT(x) = \begin{cases} \frac{1}{P_{Suc}(x)} & P_{Suc}(x) > P_{limit} \\ \frac{1}{P_{limit}} & P_{Suc}(x) \leq P_{limit} \end{cases} \tag{2.33}$$

Equations (2.31)-(2.33) show calculation of DBETX where P_{Suc} is the current Success Probability and P_{limit} is Limit Success Probability that is based on maximum MAC layer retransmission. $MaxRetry$ is the maximum MAC layer retransmission limit [124]. DBETX can also be calculated based on expected Bit Error Rate (BER) and expected Packet Error Rate (PER) in selected modulation schemes. Received power noise and Interference Estimation are parameters which is used in the calculation of Link SNIR. BER and PER on selected modulation scheme are also calculated based on Link SNIR.

$$PER(SNR) = 1 - (1 - BER(SNR))^n \tag{2.34}$$

Where n is the average packet length of the network in bit.

$$P_{Suc} = 1 - PER \tag{2.35}$$

$$E[ANT](l) = \sum_{SNIR=0}^{\infty} Prob(SNIR) \times ANT(SNIR) \tag{2.36}$$

Equations (2.35)-(2.36) show how to calculate $E[ANT]$ where Prob(SNIR) is the probability that the link l yields the given SNIR[124]. DBETX does not have the capability to consider longer paths due to lake of mechanism that can calculate the interferences among whole neighbour's links.

Expected Available Bandwidth (EAB)

EAB was proposed to cover the gap of considering links with high communication traffic in previous metrics [130]. EAB claims to provide high throughput and low average end-to-end delay while traffic is high in the network. This metrics takes into account the available bandwidth and successful transmission ratio.

$$AB(l,t) = BW_{total}(l,t) - BW_{occupied}(l,t) \tag{2.37}$$

$$P_{success}(l,t) = d_f(l,t) \times d_r(l,t) \tag{2.38}$$

$$EAB(l,t) = AB(l,t) \times P_{success}(l,t) \tag{2.39}$$

Equation (2.37)-(2.39) show how to calculate EAB where $d_f(l,t)$ is the forward delivery ratio and $d_r(l,t)$ is the reverse packet delivery ratio based on one hop broadcast probe packet. $BW_{total}(l,t)$ is the total assigned bandwidth of an individual link and $BW_{occupied}(l,t)$ is the occupied bandwidth of link l [130].
EAB is very similar to ETX plus it takes into account the available bandwidth. $BW_{occupied}$ considers the bandwidth usage and BW_{total} is the total available bandwidth. EAB is more effective than ETX as the bandwidth takes a role in the cost of each link.

Expected Data Rate (EDR)
Authors in [127] found that transmission interference behaviour is highly dependent on wireless link-loss rates. They have proposed a transmission interference model based on the IEEE 802.11 medium access control protocol. In this model. the transmission contention degree of each link is used as wireless link loss function and also the impact function of wireless link loss on medium access back off and concurrent transmission when two links do not interfere with each other. The aim of this metric is to develop a load insensitive metric. It does not support the dynamic interference on the link which is variable in time [127].
Expected Data Rate (EDR) employs some mechanisms to be used in its calculation. Distribution Coordination Function (DCF) in the IEEE 802.11 standard is used when a node wants to transmit a packet and senses the medium to check if it is free to be utilised for transmission. DCF Inter Frame Space (DIFS) is the time the medium is occupied by a node. Transmission Contention Degree (TCD) of a node is the average time that its outgoing queue is occupied and the link is going to be used. When a packet in a wireless medium is transmitted, it is kept in a system memory as an outgoing queue buffer for possibility that this packet is needed to be retransmitted. It is removed from the buffer only when its acknowledgment is received. The time that the outgoing queue is occupied means the packet is waiting for acknowledgment or needs to be retransmitted because of transmission failure or packet lost. TCD defines the average time an outgoing queue of node that is not empty over a window time.

$$TCD(k+1) = Min(1, TCD(k) \times \frac{E(k+1)}{E(k)}) \tag{2.40}$$

$$I(k) = \sum_{i=n_s}^{n_e} TCD(i) \tag{2.41}$$

Equations (2.40) and (2.41) show how to calculate TCD where $n_s, \cdots, k, \cdots, n_e$ are the links in the path which are within the interference range of link k and $E(k+1)$ and $E(k)$ are ETX value of link $k+1$ and link k respectfully [127].

$$EDR_{init}(k) = \frac{\Gamma}{E(k) \times I(k)} \tag{2.42}$$

Equation (2.42) shows EDR calculation where $E(k)$ denotes the ETX of node k and $I(k)$ denotes the total transmission contention degree of link k. Γ is the ideal maximal data rate of a one-hop link [127]. Then, Relatively Increased Contention Degree (RTCD) was taken into EDR calculation by taking the influence of contention windows size on data rates.

$$RTCD(t_k) = \begin{cases} (\frac{W(k,m)}{W(K+1,m)} - 1) \times TCD(k) & (if P_k \geq P_{K+1}) \\ (\frac{W(k+1,m)}{W(K,m)} - 1) \times TCD(k+1) & (if P_k < P_{K+1}) \end{cases} \tag{2.43}$$

Equation (2.43) shows how to calculate RTCD where P_k and P_{k+1} are loss rates of link k and $k+1$ respectfully and $W(k,m)$ and $W(k+1,m)$ are the average contention window size of nodes k and $k+1$ respectfully [127].

$$I_b = I + \sum i = t_s{}^{t_e} RTCD(i) \tag{2.44}$$

$$EDR = \frac{r\Gamma}{Emax \times I_b} \tag{2.45}$$

Equations (2.44) and (2.45) show the calculation of EDRwhere r denotes the reduction in one-hop link data rate and I_b is the total transmission interference around the highest loss rate link [127]. This new transmission interference model based metric uses an independent loss model and a temporally correlated loss model for simulating wireless link loss. EDR finds high-throughput paths in multi-hop ad hoc wireless networks. Although EDR finds the best paths in the presence of temporally correlated loss, it underestimated the path throughput in some cases and it needs more improvement.

Transmission Failures and Load-Balanced (MF)

Transmission Failures and Load-Balanced Routing Metric (MF)[146] considers transmission failures by employing the IEEE 802.11 back off mechanism. A weighted mechanism is applied such that each link in the whole path has a weight. These weights are used as path metrics and can also be used as a load balancing parameters to balance traffic across the network to avoid creating congestions.

$$B(j) = max \sum_{n \in N_j} (m' - BC_{inj}) \tag{2.46}$$

Equation (2.46) shows $B(j)$ calculation where m' is maximum back off stages that a mesh router undergoes and BC_{inj} is i^{th} back off stage router n on path j, where $i = \{0, 1, 2, .., 7\}$, N_j is set of mesh routers on path j from source to the destination, $j = (1, 2, .., P)$ where P is the possible multiple paths and $B(j)$ is called maximum back off stage value among set of values on multiple paths between each source-destination pair [146].

$$C(j) = max \sum_{e \in E_j} RC_{ej} \tag{2.47}$$

Equation (2.47) shows $C(j)$ calculation where RC_{ej} is the residual capacity of link e on j^{th} path from source to the destination, $e \in E_j$ and E_j is the set of links of path j [146].

$$MF = x \times B(j) + y \times C(j) \tag{2.48}$$

Equation (2.48) shows MF calculation where x, y are adjusted values that determine in the application or apply as constant values. $B(j)$ denotes the degree of reliability and $C(j)$ corresponds to the fulfilment of the user demand. The x, y act as balanced parameters between reliability and demand fulfilment. MF takes into account inter-flow interference, intra-flow interference, quality of link and have the ability to provide load balancing across the network [146].

Expected Link Performance (ELP)

ELP[128] was introduced in order to improve the existing ETX. ELP provides an improvement over ETX by proposing a parameter such as α which gives a weight to forward packets against the backward packets.

$$P_{Success} = \alpha \times d_f(1 - \alpha)d_r \quad 0.5 < \alpha < 1 \tag{2.49}$$

$$ELP_p = \frac{1}{\alpha d_f + (1 - \alpha)d_r} \tag{2.50}$$

Equations (2.49) and (2.50) show the calculation of $P_{Success}$ based on α as a weighted parameter. ELP_p is calculated by equation (2.50)[128]. ELP is a hybrid metric that not only takes into account link-quality; that also tries to improve ETX by giving a weighted parameter to distinguish between sending and receiving packets. It also uses interface information to make it an accurate metric in estimating link performance.

Interference Factor (IF) is a parameter in ELP that estimates the medium congestion around the node. Carrier sensing in the MAC layer gives the estimation of medium congestion. The MAC layer probes the medium periodically around 100 times per second to determine whether the channel is busy or free. The ratio of the number of times that the medium is busy in comparison to the whole windows of observation gives the estimate of the medium congestion. IF is updated every second based on a moving window of the last 10 seconds.

$$IF_A = \frac{Busy_A(Rx) + Busy_A(Tx) + Busy_A(NAV))}{TotalWindowsTime} \tag{2.51}$$

Equation (2.51) shows IF_A calculation where NAV is the channel usage for other nodes communication [128].

$$IF_{AB} = Max(IF_A, IF_B) \tag{2.52}$$

$$ELP_{AB} = \frac{1}{\alpha d_f + (1-\alpha)d_r} \times \frac{Max(IF_A, IF_B)}{1 + Max(IF_A, IF_B)} \tag{2.53}$$

Equations (2.52), (2.53) show how to calculate ELP that uses three different mechanisms to accurately determine the expected link performance. In ELP, cross-layered link interference combines with link-quality information to improve this metric [128]. Although link traffic and link-quality play important roles in ELP calculation, bandwidth as an important resource in wireless communication is not taken into consideration.

Interference and Bandwidth adjusted ETX (IBETX)

Interference and Bandwidth adjusted ETX (IBETX) is a quality link-metric that was proposed for wireless multi-hop networks [121]. IBETX is based on three parameters. Firstly, Expected Link Delivery (ELD) that is based on finding the paths with the least expected number of retransmission, such as ETX. It sends a broadcast packet with size of 143 bytes in every second and the calculation is based on a window of 10 seconds.

$$d_{exp}(mn) = d_f \times d_r \tag{2.54}$$

Equation (2.54) shows $d_{exp}(mn)$ that denotes the number of required retransmissions on a link between nodes m and n. d_f denotes the delivery ratio in forward direction and d_r denotes the delivery ratio in reverse direction. Secondly, Expected Link Bandwidth (ELB) provides the nominal bit rate to find the best path between two nodes among a set of contending links. The nodes can be on a source-destination path P or on a non source-destination path NP; however, in the same contention domain [121].

$$b_{exp}(mn) = \frac{1}{\sum_{i \in P \cap NP} \frac{1}{r_i}} \tag{2.55}$$

Equation (2.55) shows b_{exp} calculation where r_i is the transmission rate of the link i in the domain $(P \cap NP)$, P denotes the source-destination paths and NP denotes to non source-destination paths. b_{exp} encounters the longer paths that are ignored by ETX and other ETX-based metrics [121].

Third is the expected interference of the link that is calculated based on MAC information. DCF periodically probes the MAC to collect the information regarding the times that the link is busy (T_{busy}), time Request To Send (T_{RTS}), time Clear To Send (T_{CTS}), time of receiving packet (T_{R_x}) and time of sending packet (T_{T_x}).

$$i_m = \frac{T_{busy}}{T_t} \quad i_m = \frac{T_{R_x} + T_{RTS} + T_{CTS}}{T_t} \tag{2.56}$$

$$i_n = \frac{T_{T_x} + T_{R_x} + T_{RTS} + T_{CTS}}{T_t} \tag{2.57}$$

$$i_{mn} = Max(i_m, i_n) \quad I_{exp} = \frac{i_{mn}}{(1 + i_{mn})} \tag{2.58}$$

Equations (2.56)-(2.58) show how to calculate I_{exp}. The IBETX is calculated based on three parameters; d_{exp}, b_{exp} and I_{exp} as shown in equations (2.54), (2.55), (2.58) respectively [121].

$$IBEXT = \frac{d_{exp}}{b_{exp}} \times I_{exp} \tag{2.59}$$

Equation (2.59) shows IBETX calculation that as a cross-layer metric, uses the MAC layer information to maximise its throughput. It also avoids increasing the overhead by computational complexities[121]. It finds the quality links from all active links to consider longer paths to give higher throughputs.

Summary of Traffic-Aware Metrics

TABLE 2.2: Traffic-aware metrics comparison

Metrics Characteristics	DBETX	EAB	EDR	MF	ELP	IBETX
Calculation Complexity	4	3	4	3	3	3
Packet-loss Probability	✓	✓	✓	✓	✓	✓
Link Traffice Aware		✓	✓		✓	✓
Bandwidth Aware		✓	✓			✓
Inter-Flow Interference				✓	✓	✓
Intra-Flow Interference		✓	✓	✓	✓	✓
Mac-Layer Retransmission Value	✓	✓	✓	✓	✓	✓
Multi-Rate Links Support		✓	✓			✓
Transmission Contention Degree			✓		✓	
Longer Path Support			✓			
Nominal Bit Rates Aware	✓					✓
SNR & SINR Aware	✓					
Using Mac-Layer Information	✓	✓	✓	✓	✓	✓
Load Balancing Capability				✓		
Asymmetry in Link		✓			✓	

Table 2.2 shows the comparison of different metrics in this category. Most of the essential parameters considered are described in table 2.1. New parameters which were not mentioned in table 2.1 are described below: (*i*) *Link Traffic-aware* is the parameter that shows which metric aware of traffic on the communication links. (*ii*) *Inter-Flow and Intra-Flow* are the parameters that show the metrics that consider interference on the communication channel link. (*iii*) *Transmission Contention Degree* shows the metrics that take into account the amount of communication between the nodes in each link. (*iv*) *Nominal Bit Rate Aware* shows metrics that the value of bit rate is calculated in cost of each path. (*v*) *)SNR and SNIR aware* shows metrics that observe Signal-to-Noise Ratio (SNR), Signal to Interference and Noise Ratio (SINR) and measure them in link-cost. (*vi*) *Load Balancing Capability* shows the metrics that are able to manage load balancing through the network paths.

In summary, DBETX monitors variation on channel and selects paths with lower packet-loss probability. It uses SNIR, BER and PER to calculate link-quality metric. EAB uses ETX properties and bandwidth occupancy. EDR takes into account, packet-loss probability, waiting time in queue and transmission interference. MF uses back off stages for transmission failures and link capacity. ELP uses weighted parameters for forward and backward and interference factor. IBETX is calculated based on interference, bandwidth and packet-loss probability.

2.3.4 Metrics for Multi-channel Networks

Most of the traditional metrics do not support multi-channel networks and they do not provide an acceptable performance in multi-channel environment. Multi-channel metrics should collect information about all links in all channels and also they should take into account the channel switching cost in case of changing the current communication channel.

Exclusive Expected Transmission Time (EETT)

Exclusive Expected Transmission Time (EETT)[133] was published for supporting large-scale multi-radio mesh networks where traffic travels much longer than small scale networks. Channel distributions on long paths make a significant impact on the throughput performance. EETT is an interference aware routing metrics that select multi-channel routes while minimising interference for high end-to-end throughput [133].

$$EETT_i = \sum_{link \quad i \in IS(l)} ETT_i \tag{2.60}$$

Equation (2.60) shows EETT calculation where $IS(l)$ is the interference set of link l [133]. EETT as a routing metric in large-scale multi-radio mesh networks reflects on the intra-flow interference. It calculates the ETT of the links in all channels and selects the best path to the destination based on best throughput. Cost of channel changing is not taken into account and it has also the Pros and Cons of ETT. EETT does not consider the longer paths due to its inability to calculate the interferences within the whole neighbour's links.

Expected ThroughPut (ETP)

Expected ThroughPut (ETP)[122]as a MAC-aware routing metric takes into account the bandwidth sharing mechanism of the IEEE802.11 DCF and considers that slow links may degrade the throughput of neighbouring fast links. ETP calculates the throughput estimation more accurately by considering the bandwidth sharing than previous metrics [122].

$$b_k = \frac{1}{(\sum_{j\in(S_k\cap P)} \frac{1}{r_j})} \qquad ETP(k) = \frac{{P_k}^f \times {P_k}^r}{(\sum_{j\in(S_k\cap P)} \frac{1}{r_j})} \tag{2.61}$$

$$f(P) = min_{k \in P} ETP(k) \tag{2.62}$$

Equations (2.61) and (2.62) show how to calculate ETP where P is candidate path and k is a link in path P. S_k is contention domain on link k or in other word; they are nodes within communication range of this node. $S_k \cap P$ is the set of links on Path P that contend with link k. r_j is the nominal bit rate of link j and b_k is expected bandwidth received by link k. ${P_k}^f$ is packet success probability of link k in forward direction and ${P_k}^r$ is in reverse direction. Finally $f(P)$ is throughput of the link k and routing policy chooses the path with the highest routing metrics to maximize the throughput [122].
ETP is based on measuring link's expected throughput that captures bandwidth sharing mechanism of 802.11 DCF. This mechanism is more accurate than technique used in ETX, ETT and EDR. ETP is more efficient to use spatial through in the long paths than ETX and ETT. ETP is suitable for use in multi-rate and multi-radio networks although it does not have any mechanism to counter interference that causes bottleneck in the network [122].

Interface Delay Aware (IDA)

Interface Delay Aware (IDA)[132] was proposed for multi interface WMNs. IDA takes into account inter-flow and intra-flow interference within two nodes. IDA integrates packet-loss, transmission ratio and transmission delay as a metric to choose the best path. IDA selects the path with minimum interference and transmission delay to forward packets [132].

$$IDA(p) = (\alpha \times ETD(p)) + (\beta \times CLI(p)) + CSLC(p) \tag{2.63}$$

Equation (2.63) shows IDA calculation where $CLI(p)$ is the summation of traffic load transmission time of all interfering neighbours within two hops for each link along path p and $CSLC(p)$ is channel switching load cost. α and β are balanced parameters to adjust the impact of the difference in the magnitude of the three components of IDA[132].

$$ETD(p) = \frac{TD(p)}{(1 - PL(p))} \tag{2.64}$$

Equation (2.64) shows $ETD(p)$ calculation where it is an estimate of end-to-end delay along path p, $TD(p)$ is the transmission delay of a packet along path p and $PL(p)$ is the packet-loss ratio [132]. IDA as a multi-interface and multi-channel routing metric in WMN integrate inter-flow interference, intra-flow interference, transmission delay, packet-loss ratio and transmission rate in a single metric. IDA has the capability of load balancing and significant congestion avoidance [132].

Bottleneck Aware Routing Metric (BATD)

Bottleneck Aware Routing Metric (BATD) takes into account intra-flow interference, link loss rates and diverse data-transmission rates within a path. In this metric, the total transmission delay of each independent channel within one path of the links with the same carrier sense range is measured and the largest amount of the transmission delay is considered as the bottleneck channel in the path.

$$BATD(p) = \begin{cases} max(ETD_1, ETD_{12}, ETD_k) \\ ETD_c = \sum_{i=1}^{N_c} ETT_i \quad 0 \leq c \leq k \end{cases} \tag{2.65}$$

Equation (2.65) shows $BATD$ calculation where k is the number of channels in path p and ETD_c is the expected time transmission delay for channel c on path p. N_c is the number of links on channel c with path p within the same carrier sense range [147]. BATD is very similar to EETT except it has a mechanism to avoid paths with congestion. The largest amount of transmission delay shows paths with congestion and BATD considers them as bottle neck and avoids using those paths.

Improved Bottleneck Aware Transmission Delay (iBATD)

The original BATD metric is based on total transmission delay time in a multi-radio network. The Expected Transmission Delay (ETD) in each channel is computed as the total ETT values of links within the same carrier sense range. The ETT value for each individual link is calculated by $\frac{S}{B}$, where S represents the frame size and B denotes the data rate. As $\frac{S}{B}$ does not take into account the MAC layer overhead along with each packet transmission, the BATD can be improved by Improved Bottleneck Aware Transmission Delay (iBATD)[147] to increase the accuracy by using improved ETT (iETT) value instead of ETT. The iETT calculates the discrepancy of link loss rates within one path including MAC layer overheads in expected packet transmission time. iBATD is also more accurate than BATD in detecting bottleneck links.

$$iBATD(p) = \begin{cases} max(ETD_1, ETD_2, ETD_k) \\ ETD_c = \sum_{i=1}^{N_c} iETT_i \quad 0 \leq c \leq k \end{cases}$$

$$(2.66)$$

Equation (2.66) shows $iBATD(p)$ calculation where k is the number of channels in path p and ETD_c is the expected time transmission delay for channel c on path p. N_c is the number of links on channel c with path p within the same carrier sense range[147].

$$iETT = \sum_{i=1}^{n}(a_i x + b_i) \times (ETX_i) + LID_1 \tag{2.67}$$

Equation (2.67) shows $iETT$ calculation where x is the frame size in byte and a, b are parameters that are calculated based on data rates and MAC layer modulation. LID_1 is an approximate value of the extra delay caused by the discrepancy between the link with the highest loss rate and the link with the lowest loss rate[147].

$$LTD_1 = [max_{1 \leq j \leq n}(P_j) - min_{1 \leq k \leq n}(P_k)] \times (a_j x + b_j) \tag{2.68}$$

Equation (2.68) shows LTD_l calculation where $max(P_j)$ represents the maximum loss rate and $min(P_k)$ stands for minimum loss rate in the entire path within one channel[147]. iBATD as a multi-channel, multi-rate routing metric evaluates the bottleneck transmission time more accurately based on considering the MAC layer overhead and the loss rate discrepancy within one path for each individual non-overlapping channel. iBATD metric shows better performance in average network throughput and reduce average packet latency when compares with BATD[147].

Metric of Interference and Channel-switching (MIC)

MIC[125] calculation is shown in equation (2.69).

$$MIC = \frac{1}{N_n \times min(ETT)} \sum_{i=1}^{N} IRU_i + \sum_{i=1}^{N} CSC_i \tag{2.69}$$

In equation (2.69), N is the number of links in the path, N_n is the total number of nodes in the network and $min(ETT)$ is the minimum ETT which represents the minimum transmission rate of wireless interfaces. IRU is Interference-aware Resource Usage that is calculated based on ETT multiply by number of neighbour and CSC is Channel Switching Cost which is equal to w_1, if the channel is changed or equal to w_2, if the new channel is the same with the previous one[147].

$$IRU_i = ETT_i \times N_i \tag{2.70}$$

$$CSC_i = \begin{cases} w_1 & previous\ node\ channel \neq choosen\ channel \\ w_2 & previous\ node\ channel = choosen\ channel \end{cases}$$

$$0 \leq w1 \leq w2 \tag{2.71}$$

Equations (2.70) and (2.71) show how to calculate IRU_i and also CSC_i where N_i is the number of neighbours link, ETT_l is ETT of each link and IRU means the aggregated channel time of all nodes in the area which are used for transmission[148]. MIC uses the links that use the channel less. By using links with less usage, the inter-flow interference takes into metric calculation. In CSC, if the previous node in routing path use the same channel, the cost is w_2 and if the channel of the current node is different from previous node's channel in routing path, then CSC is equal to w_1. The cost is more if the channel is the same. The protocol chooses the paths with using multiple channels through the route because of avoiding intra-flow interference. MIC takes intra-flow interference into the metric calculation [148]. MIC does not consider the interference of nodes when they are in radio frequency range; however, not in data-transmission range. The interference range is always much larger than the transmission range and this makes MIC less realistic because transmission on a link can makes interference on another link although it is not in its transmission range [148].

Weighted Cumulative ETT (WCETT)

WCETT[133] is one of the routing protocols metric that considers channel diversity in multi-channel networks.

$$WCETT = (1-\alpha)\sum_{i=1}^{N} ETT_i + \alpha max_{i \leq j \leq k}(X_j) \tag{2.72}$$

Equation (2.72) shows WCETT calculation where α is a tunable parameter to balance the weights and X_j is the number of times that channel j is used or experienced intra-flow interference. N is the number of links and K is number of channels. WCETT takes intra-flow interference into account; however, not inter-flow interference [128]. WCETT gives low cost to the paths that use more diversified channels with less intra-flow interference [125]. It also does not calculate the minimum path cost as this metric is not isotonic and it makes WCETT unusable in link-state routing protocols. It can be used in Link-Quality Source Routing (LQSR) that is on-demand routing or in other distance vector routing [133].

Weighted Hop, spectrum-Awareness and sTability (WHAT)

WHAT[134] selects high performance end-to-end path in multi-hop cognitive wireless networks [134]. In a cognitive wireless networks, finding a path based on time-varying spectrums and status of primary users is more difficult than traditional networks. WHAT takes into account the opportunistic spectrum access and path stability by synthesizing channel switching frequency, usage of licensed channels and path's length to evaluate the quality in an end- to-end path [134].

WHAT uses three assumptions, first; every node has at least two cognitive radio equipments, one of them is used for control and routing management and the second one is used for data-transmission. The second radio equipment uses all licensed and unlicensed channels. The control radio equipment works on Common Control Channel (CCC) and it is responsible to scan the channels. Second; the system uses a non-interference unlicensed channel for the CCC and N non-interference licensed channels with the same bandwidth for data-transmission. Third; every node has the capability to sense each channel and usage history. Nodes use Cognitive MAC (CMAC) to negotiate channel synchronisation and communication with neighbours. This information from cognitive radios are used in processing of the routing protocols [134].

$$\sqrt{D(U_i)} = \sqrt{\sum_{f}^{f \in S_i} ((P(U_i{}^f) - E(U_i))^2) \times P(U_i{}^f)} \tag{2.73}$$

$$WHAT(L) = \sum_{i}^{i \in L} \frac{1}{(1-\beta) \times \sqrt{D(U_i)} + \beta \times \sum_{f}^{f \in S_{i,j}} p(U_i{}^f) + 1} \tag{2.74}$$

Equations (2.73) and (2.74) show calculation of WHAT that uses a tuning parameter β to weight two parts of equation, standard deviation of a node along a path and the total usage of the licensed channels used in the next hop node along the path. L is set of channels that are available for node i and $S_{i,j}$ is set of licensed channel between nodes i, j and $p(U_i{}^f)$ is the percentage of usage of channel f by node i and $E(U_i)$ is the average usage of channels by node i and $\sqrt{(D(U_i)}$ is standard deviation of all channels that are used by node i, L is end-to-end path [134].

WHAT is based on finding a stable and well-performed path for TCP with isotonicity and monotonicity simultaneously. WHAT observe channel switching frequency, usage of licensed channels, and path length to calculate the overall cost of a path. The results show WHAT can improve TCP throughput significantly [134]. WHAT is compatible with cognitive radio technologies.

Interference Aware Routing Metric (iAWARE)

interference AWARE routing metric (iAWARE)[129] metric was presented to assist routing protocols for multi-radio infrastructure mesh networks where nodes use multiple radio frequency interfaces. By using this metric, the best path is chosen based on reducing inter-flow and intra-flow interferences. This metric aim is to find paths with links that experience low loss ratio, high data rate and low level of interference [129]. The protocol uses links' interference experiences to capture the potential of interference in the network and chose the paths with less interference while improving the overall network throughput [129].

In this model, the communication between node u and v is successful if the SINR at the receiver v is above a certain threshold. The level of threshold depends on channel characteristics, data rate and other transmission parameters. $P_v(u)$ denotes the signal strength of a packet from node u at node v.

$$\frac{P_v(u)}{N + \sum_{w \in V'} P_v(W)} \leq \beta \tag{2.75}$$

Equation (2.75) shows the condition where β is a constant that depends on data rate, channel parameters and modulation schemes [129]. N is background noise, v is the set of nodes which can simultaneously transmit in this metric. Interference ratio IR is calculated by:

$$IR_i(u) = \frac{SINR_i(u)}{SNR_i(u)} \tag{2.76}$$

$$SNR_i(u) = \frac{P_u(v)}{N} \tag{2.77}$$

$$SINR_i(u) = \frac{P_u(v)}{N + \sum_{w \in \eta(u)} \tau(w) P_u(w)} \tag{2.78}$$

Equations (2.76)-(2.78) show IR_i calculation where $\eta(u)$ denotes the set of nodes which node u can receive signal from, $\tau(w)$ is the normalized rate at which node w generate traffic averaged over a period of time. $\tau(w)$ weights the signal strength based on interfering node w. It gives the fraction of time node w use the channel [129].

$$IR_i = min(IR_i(u), IR_i(v)) \tag{2.79}$$

Equation (2.79) shows IR_i calculation where i is bidirectional communication link (u, v) [129].

$$iAWARE_j = \frac{ETT_j}{IR_j} \tag{2.80}$$

$$\begin{aligned} iAWARE(p) = (1-\alpha) \times \sum_{i=1}^{n} iAWARE_i \\ + \alpha \times max_{1 \leq j \leq k} X_j \end{aligned} \tag{2.81}$$

$$X_j = \sum_{conflicting\ link\ i\ on\ link\ j} iAWARE_{i,1 \leq j \leq k} \tag{2.82}$$

Equations (2.80)-(2.82) show iAWARE calculation that as a multi-radio and interference aware routing metric tries to find paths with less inter-flow and intra-flow interferences[129]. The results in [134] show that iAWARE considers changes in interfering traffic thereby delivering higher throughput with better channel diversity. $iAWARE(p)$ is a non-isotonic metric such as WCETTT [129].

Multi Channel Routing (MCR)

Multi-Channel Routing (MCR)[149]has covered the gap of routing metrics for supporting multi-channel and multi-interface networks. It was proposed as a link layer protocol to manage multiple channels over the IEEE 802.11. In multi-interface concept, the available interfaces are classified in two different types; *Fixed interface*, denotes the interface which works in specific fixed channel and *Switchable interface* that can switch between different channels more frequently [149].

MCR selects channel with diverse routes based on taking the interface switching cost into the cost link. MCR is a version of WCETT which was designed for nodes that the number of usage channels is equal to interface number. MCR was designed for the networks where the number of available interfaces may be smaller than available channels and by interface switching, all the channels can be utilised [149].

$$P_s(j) = \sum_{\forall i \neq j} InterFaceUsage(i) \tag{2.83}$$

Equation (2.83) shows P_s calculation where $InterfaceUsage(i)$ is the fraction of time that a switchable interface is busy transmitting on channel i [149]. $P_s(j)$ is the probability that the switchable interface is on a different channel ($i \neq j$) when a packet arrives on channel j.

$$SwitchingCost(j) = P_s(j) \times SwitchingDelay \tag{2.84}$$

Where SwitchingDelay is the latency in switching between interfaces.

$$ETT = ETX \times \frac{S}{B} + SwitchingCost(i) \tag{2.85}$$

$$X_j = \sum_{\forall\ i\ such\ that\ i^{th}\ hop\ uses\ channel\ j} ETT_i \tag{2.86}$$

$$MCR = (1 - \alpha) \times \sum_{i=1} nETT_i + \alpha \times max_{1 \leq j \leq c} X_j \tag{2.87}$$

Equation (2.84)-(2.87) show MCR calculation where α is a weighting parameter between 0 and 1, n is the number of hops on the path and c is the total number of available channels. MCR is weighted in two part, first part increases the cost by using more hops in the path and second part increases if channel diverse paths are not selected [149]. MCR as a metric for multi-channel, multi-interface networks uses the available channels even if the number of interfaces per host is smaller than the number of available channels. Results in [149] show network capacity can be significantly improved by using MCR.

Cross Layer Interference-Load and Delay Aware (CL-ILD)

Cross Layer Interference-Load and Delay aware (CL-ILD) is a cross layer routing metric that take into the calculation, interference, load and delay for multi-channel WMNs. SNR and SINR are used in interference model in links in WMNs [150].

$$CL - ILD(p) = \alpha \times \sum_{linkl \in p}^{n} INLD_i + \beta \times \sum_{nodej \in p}^{n} CD_i \tag{2.88}$$

Equation (2.88) shows $CL - ILD$ calculation where α and β are constant and they are between 0 and 1. n is the number of links and m is the number of nodes in the path p. $INLD$ is the Inter-flow interference Load and Delay component and CD is Channel Diversity that calculated based on intra-flow interference [150].

$$ILD_i = (1 - IR_i \times Cn) + ETT \tag{2.89}$$

where $0 \leq IR_i \leq 1$ and $0 \leq C_n \leq 1$

Equation (2.89) shows ILD calculation where IR_i denotes inter-flow interference based on the ratio of SINR and SNR that the calculation is described in equation (2.90)and Cn denotes Channel utilisation that is describe in equation (2.91). Both IR_i and Cn have values between 0 and 1 [150].

$$IRi = \frac{SINR_i}{SNRi} \tag{2.90}$$

Equation (2.90) shows IRi calculation where based on SINR and SNR values [150].

$$Cn = 1 - \frac{Idletime}{totaltime} \tag{2.91}$$

Equation (2.91) shows Cn calculation where $Idletime$ denotes the time that the channel is not busy and $totaltime$ denotes the time of monitoring channel [150].

$$ETT = ETX \times \frac{S}{B} \tag{2.92}$$

Equation (2.92) shows ETT calculation where ETX is expected number of retransmission, S denotes to packet size and B denotes available bandwidth [150].

$$CD_i = \begin{cases} W_1 & C_{i-1} \neq C_i \\ W_2 & C_{i-1} = C_i \end{cases}$$

$$0 \leq W_1 \leq W_2 \tag{2.93}$$

Equation (2.93) shows CD_i calculation where C_i denotes the channel is used by node i and also C_{i-1} is channel used by node $i-1$ and W_1 and W_2 are the weights [150].

Cumulated Interference Metric (CIM)

Cumulated Interference Metric (CIM)[151] is multi-channel metric that take to account the inter-flow and intra-flow interferences and also link-quality. CIM selects high throughput path with low interferences by using different channels [151].

$$CIM_n(i,j) = ETX(i,j) \times \frac{S}{IBR_n(i,j)} \tag{2.94}$$

Equation (2.94) shows $CIM_n(I,j)$ that is CIM between node i and j in channel n calculation where S denotes the packet size and IBR denotes Interferer-link Bit Rate [151].

$$IBR_n(i,j) = \frac{r_n(i,j)}{|S_n(i,j)|+1} \tag{2.95}$$

Equation (2.95) shows IBR calculation where $r_j(i,j)$ represents the bit rate of the link between nodes i and j in channel n and $S_n(I,j)$ denotes the shared bit rate in channel n [151].

$$X_n = \sum_{link(i,j) \in\ P\ using\ channel\ n} CIM(i,j) \tag{2.96}$$

Equation (2.96) shows X calculation where P is the total path [151].

$$CIM(P) = (1-\beta) \sum_{link(i,j) \in P} CIM(i,j) + \beta max_{I \leq n \leq k} X_n \tag{2.97}$$

Equation (2.97) shows CIM calculation where k is number of channels [151].

Multi-Radio Optimised Link State Routing (MR-OLSR)

Multi-Radio Optimised Link State Routing (MR-OLSR)[152] is a multi-radio or multi-channel optimised link state that is improved version of OLSR. It diverse data traffic through multiple paths to avoid links with congestion and also improve channel throughput substantially. MR-OLSR uses Improved Weighted Culminated Estimate Transfer

Time (IWCETT) as link-quality metric and also by using channel allocation strategy and path scheduling algorithm offers load balancing in multi-channel networks [152].

$$CI = \frac{IFQ_A^j}{B} \tag{2.98}$$

Equation (2.98) shows CI as Congestion Indicator calculation where IFQ_A^j denotes the data queue in the node A on channel j and B denotes the bandwidth [152].

$$CI_{A-B}^j = CI_A^j + CI_B^j + \sum_{W \in (Nb_A) \cup W \in (Nb_B)} CI_W^j \tag{2.99}$$

Equation (2.99) shows CI calculation between nodes A and B where Nb_A denotes neighbours of node A and Nb_B denotes neighbours of node B. W denotes to any nodes that are in neighbours of nodes A and B [152].

$$LL_{A-B}^j = (1-\gamma) \times ETT_{A-B}^j + \gamma \times CI_{A-B}^j \tag{2.100}$$

Equation (2.100) shows LL calculation as Link Load between node A and node B where γ is smooth factor [152].

$$X_j = \sum_{Hop\ i\ in\ channel\ j} LL_i \quad 1 \leq j \leq k \tag{2.101}$$

Equation (2.101) shows X_j as the total of transmission time for multi-hop on channel j calculation where LL_i is link load in node i [152].

$$IWCETT = (1-\beta) \times \sum_{i=1}^{n} LL_i + \beta \times max_{I \leq j \leq k} X_i \tag{2.102}$$

Equation (2.102) shows IWCETT calculation where β is a weighted parameter to make a balance between link load and delay [152].

Summary of Multi-Channel Metrics

Table 2.3 shows the comparison of different multi-channel metrics. Most of the essential parameters considered are described in tables 2.1 and 2.2. New parameters which were not mentioned before are described below: (*i*) *Multi Channel Support* shows the metrics that can be used in multi frequency environment with different interfaces. (*ii*) *Channel Switching Cost* shows the metrics that consider the cost of switching channel in metric calculation. (*iii*) *Interface Switching Cost* shows the metrics that take into account the cost of changing the interface to transmit the packets.

In summary, EETT is an ETT version for multi-channel environments. ETP is more

Table 2.3: Multi-channel metrics comparison

Metrics Characteristics	EETT	ETP	IDAR	BATO	iBATO	MIC	WCETT	WHAT	iAWARE	MCR	CL-ILO	MR-OLSR	CIM
Calculation Complexity	2	4	3	3	3	3	3	3	4	4	4	4	4
Packet-loss Probability	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
Link Interface Specification	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
Link Traffic-aware			✓						✓	✓	✓	✓	✓
Bandwidth Aware	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	
Proble Size	✓			✓	✓	✓	✓			✓	✓		✓
Inter-Flow Interference			✓						✓		✓	✓	✓
Intra-Flow Interference			✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Multi-Channel Support	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Channel Switching Cost						✓		✓		✓			
MAC-Layer Retransmission Value	✓	✓	✓	✓	✓	✓	✓			✓			✓
Multi-Rate Links Support	✓	✓	✓	✓	✓	✓	✓		✓	✓			
Longer Path Support							✓						
Interface Switching Cost			✓			✓				✓			
Nominal Bit Rates Aware		✓											
SNR & SINR Aware									✓		✓		
Using MAC-Layer Information	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
Transmission Delay Aware	✓		✓	✓	✓	✓	✓			✓	✓	✓	

accurate than ETX, EDR and also ETT are based on bandwidth sharing and estimating the throughput. IDA finds best paths based on minimum interference and delay. BATD takes into account interference, link loss rate and transmission delay. iBATD is based on discrepancy of link loss rate and MAC layer overhead. MIC uses ETT and take channel switching cost into the calculation of link-quality metric. WCETT also uses ETT and parameters of channel experience of intra-flow interference. WHAT monitors channel switching frequency and usage of licensed channels. iAWARE uses ETT characteristics and signal strength and background noise by using SNR and SINR. MCR also uses ETT plus interference usage and switching cost. CL-ILD uses delay and load based on intra-flow and inter-flow interferences plus load at MAC layer. MR-OLSR is a multi-channel version of OLSR with load balancing feature that takes into account the link load and also inter-flows interference. CIM chooses the best path based on low inter-flow and intra-flow interferences in different channels.

2.3.5 Conclusion

In this section, most of routing protocol metrics in Wireless Sensor Networks are studied and the specifications of each metrics are described in detail. The metrics in general are considered as link-quality and traffic-aware metrics. In link-quality metrics, mETX is a modified version of ETX that is based on average and variance of the error probability. ENT as the next version of mETX which takes into account the visibility of packet-loss rate for upper-layers protocols are more popular metrics in this category. In traffic-aware metrics, EDR as a load insensitive metric which is based on a transmission interference model in the IEEE 802.11 medium access control protocol and it is used in many routing protocols. In multi-channel networks, iAWARE as a multi-channel metric finds paths with links with low packet-loss ratio, high data rate and low level interference experience. MCR as a version of WCETT is suitable for networks where the number of available interfaces may be smaller than the available channels. WHAT is a metric suitable for cognitive radio environment that selects high performance end-to-end path in multi-hop cognitive wireless mesh networks.

ETX-Embedded, SERM and mETX are suitable metrics for low power devices such as WSN. MTM as a multi-rate metric is a suitable and effective routing metric that avoid long distance paths while ETP is an accurate metric suitable for long paths. IBETX and IDA are more sophisticated metrics that take most of the parameters of link-quality into the calculation of path cost. ETD as multi-channel metrics considers interferences, delay, packet-loss rate and congested path in its calculation and it is more accurate metrics for multi-channel environment.

TABLE 2.4: Metrics comparison

	Hop-Count	ETX	AETX	ETXMulti	ETX-Embeded	BETX	mETX	MTM	PTC	SERM	MF	EETT	EFW	EMTT	ENT	EstdTT	ETT	ETP	WIM	BATD	DBETX	EAB	EDR	ELP	BATD	AWARE	DAR	MCR	MIC	WCETT	WHAT
Calculation Complexity	√																														
Packet loss probability		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√	√	√	
Link Interface Specification												√		√		√									√	√	√				
Link Trafic Aware						√																√	√	√		√	√				
Bandwidth Aware						√		√				√		√		√	√	√		√		√	√		√	√		√	√	√	
Prob Size						√		√				√		√	√	√	√			√					√	√		√	√	√	
Inter-Flow Interference						√					√													√		√	√				
Intra-Flow Interference						√					√									√		√	√	√	√	√	√			√	√
Multi Channel Support																		√		√					√	√	√	√	√	√	√
Channel Switching Cost																												√	√		√
Mac-Layer Retransmission		√	√	√	√	√	√		√	√		√	√	√	√		√	√	√		√	√	√	√		√		√	√	√	
Multi-Rate Links Support						√		√				√		√		√	√	√				√	√			√	√	√	√	√	
Transmission Contention Degree																							√	√							
Longer Path Support					√	√		√															√			√				√	
Interface Switching Cost																											√	√	√		
Nominal Bit Rates Aware						√												√			√					√					
SNR & SINR aware																					√					√					
Using Mac-Layer Information		√	√	√	√	√	√		√	√		√	√	√	√	√	√	√	√		√	√	√	√				√	√	√	√
Load Balancing Capability											√																				
Selfishment Recognition Facility													√																		
Using Packet loss Statistic Analysis							√			√					√																
Transmission Delay Aware												√					√		√	√					√		√	√	√	√	
Asymmetry in Link																								√							

2.4 Localisation in WSN

Location of sensor is one of the critical information that merge with other information which are collected from sensor and together make a proper vision from the point where the sensor was installed. In some scenarios, the sensors are installed manually and location of each sensor is planned in advance. In this case, when the number of sensors turns on, keeping the location of each sensor is a major job. In some scenarios, the wireless sensors are deployed in uncharted area and most of the times it is not possible to find the location of sensors manually. Finding the location of wireless sensors automatically is a need in some scenarios for updating database in case of replacing or changing in sensor networks. Localisation in wireless sensor networks WSN is a new challenge and it is also interesting area for research [153][154]. Finding exact location of wireless sensors need extra device such as GPS module to find their location more accurately and on time. GPS module makes the very tinny wireless sensors more expensive and consumes more energy. Most wireless sensors are battery operator and adding GPS modules decreases their life-time period. In most of the scenarios, life-time is a critical key in application layer, such as deploying wireless sensors in uncharted areas make them infeasible to send somebody for changing their batteries. Wireless sensors are very tinny devices which have limited functionality with limited source of memory and energy. These devices are in sleep mode in most of the time and energy consumption is a major issue in this area. Finding a balance point between huge positioning calculation, energy and other resources consumption are a big challenge in this area [155][156][157].

2.4.1 Location Based Services

Location based services are divided into two different categories, location based applications and location aided network functionality. In location-based applications, the localisation information is used in the application layer, in this case for example temperature sensors which are deployed in a forest shows the temperature of each location. In this application the position information is directly used in the application. In location aided network functionality, the positioning information is used to help the functionality of the network for instance it can be used for routing protocols to aid the routing protocols to find the best route to forward the packets to reach to their destinations. In another case, the localisation can be used in topology control or coverage in the network or many other usages in the network [158][159]. Localisation Methodes:
Physical Measurement:

- 1. Distance measurement is in three methods: a. RSS radio Signal strength b. Time of Arrival (ToA) c. Time difference of arrival (TDoA)
- 2. Angle Measurement
- 3. Area Measurement: a. Single Reference Area Estimation b. Multireference Area Estimation
- 4. Hop-count Measurement
- 5. Neighbourhood measurement

Location Aided Network functions are used for: a. Routing Protocols b. Topology control c. Coverage area d. Boundary detection e. Clustering the networks Local Positioning System (LPS) are used by employing technologies such as Bluetooth or WiFi to find local position in the building

2.4.2 Localisation in WSN

Localisation methods are used for several purposes such as physical measurement or in location aided network functions. Localisation in physical measurement can be provided by distance, angle, area, hop-count and neighbourhood measurements. Some techniques can be used for measuring the distance between two wireless nodes. These techniques use the properties of the received signal with the neighbours' information to find the distance between two wireless nodes[160][161][162].

2.4.2.1 RSS Radio Signal Strength

This technique is based on measurement of strength of the signal in the receiver. As when a signal passes through a media, its strength is decreased based on media and the distance that the signal passes.

$$P_r(d) = \left(\frac{\lambda}{4\pi d}\right)^2 P_t Gt Gr[W] \tag{2.103}$$

P_r = Received power in distance d in watt
P_t = Transmit Power in transmitter in watt
Gt, Gr = Gain Antennas
λ = Wave length (meter)
It is a condition in this equation that d must be much bigger than λ ($d >> \lambda$) as in the wireless sensor network frequency (from 868 MHz up to 2.4 GHz) the wave length is around 12.3 cm up to 34 cm and the condition can be correct [163][164]. By this

method, we can measure distance between two wireless devices by measuring strength of signal in the receiver and compare it with original signal. Shadowing and reflecting of the signal wave may affects this calculation and decrease accuracy in this calculation. As the shadowing and reflecting are not predictable, by using a model based on log normal distributed random variable [165] provide this formula for distance estimation:

$$P_r(d) = P_0(d_0) - \eta 10 log_{10}(\frac{d}{d_0}) + X_\sigma \tag{2.104}$$

Where : $Pr(d)$ = Received power at distance d
η = Path Loss exponent
X_σ =X_σ is a zero mean Gaussian distributed random variable with standard deviation σ and it accounts for the random effect of shadowing
Maximum likelihood estimation for distance based on a known path loss exponent is:

$$\hat{d} = d_0 \left(\frac{P_r}{P_{0(d_0)}} \right)^{\frac{-1}{\eta}} \tag{2.105}$$

And ground distance can formulate as:

$$\hat{d} = d10 \frac{-X_e}{10\eta} = de^\alpha \frac{X_e}{\eta} \alpha = \frac{ln10}{10} \tag{2.106}$$

Environment properties such as temperature, humidity and also rain, snow or fog can affect the speed of signal and distance calculation. Also other geographical obstacle can affect signal speed and distance calculation. Regarding the cost and energy consumption, this solution can make a reasonable estimation of distance between two wireless devices [166][167].

2.4.2.2 Time of Arrival (ToA)

This method can be implemented in two-ways, One-way and round-trip propagation time estimate. In One-way propagation time estimate, the transmitter sends two different types of signals then the receiver by calculation time slot between receiving two different signals can calculate the distance. Speed of radio frequency is around m/s and the speed of sound signal is around 340 km/h. If we send two different signals in a specific distance then by knowing the speed of these two signals and the travelling time we can calculate distance between transmitter and receiver [168][169].

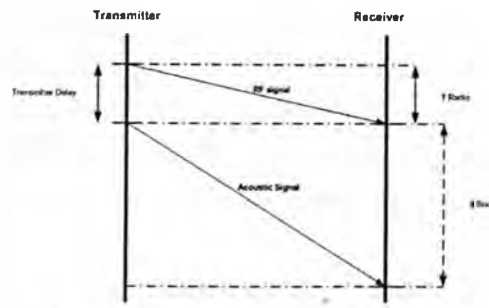

FIGURE 2.6: Time of Arrival Diagram

$$d = Vs \times Ts \tag{2.107}$$

$$d = Vr \times Tr => d = ((Vr \times Vs)/(Vr - Vs))(Ts - Tr) \tag{2.108}$$

$$if Vr >> Vs => d = Vs(Ts - Tr) \tag{2.109}$$

if T$delay = 0$ then

$Ts - Tr$ =the time between receiving RF signal and Sound signal

By assuming the speed of sound and radio signals, by having the travel time, we can calculate the distance between transmitter and receiver. This method has some advantages such as it is not necessary that transmitter and receiver be synchronized and the accuracy of centimetres in distance more than 10 meters [170]. The disadvantage of this methods are both devices need to have two different transmitter and receiver equipment which are operating on different frequency to make them more expensive, complicated and consuming more energy [171].

2.4.2.3 Round-trip propagation time estimation RTT

In this method, only one signal is used and it has advantage from Time of Arrival (ToA) method that two types of sender and receiver are needed in transmitter and receiver nodes. RTT method is used to estimate the distance by sending a signal from transmitter to receiver and then from receiver to transmitter and round trip is completed. By having delays in both sides, it is possible to calculate the distance between sender and receiver.

$$d = v(t1 - t2)/2 \quad and \quad d = v(t3 - t4)/2 \quad or \tag{2.110}$$

$$d = v[(t1 - t2) + (t3 - t4)]/4 \tag{2.111}$$

$$if \quad t2 = 0 \quad and \quad t4 = 0 \quad then \quad d = v(t1 + t3)/4 \tag{2.112}$$

This method does not need for synchronisation between transmitter and receiver and it is one of the benefits from this method. This method does not need to employee any extra devices and it makes this method very attractive regarding cost, complexity and energy consumption.

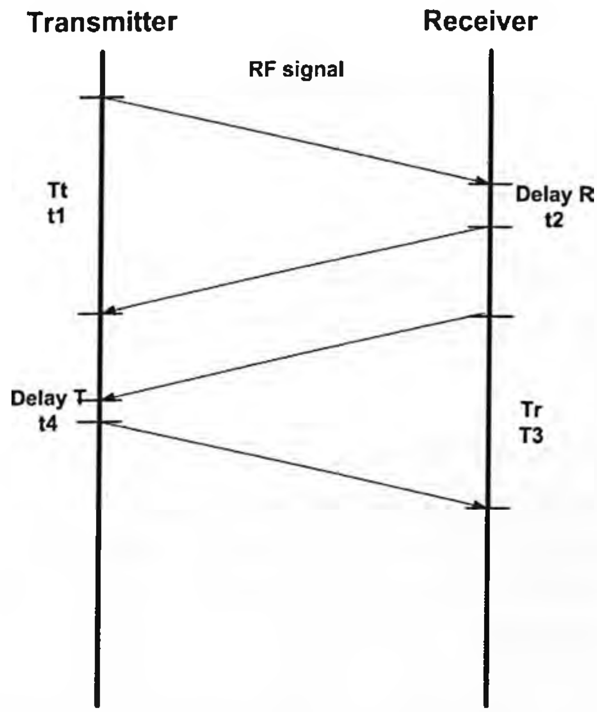

FIGURE 2.7: RTT diagram

The disadvantage of this method is accuracy of this method. The speed of radio signal is related to environment for instance temperature, rain, snow and physical obstacles and it makes the accuracy of this method be depend on media channel environment.

2.4.2.4 Time Difference of Arrival TDoA (Range difference)

This method is used when we have some reference nodes in the range of communication that their location is known. The node sends a signal to all reference nodes and then the distance can be calculated [172].

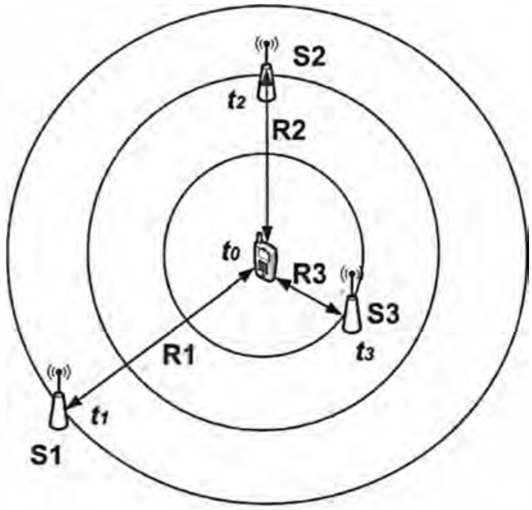

FIGURE 2.8: TDoA method

In Time Different of Arrival (TDoA) figure, S1, S2 and S3 are three nodes that their positions are known and a wireless device that is in communication range of these three devices sends a signal in time t0, node S1 receives the signal in time t1 and the distance with the new device is R1 and node S2 is in distance R2 and receives the signal in time t2 and so on for station S3.

$$\Delta t12 = (t1 - t0) - (t2 - t0) = t1 - t2 = \frac{1}{c}(||r1|| - ||r2||) \tag{2.113}$$

C = speed of the signal and $||ri||$ is Euclidian norm that in three-dimension space it is

$$||ri|| = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2} \tag{2.114}$$

In this method speed of the signal is assumed to be known as a prior. This method has two issues, although synchronisation between transmitter and receivers is not necessary, the synchronisation between receivers is a major factor in this method. Any small difference between current clock in the receivers make a big impact in accuracy as the speed of the signal is a big value and any microsecond fault can make 300,000 meters difference in output [173]. Another issue in this method is signal detection, detection method, SNR and any delay in modules can make a big impact in output. The widely used method to measure the TDoA of a signal in two different receivers is the generalized cross correlation [174]. The signals in two receivers are modelled as:

$$X1(t) = S1(t) + n1(t) \tag{2.115}$$

$$X2(t) = \alpha S1(t + D) + n2(t) \tag{2.116}$$

Where $S1(t)$ is assumed to be uncorrelated with $n1(t)$ and $n2(t)$. D is delay and $X1(t)$ and $X2(t)$ are signals in the receiver 1 and 2τ is estimate of delay and the estimate of the cross correlation is given by:

$$\hat{R}_{x1,x2}(\tau) = \frac{1}{T-\tau}\int_{\tau}^{T} \mathrm{x1(t)x2(t}-\tau)dt \tag{2.117}$$

Where T is observation interval and τ is estimate of delay.

2.4.2.5 Angle Measurement (AoA)

In angle measurement or Angle Location Measurement (AoA) methods, the receiver has different antennas and it can distinguish signal angles and based on these angles it can find its position.

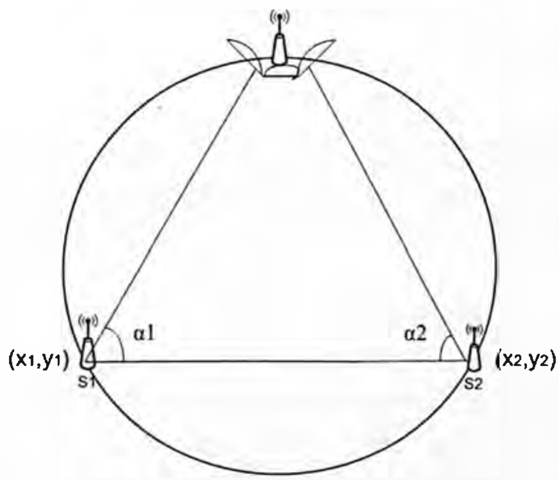

FIGURE 2.9: AoA method

Accuracy of this method is depend on number of directional antenna in the receiver node and any more antennas makes the device more expensive and consumes more energy.

2.4.2.6 Approximate point in triangle (APTI)

Approximate Point in Triangle (APTI) is an approach that works based on triangles calculation rather than signal coverage. This method is based on two stages, stage one is triangle intersection and the next stage is Point in Triangular (PIT) test. Triangles are formed by three arbitrary reference nodes. And then the node distinguish that it is inside the triangle or outside it by PIT test. Once the process is complete, the node decides the centred of the reference triangles that contain itself as its position [175].

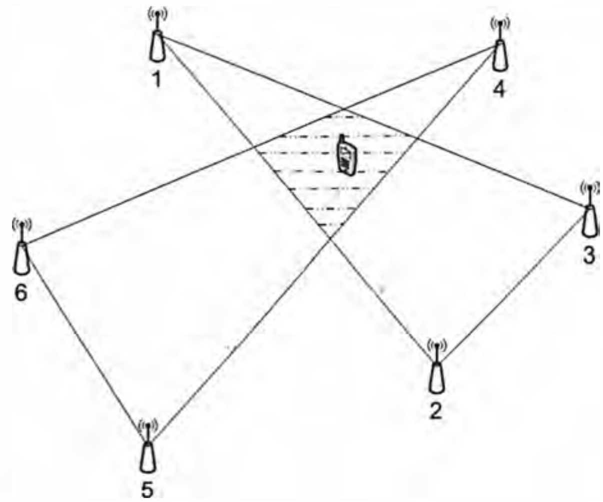

FIGURE 2.10: Approximate point in Triangle (APTI)

2.4.2.7 Hop-count Measurement

In hop-count measurement, the number of hops between sender and receiver is based as hop-count. As each node that is in range of communication with other hop that means the distance between these two hops less than the maximum range of communication.

$$dij = Nhop - count \times dper - hop \tag{2.118}$$

Where dij donate to distance between node i and node j , $Nhop-count$ is the hop-count between node i and node J and $dper - hop$ is average distance between hops.

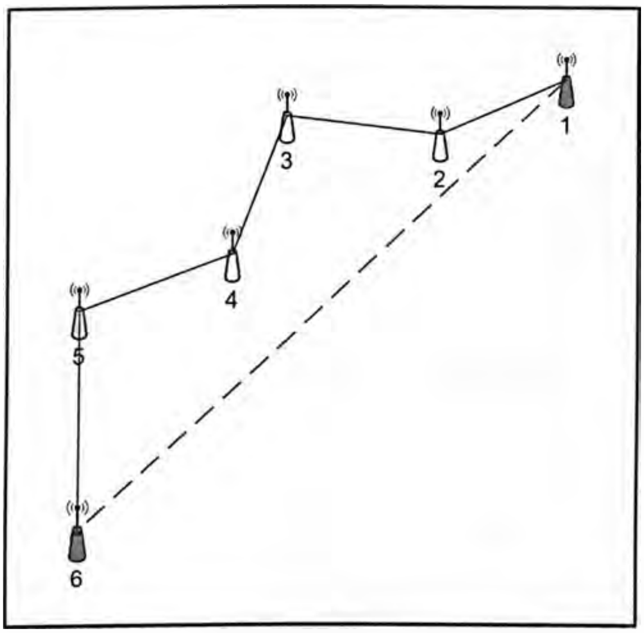

FIGURE 2.11: Hop-count measurement

If node i and j are Sinks and know about their positions and then the actual distance between node i and node j is known and then d-per-hop can be calculated by:

$$dper - hop = \frac{dij}{Nhop - count} \tag{2.119}$$

2.4.2.8 Neighbourhood measurement

Being in the range of radio frequency communication shows that sender and receiver are in a distance less than maximum range of communication. This method is very simple and does not need any additional hardware and it is a cost-effective method. In neighbourhood measurement method, node that its position is unknown uses the information of neighbours that there is at least one that knows its location. In this case the unknown node uses its neighbour position as its. In this case with minimum computation, nodes has a location that accuracy depend on density of known location nodes in the area.

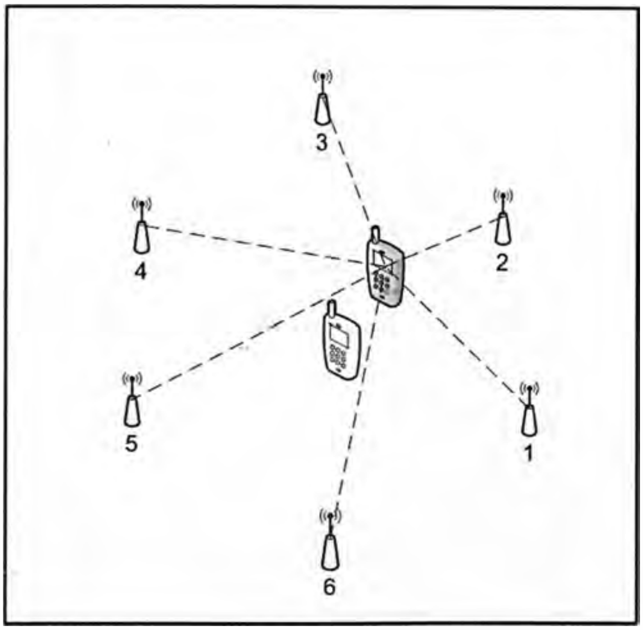

FIGURE 2.12: Neighbourhood measurement

Figure 2.12 shows neighbourhood measurement that an unknown node uses location of 6 neighbours to calculate its location. The fade node picture is representative of calculated position that can be different from actual position. The number of nodes that come to account for node localisation is called k-neighbour proximity [176].

2.4.2.9 Hybrid techniques

Hybrid techniques use more than a technique to increase accuracy in the system. RTT and ToA can be used in a system to calculate distance and decrease the unknown parameters of the channel such as fading, temperature or other parameters. ToA can combain by RTT to make a hybrid technique to calculate the distance with more accuracy.

2.4.3 Localisation Methods in a Glance

Figure 2.13 compares different measurement techniques in three-dimension. Hardware cost, accuracy and computation cost. they are three major parameters that is studied in this research to compare position measurement techniques. AoA and ToA need more expensive hardware than other methods and instead they are in high accuracy area with low computation cost.

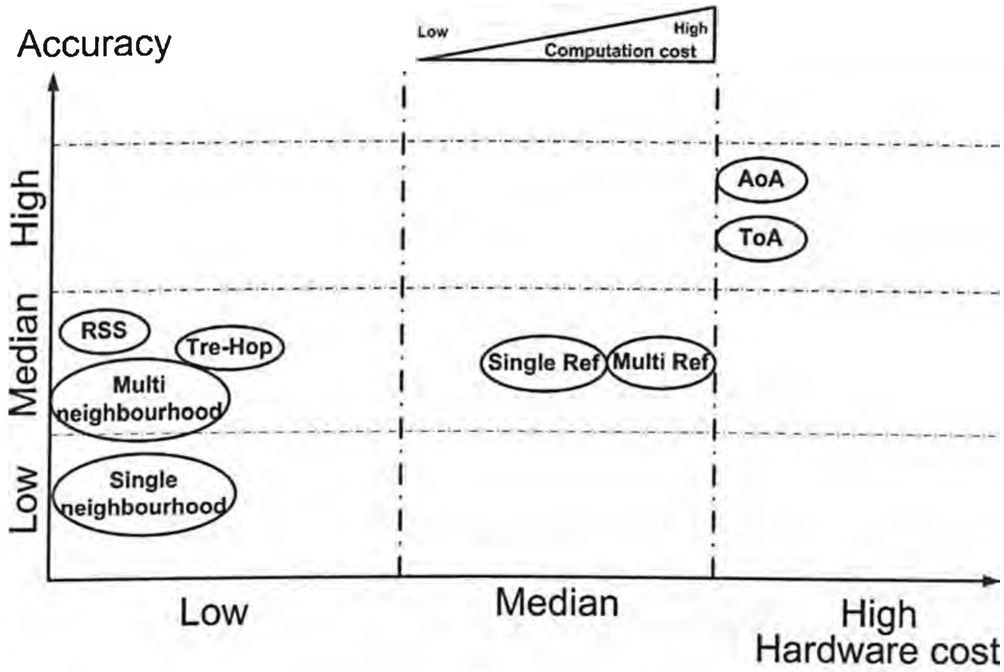

FIGURE 2.13: Distance measurement comparison diagram

2.4.4 Conclusion

This section has presented a survey and taxonomy on measurement techniques for localisation in wireless sensor networks. Advantage and disadvantage of each technique is studied and they are compared in three different directions: accuracy, hardware and computation cost. In the end, hybrid techniques which are used for more accuracy are considered.

Chapter 3

A New Proposed Metric and Deployment Parameters in Wireless Sensor Networks

3.1 AETX: A New Proposed Link-quality Metric

WSN is a communication system of wireless devices that can make a distributed network without the need of pre-existing infrastructure. A WSN must have the ability to work while nodes are mobile and these nodes should co-operate with each other to provide routing services [177]. To use mobile devices in a WSN, it is necessary that the routing protocol cooperatively forwards the packets to the destination by the best route. This cooperative routing behaviour requires substantial processing and signalling resources to operate. Network scalability and dynamism are a big challenge towards calculating the best way sending packet to the destination. Node movement changes the network topology each time and the network should be capable to update information about the dynamic topology within milliseconds[178]. Link-cost is one of the main factors considered by routing algorithms for finding the best routing paths. Hop-count is used as the path cost in distance-vector routing protocols or link-cost in link-state routing protocols. Link-cost in link-state routing protocols in wireless links is not easy to calculate because besides knowing if devices are connected, the quality of communication channel is another important factor that affects calculation of actual link-cost. Expected Transmission count (ETX) is a mechanism to calculate link-cost that is based on link-quality that is deeply considered in the previous chapter. In this chapter a new routing protocol metric is proposed based on observation of ETX behaviour in a real test-bed environment. AETX is a novel metric proposed in this study and it is a new version of ETX that shows better performance based on collected data from a setup test-bed [179].

3.1.1 Methodology

3.1.2 Investigation process

At this stage, in order to study the wireless data communication, two reliable wireless mobile devices are required. The mobile devices were used to test different scenarios in the open space fields. For these experiments, two portable computers with wireless card with 802.11 a/b/g capability were used. Ubuntu 9.10 (Karmic Koala version) was used as operating system on both laptops and OLSRD release 0.6.1 was used as the test routing protocol with ETX link determination preinstalled.

FIGURE 3.1: test environment

3.1.3 Expected Transmission Count (ETX)

Expected Transmission Count or ETX was proposed by De Couto et al as a routing metric in 2004[179]. ETX was described in previous chapter. ETX is defined as one over probability of successful transmission as shown in Equation (3.1):

$$ETX = \frac{1}{(df \times dr)} \tag{3.1}$$

Expected Transmission Time or ETT is another metric that is based on ETX [180]. This parameter estimates the time that it would take to transmit through the link. ETT is calculated by multiplying ETX to the size of packet and finally divided by link capacity. Equation (3.2) shows ETT calculation.

$$ETT = ETX \times \frac{S}{B} \tag{3.2}$$

Where S represents the Size of Packet and B represents channel capacity, ETX which is used in this chapter as link-cost is calculated as in OLSRd [181].

3.1.4 Nature of ETX in the real test-bed

Instability of ETX during the investigation time period is obvious in Figure 3.2. Changing the value of ETX during the investigated time shows that it does not always imply that link-quality between two nodes was changed.

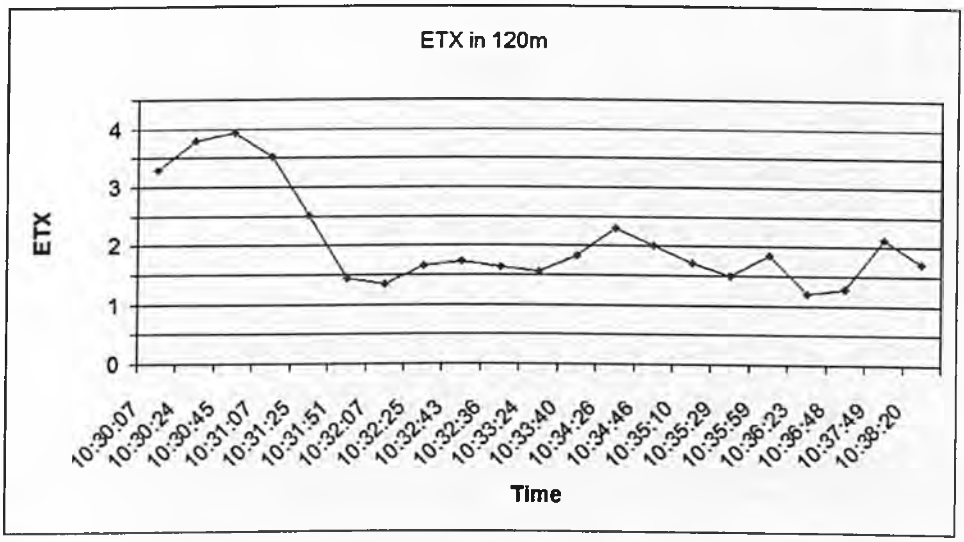

FIGURE 3.2: ETX value in 120m

By studying the results, it can be observed that ETX is not steady during all scenarios. ETX as a link-quality or cost of the link in the routing protocols is changed without any change in the node situation or in topological states. To find the best path to a destination based on this ETX, the routing protocols use different routes with ETX fluctuation however the nodes situation is not changed.

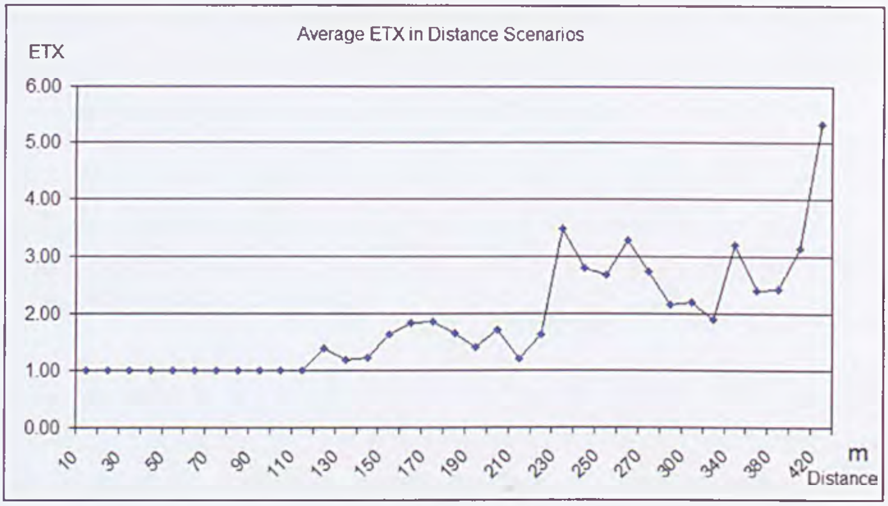

FIGURE 3.3: ETX in Distance Scenarios

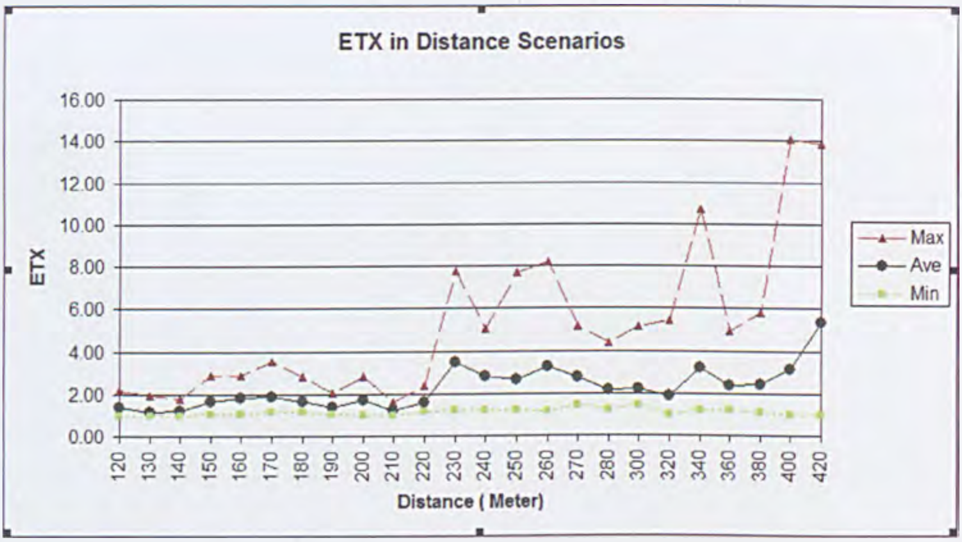

FIGURE 3.4: Max, Min and Ave ETX in Distance Scenarios

3.1.5 Deterministic Model

ETX value is a determined value that shows the probability of successful transmission as a combinational of forwarding and reverse link successful pack delivery rate. This determined value model with proper calculation can provide a close approximation to link-quality metric between two wireless nodes.

3.1.6 Proposed Solution

The first problem to consider is how to use ETX as a link-cost because in this case, the real ETX is not stable and jittery. Thus the routing table would not be able to correctly find the best path. The second problem is as the changes in the ETX value does occur, how actual changes in node position can be correctly identified and factored in the ETX observation. Our solution should therefore provide a parameter that represents link-cost based on ETX while being more stable and also being flexible enough to identify and factor in any changes in the wireless link. These two parameters, stability and flexibility are antagonistic in nature and the best solution is to find a balanced ETX-based link-metric model considering these two factors. After analyzing the graphs in different scenarios, it is obvious that average of previous ETX can be a new solution. Using any more previous ETX in calculating the proposed ETX make it more stable; however, on the other hand make it less flexible in case of the topology changes. The challenge in this research is to find how many of previous ETX values should be factored in proposed ETX calculation to provide a sufficient balance between flexibility and stability of link-metric. At this stage, we should find the balance point between using less numbers of ETX in order to use less computational memory and energy consumption and being more flexible; however, also more stable. Another parameter that we should consider is that the proposed calculation should be close to the real ETX observation. Equation (3.3) shows the utility function that is the goal of this metric. It should minimised fluctuation, difference between new metric and actual ETX and also usage of memory.

$$UtilityFunction = Min(FluctuationFactor; DifferenceFactor; Memoryusage) \tag{3.3}$$

Fluctuation factor (FF) is used as factor that shows how much the ETX change. Calculation of FF factor is shown in Equation (3.4):

$$FF = \frac{\sum_{i=2}^{n}(ETX(i) - ETX(i-1))}{ETX(i) \times (n-1)} \times 100 \tag{3.4}$$

Difference factor (DF) is the factor that shows how much the calculation ETXs have difference with the real ETX. Calculation of this factor is shown in equation (3.5):

$$DF = \frac{(\sum_{i=1}^{n} |(ETX(i) - \frac{\sum_{i=n-1}^{n-m} ETX(i)}{m})|)}{n} \times 100 \tag{3.5}$$

Where n is number of observation and m is number of the last previous ETX. To compare the proposed calculation, a new factor was proposed as DFF that is calculated by equation (3.6):

$$DFF = FF + DF \tag{3.6}$$

TABLE 3.1: DEE and NDFF Results

Number of Average	DFF	NDFF
2	1.91	0.16
3	1.82	0.15
4	1.90	0.16
5	1.98	0.16
6	2.11	0.18
7	2.28	0.19

Equation (3.7) shows calculation of normalized DFF (NDFF) where NFF is normalized FF and NDF is normalized DF by dividing FF and DF by avarage of ETX in each scenarios.

$$NDFF = NFF + NDF \tag{3.7}$$

Table 3.1 shows the result of DFF and NDFF in 6 different ETX proposed calculations. As it is obvious from that table which come out after calculation on row data that are collected from the test field, the three last averages has the best result regarding to the stability and closing to the real ETX as its DFF is smallest and NDFF is the minimum by the value 0.15. In addition, three last averages uses less memory than the other calculations except using two last averages; however, its performance is not better than three last averages. We have called this new ETX calculation as Average-ETX (AETX), as defined in Equation (3.8):

$$AETX = \frac{\sum_{i=n-1}^{n-3} ETX(i)}{3} \tag{3.8}$$

3.1.7 Conclusion

The deployment of wireless sensor networks compared to traditional infrastructure based networks offers several advantages such as fully distributed mobile operation, easy discovery of joining wireless devices and quick cheap network setup. The design of an effective routing protocol is one of the main challenges in the ad-hoc networking paradigm and the utilisation of an adequate link-cost metric is essential. In this research, the validity of ETX (Expected Transmission Count) as a link-cost metric is investigated by studying its behaviour in real-time testbeds. In our performance evaluation, the ETX performance was studied in different distance scenarios. Subsequently, the main observation was that ETX values was not steady over time and usually fluctuated for a fixed scenario. Fluctuation in the ETX values affects a routing protocol in wrongly identifying the best path based on current ETX link-cost and therefore new methods for ETX calculation are proposed in this research. These different methods for ETX link-cost calculation are compared with each other and the best link-cost formula is proposed as a new method for ETX calculation towards the end of the research. The new ETX calculation is called AETX that can be used as a link-cost in routing protocols that reflects the balance required between the consistency of a link-metric value over time for fixed scenarios and the flexibility required to detect actual changes in link-metric values. We finally provide conclusions about our research and some avenues for future work. In this research, ETX as a link-cost routing metric is observed in real test-bed. To have a valid observation, external interference noise minimised as the test were carried in an open stable environment. Even in such a situation, the results show the value of the ETX is not stable during the investigated time period. To improve validity of this research, minimum 16 samples were collected from 24 different scenarios. Moreover in this research, some new ETX calculation techniques were proposed to replace the current ETX protocol as a link-cost. The proposed ETX calculations were compared using parameters defined such as DF (as a difference factor) and FF (as a fluctuation factor) and minimising the nodes memory usage. DF and FF were used to compare the proposed ETX calculations with energy consumption considered as the limiting factor towards optimal link-cost calculation. After careful calculation and comparison, the average of the last three ETXs shows better performance than other proposed ETX calculation. This proposed version of ETX is called AETX.

3.1.8 Future Directions

Future work can be working on ETX calculation to make it more flexible and stable with measuring the link capacity with proper packet size close to MTU size and adding the link speed as the other parameter in link-cost or into the ETX. The future works also can be calculating the cost of the link by parameters such as bandwidth, delay, ETX and jitter with different weights indicating importance of factors as required by different applications. For example, real streaming applications require links with minimum delay and in another case, the bulk transferring data applications care less about delay; however, require better link bandwidth. In future link-cost can be defined as in Equation (3.9):

$$Link - cost = f(Bandwidth, Delay, AETX, Jitter) \tag{3.9}$$

Link-quality metrics can be formed based on application layer and the quality specification that application layer need. Routing protocol can use different metrics based on different type of data-packets. Data-packets for real-time application can route based on link-quality metrics which the delay and jitter accounts and bulk application data-packets are delivered based on link-quality metrics which bandwidth is taken into account.

3.2 Deployment Parameters in Wireless Sensor Networks

The rapid progress of wireless communication and embedded micro cheap technologies have made WSN to be grown up in industries. They are used to monitor environment variables and also are used in automation systems in buildings and factories. ZigBee specification based on the IEEE 802.15.4 was released on December 2004 [182]. ZigBee specification defines application framework, network layer and also security services. ZigBee was defined for low power devices which are limited in recourses and for this reason tree and star network topologies are used. These topologies are self-forming and self-healing and can address up to 65000 nodes [183–186].

Isabella Plantation in Richmond Park was selected as a testing field. Richmond Park is a national nature reserve park in south-west London. It was created by Charles I in 1634 as a deer park and now has over 600 deer. Richmond park is the second largest park in London measuring 3.69 square miles. Isabella Plantation is part of Richmond park that Between 1819 and 1835, Lord Sidmouth, deputy ranger, established it by several new plantations and enclosures and After World War II the existing woodland at the Isabella Plantation was transformed into a stunning woodland garden, and is organically run, resulting in a rich flora and fauna [187].

Deploying wireless sensors to measure the temperature and humidity of soil is important for scientists who study on Isabella Plantation. Deploying randomly sensors in Isabella Plantation makes it a testing field. In this research the effect of different parameters of tree and star topology in random deployment of wireless sensors is studied. Area of study is 967*926 (m) and we study lost nodes in random deployment. The parameters that are studied are Radio Range, Protocol type (star, tree), Maximum Number of children per parents and Number of coordinators.

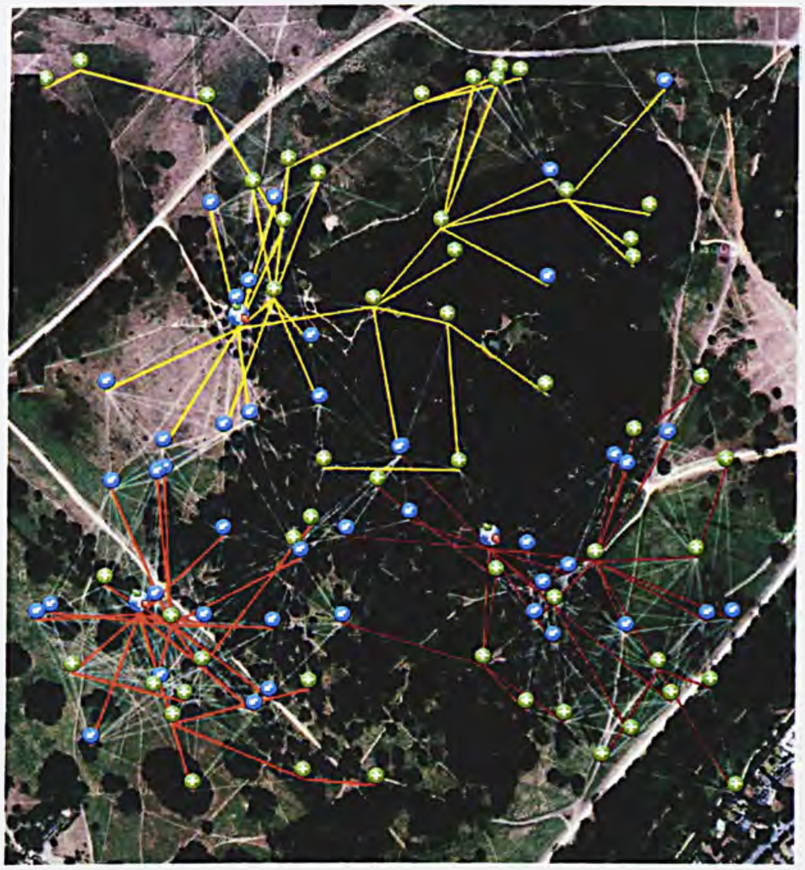

FIGURE 3.5: Random deployment of wireless nodes in Isabella Plantation

3.2.1 System Model

ZigBee uses the IEEE 802.15.4 2003 specification in MAC layer and physical layer. The IEEE 802.15.4 support star, tree, cluster tree, and mesh network topologies [188]. It uses an association hierarchy as a child and parent; a device joining the network can either be a router or an end device, and routers can be as a parent and accept more devices as its child.

3.2.1.1 Star topology

The star topology consists of a coordinator and several nodes which work as end device. In this topology, the end device communicates only with the coordinator. Packets exchange only between end devices and coordinator. The disadvantage of this topology is that the key point of the operation is the coordinator of the network. All packets between devices must go through coordinator and for this reason the coordinator may become a bottleneck and there is no other alternative path from source to destination.

The advantage of star topology is that it is simple to implement and packets travel through at most two hops to reach their destination.

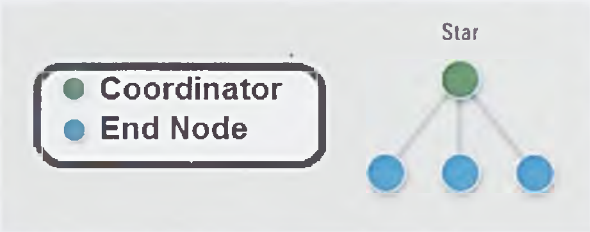

FIGURE 3.6: Star topology

3.2.1.2 Tree topology

In this topology, the network consists of a central node or a root tree, which it is a coordinator, several routers and end devices. The routers nodes extend the network coverage. The end nodes connect to the coordinator or the routers. End nodes act as a child and routers and the coordinator can have children and act such as their parents. Each end device is able to communicate with its parent (router or coordinator) only. An end device cannot have children and, therefore, may not become a parent.

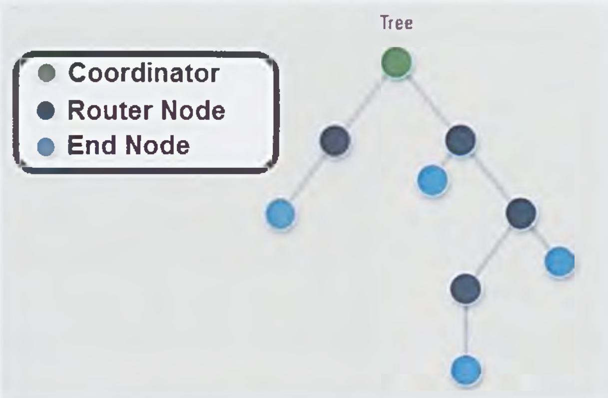

FIGURE 3.7: Tree topology

The advantage of tree topology is that it can extend the network coverage in comparison with the star topology. The disadvantage of tree topology is if one of the parents becomes disabled, the children of the disable parent cannot communicate with other devices in the network. Another weak point is even if two nodes are geographically close to each other, they cannot communicate directly and they should communicate through their parents. A cluster tree topology is a special case of tree topology in which a parent with its children is called a cluster that each cluster is identified by a cluster ID. ZigBee does not support cluster tree topology; however, the IEEE 802.15.4 does [188].

3.2.1.3 Mesh topology

Mesh topology consists of one coordinator, several routers and end devices and it also referred as a peer-to-peer network. A mesh topology is a multihop network that packets pass through multiple hops to reach their destination. The range of the network can be increased by adding more devices to the network. A mesh topology uses a self-healing mechanism that means if a path fails during packet transmission, the node can find an alternate path to the destination and it can manage to not have a dead zone. Devices which are close to each other, they can use less power to communicate. Managing the devices is easy and the devices can Add or remove to/from topology easily [189].

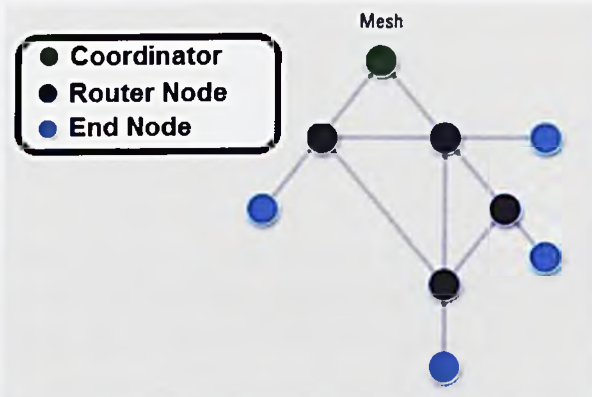

FIGURE 3.8: Mesh topology

3.2.2 Related works

Kim Boon Chia et al [190] were studied on performance of tree and star topologies and their resilient scale-free in WSNs. The scale-free principal was evaluated with the IEEE 802.15.4 and ZigBee protocols. They have found that orphaning effects the performance of the network and compromising the resilience. They have found that topology and protocol design must be chosen with care of improvement of resilience of the network and addressing the orphaning [190]. Wee Peng Tay et al [191] was discovered the error probability in tree networks increases exponentially with the number of nodes and also in the sufficient conditions, the architecture of the network does not affect the detection of error exponent [191]. Weitao Xu et al [192] have studied on star deployment strategy and they have proposed a strategy scheme to improve connectivity probability in WSNs. Yuan-Tao Shih et al [193] have done a research on node deployment and tree construction on ZigBee wireless networks and then they have proposed a scheme to deploy the nodes and construct a tree topology. In their scheme, the mobility information is used to construct the framework and topology deployment [193]. Min Chen [194] has proposed Multi-level MAC-layer QoS (MM-QoS) as a level-based QoS routing protocol based on the IEEE 802.15.4 for tree topology. He has verified the effectiveness of the proposed routing protocol in Body area Network (BAN) by simulation results and proved its compatibility with the existing the IEEE 802.15.4 protocol [194].

3.2.3 Methodology

In this research deployment parameters of two different topologies (tree and star) in ZigBee pro in WSN are studied in a testing field environment. The simulation that is used for calculation the parameters of the topologies is a web program that is developed by SMIR research group of LIMOS (Blaise Pascal University) and it is called Live Wireless Sensor Platform. The deployment type is random and the deployment area is selected to be in Isabela Plantation in the address 51.445609,-0.287962 by the area of 967.14*926.06 square meters. The parameters of deployment are Number of Nodes (NN) and Radio Range (RR). The parameters of star topology are Number of Children (CM) and Number of Coordinators (CO). The parameters of tree topology are Number of children (CM), Number of Child Routers (RM), Network Depth (LM) and Number of Coordinator (CO). The results were collected after 7 times of random deployment on each scenario and then the average of the 7 different deployments' data were used in results. The parameter to measure the deployment evaluation is number of lost nodes that show the value of nodes that cannot connect to the network and their data is not sent to any destination.

3.2.4 Deterministic Model

When node position is considered in this research, it is assumed, it is a determined values that show the spatial location of each node in the field with accuracy of 1 meter. This determind values can provide two-dimension for each node that can be close approximation to the location of each node in experimental field.

3.2.5 Results

The first deployment is to study on the effect of radio range in two different topologies. The result shows that increasing radio rang in wireless sensors are more effective in decreasing the lost nodes in tree topology instead of star topology. Figures 3.9 shows the effect of radio range on lost nodes in star and tree topologies. Radio range has a strong negative impact on lost nodes in star topology instead of tree topology.

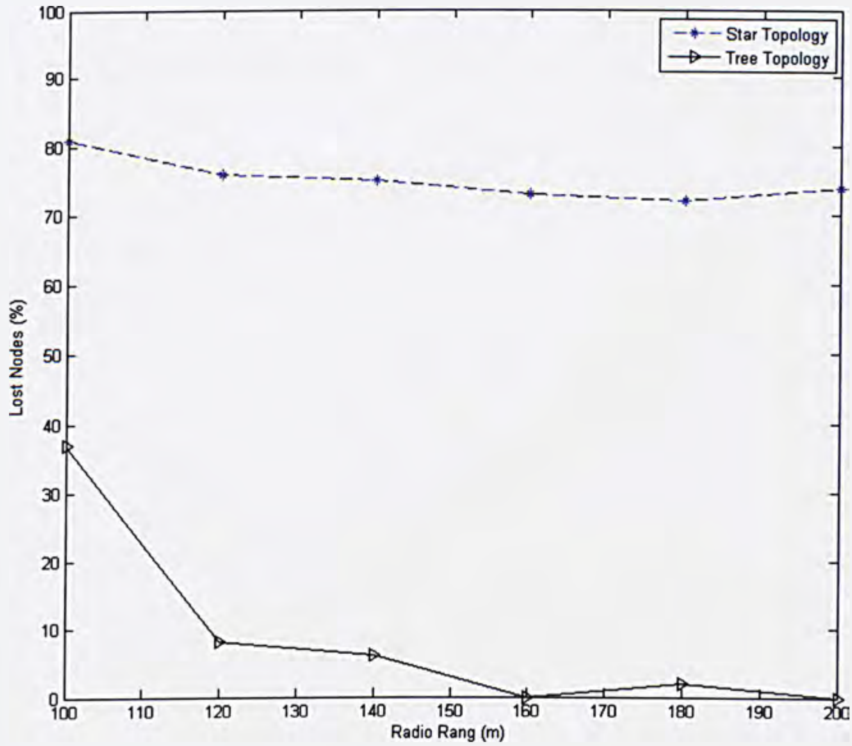

FIGURE 3.9: Lost Nodes in different WSN radio range

Figure 3.9 shows the percentage of lost nodes in different number of coordinators and also different number of child in tree topology. This result shows that number of child does not have a huge difference in performance of deployment; however, number of coordinators has a huge impact on deployment performance.

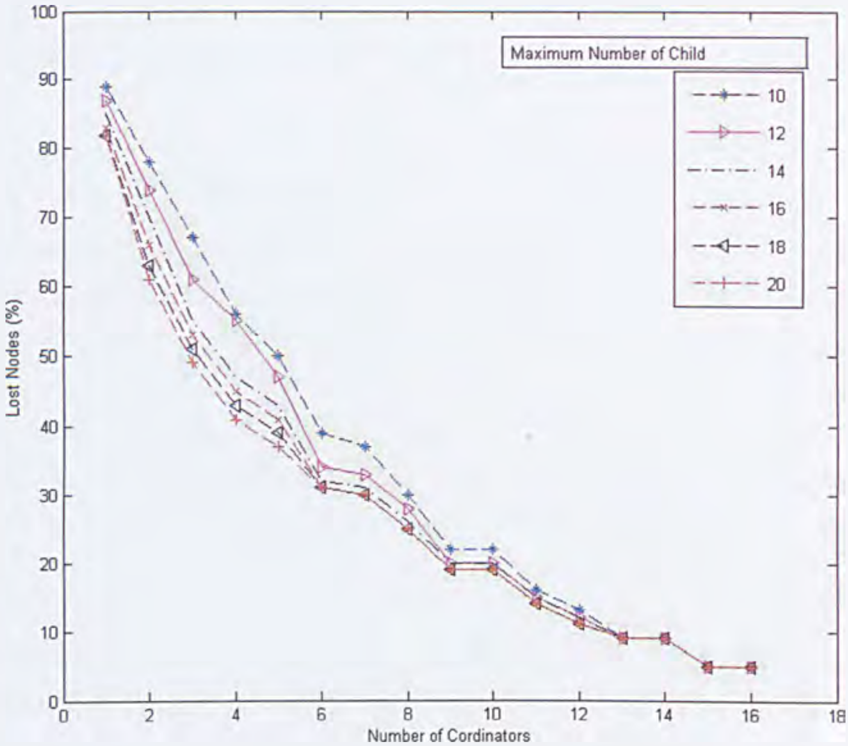

FIGURE 3.10: Lost Nodes in different number of coordinators

The next figure shows the impact of number of coordinators and number of nodes in deployment performance. Figure 3.10 shows the performance of deployment in field by increasing number of nodes in fields by different number of coordinators. The coordinators were set up from($\frac{n}{10}$) up to ($\frac{n}{10} - 6$) where the results is equal or greater than 1 and it shows that the factors of number of nodes and numbers of coordinator has major impact to deployment performance. The trends in figure 3.10 show number of nodes in field that has more influence than number of coordinator.

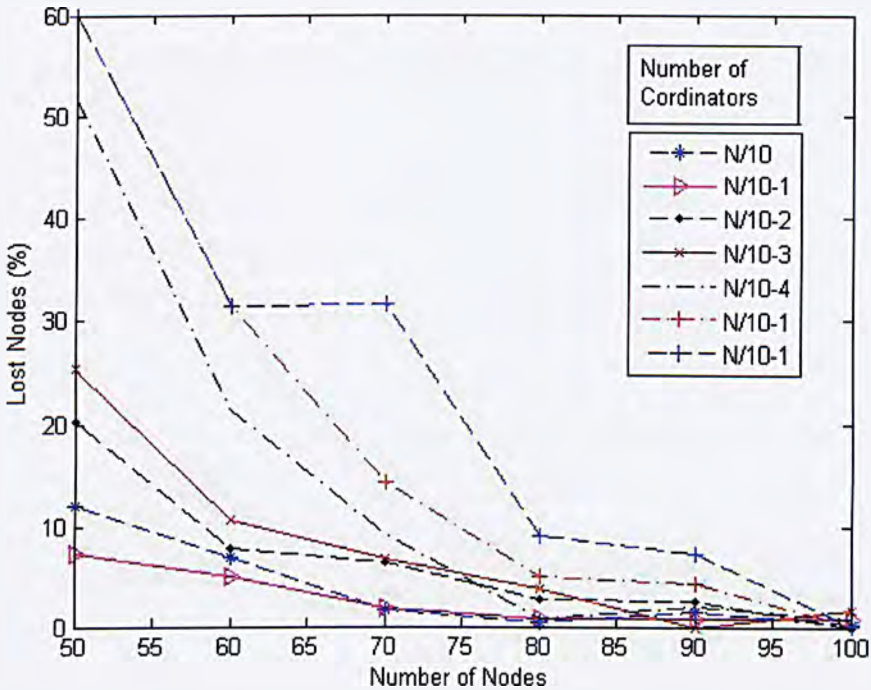

FIGURE 3.11: Lost Nodes in different number nodes and coordinators

In the next experience, tree and star topologies is compared by deploying different number of nodes in the fields. Figure 3.11 shows the trends of two topologies in random deployment by different number of nodes. The figure shows the tree topologies acts with better performance than star topology in random deployment. Star topology has 28% lost nodes when deploying 50 nodes into the field and it comes down to 8% when we are using 100 nodes in deployment. The tree topology has 0% lost nodes when it deploys 50 or 100 nodes.

TABLE 3.2: Density of nodes in fields and percentage of lost nodes (Radio Range 200 meters)

Number of Nodes	Percentage of Lost Nodes	Sq meters per Nodes
50	34.00	17912.59
60	16.00	14927.16
70	10.00	12794.71
80	3.00	11195.37
90	3.00	9951.44
100	1.00	8956.30

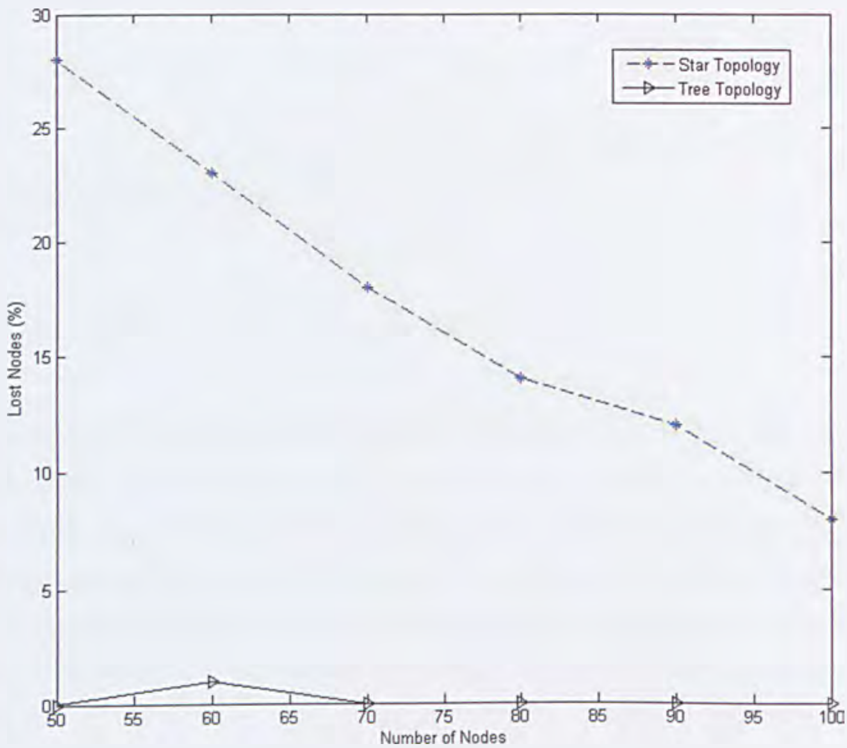

FIGURE 3.12: Deployment performance in tree and star topologies

The last experience is to find the number of nodes per fields to have a reasonable performance in tree topology. The result shows that if we are looking to have the maximum of 3% of lost nodes in the fields we should have 11195.37 sq meters per node in radio range of 200 meters. Table 3.2 shows the experience of lost node percentage in row with the density of nodes in field.

3.2.6 Conclusion

In this section WSNs topologies (tree, star and mesh) are studied in theory and then after, a randomly deployment is experienced by wireless sensors in the testing field. In this research, two WSN topologies (tree and star) are studied. Number of lost nodes as a parameter of deployment performance is selected and different deployment parameters are examined in different scenarios. The results have strongly proved that tree topology has better performance than star in random deployment.

Chapter 4

Statistical Analysis on WSN link-quality Metrics

WSNs are used in different scenarios. Monitoring the environment in a targeted area is more interesting in WSN implementations. The data from sensors should be collected and finally received and analysed in Sink. In most of the scenarios, Sink/Sinks are not in radio frequency range of wireless sensors and intermediate nodes should relay the data toward the Sink. Using a proper and efficient routing protocol affects reliability and life-time of the network. Routing protocols use metric to find the best path to the Sink. To measure and maintain link-quality, the protocols should send packets and use RF module. To save more energy in RF module for sending and receiving packets to maintain link-quality measurement, using Received signal strength indication (RSSI) or Link-Quality Indication (LQI) is proposed in this research. RSSI is a dimensionless quantity that is measured at the receivers antenna. It represents the signal strength observed at receiver at the moment of reception of packet. Accurate measuring of RSSI suffers from floor noise and current interfering transmission. We assumed that WSNs are used in outdoor environments where is not notable noise or interference is in very low level based on time division technique that avoids concurrent communication. RSSI is provided by the most of wireless sensor chips. Microcontroller CC2420 [195] has a built-in RSSI measurement that provide a digital value. LQI is a link-quality metric that is measured in the most of wireless sensor chips. Microcontroller CC2420 provides LQI measurement based on a characterisation of the strength and quality of a received packet as it defined by the IEEE802.15.4. In this chapter RSSI, ETX and LQI are measured in the real test-bed environments and they are studied by statistical analysis to find relations between these three metrics.

4.1 Background and previous works

In this section RSSI, ETX and LQI are deliberated in details and it shows how these metric are calculated and related works regarding finding relations between these metrics is studied.

4.1.1 RSSI

RSSI is a parameter that shows the signal strength in the receiver. Signal propagation follows the rule of Inverse square law. Figure 4.1 shows the Inverse-Square law. Intensity

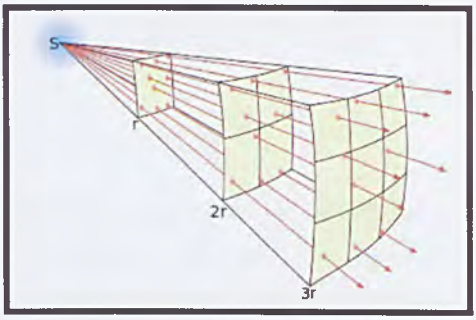

FIGURE 4.1: Inversely proportional of the square of the distance in Intensity of Signal

of signal in the receiver is inversely proportional of the square of the distance from the source.

$$SignalIntensityPower = K\frac{1}{distance^2} \tag{4.1}$$

where K is a constant value.

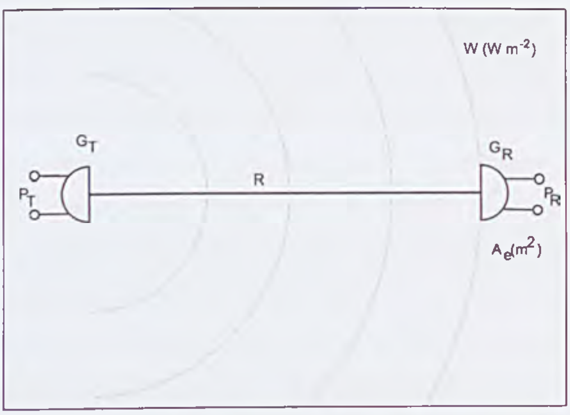

FIGURE 4.2: Free Space Path Loss

$$P_R = \frac{P_T}{4\pi R^2} G_T \alpha_e \tag{4.2}$$

Based on figure 4.2 and equation (4.2), P_R denotes power in the receiver, P_T denotes signal power in transponder and R is distance between transponder and receiver. P_R is calculated based on distance between transponder and receiver antennas and also some other parameters such as gains in antennas. Power of signal in reception or P_R is calculated as:

$$P_R = P_T G_T (\frac{\lambda}{4\pi R})^2 G_R [W] \tag{4.3}$$

$$\alpha_e = \frac{\lambda^2}{4\pi} G_R \tag{4.4}$$

$$P_R(RSSI) = P_T + G_T - 20log_{10}(\frac{4\pi R}{\lambda}) + G_R[dBW] \tag{4.5}$$

In equation (4.5), λ denotes the wave length, R is distance between transponder and receiver, G_R denotes antenna gain in the receiver and G_T denotes antenna gain in Transponder and α_e denotes the effective area of antenna in the receiver.

$$L_{FSPL} = K + 10nlog_{10}(\frac{R}{R_0}) \tag{4.6}$$

$$K = 20log_{10}(\frac{4\pi}{\lambda}) \tag{4.7}$$

In equation (4.6), $FSPL$ denotes Free-Space Path Loss and K is a constant value that is calculated based on λ (wave length) that is shown in equation (4.7). n is equal to 2 and R_0 denotes the reference distance that measuring the gain of transponder that is one meter. L_{FSPL} denotes power lost based on distance between transponder and receiver. RSSI is measurement of the power of the signal that is presented in the receiver antenna. RSSI is an indication of the power level that is measured in the receiver antenna. Therefore, The stronger the signal, the higher RSSI value and then comparing to the transponder signal power in the same hardware and environment we can find how far we are from the transponder antenna. There is no standard in 802.11 regarding the RSSI reading and any particular physical parameter of the radio signal. The relation between RSSI value and power level in mW or dBm was defined by vendors and chipset makers. They provide RSSI value from 0 to a maximum based on their accuracy, granularity and the actual power measured in mW or dBm.

4.1.2 LQI

LQI is a link-quality metrics that was introduced in the IEEE 802.15.4-2003 standard [196]. LQI was described in this standard as a characterisation of the strength and/or quality of received packet. The standard lets the implementations use Energy Detection (ED), Signal-to-noise ratio or a combination of these parameters. LQI value was defined to be in range of 0x00 and 0xff (0-255) that should be associated with the lowest and highest quality signal at receiver. The details of how LQI is calculated and which parameters should use in LQI calculation is not specified in the standard. Microcontroller CC2420[195] is RF chip that is used in the most wireless sensors. Microcontroller CC2420 provide LQI as a build in parameter that can be obtained from the chip. Microcontroller CC2420 uses average correlation value of RSSI for each incoming packet based on the 8 first symbols follows the Start of Frame Delimiter (SFD). The average correlation value for the 8 first symbols is added to each received frame with the RSSI and Cyclic Redundancy Check (CRC). Correlation value is between ∼50 to ∼110 that ∼110 indicates the maximum quality frame estimation and ∼50 indicates the lowest quality frame estimation. The software converts the correlation value to the range of LQI that is 0-255.

$$LQI = (CORR - \alpha) * \beta \tag{4.8}$$

Where α and β are found empirically based on PER measurements as a function of the correlation value. Authors in [197] have firstly proposed a calculation mechanism of LQI that may be used in Microcontroller CC2420. In a experimental study, they have found correlation between LQI and SNR as a linear.

$$LQI = A \times SNR + B \tag{4.9}$$

where A, B are the factors obtained using linear regression. They have found $A = 5.3145$ and $B = 97.0477$. Then they have obtained estimated SNR based on a analytical model.

$$SNR_{est} = \frac{2\mu_{CORR}^2}{Cii^2\sigma_{CORR}^2} \tag{4.10}$$

where μ_{CORR} and σ_{CORR}^2 denote mean and variance of Chip Correlation (CORR). CORR is provided by Microcontroller CC2420 chip maker as an average correlation value for each received packet. It is based on the first 8 symbols that coming after frame delimiter.

4.1.3 ETX

ETX[124] is calculated based on packet-loss rate collected from MAC layer and it is the predicted value of data-transmissions that deliver a packet successfully over a wireless link. ETX is a metric that is described deeply in chapter 2. ETX sends a small packet in every second and calculate the delivery ratio based on a large window that it typically is 10 seconds that try to damp the variation in the delivery ratio due to interference [128].

4.1.4 Related Work

In literature, RSSI and LQI often cannot convince researcher to be accepted as link-quality metrics. RSSI is a signal-based indicator and it is not directly related to the received packet indicators such as Packet Reception Rate (PRR) or Packet-loss Rate (PLR). It also is affected by noise or interference of neighbour transmission. [198] shows a high RSSI does not directly imply a high PRR and it is affected by link asymmetry. [199] analysed the behaviour RSSI on TR1000 sensors and they have found even in simple flooding algorithm it had significant complexity due to link asymmetric. They suggest the unreliability of RSSI is result of miscalibrations of the radio chip that is used. They have found that RSSI does not always have any correlation with PRR. They claim the asymmetries in links makes complexity scale when using RSSI. [200, 201] show in their experimental region any value of RSSI may represent a wide range of PRR values and it is not a correlation between RSSI and PRR. [201] found a better correlation between LQI and PRR in certain circumstances. [202] was studied on correlation between PRR and distance and they have found there is no correlation. [203] have found there is no correlation between PRR and distance in the radio communication range above 50% and they have reported that asymmetric links were between 5% to 30%. [198] have studied on Mica mote with TE1000 chip and they have found that links with PRR over 95% in the links with high RSSI value. [204] have observed RSSI, LQI and PRR on Telos mote based on Microcontroller CC2420. They have found the average of LQI has correlation with PRR; however, they cannot find any relation between RSSI and PRR. [205] have studied on behaviour of PRR, RSSI and LQI on test-bed and then they have proposed a new link-quality metric based on normalized RSSI and PRR. They have proved reliability and stability of this new link-quality metric. [206] have studied the IEEE 802.15.4 link-quality in a factory. They have observed RSSI, LQI and PER. They have found that RSSI depends on surrounding structures and RSSI and LQI show that they were stable in good radio communication range and average LQI shows better correlation with packet success probability rate than average of RSSI. [199, 207] have done a series of empirical studies on radio link-quality in WSNs. They have found that the radio channel and communication cover range is not same in different directions. They have tried to define a mathematical model for this irregularity. [208, 209] have proposed some models for path lost and fading for WSN radio channel. They did not study on relations of RSSI, LQI and PER. [210] have studied on correlation in shadow fading in outdoor environment and proposed a model for shadow fading. [211] have proposed a K metric that measures inter link correlation and do not come to conclusion of a relation between RSSI and success probability of PDR. Some researchers have studied link-quality performance in temporal characteristics. [212] proposed a real-time reliability estimator and [213] proposed a metric to measure link burstiness and also consider packet-loss rate. [214] have studied a statistical analysis of spatial and temporal of the channel measurement in different environment. They have investigated RSSI, LQI and PLR. They have proposed a mathematical model to show correlation between PLR, RSSI and LQI with distance. They have also proposed a model to describe the relation between link-quality and time. [215] proposed Resource-aware and Link Quality metric (RLQ) as a routing protocol for WSNs based on LQI and energy efficiency. This study was based on empirical measurements on test-bed environments. They have claimed that LQI can reflect to PLR better than RSSI. [216] offered RPLRE as a WSNs routing protocols based on LQI and residual energy. RPLRE such as LEPS uses LQI as link-quality for path cost in routing protocol. [217] have studied on RSSI, LQI, PDR and BER to determine accurately link-quality. They have suggested that the careful consideration of the limitations of each metrics is essential and makes them capable to use in specific purpose. [218] have observed of using RSSI and LQI for evaluating distance between nodes. They have reached to this conclusion that reflection, scattering, physical obstacles and other radio channel specification have an extreme impact on RSSI and it is not possible to find a correlation between RSSI and distance between the nodes. [219–221] have proved a strong correlation between LQI and PDR. [222] proposed CLQR based on LQI and they have proved the strong relation between LQI and Packet Received Ratio (PRR). [218, 223, 224] suggest using RSSI for link-quality regarding route selection and also [202, 225, 226] have provided that RSSI is not an accurate index. [227] have demonstrated that LQI reflects the signal-to-noise (SNR) at receiver and also define relation between LQI and the Microcontroller CC2420 CORR and finally proposed an analytical model based on LQI to predict link-quality. [228] proposed a distance estimation system based on RSSI and LQI. They have tested their hypothesis by experimental measurement in a real test-bed. [229] proposed a $RSSI - aware$ routing protocol metric for WMN. They have found that this proposed metric performed better than hop-count and even ETX. [230] have studied on RSSI based on Microcontroller CC2420 radio specification and proposed a way to improve the RSSI reliability by collecting samples in different frequencies. They have found the performance is improved by obtaining average of RSSI in different channel frequency based on results. [231] have proposed a technique to improve reliability and efficiency of the LQI based routing protocols in WSNs. They have proved the performance of proposed technique based on simulation results. [232] have proposed OR-RSSI, a RSSI-based opportunities routing protocol for Mobile Wireless Sensor Network (MWSN)s. OR-RSSI shows that it is more feasible for sparse networks and it performs better regarding successful delivery ratio and also overhead and energy consumption. [233] have proposed an indoor localisation system based on RSSI measurement in WSNs. They have offered position estimation error with less than 2m when deployment density of sensor nodes is more than 0.27 $nodes/m^2$.

4.2 Experimental Setup

The experiments were conducted on a series of wireless sensor test-beds. The test-bed is consisting of TelosB sensors based on the original open-source TelosB / Tmote Sky platform developed and published by the University of California, Berkeley. The wireless nodes have deployed in different scenarios. The scenarios content indoor and outdoor environments. Indoor scenarios were in office in university. Outdoor scenarios were in universitys parking, open area and forest. For avoiding interference in outdoor scenarios, Two wireless sensors were used one as a wireless node and another one as a base-station or Sink. For increasing stability in each point, I have waited for 5 minutes before collecting data. The parameters of network measure every second. LQI, RSSI, ETX and GETPOWER was collected. GETPOWER is the power that to be set in transponder to send the signal to receiver. The amount of GETpower was variable and depends on location of the receiver. Microcontroller CC2420 as radio frequency module provide RSSI and LQI and GETPOWER. RF modules increase power in transponder to reach a point as an optimum power set for sending signals. The data after stabilizing the transponder power took into account and the records for period that signal strength was not stable were not taken into account. Matlab R2013b and IBM SPSS Statistics version 21 were used for statistical analysis. Some data in this study was collected from previous experience which was done by University of Padova Italy [234].

4.3 Rigorous Hypotheses testing

Hypotheses testing have been defined for scenario less than 10 meter and they test asymmetry of RSSI and LQI in two directions from node A to node B and also returning path from node B to node A. Also another hypotheses testing have been defined to find correlation between RSSI, LQI and ETX:

1. Asymmetry testing of RSSI in scenarios less than 10 meter

2. Asymmetry testing of LQI in scenarios less than 10 meter

3. Correlation testing between RSSI and ETX for scenarios less than 10 meter

4. Correlation testing between RSSI and LQI for scenarios less than 10 meter

5. Correlation testing between LQI and ETX for scenarios less than 10 meter

4.4 Results

Some statistical tests were done based on different distributions on RSSI and LQI records .The results of statistical tests show some distributions fit to RSSI and some fit to LQI. These results would help to forming mathematical models for these parameters. The results come in tables 4.1,4.2 .

TABLE 4.1: Statistical Distributions I - Distributions fit to RSSI

Distribution	Measurement	Parameters
Lognormal	RSSI $A \rightarrow B$	$\mu = 4.0171$ $\sigma = 0.1664$
	RSSI $B \rightarrow A$	$\mu = 4.0051$ $\sigma = 0.17335$
Poisson	RSSI $A \rightarrow B$	$\lambda = -56.2892$
	RSSI $B \rightarrow A$	$\lambda = -55.6765$
Rayleigh	RSSI $A \rightarrow B$	$B = 40.3033$
	RSSI $B \rightarrow A$	$B = 39.8996$
Weibull	RSSI $A \rightarrow B$	$A = -60.073$ $B = 7.1670$
	RSSI $B \rightarrow A$	$A = -59.518$ $B = 6.9526$

TABLE 4.2: Statistical Distributions II - Distributions fit to LQI

Distribution	Measurement	Parameters
Lognormal	LQI $A \rightarrow B$	$\mu = 4.6701$ $\sigma = 0.00935$
	LQI $B \rightarrow A$	$\mu = 4.6671$ $\sigma = 0.01192$
Normal	LQI $A \rightarrow B$	$\mu = 106.809$ $\sigma = 0.9952$
	LQI $B \rightarrow A$	$\mu = 106.395$ $\sigma = 1.26128$
Poisson	LQI $A \rightarrow B$	$\lambda = 106.809$
	LQI $B \rightarrow A$	$\lambda = 106.395$
Rayleigh	LQI $A \rightarrow B$	$B = 75.5286$
	LQI $B \rightarrow A$	$B = 75.2376$
Rician	LQI $A \rightarrow B$	$s = -106.804$ $\sigma = 0.9940$
	LQI $B \rightarrow A$	$s = -106.387$ $\sigma = 1.2598$
t Location-Scale	LQI $A \rightarrow B$	$\mu = 106.858$ $\sigma = 0.91833$ $\nu = 13.5576$
	LQI $B \rightarrow A$	$\mu = 106.506$ $\sigma = 1.0917$ $\nu = 7.7707$

Results from statistical distribution analysis show some distributions fit to RSSI data. *Poission, Rayleigh, Loglogistic, Lognormal, Gamma, Exponential, Weibull* and *Birnbaum-Saunders* distributions fit to RSSI records and *t-Location-Scale, Rician, Rayleigh, Poission, Normal, Lognormal, Loglogistic, Kernel, Extreme Value, Exponential* and *Birnbaum-Saunders* distributions fit to LQI data. The statistical analysis was done by IBM SPSS Statistics version 21. The data collected from empirical experiences was used by the software to test different distributions and find the values of different distributions. In tables 4.1, 4.2 different statistical distributions with the value of fitness to the actual data were provided. Results of this research was published in the IEEE Vehicular Technology Journal [18]. The study has continued by doing different statistical correlation tests on two parameters RSSI and LQI. The data for each parameter was collected from sending signal from node A to node B and then RSSI and LQI were measured in node B then in the same time, signal was sent from node B to node A and RSSI and LQI were recorded in node A. RSSI($A \rightarrow B$) denotes the signal strength was measured by node B from node A and $RSSI(B \rightarrow A)$ denotes the signal strength was measured by node A from node B.

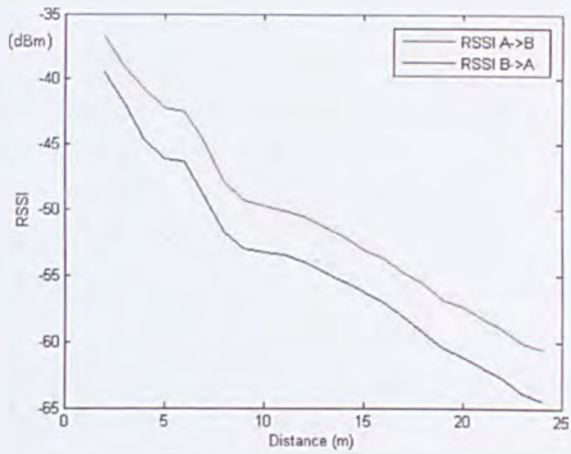

FIGURE 4.3: RSSI in node B for the signal from node A (RSSI $A \rightarrow B$) in different distances and also RSSI in node A for the signal from node B (RSSI $B \rightarrow A$)

Figure 4.3 shows the signal strength measured by node A from node B and also the signal strength measured by node B the signal received by node B.

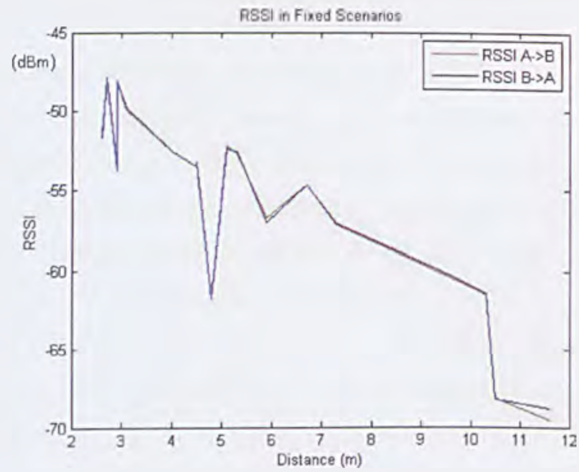

FIGURE 4.4: RSSI in two directions measuring in node A, the signal from node B and in other direction in different distances in fixed scenarios

Figure 4.4 shows the signal strength measured by node A from node B and also the signal strength measured by node B the signal received by node B in fixed scenarios.

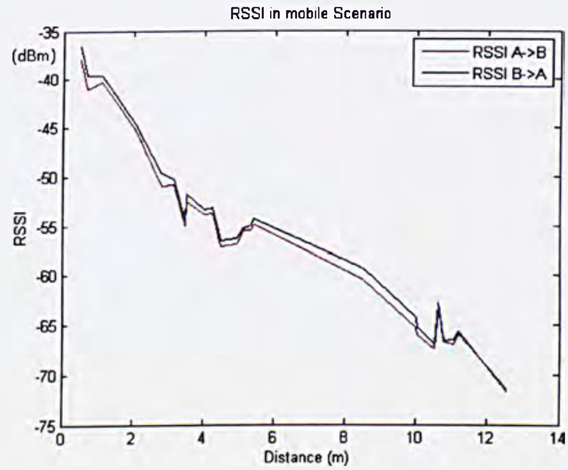

FIGURE 4.5: RSSI in two directions measuring in node A, the signal from node B and in other direction in different distances in mobile scenarios

Figure 4.5 shows the signal strength measured by node A from node B and also the signal strength measured by node B the signal received by node B in mobile scenarios.

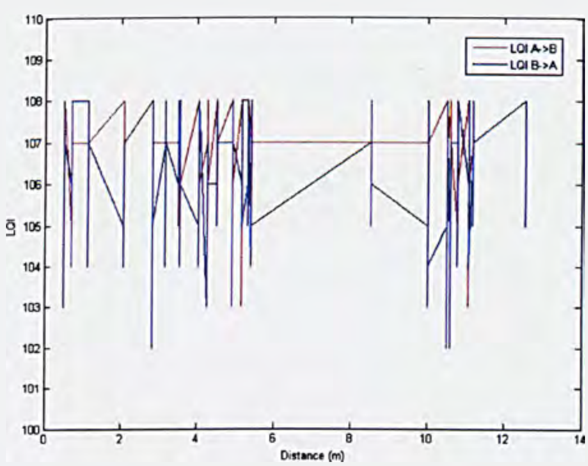

FIGURE 4.6: LQI node B for the signal from node A (LQI $A \rightarrow B$) in different distances and also LQI in node A for the signal from node B ($LQIB \rightarrow A$)

Figure 4.6 shows the LQI measured by node A from node B and also the LQI by node B the signal received by node B. Figure 4.7 shows the LQI measured by node A from node B and also the LQI by node B the signal received by node B in fixed scenarios. Figure 4.8 shows the LQI measured by node A from node B and also the LQI by node B the signal received by node B in mobile scenarios. To evaluate correlation of RSSI and LQI in both directions, some statistical correlation test were employed. *Pearson* χ^2, *Goodman*,

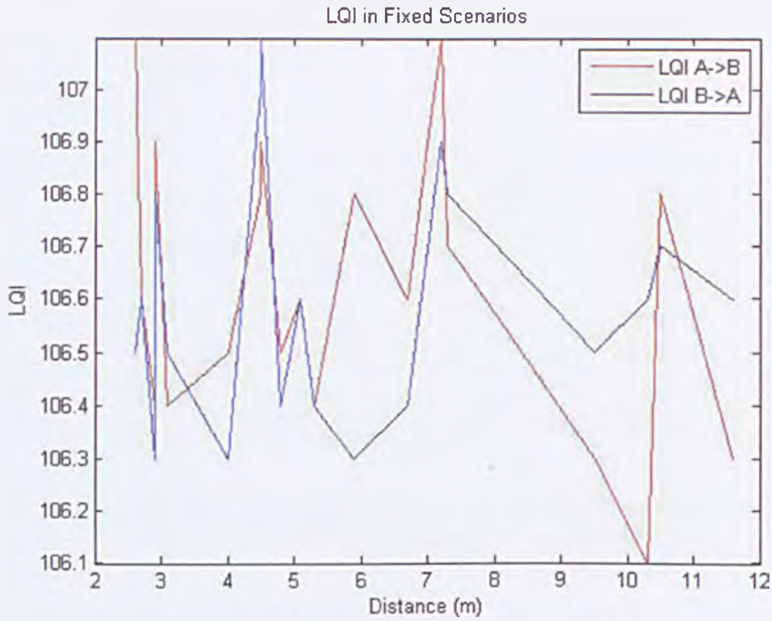

FIGURE 4.7: LQI in two directions measuring in node A, the signal from node B and in other direction in different distances in fixed scenarios

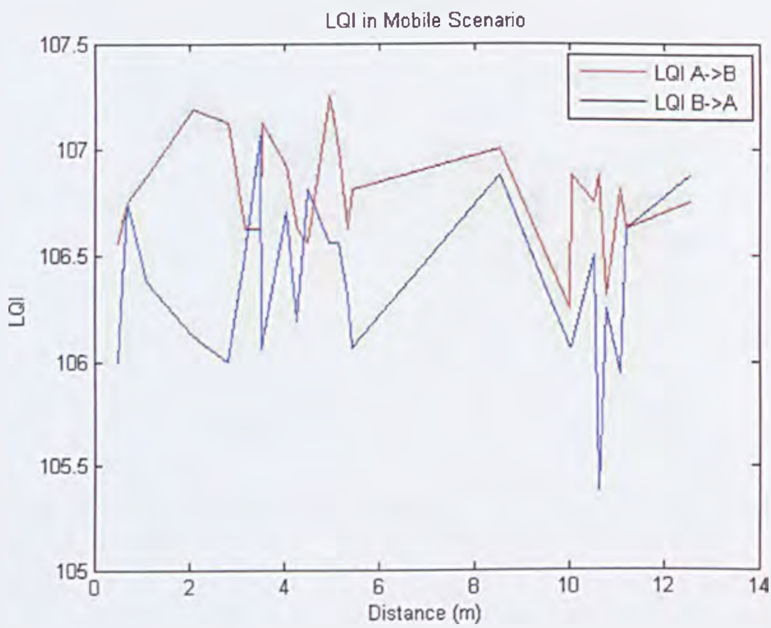

FIGURE 4.8: LQI in two directions measuring in node A, the signal from node B and in other direction in different distances in mobile scenarios

Somers' d, Kruskal tau, Cramer's V, Contingency Coe, Gamma, Spearmen Correlation, Pearson's R and *Kappa* have used to test the hypothesis. The results from different correlation tests show in table 4.3 and they show a very strong correlation between $RSSI(A \rightarrow B)$ and $RSSI(B \rightarrow A)$ and also a weak correlation between $LQI(A \rightarrow B)$

and $LQI(B \to A)$.

TABLE 4.3: Correlation tests for RSSI and LQI in two directions

Statistical Tests	RSSI	LQI
$Pearson\chi^2$	6205.7	26.17
λ	0.494	0.0
Goodman	0.433	0.019
Somers' d	0.945	0.028
Kruskal tau	0.392	0.011
Phi and Cramer's V	3.00	0.253
Contingency Coe	0.960	0.246
Kendall's tau-b	0.945	0.028
Kedall's $tau - c$	0.9119	0.024
Gamma	0.977	0.039
Spearmen Corr	0.988	0.034
Pearson's R	0.993	0.064
Kappa	0.389	-0.052

Table 4.3 shows result of different tests regarding correlation between RSSI and LQI. In the next stage of our experimental study, we have tried to find correlation between link-quality metrics, RSSI, LQI and ETX. Figure 4.10 shows scatter figures of RSSI-LQI, RSSI-ETX and LQI-ETX based on different scenarios. The results show there is not a significant correlation between RSSI, LQI and ETX and it is not possible to use any of them in place of the others.

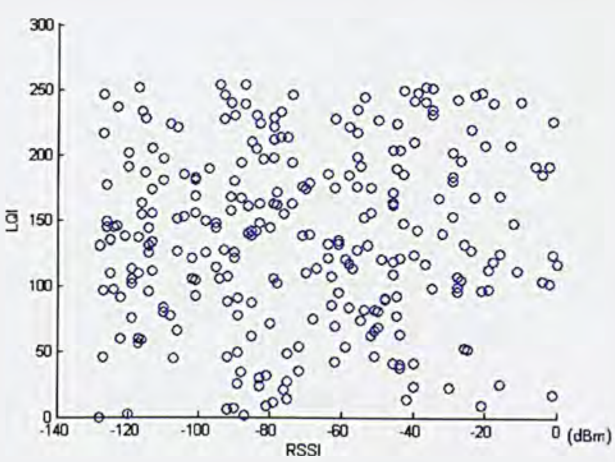

FIGURE 4.9: RSSI and LQI

Figure 4.9 shows scatter figures of RSSI and LQI based on different scenarios.

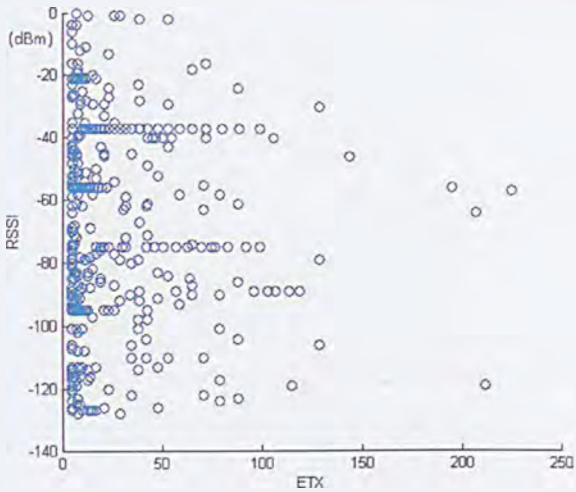

FIGURE 4.10: ETX and RSSI

Figure 4.10 shows scatter figures of ETX and RSSI based on different scenarios.

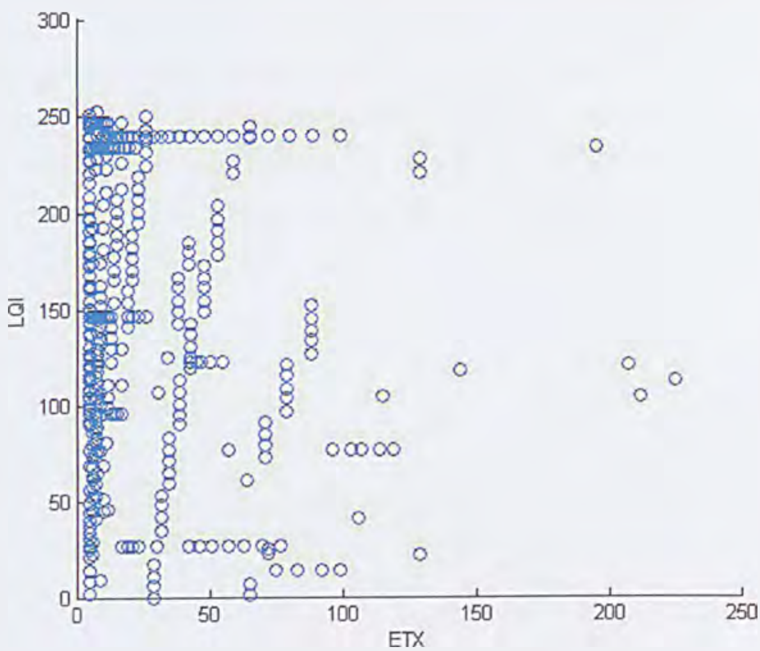

FIGURE 4.11: ETX and LQI

Figure 4.11 shows scatter figures of ETX and LQI based on different scenarios.

Table 4.4: Statistical Parameters for ETX, RSSI and LQI

Pairs	Mean	Std. Deviation	Std. Error Mean
ETX	33.0166	48.11007	1.23603
RSSI	−63.8766	26.67934	0.68544
LQI	144.4238	89.82871	2.30786

Table 4.4 shows the statistical parameters of ETX, RSSI and LQI. Means, Standard deviation and standard error mean are the parameters that were calculated in this study.

Table 4.5: Statistical Correlations test for ETX, RSSI and LQI

Pairs	Correlation	Sig.
RSSI−ETX	−0.212	0.000
RSSI−LQI	−0.473	0.000
ETX−LQI	−0.136	0.000

The correlation in 0.01 significant level (2-tailed)

Table 4.5 shows the statistical correlation test between parameters of ETX, RSSI and LQI. The Correlation and the significant values show that there is no correlation between these three parameters.

Table 4.6: One-sample kolmogorov-smirnov test

Statistical test		Distance	RSSI
Normal Parameters	Mean	6.29	-56.11
	Std. Deviation	3.588	8.884
Most Extreme Differences	Absolute	0.110	0.114
	Positive	0.097	0.114
	Negative	-0.110	-0.066
One Sample Test Statistic		0.110	0.114
Asymp Sig. (2-tailed)		0.00	0.00
$Kendall'stau_b$	Correlation coefficient	1.000	-0.822
	Sig.$(2-tailed)$	0.000	0.000
Spearman's rho	Correlation coefficient	1.000	-0.945
	Sig.$(2-tailed)$	0.000	0.000

Asymp Sig is Lilliefors Significance Correction

Table 4.6 shows the results of One-sample kolmogorov-smirnov test for two parameters, RSSI and distance. Normal parameters, Mean and standard deviation and also most extreme difference were measured in this test. The one-sample test results show a significant correlation between RSSI and distance.

TABLE 4.7: Chi-Square test for Distance and RSSI

Statistical test	Distance	RSSI
Chi-Square	999.680	2811.242
df	82	46
Asymp Sig	0.00	0.00

The correlation in 0.01 significant level (2-tailed)

Table 4.7 shows the results of Chi-square test for two parameters, RSSI and distance. The Chi-Square results show a significant correlation between RSSI and distance in short distance scenarios.

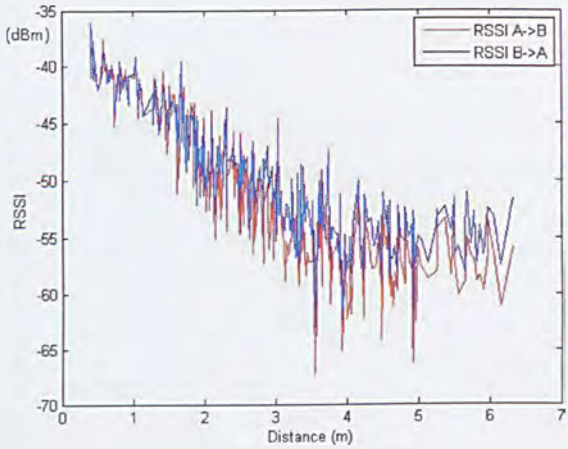

FIGURE 4.12: RSSI in different distance between Transponder and Receiver and reverse

Figure 4.12 shows RSSI in two directions in different distances. Although there are some fluctuations during the observation; however, in general RSSI decreases by distance and it makes RSSI capable as a link-quality metric in devices for which energy consumption is vital.

4.5 Future Works

The future works in this topic can be finding more metrics that suite for special devices such as tiny devices with limited resources. Using some parameters of received signal to estimate and discover link-quality metrics. PER, BER and CRC can be some examples of internal parameters that may can be used to discover link-quality. Preparing simulations or test-beds to study more about the performance of different metrics in different scenario can be a future path in this filed.

4.6 Conclusion

Routing protocol plays an important role in data communication. WSN is usually deployed in scenarios where efficient and energy-aware routing protocols are desired. In wireless sensors, the RF modules consume most of the energy in the whole system. Routing metrics are important in the determination of paths and maintaining quality of service in routing protocols. Most efficient metrics need to send packets to maintain link-quality measurement by using RF module. In this research, two prominent link-quality metrics: RSSI and LQI are introduced, the symmetry of RSSI and LQI in two directions is studied and also relations between ETX, RSSI and LQI as link-quality metrics are analysed. The evaluation in this research is based on a series of WSN test-bed in real scenarios. The collected data from test-bed shows symmetry in RSSI in both directions and also a significant correlation between RSSI and distance to make it a capable link-quality metric to be employed in routing protocols for devices that work in limited resources scenarios [18]. This research studies on link-quality metrics and some features of RF characteristics and signal properties. The statistical analysis is tested on RSSI and LQI to find the distributions which fit to them. And also some statistical tests were done on asymmetry in RSSI and LQI. They show a significant correlation between two directions in RSSI; however, a weak correlation between two directions in LQI. The ETX, RSSI and LQI are studied two by two to find any correlation between these three link-quality metrics; however, the results do not show any rational relation between those parameters. The correlation between RSSI and distance is observed in based on real test-bed scenarios. Statistical tests on the collected data show a significant correlation between RSSI and distance in short distance scenarios and it makes RSSI as a routing protocol link-quality metric that can be used in devices with limited energy.

Chapter 5

Proposed Routing Protocols

This chapter presents and evaluates RCTP as an enhanced version of CTP with regard to the implementation of routing protocols in limited power supply devices in WSNs. CTP does not show good performance in dynamic environments. RCTP as a proposed routing protocol uses AETX as link-quality metric that was shown to be more stable than ETX. It also uses a new mechanism in parent selection to make it more accurate in terms of forming a tree topology. This chapter also presents and evaluates an Energy-efficient Position Based Adaptive Real-Time Routing protocol (EFPBARP) as a novel, real-time, position based and energy-efficient routing protocol. EFPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel Parent Forwarding Region (PFR) algorithm. Three Dimension Position-Based Adaptive Real-Time Routing Protocol (EFPBARP) as a Geographical Routing Protocols (GRP) reduces the number of forwarding nodes and thus decreases traffic and packet collision in the network. WSNs are also used in 3D scenarios such as sea or land surfaces with different levels of height. This chapter presents and evaluates Three Dimension Position-Based Adaptive Real-Time Routing Protocol (3DPBARP) as a novel, real-time, position based and energy-efficient routing protocol for WSNs. 3DPBARP is a lightweight protocol that reduces the number of nodes which receive the RF signal using a novel PFR algorithm. 3DPBARP as a GRP reduces the number of forwarding nodes and thus decrease traffic and packet collision in the network.

5.1 Design Objects

CTP is a lightweight routing protocol for WSNs. It is an efficient, robust and also reliable routing protocol. CTP as a cross-layer routing protocol is also a platform-independent protocol. It uses the Trickle algorithm to optimise overhead cost and the algorithm also makes CTP quickly adaptable to changes in topology. The basic foundation of CTP is link-quality identification and it uses ETX as radio link-quality estimation between nodes. The Rainbow mechanism is used in RCTP to detect and route around connectivity nodes and avoid routes through dead-end paths.

5.1.1 Collection Tree Protocol

CTP is a data-collection protocol based on tree topology. It forms routes to a single or a small number of designated roots (Sinks) in a network of wireless sensor devices. The two principals of CTP are data-path validation and adaptive beaconing [235]. Based on these two principals, goals of reliability, robustness, efficiency and hardware independence can be achieved. In terms of reliability, the packet delivery ratio should not be less than 90% in end-to-end delivery ratio and 99.9% in simple delivery. Robustness guarantees that the network works without any configuration or tuning with regard to working in a wide range of network conditions such as different channel characteristics, number of nodes and even payload. Efficiency is relevant to the use of resources, which should be as small as possible and energy consumption in the total system should be minimal. Hardware independence implies that there is no need for special hardware or specific radio chips and that the design should apply to all existing WSN platforms [235]. A few nodes in the network advertise themselves as tree roots. Other nodes in the network form a tree-network topology and send data toward the root nodes. Each node chooses the path to root by selecting the next hop based on a routing gradient [11]. CTP uses ETX as its routing gradient. Each node is labelled as an ETX value. ETX root values are 0 and others the value of other nodes is calculated by equation (5.1):

$$Node(ETX) = Parent(ETX) + Link(ETX) \tag{5.1}$$

Each node selects its parent from a group of its qualified neighbours that have already advertised their ETX values. The neighbour that is selected as the node's parent is the neighbour with less ETX value. Routing loop can occur connectivity with the current parent is lost and the selection of a new parent has a higher ETX value than that of the previous parent. If the new route to the Sink includes the current node, then a loop occurs in packet transmission. CTP uses data-path validation mechanisms to avoid making loops in the topology. If CTP receives a data-packet wherein the ETX value of sender is equal or less than its own ETX, it shows an inconsistency in the tree topology and sets a trigger to reconsider the topology. If the tree topology is set up properly, the packet travels from source to the sink by travelling to the routers and each router should be closer to the sink with ETX value or cost of reaching to the sink lower than the previous router. If a data-packet arrives at a router and its ETX value is higher than the previous router, it shows that it is not travelling toward the destination and it is going further from the Sink [235]. CTP uses the best-quality available links in the path and also avoids them when they fail. CTP considers link estimation in every five packets to maintain accuracy with agility.

Packet duplication is another challenge in WSNs that affects total energy consumption in a system. When a packet has successfully arrived at a node and the receiver node sends ACK to the sender and this ACK is not received by the sender, the sender considers sending the data-packet again and thus creates packet duplication in the network. This data duplication propagates through others nodes in the network and grows exponentially. CTP also uses Time Has Lived (THL) value to suppress duplicated packets. THL is decremented by the network layer on each hop. CTP keeps originating address, sequence number and THL value of each transmitting packet. When a packet arrives, CTP compares these values with its own keeping table and drop a packet that was transmitted before [235]. CTP does not show good performance in dynamic environments [8–11]. [236] and [235] proposed that typical ETX or delivery ratio is between 70-90%. [237] and [238] have shown that the typical delivery ratios can even be worse at 20-40%. The reasons that successful delivery ratios significantly fluctuate are the objects entering into the communication area such as rain or wind that affect radio-frequency propagation. Even other equipment that is operating on the same radio-frequency band can interfere with data communication [239].

Parent selection is one of the main features in CTP routing protocol. This procedure is repeated based on triggers or periodically. Parent selection involves in choosing a parent between qualified neighbours based on their ETX values. These values are represented as the cost of transmission from each neighbour to the Sink. In CTP parent selection, link-cost to each parent candidate is not taken into account. In the worst-case scenario, it is possible to choose a parent with a lower ETX value however, one with high link-cost and the total cost may be higher with other available candidates.

5.1.2 Rainbow Mechanism

This section demonstrates how the Rainbow mechanism is used in proposed routing protocols to avoid dead-end routes. The principle of Rainbow is forwarding packets toward the Sink. In this mechanism, every node has a colour code based on how far it is from the Sink. The order list of colours shows that how the next relay node can travel toward the Sink. Let $C_J(i)$ be the colour code of node i and node i forwards only to next relay node with a colour code equal to C_{J-1} or C_J. This guarantees that the packets travel toward the Sink and avoids sending packets down dead-end routes [240].

Figure 5.1 shows how the nodes select their parents based on the Rainbow mechanism. Each node selects its parents by its colour code or with a colour code to be close to the Sink.

The colour code in each node is calculated based on a counter. The Rainbow counter

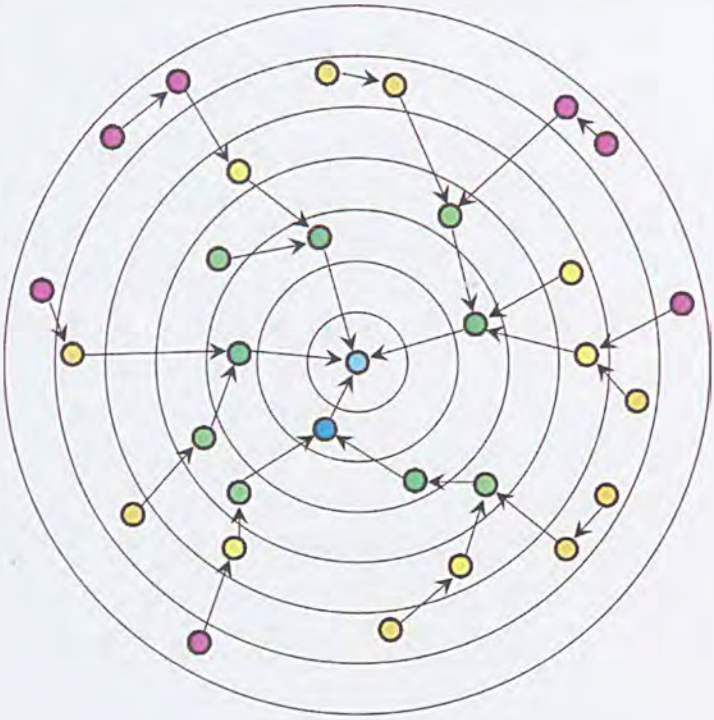

FIGURE 5.1: Rainbow colou ring technique

is the number of received packets from the Sink. Any node with value higher than this counter shows that it is closer to the Sink than other nodes with a lower value.

5.1.3 Energy Consumption Model

Energy consumption models are compared by study [241] that shows the components that consume energy in WSNs. In this research, it is assumed that the power energy that is consumed is mostly derived by the RF module for transmission signals that are involved in sending and receiving packets in wireless sensor nodes. Following research in [242][243][244], the mathematical model for energy consumption by transmitting and receiving packets per bits of each sensor node are calculated as follows. Energy consumption in RF module in the receiver is given as:

$$E_{Rx}(k) = E_{elec} \times k \tag{5.2}$$

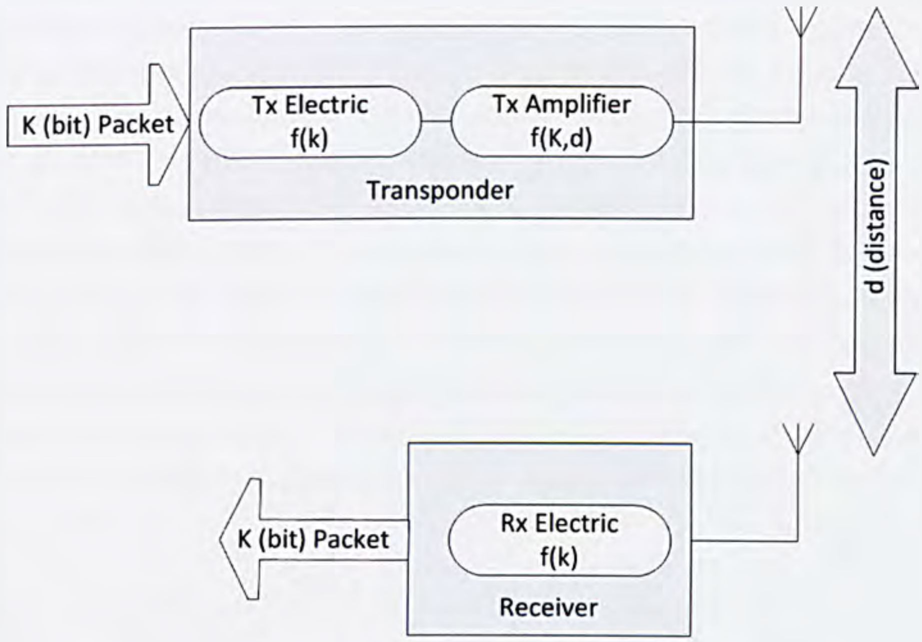

FIGURE 5.2: Energy Model System

Where E_{Rx} is energy consumption in the receiver node, E_{elec} is the energy required to process one bit in the electronic modules and k is the length of message (bit) and energy consumption in transmitter RF module is given as:

$$E_{Tx}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^2 \tag{5.3}$$

Where E_{Tx} is energy consumption in transmitter node, E_{amp} is the energy required to transmit one bit in the RF module and k is the length of message (bit) and d denotes the distance between transmitter and receiver measured in metres.

5.2 RCTP

In this section, the problem of instability of ETX in real environment is considered and a new method to improve CTP is proposed. The proposed method does not increase overhead in terms of increasing the number of packets to maintain topology. Cross-layer protocol is named RCTP based on data-collection protocol and is a lightweight routing protocol fit for low-power devices. In the proposed routing protocol, link-quality metric between nodes changed from ETX to AETX to make the protocol more stable. RCTP enhances greedy forwarding by considering congestion and packet-delivery information when making decisions to find the best path to the destination. The new relay-selection scheme, which implements MAC and routing-protocol functions in a cross-layer combination, makes an achievement in terms of routing-protocol performance. RCTP uses a new mechanism to choose a parent that it is based on AETX value of each neighbour plus the AETX value of the link. In total, this mechanism chooses the best possible parent between existing qualified neighbours. RCTP avoids the occurrence of a loop in the topology. RCTP shows better performance in terms of energy efficiency, packet-delivery ratio and packet end-to-end delivery time. These properties make RCTP able to guarantee packet delivery in realistic deployment. The Rainbow mechanism is used in RCTP to avoid using dead-end routes. The principal of Rainbow is to avoid forwarding packets away from the Sink. This guarantees that packets travel toward the Sink and avoids sending packets down dead-end routes. RCTP uses a detection mechanism during data-packet transmission to validate the routing path and topology. This mechanism makes RCTP avoid loops. It also uses the link-layer distance estimate in each packet to validate the topology.

5.2.1 Motivation

WSN consists of small devices for which energy consumption is a vital. Any protocols that are used should be energy-aware. CTP is a lightweight, simple and efficient routing protocol and also is a best-effort, reliable and many-to-one routing protocol. This simple and effective routing protocol is the foundation for sensor applications that can work on top of the network layer. For almost a decade, CTP has suffered from poor performance with delivery ratios of 2-68% as it is found in [8–11]. Adding a simple mechanism can improve CTP performance and make it more efficienct. Previous research experience in considering different metrics and finding a stable version of ETX was a key motivation to improve CTP. RCTP a new version of CTP with better performance due to the implementation of AETX as a link-quality metric in CTP, improved parent selection and the application of the Rainbow mechanism.

5.2.2 Related Works

CTP Neo [235] was proposed to employ two mechanisms, validating data-path and using 4-bit link estimator. CTP Neo was used in 12 different test-beds and results show delivery ratio improved more than 90%. Results also show that CTP Neo uses on average 73% fewer beacons in comparison with standard beaconing. CTP-TICN [245] is another version of CTP. CTP-TICN has done some changes in link estimation calculation and also provides load balancing. It uses Extra Expected Transmission Count (EETX) instead of ETX, that is the Extra Expected Transmission is calculated based on probability of successful receipt of a packet on both sides of a link. CTP-TICN uses a weighted mechanism that uses old EETX and current EETX based on an implementation parameter. POCTP [246] is a QoS routing protocol based on CTP. POCTP is based on the definition of Pareto optimal route that was evaluated by using hierarchical Petri Net modelling technology. BCTP [197] is a balanced version of CTP. It enhances CTP by enabling the nodes to balance traffic by avoiding nodes that drain their energy because all traffic passes through them. It uses a strategy to balance the load through the network to balance energy consumption. ICTP [240] is a load-balanced version of CTP. The concept of ICTP is based on using both long path with a good link-quality and also short path with a weak-quality link. On one side, this decreases reliability and on the other, it avoids congestion and thus improves reliability. With the combination of two above factors, results show ICTP performs better than CTP. O-CTP [239] is based on investigation of WSN routing-protocol behaviour in networks that are affected by interference. O-CTP is a hybrid routing protocol that uses high packet-delivery ratio of opportunistic routing in error-prone networks and is also an energy-efficient routing protocol. ICTP [247] uses both long path with good link-quality and short path with bad link-quality. This can decrease reliability; however, it improves efficiency by avoiding congestion. It showed that energy consumption in ICTP is less than CTP in same scenarios based on the possible reduction in congestion. BCTP [240] is a balanced version of CTP that enables the network to avoid heavy traffic nodes. It uses average transmission rate as a metric. BCTP was evaluated by a test-bed and results show that the load in hot spots drops by 61.9%.

5.2.3 RCTP The improved version of CTP

5.2.4 Challenges

CTP as a light and efficient routing protocol in WSNs has suffered from poor performance for almost a decade. Some deployments report a delivery ratio of 2-68% [235] and it is not clear why CTP performance is poor in practical terms even in low-data rates. The challenge is to improve CTP performance and makes it a robust and efficient routing protocol with high reliability in WSNs. CTP uses ETX as a link-quality metric and the ETX value fluctuates even when all environment properties are fixed. The reasons that successful delivery ratios significantly fluctuate are objects entering into the communication area or interference is made by other equipment operating in the same radio-frequency band. This ETX fluctuation may cause routing protocols to make a wrong decision regarding finding the best path to the destination. RCTP uses AETX that has proven to be more stable than ETX. Some CTP implementation uses a weighted system to use current ETX and old ETX. The challenge is to improve CTP performance in dynamic environments and the goas is to improve packet-delivery ratio. Parent selection is one of the main factors in CTP routing protocol. This procedure is repeated periodically or based on triggers. The parent-selection trigger is set in these scenarios: a parent is unreachable; the current parent gets congested; one or some neighbours are no longer congested; a special beacon arrived; there is inconsistency in transferring a packet by processing the packet header. Parent selection chooses the parent between qualified neighbours based on the ETX value of each neighbour. The ETX values of each neighbour represent the cost of transmission from each neighbour to the root. CTP chooses the neighbour with lower ETX to be its parent and it is the best possible parent amongst neighbours. In CTP parent selection, link-cost to each parent candidate is not taken into account. In worst-case scenarios it is possible to choose a parent with lower ETX value but with high link-cost and thus total cost may be higher than with other available candidates. Figure 5.3 shows a topology that node 8 is going

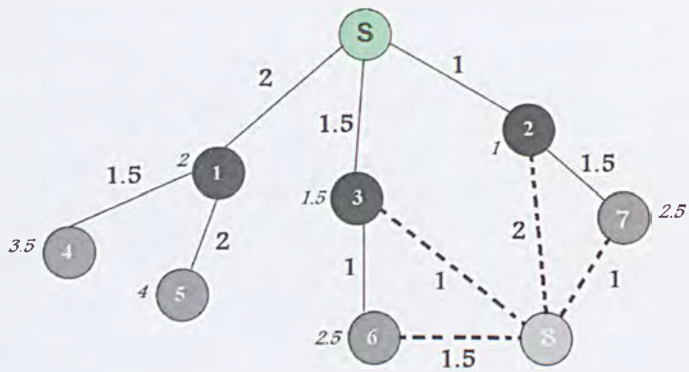

FIGURE 5.3: CTP Parent Selection

to select its parent. Node 8 is in the communication area with nodes 2, 3, 6 and 7 and these four neighbouring nodes send their ETX values to this node 8. CTP parent selection mechanism chooses parents with lower ETX values. Based on this information: $ETX_2 = 1, ETX_3 = 1.5, ETX_6 = 2.5$ and $ETX_7 = 2.5$ and $ETX_7 = 2.5$, CTP chooses node 2 as the parent of node 8. It can be seen that link-cost between node 8 and node 2 is equal to 2 ($ETX_{82} = 2$) and also that link-cost between node 8 and node 3 is equal to 1 ($ETX_{83} = 1$). The actual cost from node 8 to the sink through node 2 is equal to 3 and the total cost through node 3 is 2.5 even its parent ETX value is higher. RCTP uses the total cost to select the parent. In RCTP protocol, node 8 selects node 3 as its parent because total cost through node 3 is 2.5 and that is lower than the cost through node 2, which is 3.

5.2.5 Design

AETX is a moving average of the last three ETXs. [13] ran several simulation scenarios and, based on huge data that was collected through the simulations, shows the average of the last three ETXs is more stable and also senses variation on RF channel. [13] Using the last three ETX makes AETX more stable than ETX and also makes it flexible enough to follow changes in the network.

$$AETX = (\sum_{i=n,-1}^{n-3} ETX(i))/3 \tag{5.4}$$

RCTP uses AETX in all calculations rather than ETX. It also contains a change in the parent-selection procedure. The parent-selection procedure is repeated periodically or is run when the network notes inconsistency. Inconsistency happens when a node receives a beacon that asks to reconsider the topology, a neighbour comes out from congestion mode, a parent is unreachable or the node receives a data-packet that the AETX value of sender is equal or smaller than its own AETX. The parent is selected amongst neighbours that are not congested and that are not the child of the current node. All eligible neighbours have already reported their AETX values. The parent cost is selected based on the equation (5.5):

$$AETX_j = AETX_{ji} + AETX_i \tag{5.5}$$

$$Parent_j = Min_{i \in Neighboursofj}(AETX_{ji} + AETX_i) \tag{5.6}$$

Where $AETX_{ji}$ is the AETX value of link between nodes j and i and $AETX_i$ and $AETX_j$ are the AETX values of nodes i and j respectfully.

5.2.6 Loop avoidance in RCTP

RCTP uses a detection mechanism during data-packet transmission to validate the routing path and topology. This mechanism makes RCTP avoid loops by checking the last 7 nodes that packet comes to this node through them. If the current node is in the list of 7 last nodes, the network loop would be occurred and reconsidering the topology is need to be in order. It also uses the link-layer distance estimate in each packet to validate the topology. If the distance estimate of the packet that is received to this node is equal or less than the distance estimate of its own then the topology needs to be revised and RCTP takes an action to review the topology. This is another mechanism of RCTP uses

TABLE 5.1: Omnet ++ Simulation Parameters in RCTP

Simulation Parameters	
Number of nodes	10,20,..,100
Node Deployment	Random
Field Area	200 X 200 (m)
Simulation time	18-3000 Sec
Wireless Channel Sigma	0,1,3,5
Radio Parameters	CC2420
Routing Protocols	CtoNoe, RCTP, REL
Application	CtpTesting
App Packet Rate	5
APP Payload	Constant 2000 bytes
Max Frame Size	2500 byte
Radio Tx Power	-5 dBm
Radio Collision Model	1 (more collision)
Mobility Manager	LineMobilityManager

to avoid loops in the network.

5.2.7 System Model

The evaluation was done through a series of simulations. Omnet++ [1] was used as WSN simulator. Each scenario runs more than 20 times to collect the reliable results. The simulation run on a field area of $200 * 200$ meters and the radio feature microcontroller CC2420 was used as radio module. The time of simulation was run from 18 seconds up to 3000 seconds. The variety of radio channel was set up by Wireless Channel Sigma that are 0,1,3,5. Wireless Channel Sigma shows the standard deviation of communication channel variety. Radio Collision Mode was selected to 1 that puts more collision than normal. The scenario is based in mobility of Sink in the field. The Sink and some nodes are mobile based on LineMobilityManager model. The Sink moves with speed of 15 m/s into the field. The application for these scenarios is CtpTesting that was designed to test CTP functionality. It sends 5 packets every second with the payload of 2000 bytes.

5.2.8 EVALUATION

The results were collected in different scenarios with different number of nodes in the field. In general CTP and RCTP behave the same in quiet scenarios especially in scenarios with less than 70 nodes into the field. The results show the difference between CTP and RCTP when the radio channel is busier especially in scenarios with more than

70 nodes in the field.

The application layer measures the level of packet latency in (ms). Figure 5.4 shows

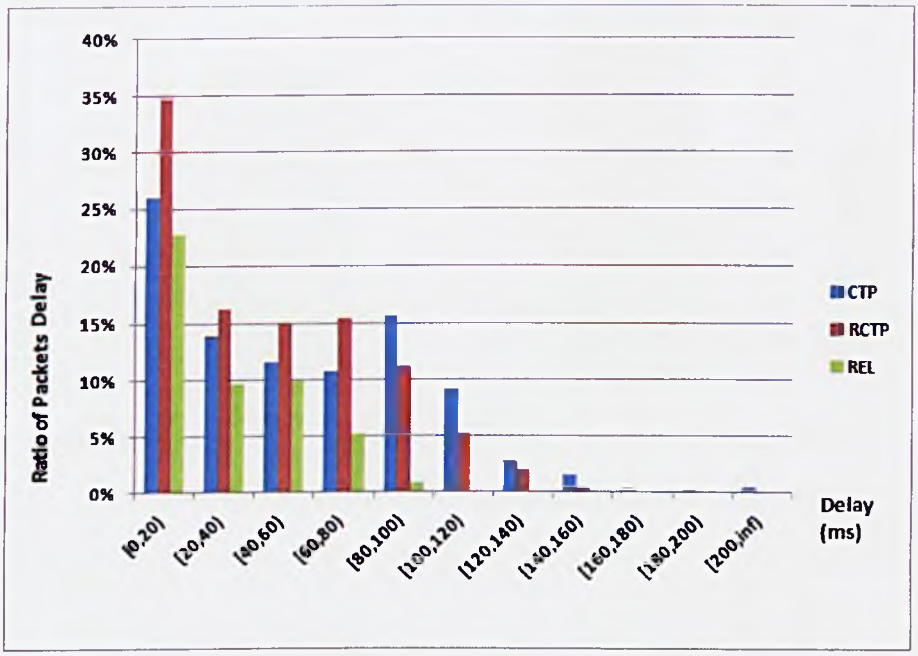

FIGURE 5.4: Packet Delivery Delay time in CTP, RCTP and REL

the packet delivery delay level in three routing protocols: CTP, RCTP and Routing by Energy and Link-quality indicator (REL). The results show that RCTP has better performance than CTP and also REL in term of packet delivery delay. RCTP has delivered in average about 35% of packets in less than 20 ms instead of CTP that it delivered about 26%. It is obvious that RCTP has better performance than CTP in term of packet delivery delay time.

Application layer also measures the percentage of packet delivery ratio that it shows the amount of packets that successfully received in their destinations.Figure 5.5 shows the packet delivery ratio in three routing protocols. The results show CTP and RCTP has the same result in term of packet deliver ratio in scenarios that wireless nodes are less than 70 nodes. When the nodes in the fields increase more than 70 nodes, it is obvious that RCTP can deliver more packets than CTP. In scenario with 100 nodes in the fields, RCTP packet delivery ratio is 55% where CTP can manage to deliver around 47% of the packets.

Figure 5.6 shows the parameters of collection tree protocol engine. It is obvious that the most parameters do with better performance in RCTP than CTP e.g. RX-forwarded total that shows the number of packets that received after forwarding, it is slightly better in RCTP than CTP. Figure 5.7 shows energy consumption based on received and transferred packets by collection tree protocol engine. It shows that RCTP performs better than CTP in term of energy consumption in nodes.

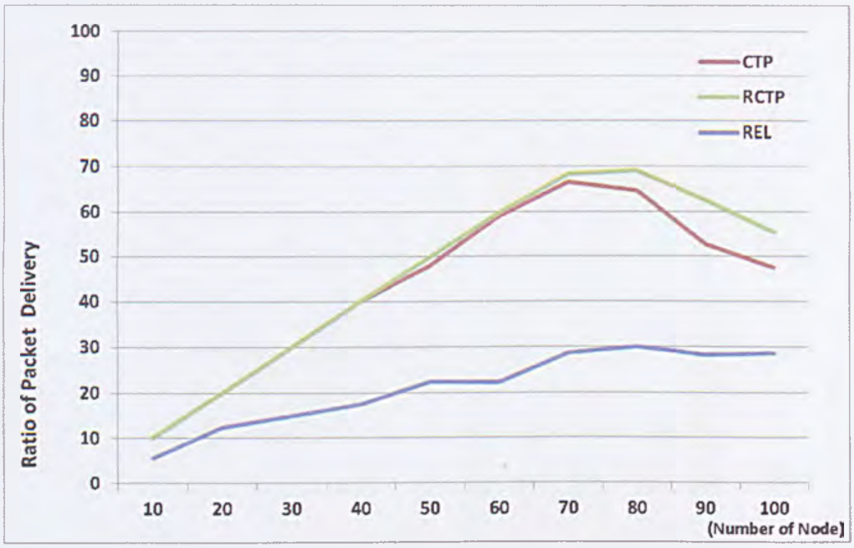

FIGURE 5.5: packet delivery ratio based on CTP, RCTP and REL

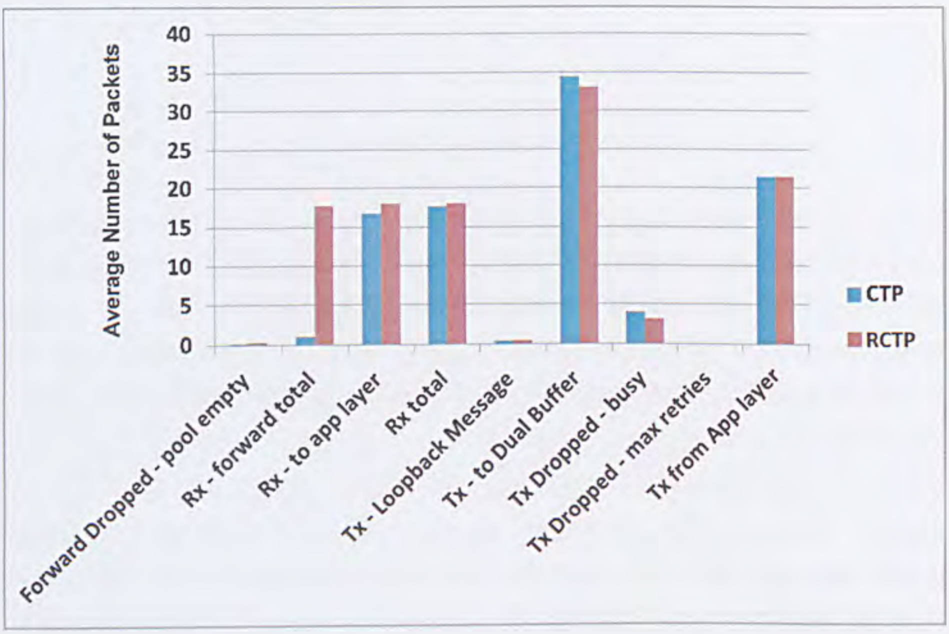

FIGURE 5.6: Collection Tree Protocol Engine Parameters

Figure 5.8 shows the ratio of Radio Reception with Interference based on three routing protocols: CTP, RCTP and REL in different scenarios. RCTP performs slightly better than CTP in packet reception with no interference and also in failed reception in case of existing interference. It can be considered as a result of finding better parents to form a tree topology in different scenarios.

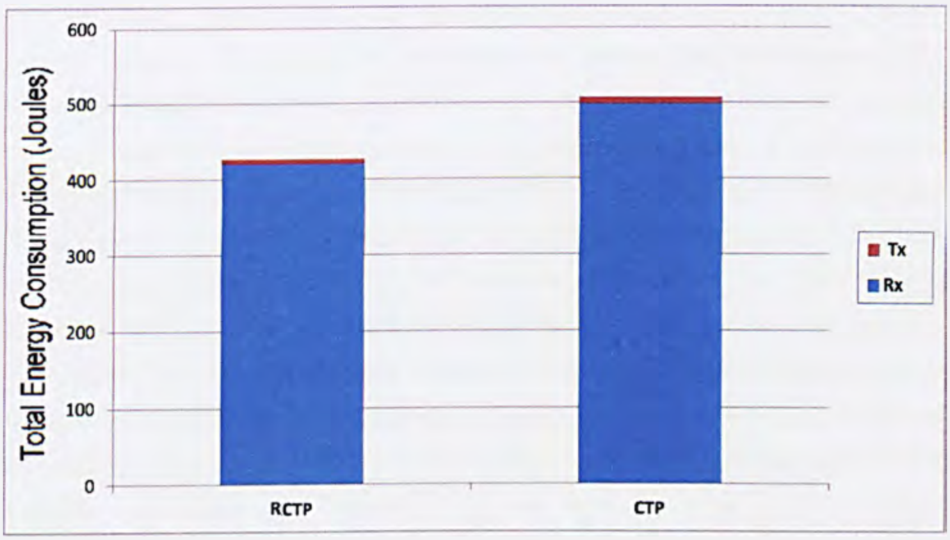

FIGURE 5.7: Energy Consumption in CTP and RCTP

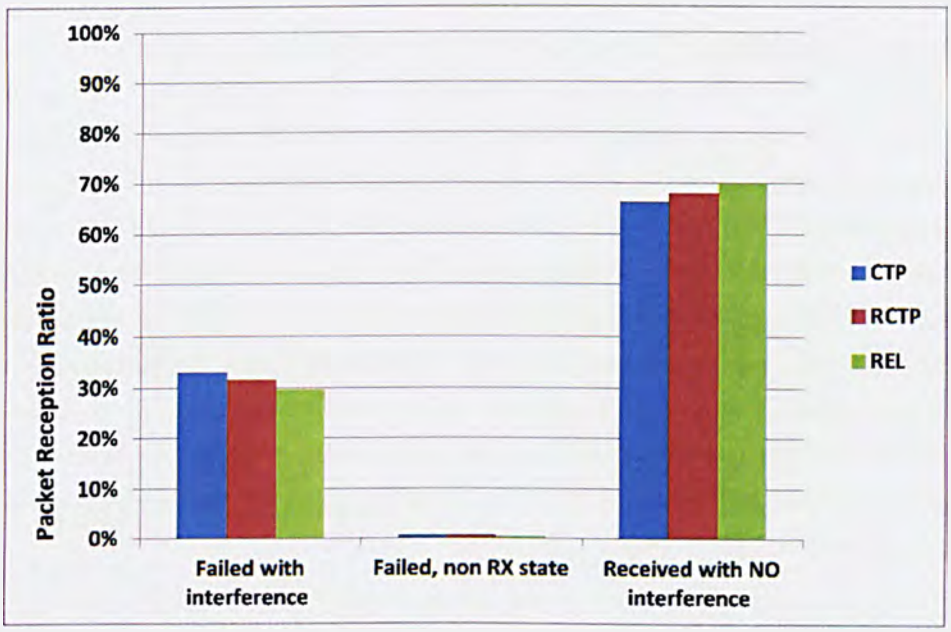

FIGURE 5.8: Radio Reception and Interference

5.3 Position Based and Energy-efficient Routing Protocols

ERCRP is one of the many-to-one routing protocols which is based on spanning tree method [245][246]. ERCRP establishes at least one data collection tree with a Sink as the root node in the topology. All data which is produced by sensors is forwarded to the root node. Each node is not only responsible for sending its own data; however, also for relaying other's data so that they cover more distance to root node [197]. Trickle algorithm [248] optimises the overhead cost and makes the routing protocols more flexible. The control protocol packets are sent based on changes in topology and if there is no change in topology, the interval times (duration) between when updates are sent is increased with a resulting decrease in the number of control packets. It also makes routing protocols react quickly and be adaptable to any changes in topology and if any change in topology is sensed then the interval time is reset to minimum in order to update the topology very quickly [235]. ERCRP maintains the topology with the low level of overhead and also uses link-quality metric AETX instead of ETX that was shown to be more stable [13]. ERCRP enhances greedy forwarding by considering congestion and packet delivery information when looking the best path to the destination. ERCRP uses a mechanism for choosing a parent that it is based on AETX value of each neighbour plus the AETX value of the link that in the total chooses the best possible parent between existing qualified neighbours. ERCRP avoids the occurrence of a loop in the topology. It also uses the Rainbow mechanism to make ERCRP able to avoid dead-end routes. ERCRP uses a new mechanism to make it more energy-efficient than other existing algorithm. The proposed protocol uses a unique restricted PFR based on the algorithm that limits the number of nodes that receive the packets. It is a cross-over routing protocol that decreases the RF range to the minimum to cover the nodes parent only and for this reason other nodes do not consume energy to receive the signal and retransmit them. GRPs make all nodes able to learn more about its location and also the position of neighbours and the Sink. GRPs can make decisions with better performance in real-time and dynamic scenarios. GRP decreases the overhead of the protocols significantly and makes them more efficient. The disadvantages of GRP are the cost of additional hardware and also the accuracy of location determination which depends on the mechanism and techniques whether the location of each node are calculated. Some techniques such as radio ranging have less accuracy and some techniques such as GPS have more accuracy [249][250].

5.3.1 Motivation

WSN consists of small devices for while energy consumption is a vital. Any protocols that are used have to be energy-aware. ERCRP is a lightweight, simple reliable, efficient, best-effort, many-to-one routing protocol. Whereas the foundation for sensor applications can work on top of the network layer. Decreasing the number of nodes that receive unrelated signals decrease the number of retransmissions can save more energy. Energy in a transponder is based on the range of the coverage by RF, energy consumed in transponder being proportional to the square of RF range radius. Any reduction in RF transmission range can save significant energy in wireless nodes.

5.3.2 Design

5.3.3 Parent Selection in ERCRP

ERCRP uses AETX in all calculations instead of ETX as link-quality metric. It also uses a novel technique in parent selection procedure. Parent selection procedure is repeated periodically or it is run when the network detects inconsistency. Inconsistency happens when; a node receives a beacon that asks it to reconsider the topology, a neighbour comes out from congestion mode, a parent is unreachable or the node receives a data-packet that the AETX value of sender is equal or smaller than its own AETX. A parent node is selected from among the neighbours that are not congested and are not the child of the current node where all eligible neighbours have reported their AETX values. The parent cost is calculated as [13]:

$$AETX_j = AETX_{ji} + AETX_i \tag{5.7}$$

$$Parent_j = Min_{i \in Neighboursofj}(AETX_{ji} + AETX_i) \tag{5.8}$$

Where $AETX_j$ denotes AETX value of node j and $AETX_{ij}$ denotes link-quality value between node i and node j. ERCRP uses the link-layer distance estimation in each packet to validate the topology. If the distance estimate of the packet that is received at this node is equal or less than the distance estimate of its own then the topology needs to be revised and ERCRP takes an action to review the topology. This is another ERCRP mechanism to avoid loops in the network [13].

5.3.4 Loop avoidance in ERCRP

ERCRP uses a detection mechanism during data-packet transmission to validate the routing path and topology. This mechanism makes ERCRP avoid loops by checking the previous 7 nodes that packet comes through. If the current node is in the list of 7 last nodes, a network loop occur and reconsidering the topology is needed to put this in order. ERCRP uses a detection mechanism during data-packet transmission to validate the routing path and topology. This mechanism makes ERCRP avoid loops by checking the last 7 nodes that packet comes to this node through.

5.3.5 Related Works

O-CTP [239] is based on investigation of WSN routing protocols behaviour in networks that are affected by interference. O-CTP is a hybrid routing protocol that uses the high packet delivery ratio of opportunistic routing in error-prone networks and also is energy efficiency routing protocol. ICTP [247] uses of both long with good link-quality path and short with bad link-quality. It may decrease the reliability; however, it improves efficiency to avoid congestion. They have shown that energy consumption in ICTP is less than CTP in same scenarios based on reducing possibility of congestion. BCTP [251] is balanced version of CTP that enables the network to avoid the heavy traffic nodes. It uses average transmission rate as a metric. BCTP was evaluated by a test-bed and the results show that the load in hot spots drop by 61.9%. (give ref) RAP [252] is a real-time GRP which uses the velocity of each packet as a gradient to deliver the packets. Each velocity is calculated based on the distance to the destination and its delivery deadline. The packets with higher velocities can be sent earlier than packets with lower velocities. However, this protocol does not provide any guarantee in end-to-end real-time delivery. EDF [253] provides a real-time decentralised scheduling that guarantees the end-to-end delivery; however, it needs a priori defined schedule that is not feasible in most of WSNs applications. SPEED [254] is a real-time GRPs that uses neighbour information to estimate distance in routing protocol. SPEED lets each node decides which neighbour be the next hop forwarding node and in case of not existing any suitable node in neighbours, the node with the lowest miss ratio is used for forwarding the packets. MMSPEED [255] is an enhanced version of SPEED that focuses on reliability levels and multiple timelines. It uses resources with better performance than SPEED. RTLD [253] is a real-time routing protocol with load balancing based on link-quality, packet delay and remaining power in the next hop neighbours. All the above mentioned protocols are based on Two Dimension Coordinate System (2D) coordinate systems and need neighbour information to decide about next hop to forward the packets.

5.3.6 ERCRP

It is assumed that the nodes are deployed in a static scenario in a uniform randomly distributed manner. All nodes are in the same spherical transmission range and they are identical and every node knows its own location. The location of each node is represented in a Cartesian coordinates system (X,Y) which can be obtained from GPS module. The GPS module calculates the position of each node and it is used only at the time of deployment and after that it is switched off to save energy[16]. The goal of the proposed protocols is to minimize the RF range based on parent location. After parent selection in ERCRP, in PFR, the position of parents is sent to all its child(s). PFR technique in ERCRP uses the position's data to minimize the RF range. The RF range is calculated in location management phase and the transponder of the node set the transponder power to cover only the minimised RF range that is calculated based on node and parent locations. Location management phase is one of the main factors

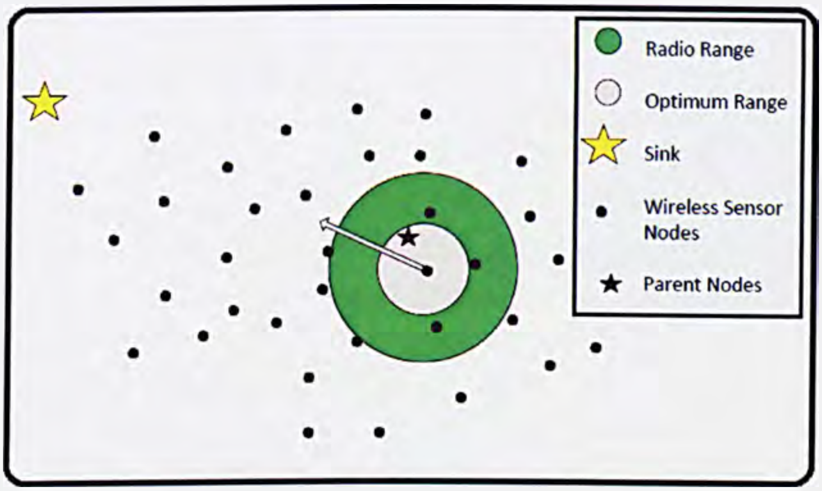

FIGURE 5.9: Optimum Transmission Rang

in ERCRP. The Parent Forward Region (PFR) is calculated in location management phase to ideally contain minimum forwarding nodes to limit the number of retransmitting nodes in group of one hop neighbours. In PFR, the parent location denotes as (Xp, Yp) and the node location denotes as (Xn, Yn). The parent location information is provided to nodes during parent selection mechanism. Then the neighbours' node calculates the distance between node to its parent.

$$MTD = \sqrt{(Xp - Xn)^2 + (Yp - Yn)^2} \tag{5.9}$$

In forwarding management phase to avoid redundant packet transmission in the network, the transponder power set to cover only the Minimum Transmission Distance (MTD). The second goal of proposed protocols is to use the Rainbow mechanism to solve Void Node Problem (VNP) or nodes in dead-end routes to enhance the reliability of protocol and increase the packet delivery ratio. The proposed protocol has three main functionalities, parent selection that selects the best parent from the qualified neighbours of the node, location management that calculates the position of each node and the minimum radius of RF range and the VNP handling that avoids to forward the packets toward the hole or dead-end.

5.3.7 System Model

The system evaluation was performed through massive simulations. Omnet++ [1] was used as WSN simulator and Matlab was used for simulating the energy model. Each scenario runs more than 20 times to collect the reliable results with confidence intervals of 0.95.

5.3.8 System Channel Model

The simulations run on a field area of $200 * 200$ meters and the radio feature microcontroller CC2420 [195] was used as radio module operating on the IEEE 802.15.4 standard [256]. Simulations were run from 18 seconds up to 3000 seconds. The variety of radio channel was set up by Wireless Channel Sigma that are 0,1,3,5. Wireless Channel Sigma shows the standard deviation of communication channel diversity. The received signal strength at a wireless node in real scenarios does not only depend on distance from the transmitter; however, also on shadowing effects. The sigma parameters represent the random shadowing effects in the wireless channel parameters. Radio Collision Mode was selected to 1 that puts more collision than normal. The application for these scenarios is CtpTesting that was designed to test CTP functionality. It sends 5 packets every second with the payload of 150 bytes.

5.3.9 Performance Evaluation

The results were collected in different scenarios in different number of nodes in the field, RF range and the number of packets with confidence intervals of 0.95. In this experience CTP, ERCRP and Directed Flooding Routing Protocol (DFRP) were compared. Table 5.2 shows the parameters of simulations. Omnet++ [1] was employed as simulation to measures PDR and delay. End-to-end delay was measured in all three routing protocols and also PDR. Matlab was used for simulating the energy model. The total energy, number of retransmitted messages and also numbers of received messages in different scenarios were investigated in this research. The scenarios contain different wireless nodes in the field, different RF range and also different number of messages.

TABLE 5.2: Omnet ++ Simulation Parameters in ERCRP

Simulation Parameters	
Number of nodes	10,20,..,100
Node Deployment	Random
Field Area	200 X 200 (m)
E_{elec}	50 nj/bit
E_{amp}	100 $pj/bit/m^2$
Simulation time	18-3000 Sec
Wireless Channel Sigma	0,1,3,5
Radio Parameters	CC2420
Routing Protocols	CtoNoe, ERCRP, DFRP
Application	CtpTesting
App Packet Rate	5
APP Payload	Constant 150 bytes
Max Frame Size	2500 byte
Radio Tx Power	-5 dBm
Radio Collision Model	1

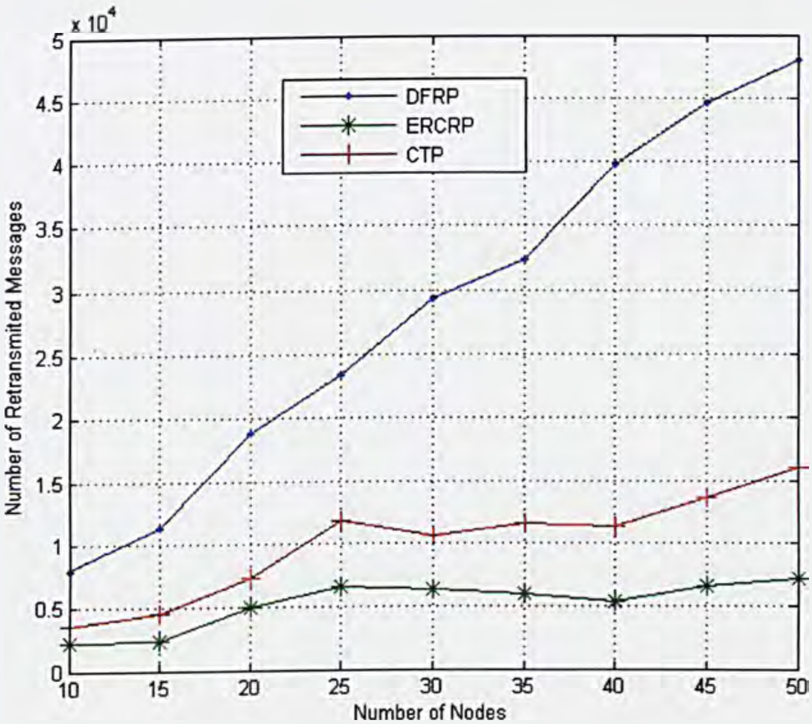

FIGURE 5.10: Retransmitted Messages and Number of Nodes

Figure 5.13 shows the number of received and retransmitted messages and also the total energy consumption in different radio frequency ranges in wireless nodes in the field.

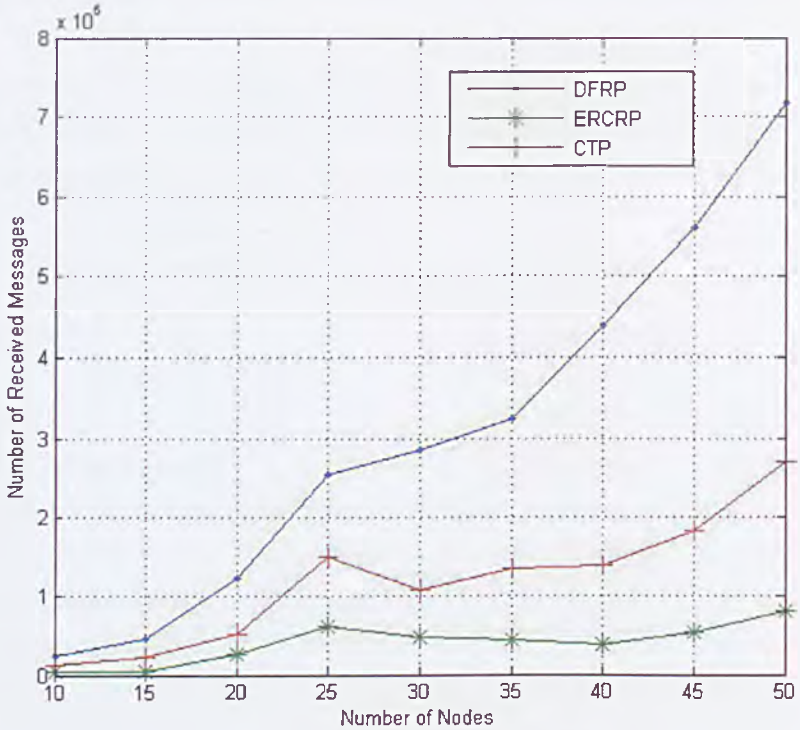

FIGURE 5.11: Received Messages and Number of Nodes

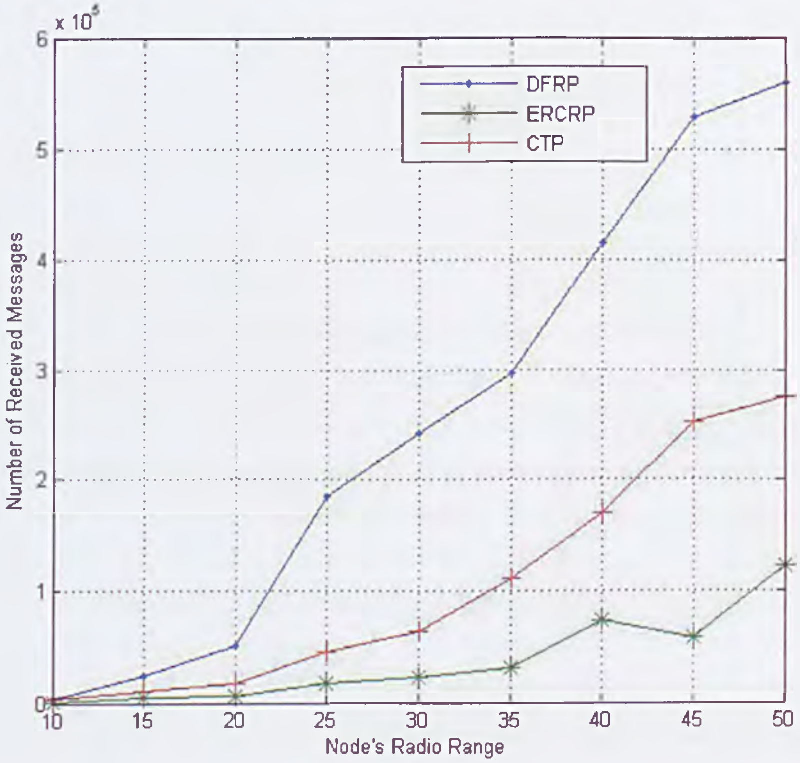

FIGURE 5.14: Received Messages and Radio Range

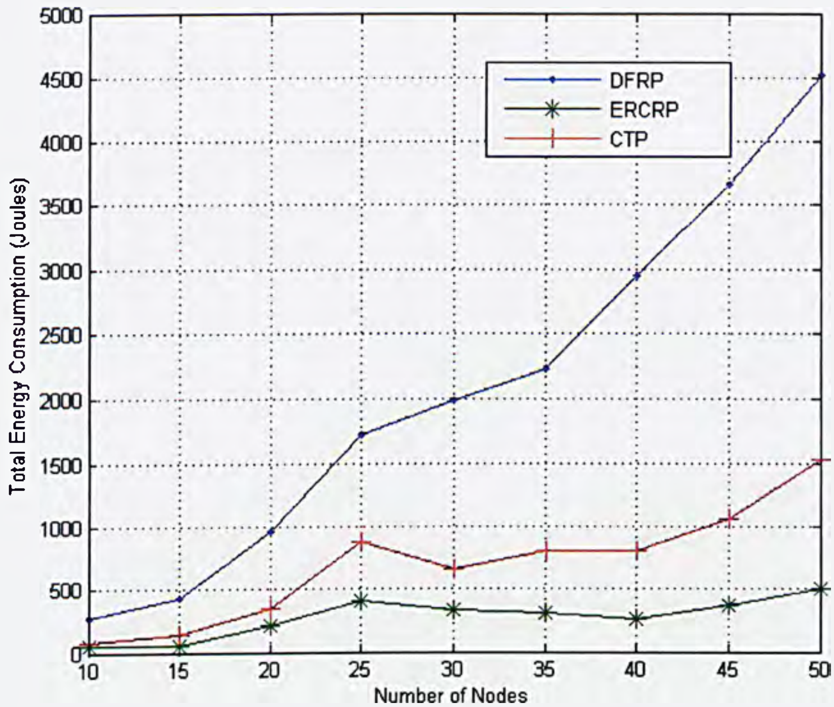

FIGURE 5.12: Total Energy Consumption and Number of Nodes

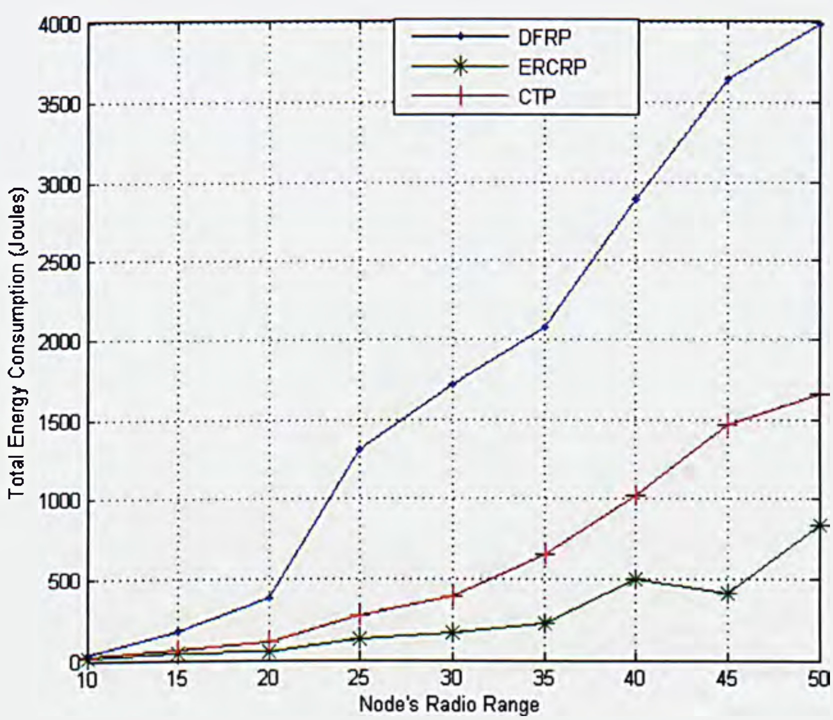

FIGURE 5.15: Total Energy Consumption and Radio Range

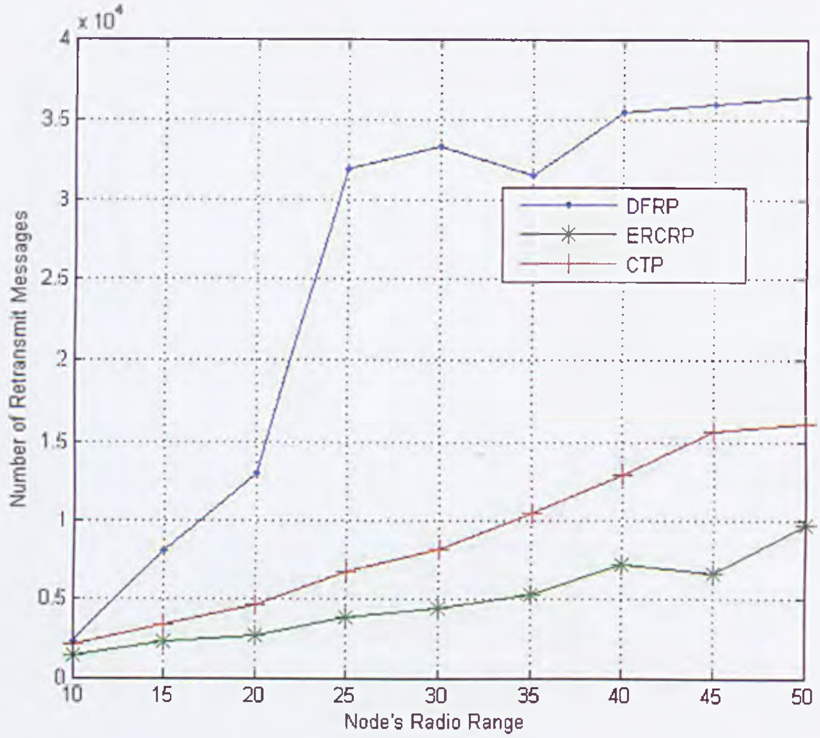

FIGURE 5.13: Retransmitted Messages and Radio Range

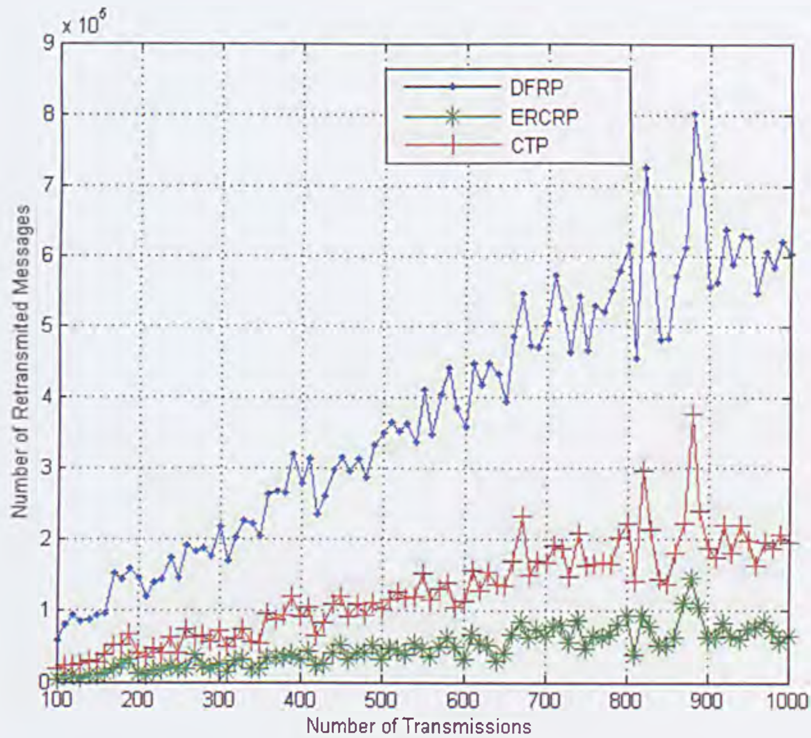

FIGURE 5.16: Number of Retransmitted messages in ERCRP, CTP and DFRP

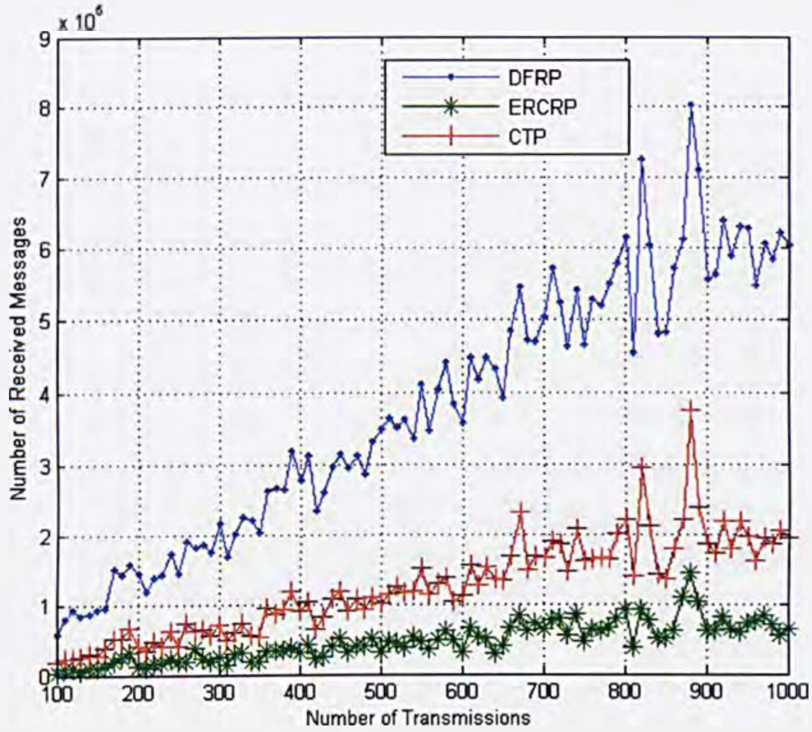

FIGURE 5.17: Number of Received messages in ERCRP, CTP and DFRP

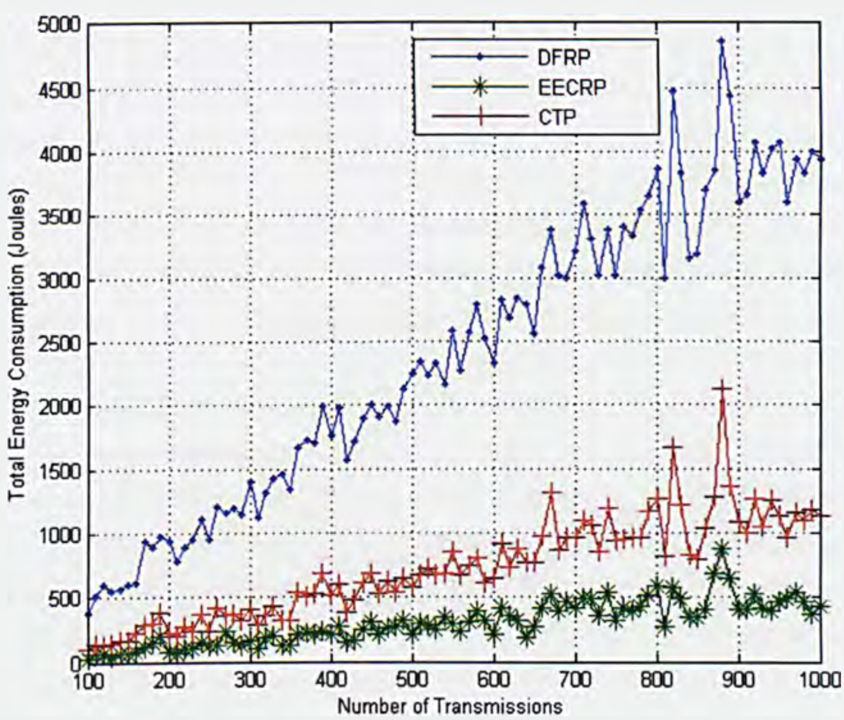

FIGURE 5.18: Total Energy Consumption in ERCRP, CTP and DFRP

5.4 3DPBARP

The main duty of WSN as a distributed computing network is collecting data from a large number of nodes that have the capacity to sense the environment, process data and also communicate over a short range. WSN applications collect data from wireless sensors and an appropriate routing protocol can help them to achieve scalability and improve performance. In real-life's WSN applications, wireless sensor nodes are deployed in 3D environments such as mountains or sea surfaces. Most of the Position Based routing protocols consider the topology as a two-dimension scenarios. In this research deploying wireless sensors in 3D environments are considered. WSNs work based on limited power supply. The WSN's energy is provided by battery or energy harvesting systems. Energy-aware design for WSNs makes them be able to work with lower energy that can be provided through very limited energy captures from an ambient energy source such as solar cells or vibration in environment. In case of using battery as power source for supplying energy to WSN, the energy-aware designed make the sensors work with longer life-time. Energy-efficient systems and designs make WSN be able to be used by consumer electronics in some applications.

Data collection protocols can form planner or tree topology that can be in cluster or mixed data collection form. 3DPBARP is one of the many-to-one routing protocols which is based on spanning tree method [245][246]. 3DPBARP establishes at least one data collection tree with a Sink as the root node in the topology. All data which is produced by sensors are forwarded to the root node. Each node is not only responsible for sending its own data; however, also for relaying other's data, so that they cover more distance to root node [197]. Trickle algorithm [248] optimises the overhead cost and makes the routing protocols more flexible. The control protocol packets are sent based on changes in topology and if there is no change in topology, the interval times (duration) between when updates are sent is increased with a resulting decrease in the number of control packets. It also makes routing protocols react quickly and be adaptable to any changes in topology and if any change in topology is sensed then the interval time is reset to minimum in order to update the topology very quickly [235]. 3DPBARP enhances greedy forwarding by considering congestion and packet delivery information when looking the best path to the destination. 3DPBARP uses a mechanism for choosing a parent that it is based on Spherical Distance (SD) value of each neighbour that chooses the best possible parent between existing qualified neighbours. 3DPBARP avoids the occurrence of a loop in the topology by using some mechanism. It also uses the Rainbow mechanism to make 3DPBARP be able to avoid dead-end routes. 3DPBARP uses a new mechanism to make it more energy-efficient than other existing algorithm. The proposed protocol uses a unique restricted PFR based on the algorithm that limits the number of nodes that receive the packets. It decreases the RF range to the minimum to cover the nodes parent only and for this reason other nodes do not consume energy to receive the signal and retransmit them. GRPs make all nodes be able to learn more about its location and also the position of neighbours and the Sink. GRPs can make decisions with better performance in real-time and dynamic scenarios. GRPs decrease the overhead of the protocols significantly and makes them more efficient. The disadvantages of GRPs are the cost of additional hardware and also the accuracy of location determination which depends on the mechanism and techniques whether the location of each node is calculated. Some techniques such as radio ranging have less accuracy and some techniques such as GPS have more accuracy [249][250].

5.4.1 Related Works

Previous and related works are considered in this section. Data collection protocols based on CTP are consider in 2D and then 3D routing protocol systems are studied later.

O-CTP [239] is based on investigation of WSN routing protocols behaviour in networks that are affected by interference. O-CTP is a hybrid routing protocol that uses the high packet delivery ratio of opportunistic routing in error-prone networks and it also is energy efficiency routing protocol[18]. ICTP [247] uses of both long with good link-quality path and also short with bad link-quality. It may decrease the reliability; however, it improves efficiency to avoid congestion. They have shown that energy consumption in ICTP is less than CTP in same scenarios based on reducing possibility of congestion. BCTP [251] is balanced version of CTP that enable the network to avoid the heavy traffic nodes. It uses average transmission rate as a metric. BCTP was evaluated by a test-bed and the results show that the load in hot spot drops by 61.9%. RAP [252] is a real-time GRP which uses the velocity of each packet as a gradient to deliver the packets. Each velocity is calculated based on the distance to the destination and its delivery deadline. The packets with higher velocities can be sent earlier than packets with lower velocities. However, this protocol does not provide any guarantee in end-to-end real-time delivery. EDF [253] provides a real-time decentralised scheduling that guarantee the end-to-end delivery; however, it needs a priori defined schedule that is not feasible in most of WSNs applications. SPEED [254] is a real-time GRPs that uses neighbour information to estimate distance in routing protocol. SPEED lets each node decides which neighbour be the next hop forwarding node and in case of not existing any suitable node in neighbours, the node with the lowest miss ratio is used for forwarding the packets. MMSPEED [255] is a enhanced version of SPEED that focused on reliability levels and multiple timeline. It uses resources with better performance than SPEED. RTLD [253] is a real-time routing protocol with load balancing based on link-quality, packet delay and remaining power in the next hop neighbours. All the above mentioned protocols are based on 2D coordinate systems and need neighbour information to decide about next hop to forward the packets. ABLAR [257] is a 3D GRP that delicate to VNP and it restricts the packet forwarding to a cubical region only. 3D Greedy routing[258] is a 3d GRP that is based on density populated of wireless nodes and it also has issue regarding VNP in low density populated nodes' scenarios. 3DPBARP[250] is a 3D GRP that control the number of forwarding nodes and delivers packets within a specific deadline. In this protocol, the forwarding decisions depend on the expected number of nodes toward the Sink and also the queuing delay in the forwarding nodes.

5.4.2 Motivation

WSN consists of small devices for while energy consumption is a vital. Any protocols that are used have to be energy-aware. 3DPBRP is a 3D and position based version of CTP as a lightweight, simple reliable, efficient, best-effort, many-to-one routing protocol. Using the CTP concept in a 3D routing protocol is one of the motivations of this research. Adding energy consuming efficiency in current routing protocols is another motivation for tis research. Decreasing the number of nodes that receive unrelated signals decreases the number of retransmissions and can save more energy. Energy consuming in a transponder is based on the range of the coverage by RF, energy consumed in transponder being proportional to the square of RF range radius. Any reduction in RF transmission range can save significant energy in wireless nodes.

5.4.3 3DPBARP

It is assumed that the nodes are deployed in a static scenario and in a uniform randomly distributed manner. All nodes are in the same spherical transmission range and they are identical and every node knows its own location. The location of each node is represented in a Cartesian coordinates system (X,Y,Z) which can be obtained from GPS module. The GPS module calculates the position of each node and it is used only at the time of deployment and after that it is switched off to save energy. The goal of the proposed protocols is to minimize the RF range based on parent location. After parent selection in PFR, the position of parents is sent to its entire child. PFR technique in 3DPBARP uses the position's data to minimize the RF range. The RF range is calculated in location management phase and the transponder of the node set the transponder power to cover only the minimised RF range that is calculated based on node and parent locations. Location management phase is one of the main factors in 3DPBARP. The Parent Forward Region (PFR) is calculated in location management

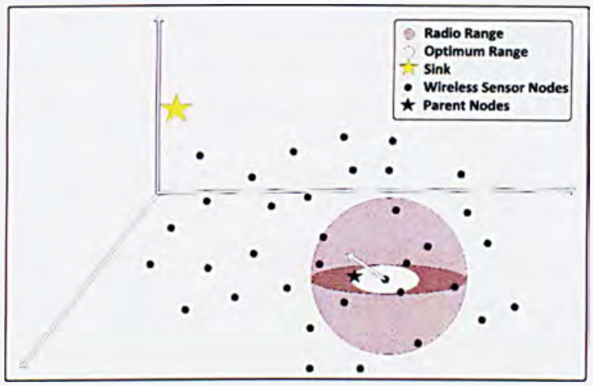

FIGURE 5.19: Optimum Transmission Rang

phase to ideally contain minimum forwarding nodes to limit the number of retransmitting nodes in group of one hop neighbours. In PFR, the parent location denotes as (Xp, Yp, Zp) and the node location denotes as (Xn, Yn, Zn). The parent location information is provided to nodes during parent selection mechanism. Then the neighbours' node calculates the distance between node to its parent. In forwarding management phase to avoid redundant packet transmission in the network, the transponder power set to cover only the Minimum Transmission Distance (MTD).

$$MTD = \sqrt{(Xp - Xn)^2 + (Yp - Yn)^2 + (Zp - Zn)^2} \tag{5.10}$$

Where (X_p, Y_p, Z_p) denotes to position of parent and (X_n, Y_n, Z_n) denotes to position of the node. Each node selects its parent from a group of its qualified neighbours that have already advertised their Minimum Root Distance (MRD) values. The neighbour that is selected as the node's parent is the neighbour with the least MRD value. The second goal of proposed protocols is to use the Rainbow mechanism to solve VNP to enhance the reliability of protocol and increase the packet delivery ratio. The proposed protocol has three main functionalities, parent selection that selects the best parent from the qualified neighbours of the node, location management that calculates the position of each node and the minimum radius of RF range and the VNP handling that avoids to forward the packets toward the hole or dead-end.

5.4.4 Parent Selection in 3DPBARP

A few nodes in the network advertise themselves as Sink. Other nodes in the network form a tree-network topology and send data toward these root nodes. Each node chooses the path to root by selecting the next hop based on a routing gradient [11]. 3DPBARP uses Surface Distance (SD) as its routing gradient. Each node is labelled as a MRD value. Roots MRD value is 0 and others nodes' value is calculated by (2).

$$Node(MRD) = Parent(MRD) + Link(SD) \tag{5.11}$$

$$Link(SD) = \sqrt{(Xp - X)^2 + (Yp - Y)^2 + (Zp - Z)^2} \tag{5.12}$$

Where $Link(SD)$ denotes to surface distance of node and (X_p, Y_p, Z_p) denotes to position of parent an (X, Y, Z) denotes to position of the node. Each node selects its parent from a group of its qualified neighbours that have already advertised their MRD values. The neighbour that is selected as the node's parent is the neighbour with the least MRD value.

5.4.5 Loop avoidance in 3DPBARP

3DPBARP uses a detection mechanism during data-packet transmission to validate the routing path and topology. This mechanism makes 3DPBARP avoid loops by checking the previous $N(l)$ nodes that packet comes through. If the current node is in the list of $N(l)$ last nodes, a network loop occurs and reconsidering the topology is needed to put in order. 3DPBARP uses a detection mechanism during data-packet transmission to validate the routing path and topology. This mechanism makes 3DPBARP avoid loops by checking the last $N(l)$ nodes that packet comes to this node through. $N(l)$ sets in the initiate stage.

5.4.6 System Model

The system evaluation was performed using extensive simulations. Omnet++ [1] was used as WSN simulator and Matlab was used for simulating the energy model. Each scenario was run more than 20 times to collect the reliable results with confidence intervals of 0.95.

5.4.7 System Channel Model

The simulations run on a field area of $200 * 200 * 100$ meters and the radio feature micro-controller CC2420 was used as radio module operating on the IEEE 802.15.4 standard [256]. Simulations were run from 18 seconds up to 3000 seconds. The variety of radio channel was set up by Wireless Channel Sigma that are 0,1,3,5. Wireless Channel Sigma shows the standard deviation of communication channel diversity [16]. The received signal strength at a wireless node in real scenarios does not only depend on distance from the transmitter; however, also on shadowing effects. The sigma parameters represent the random shadowing effects in the wireless channel parameters. Radio Collision Mode was selected to 1 that puts more collision than normal.

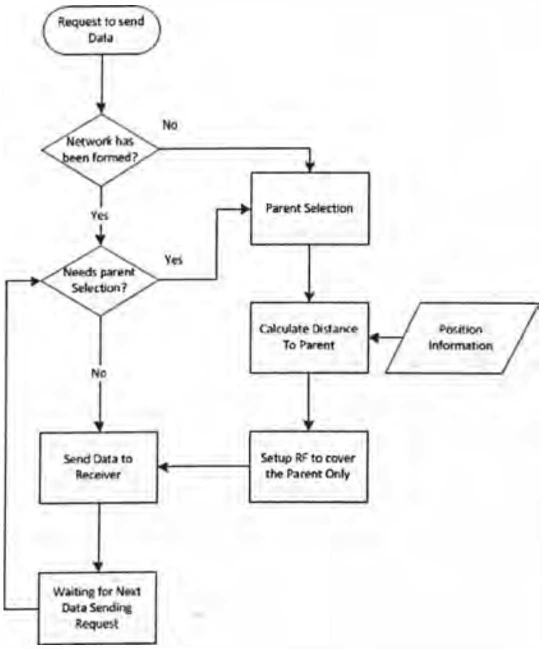

FIGURE 5.20: 3DPBARP Algorithm

5.4.8 Performance Evaluation

The results were collected in different scenarios in different number of nodes in the field, RF range and the number of packets with confidence intervals of 0.95. In this experience 3DPBRP as 3D and position based version of CTP, 3DPBARP and DFRP were compared. Table 5.3 shows the parameters of simulations. Omnet++ [1] was employed as simulation to measures PDR and delay. End-to-end delay was measured in all three routing protocols and also PDR. Matlab was used for simulating the energy model. The total energy, number of retransmitted messages and also numbers of received messages in different scenarios were investigated in this research. The scenarios contain different wireless nodes in the field, different RF range and also different number of messages.

Figure 5.21 shows the number of received and retransmitted messages and also the total energy consumption in different number of nodes in the field. Figure 5.24 shows the number of received and retransmitted messages and also the total energy consumption in different radio frequency ranges in the field. The application layer measures the level of packet latency in (ms). The results show 3DPBARP has better performance than 3DPBRP and also DFRP in term of packet delivery delay. 3DPBARP has delivered in average about 35% of packets in less than 20 ms instead of 3DPBRP that it delivered about 26%. It is obvious that 3DPBARP has better performance than 3DPBRP in term

TABLE 5.3: Omnet ++ Simulation Parameters in 3DPBARP

Simulation Parameters	
Number of nodes	10,20,..,100
Node Deployment	Random
Field Area	200 X 200 X 100 (m)
E_{elec}	50 nj/bit
E_{amp}	100 $pj/bit/m^2$
Simulation time	18-3000 Sec
Wireless Channel Sigma	0,1,3,5
Radio Parameters	CC2420
Routing Protocols	CtoNoe, 3DPBARP, DFRP
Application	CtpTesting
App Packet Rate	5
APP Payload	Constant 150 bytes
Max Frame Size	2500 byte
Radio Tx Power	-5 dBm
Radio Collision Model	1

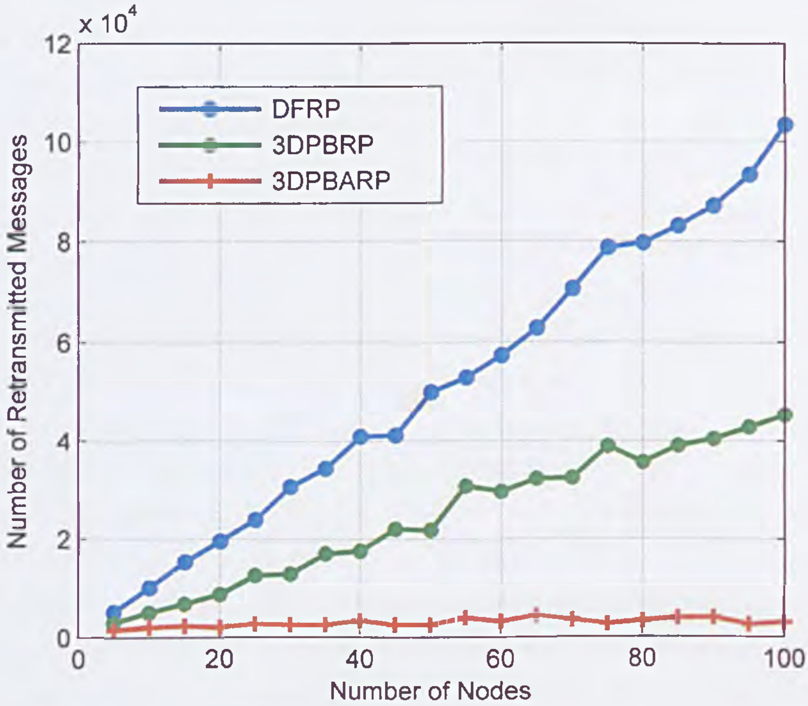

FIGURE 5.21: Retransmitted Messages and Number of Nodes

of packet delivery delay time.

Application layer also measures the percentage of packet delivery ratio that it shows the amount of packets that successfully received in their destinations. The results show 3DPBRP and 3DPBARP have the same result in term of packet delivery ratio in scenarios that wireless nodes are less than 70 nodes. When the number of nodes in the

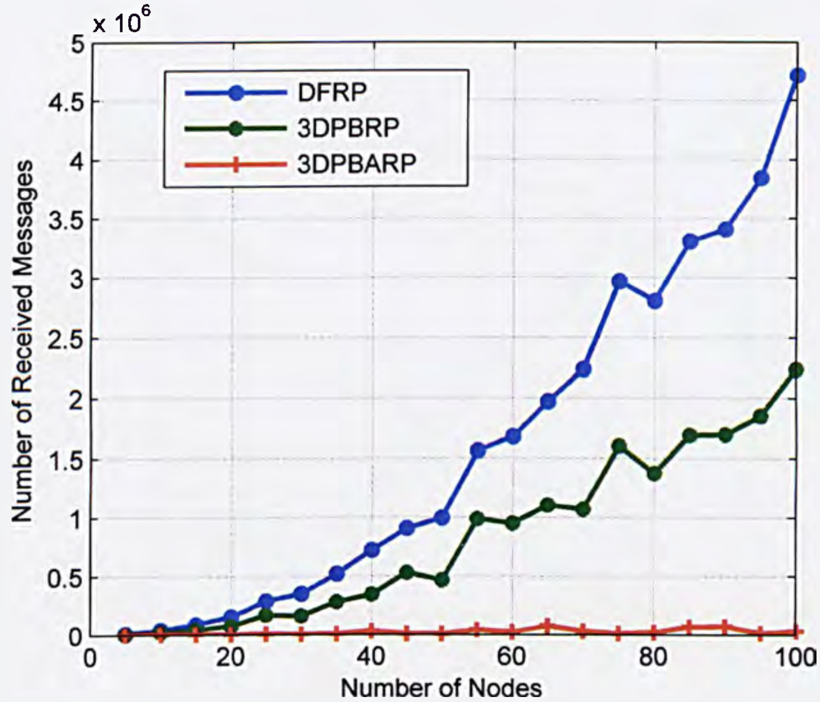

FIGURE 5.22: Received Messages and Number of Nodes

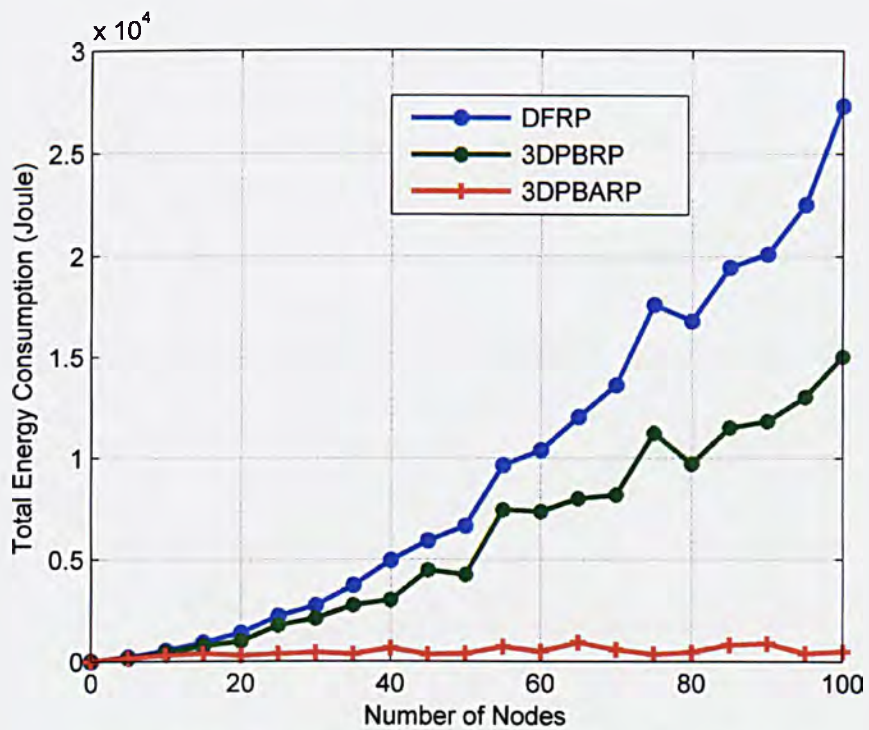

FIGURE 5.23: Total Energy Consumption and Number of Nodes

fields increases to 70 nodes, it is obvious that 3DPBARP can deliver more packets than 3DPBRP. In scenario with 100 nodes in the fields, packet delivery ratio in 3DPBARP

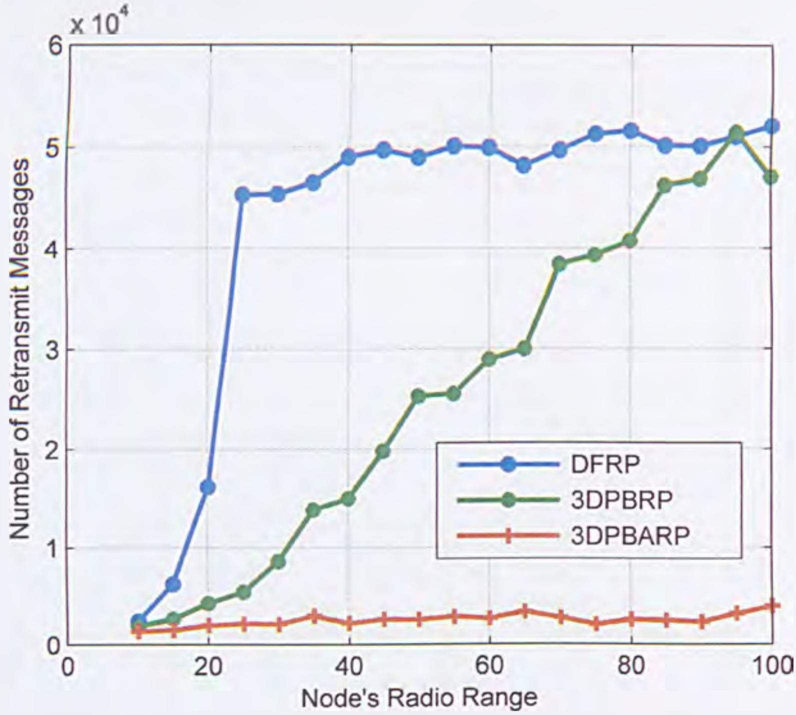

FIGURE 5.24: Retransmitted Messages and Radio Range

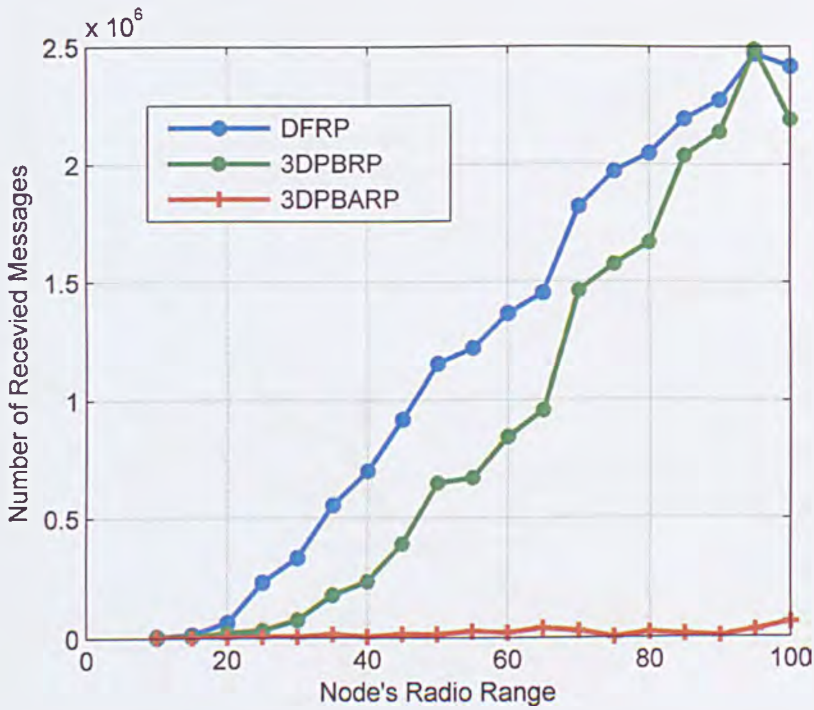

FIGURE 5.25: Received Messages and Radio Range

is 55% and 3DPBRP can manage to deliver around 47% of the packets.

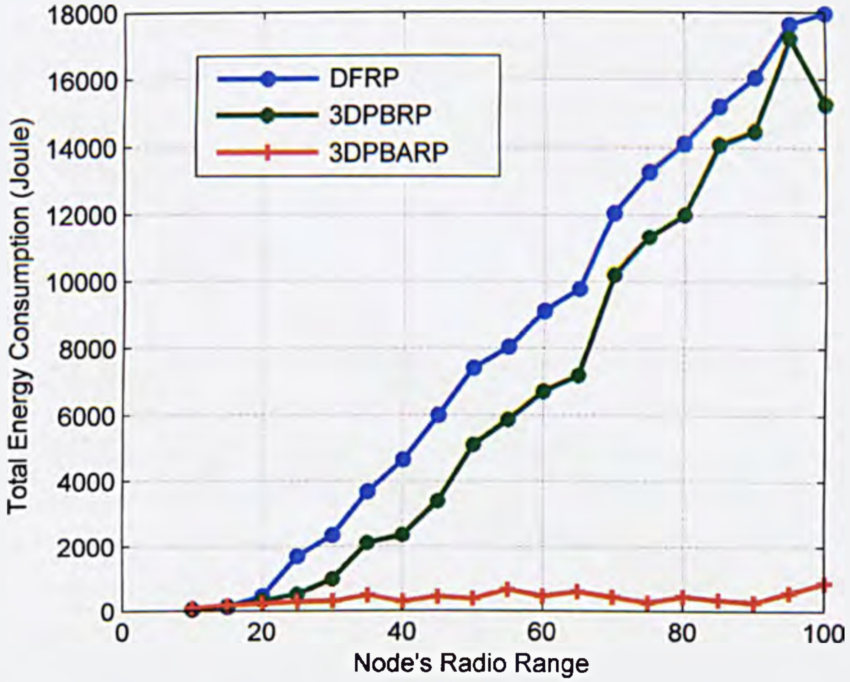

FIGURE 5.26: Total Energy Consumption and Radio Range

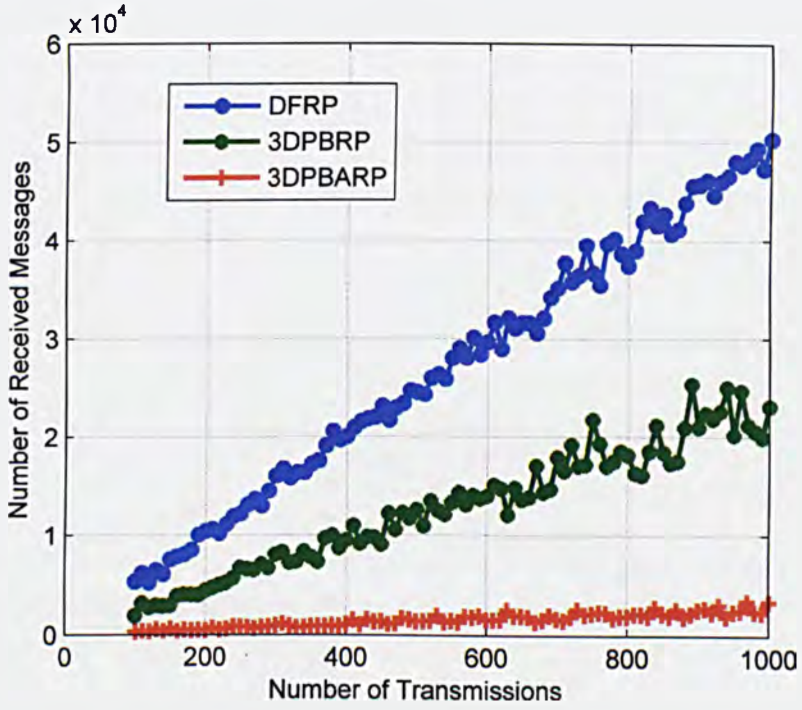

FIGURE 5.27: Number of Retransmitted messages in 3DPBARP, 3DPBRP and DFRP

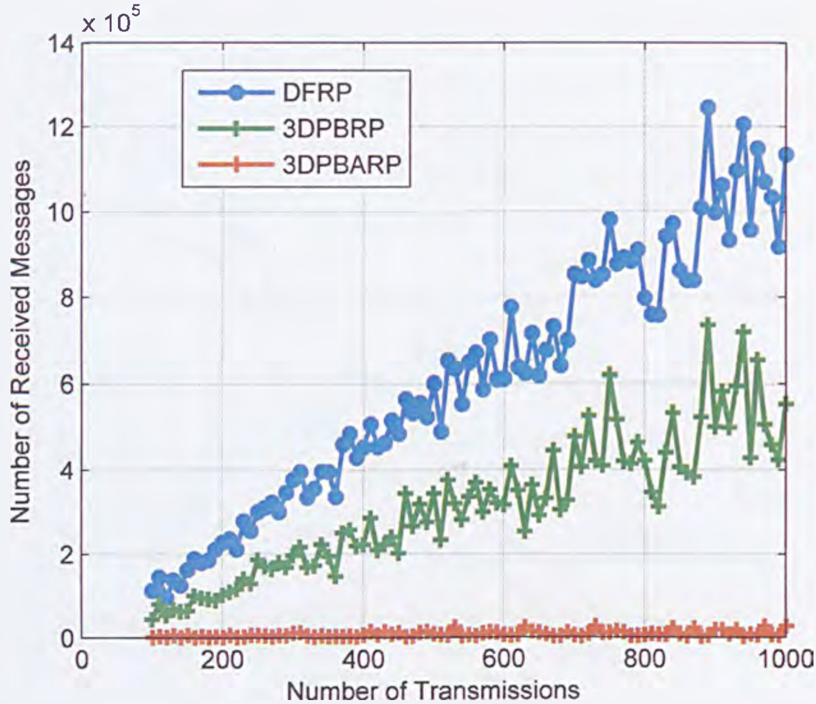

FIGURE 5.28: Number of Received messages in 3DPBARP, 3DPBRP and DFRP

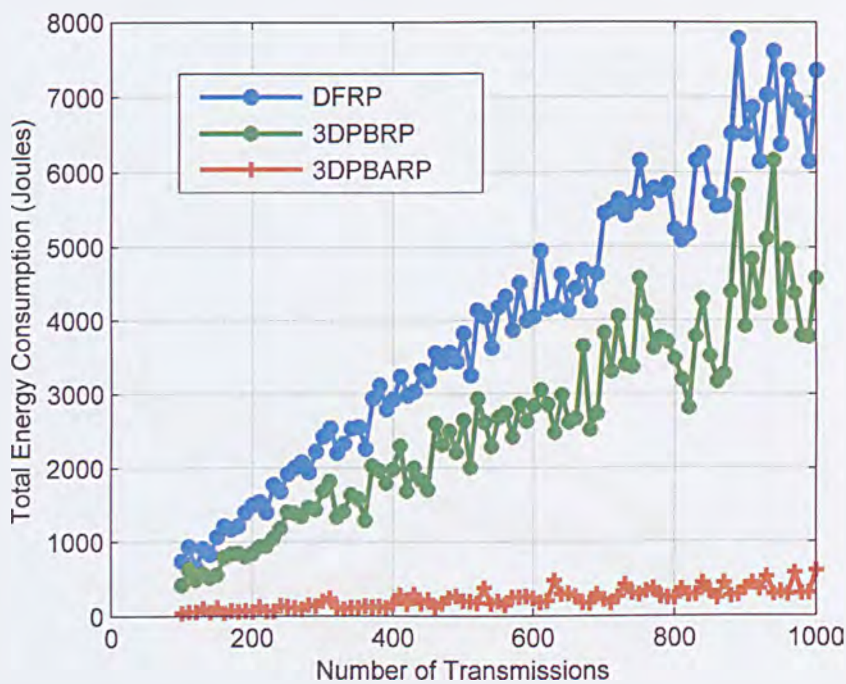

FIGURE 5.29: Total Energy Consumption in 3DPBARP, 3DPBRP and DFRP

Figure 5.27 shows the number of retransmitted messages in different number of messages scenarios. In average the 3DPBARP retransmits messages 82% less than DFRP and 48% less than 3DPBRP. Figure 5.28 shows the number of received messages in different number of messages scenarios. In average, the 3DPBARP retransmits messages 88% less than DFRP and 66% less than 3DPBRP. Figure 5.29 shows the total energy consumption in different number of messages scenarios. In average the 3DPBARP consumed energy 87% less than DFRP and 61% less than 3DPBRP.

5.4.9 Conclusion

CTP as a well-known routing protocol with light overhead is a suitable routing protocol for wireless networks with low-energy consumption. This research proposed RCTP as an enhanced version of CTP. RCTP has showed a significant performance improvement by using AETX instead of ETX. The researches show ETX has fluctuations in the real environment. RCTP performs with more stability by using AETX and also it uses a new parent selection mechanism to choose the parents with more accuracy. It also employs some techniques to avoid loops in topology. A massive simulation results prove that RCTP provides better performance in busy and noisy environments in term of packet delivery time and the ratio of successful packet delivery. It also shows better performance regarding energy consumption rather than CTP in the same scenarios. This research also proposed ERCRP as an Energy-efficient Rainbow Collection Routing Protocol. ERCRP has showed a performance improvement in packet delivery parameters by using AETX as link-quality gradient. ERCRP performs with more accuracy by using a new parent selection and the Rainbow mechanisms to choose the parents with more accuracy. It also employs techniques to avoid loops in the topology. ERCRP as a GRP decreases the RF range in each node by reducing the number of nodes which receive the signal, using a PFR technique. In PFR phase the nodes reduce the RF range to cover their parents only and not any nodes with further distance. A massive simulation on ERCRP shows a significant improvement in performance regarding energy consumption compared to CTP and DFRP in different scenarios. ERCRP shows that it can save more than 80% of the total energy consumption in the network by using the special technique in PFR. It also provides better performance in busy and noisy environments in terms of packet delivery time and the ratio of successful packet delivery. In this research, 3DPBARP is proposed as an Energy-efficient Rainbow Collection Routing Protocol. 3DPBARP has showed a performance improvement in packet delivery parameters. 3DPBARP performs with more accuracy by using a new parent selection and the Rainbow mechanisms to choose the parents with more accuracy. It also employs techniques to avoid loops in the topology. 3DPBARP as a GRP decreases the RF range in each node by reducing the number of nodes which receive the signal, using a new PFR technique. Nodes reduce the RF range to cover their parents only and not any nodes with further distance in location management phase and PFR. A massive simulation on 3DPBARP shows a significant improvement in performance regarding energy consumption compared to 3DPBRP and DFRP in different scenarios. 3DPBARP shows that it can save more than 80% of the total energy consumption in the network by using the special technique in PFR. It also provides better performance in busy and noisy environments in terms of packet delivery time and the ratio of successful packet delivery.

Chapter 6

Conclusion and Recommendation

6.1 Routing Protocols in WSNs

In this section, routing protocols for WSNs in Network Structure, Communication model and Technology-based schemes were considered. Network Structure is a category that considers routing protocols based on node uniformity. In this category, routing protocols were studied based on the formation of the network topology based on type of nodes. Routing protocols in network-structure schemes were considered in two categories: Flat Network and Hierarchical model schemes. Flat routing protocols can be categorised as table-driven or demand-driven schemes. Hierarchical routing protocols are more energy-aware than flat routing protocols and are suitable for coverage of a large area without degrading quality of service. They are more stable with capability of scalability. Hierarchical protocols consume less energy and the network has more lifetime than with flat routing protocols. High delivery ratio and scalability are characteristics of these routing protocols. The main disadvantages are that nodes are depleted around the base station or cluster head faster than other nodes in the network and there is non-connectivity in the part of network based on a single point of failure in the topology [43].As an overview, some of hierarchical routing protocols are more scalable than others such as LEACH, PEGASIS, TEEN, VGA, SWRP, GBDD, NHRPA, SHIPER and DHAC. Regarding the use of greedy routing with the aim of reducing energy consumption in the system, routing such as PEGASIS, VGA, GBDD, ELCH and TIDD operate with better performance. Some routing protocols have more robustness such as LEACH, PEGASIS, TEEN, VGA, SWRP, GBDD, NHRPA, SHPER and DHAC [43].

The Communication Model Scheme refers to a group of communication-based routing protocols. They form a network based on data query and in some scenarios data-processing passes to some sensing nodes or intermediate nodes. This category is divided into three sub-categories: query-based, coherent data processing based and negotiation-based routing protocols. Query-based routing protocols work based on data queries that are broadcast by destination nodes. DD and COUGAR select the path based on less energy consumption and can only support limited mobility. DD is more scalable than COUGAR. ACQUIRE selects the path based on short path to the destination to save more energy and it is less scalable than DD and COUGAR. Some other protocols can categorised as query-based routing protocols such as RR, SPIN-PP, SPIN-EC, SPIN-BN and SPIN-RL[43]. WSN as distributed data network in some scenarios is required to pass some data-processing tasks to nodes in order to distribute the processing load and balance it within the network. The mechanism can be categorised into two routing protocol groups: Coherent and Non-Coherent Data Processing-based Routing [85]. Coherent Data Processing based routings are energy-aware routing protocols for WSN which allow running minimum processing task by sensor nodes such as time stamping and checking duplicated message. The nodes run the tasks with minimum processing effort and the message is then forwarded to the aggregators [43]. Non-Coherent Data Processing based routings allow nodes to process data. Sensor nodes process the collected data locally and then forward it to other nodes for further process. Aggregator is the next node which runs the further process when receiving a message from sensor nodes. SWE and MWE are two routing protocols in this category. SWE is more scalable than MWE and MWE is a more sophisticated routing protocol that computes the paths to source node for each node based on minimum energy consumption. Negotiation-based Routing Protocol uses a data-centric routing mechanism that is also called Sensor Protocol for Information via Negotiation (SPIN). SPIN-PP, SPIN-EC, SPIN-BC and SPIN-RL are energy-aware routing protocols in this category with mobility support. These protocols send a message if the node has data to send and also minimise energy consumption in the system. The SPIN protocols are scalable and can maintain the network regardless of size and performance and are not related to the size of network. Finally, they are categorised as the most robust routing protocols [43]. Technology Based Scheme is a category of routing protocols which using technologies such GPS to aid protocol to find the best path to the destination in an optimised manner. In this category, location-based routing protocols and mobile-agent-based routing protocols were studied. This kind of routing protocol benefits from the influence of physical distance and nodes distribution in the field in network performance. DREAM, IGF, PAGER-M, HGR and DHGR use lower energy consumption during an operation and also support node mobility. GEM and GDSTR use shortest path for sending data-packet to minimise energy consumption. GEM, IGF, PAGER-M, HGR and DHGR avoid periodically maintaining the network message to minimise energy consumption in the system. GEM, OGF, PAGER-M, HGR and DHGR are more scalable than others protocols in this category. Mobile Agent Protocol (MAP) [100] is used for high-level interference and surveillance applications in

WSNs where bandwidth and power consumption are the main concerns. MAP employs migrating code to provide re-tasking, local processing, collaborative signal and data processing. MAP adds more flexibility to WSN and enables conventional tasks based on a client-server computing model. The main attribute of MAP is a significant reduction in the amount of bandwidth by moving the data processing from the base-station or a central Sink to sensor area, wherein the majority of energy consumed in the WSNs is in transmission of raw data. [43]. Reliable Routing Scheme is a category of routing protocols that using techniques such as multi-path Routing or Quality-of-Service QoS parameters to guarantee packet delivery within certain properties. In this category, two sub-categories as multi-path routing and QoS-based routing are considered. Multi-path Routing Protocols - as is obvious from the term use several paths to send data toward the Sink or destination instead of trusting only one path. The protocols benefit from load balancing in the whole network and are more resilient against node failure [103]. The routing protocols in this category have the advantage of lower routing overhead and also lower delay and avoiding congestion in comparison with single-path routing protocols. QoS-Based Routing Protocols balance between energy consumption in the network and QoS requirements at the application level [112, 113]. The network may need to achieve certain QoS metrics such as delay, energy level, bandwidth, etc. In best-effort routing protocols, increasing the throughput and decreasing end-to-end delay are the main concerns. Most of the proposed mechanisms for QoS-based routing for multimedia data in wired based networks are not applicable in wireless communication due to the nature of the media or limited energy sources in the nodes.

6.2 Link-quality Metrics in WSNs

In this research, most of the routing protocol metrics in Wireless Mesh Networks were studied and the specifications of each metric were described in detail. The metrics in general were considered as link-quality and traffic-aware metrics. In link-quality metrics, mETX is a modified version of ETX that is based on average and variance of the error probability. ENT as the next version of mETX which takes into account the visibility of packet-loss for upper-layers protocols and are more popular metrics in this category. In traffic-aware metrics, EDR as a load insensitive metric which is based on a transmission interference model in the IEEE 802.11 medium access control protocol and it is used in many routing protocols. In multi-channel networks, iAWARE as a multi-channel metric finds paths with links with low loss ratio, high data rate and low-level interference experience. MCR as a version of WCETT is suitable for networks where the number of available interfaces may be smaller than available channels. WHAT is a metric suitable for a cognitive radio environment that selects high performance end-to-end path in

multi-hop cognitive wireless mesh networks.
ETX-Embedded, SERM and mETX are suitable metrics for low-power devices such as WSN. MTM as a multi-rate metric is a suitable and effective routing metric that avoids long-distance paths while ETP is an accurate metric suitable for long paths. IBETX and IDA are more sophisticated metrics that take most of the parameters of link-quality into the calculation of path-cost. ETD as multi-channel metrics considers interferences, delay, packet-loss and congested path in its calculation and is a more accurate metric for multi-channel environment.

6.3 Localisation Techniques in WSNs

This section presented a survey and taxonomy on measurement techniques for localisation in wireless sensor networks. The advantages and disadvantages of each technique were compared from three different perspectives: accuracy, hardware and computation cost. In the end, hybrid techniques were considered for the purposes of greater accuracy.

6.4 AETX

Deployment of wireless ad-hoc networks compared to traditional infrastructure based networks offers several advantages such as fully distributed mobile operation, easy discovery of joining wireless devices and quick cheap network setup. The design of an effective routing protocol is one of the main challenges in the ad-hoc networking paradigm and the utilisation of an adequate link-cost metric is essential. In this section, the validity of ETX (Expected Transmission Count) as a link-cost metric was investigated in term of its behaviour in real-time test-beds. ETX performance was studied in different distance scenarios. The main observation was that ETX values were not steady over the observation period and usually fluctuated for fixed scenarios. Fluctuation in ETX values affects a routing protocol by wrongly identifying the best path based on current ETX link-cost. Therefore, new methods for ETX calculation were proposed. These different methods for ETX link-cost calculation were compared and the best link-cost formula was proposed as a new method for ETX calculation. The new ETX calculation is called AETX and can be used as a link-cost in routing protocols that reflect the balance required between consistency of a link-metric value over the time for fixed scenarios and flexibility required to detect actual changes in link-metric values. In this section, ETX as a link-cost routing metric was observed in a real test-bed. To have valid observations, external interference noise was minimised as the tests were carried in an open stable environment. Even in such a situation, results showed the value of the ETX was not stable during the investigated time period. To improve validity of this research, a minimum of 16 samples were collected from 24 different scenarios. Moreover, in this section, some new ETX calculation techniques were proposed to replace current ETX protocol as a link-cost. The proposed ETX calculations were compared using parameters defined such as DF (as a difference factor) and FF (as a fluctuation factor) and minimising memory usage of the nodes. DF and FF were used to compare the proposed ETX calculations with energy consumption, as this is considered as the limiting factor to optimal link-cost calculation. After careful calculation and comparison, the average of the last three ETXs shows better performance than other proposed ETX calculations. This proposed metric is called AETX.

6.5 Deployment parameters in WSNs

In this section, WSN topologies (tree, star and mesh) were studied in theory. Subsequently, a test-bed was initiated by randomly deploying wireless sensors in the field. In the test-bed research, two WSN topologies (tree and star) were studied. The number of lost nodes as a parameter of deployment performance was selected and different deployment parameters were examined in different scenarios. The results strongly proved that tree topology has better performance than star topology in random deployment.

6.6 ETX - LQI - RSSI

Routing protocols play an important role in data communication. WSN is usually deployed in scenarios where efficient and energy-aware routing protocols are desired. In wireless sensors, RF modules consume most of the energy. Routing metrics are important in the determination of paths and maintaining quality of service in routing protocols. The most efficient metrics need to send packets to maintain link-quality measurement by using the RF module. Two prominent link-quality metrics were introduced in this research: RSSI and LQI. The symmetry of RSSI and LQI from two directions was studied as were the relations between ETX, RSSI and LQI as link-quality metrics. The evaluation in this research was based on a series of WSN test-beds in real scenarios. Collected test-bed data showed RSSI symmetry in both directions, as well as a significant correlation between RSSI and distance. This makes it a capable link-quality metric to be employed in routing protocols for devices that work in limited-resource scenarios. This research examined link-quality metrics and some features of RF characteristics and signal properties. The statistical analysis was tested on RSSI and LQI to find the distributions which fit them. Also, statistical tests were done on asymmetry in RSSI and LQI. These showed a significant correlation between two directions in RSSI; however, there was a weak correlation between two directions in LQI. ETX, RSSI and LQI were studied two-by-two to find a correlation between these three link-quality metrics. Results, however, did not show any rational relation between the parameters. Correlation between RSSI and distance was observed based on real test-bed scenarios. Statistical tests on the collected data showed a significant correlation between RSSI and distance in short-distance scenarios. Results show that RSSI is a routing-protocol link-quality metric that can be used in devices with limited energy.

6.7 RCTP

CTP as a well-known routing protocol with light overhead is a suitable routing protocol for wireless networks with low energy consumption. This research proposed RCTP as an enhanced version of CTP. RCTP showed a significant performance improvement when using AETX instead of ETX. The research shows that ETX has fluctuations in a real environment. RCTP performs with more stability by using AETX and also uses a new parent-selection mechanism to choose parents with more accuracy. It also employs techniques to avoid loops in topology. Massive simulation results prove RCTP provides better performance in busy and noisy environments in terms of packet-delivery time and the ratio of successful packet delivery. There is also better performance regarding energy consumption than with CTP in the same scenarios.

6.8 ERCRP

This research proposed ERCRP as an Energy-efficient Rainbow Collection Routing Protocol. ERCRP showed performance improvement in packet-delivery parameters by using AETX as link-quality gradient. ERCRP performs with more accuracy by using a new parent selection and the Rainbow mechanisms to choose parents with more accuracy. It also employs techniques to avoid loops in the topology. ERCRP as a GRP decreases the RF range in each node by reducing the number of nodes which receive the signal, using a PFR technique. In the PFR phase, nodes reduce the RF range to cover only their parents and not any nodes with further distance. A massive simulation on ERCRP showed significant improvement in energy consumption compared to CTP and DFRP in different scenarios. ERCRP showed that 80

6.9 3DPBARP

This research proposed 3DPBARP as an Energy-efficient Rainbow Collection Routing Protocol. 3DPBARP showed improvement in packet-delivery parameters. 3DPBARP performs with more accuracy by using a new parent selection and the Rainbow mechanisms to choose parents with more accuracy. It also employs techniques to avoid loops in the topology. 3DPBARP as a GRP decreases the RF range in each node by reducing the number of nodes which receive the signal, using a new PFR technique. Nodes reduce the RF range in a three-dimension space to cover only their parents and not any nodes with further distance in the location-management phase and PFR. A massive simulation of 3DPBARP showed significant improvement in performance regarding energy consumption compared to 3DPBRP and DFRP in different scenarios. 3DPBARP can save more than 80

Appendix A

Appendix : List of Publications

Journal Papers

1. Entezami, Fariborz and Politis, Christos (2015) Three dimensional position-based adaptive real-time routing protocol for wireless sensor networks. EURASIP Journal on Wireless Communications and Networking (EURASIP JWCN), 197, ISSN (print) 1687-1472

2. Entezami, Fariborz, Tunicliffe, Martin and Politis, Christos (2015) RCTP: An Enhanced Routing Protocol Based on Collection Tree Protocol. International Journal of Distributed Sensor Networks, 2015(363107), ISSN (print) 1550-1329

3. Entezami. Fariborz and Politis, Christos (2015) An Energy Efficient Position Based Adaptive Real-Time Routing Protocol for WSNs. International Journal of Sensors, Wireless Communications and Control, 5(2), ISSN (print) 2210-3287

4. Entezami, Fariborz and Politis, Christos (2014) An Analysis of Routing Protocol Metrics in Wireless Mesh Networks. Journal of Communications and Networking, 4(12), ISSN (print) 2160-4258

5. Entezami, F., Tunicliffe, M. and Politis, C. (2014) Find the Weakest Link: Statistical Analysis on Wireless Sensor Network Link-Quality Metrics. IEEE Vehicular Technology Magazine, 9(3), pp. 28-38. ISSN (print) 1556-6072.

Conference Papers

1. Entezami, Fariborz and Zhu, Meiling (2015) How much energy needs for running energy harvesting powered wireless sensor node? In: 10th Energy Harvesting Workshop; 13-16 Sep 2015, Blacksburg, Virginia.

2. Entezami, Fariborz and Politis, Christos (2015) 3DPBARP: A three dimensions position based adaptive real-time routing protocol for wireless sensor networks. In: IEEE NTMS'2015 Seven IFIP International Conference on New Technologies, Mobility and Security ; 27-29 Jul 2015, Paris, France.

3. Entezami, Fariborz and Politis, Christos (2015) Energy Efficient Rainbow Collection Routing Protocol for Wireless Snesor Networks. In: Wireless World Research Forum Meeting 34; 21-23 April 2015, Santa Clara, California, U.S.A..

4. Entezami, Fariborz and Politis, Christos (2014) Deploying Parameters of Wireless Sensor Networks in Test Bed Environment. In: IEEE Wireless Communications and Networking conference; 4-9 April 2014, Istanbul, Turkey.

5. Entezami, F. and Politis, C. (2013) Routing protocol metrics for wireless mesh networks. In: Wireless World Research Forum Meeting 30; 23-25 April 2013, Oulu, Finland.

6. Entezami, Fariborz and Politis, Christos (2012) Survey on measurement localization techniques on wireless sensor networks. In: 29th Wireless World Research Forum (WWRF): The Future of the Wireless Internet: Communication in the 2020s; 23-25 Oct 2012, Berlin, Germany.

7. Entezami, Fariborz, Ramrekha, Arvind and Politis, Christos (2012) An enhanced routing metric for ad hoc networks based on real time testbed. Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), pp. 173-175.

8. Entezami, F., Ramrekha, T. Arvind and Politis, Christos (2012) Mobility impact on 6LoWPAN based Wireless Sensor Network. In: 28th Wireless World Research Forum meeting; 23-25 Apr 2012, Athens, Greece.

Appendix B

Appendix : Routing Protocols in WSNS

The main duty of a WSN as a distributed computing network is collecting data from a large amount of nodes that have the capacity of sensing the environment, processing data and also short-range communication. WSN applications collect data from wireless sensors and a proper routing protocol can help them to achieve scalability and improve system performance. Figure B.1 shows data flow diagrams in three routing schemes:

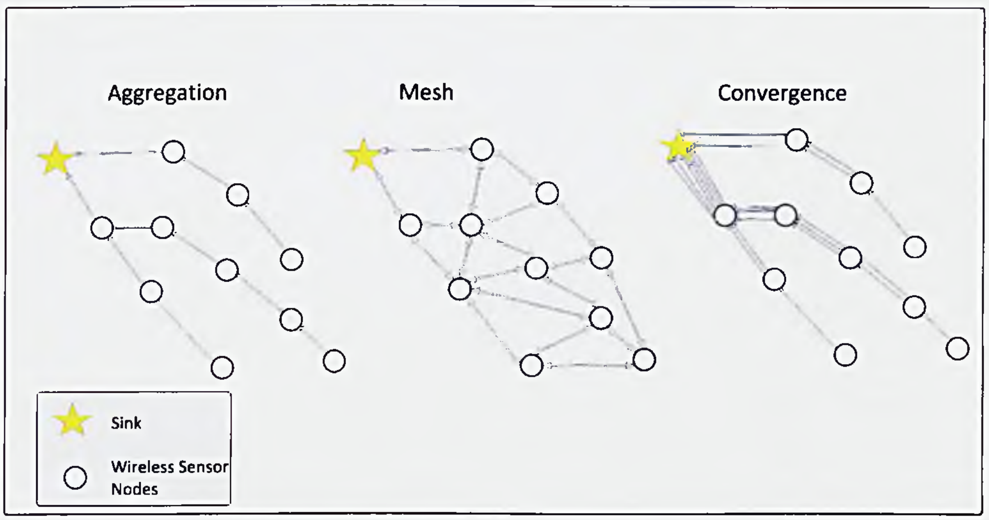

FIGURE B.1: WSN Patterns

aggregation, mesh and convergence. In the aggregation scheme, the sensor nodes send their data to their parents. The parents merge the received data with collected data and then send to its parent and then finally all data is delivered to the Sink. In the mesh scheme, all wireless nodes have two-way communication with all their neighbours and communication can occur as a mesh network. The Sink can communicate with each

sensor node and reverse. In the convergence scheme, all nodes send their data to their parents and the parents retransmit any received messages to their parent until they are arrived in the Sink.
In this research, routing protocols in WSNs are considered in four categories: Network structure, communication model, technology based and reliable routing-protocol schemes.

B.0.1 Network Structure

Network Structure is a category that considers routing protocols based on node uniformity. In this category, routing protocols are studied based on the formation of the network topology based on type of nodes. In some routing protocols, a uniform type of nodes is used. These form the topology and all nodes in the topology have the same task. In some routing protocols, two or more types of nodes form the network topology and node tasks are related to node type. Routing protocols in network structure schemes are considered in two categories: Flat Network and Hierarchical model schemes.

B.0.1.1 Flat Networks

Flat routing protocols can be categorised as table-driven or demand-driven schemes. In a table-driven scheme, each node sends data to the destination based on destination table that keeps it up-to-date. In a demand-driven scheme or source-initiated, a destination node floods the network with its demand and then the source sends data back based on the asked demand.
Flat networks routing protocols are classified in three categories, Proactive, Reactive and Hybrid routing protocols. Proactive routing protocols collect network information and discover the routes before need to send data. Reactive routing protocol discovers the rout as soon as need to send a data-packet to a destination. Hybrid routing protocol is a combination of proactive and reactive routing techniques that try to use both benefits to reduce the overhead. In the following chapters, routing protocols for wireless sensor networks in Flat Network schemes are considered with more details.

WRP
Wireless Routing Protocol (WRP) [44] is a proactive or table-driven routing protocol that uses the distributed Bellman-Ford algorithm. It uses a set of tables to maintain an up-to-date network viewpoint to make it capable to make a decision based on accurate information. It keeps Distance Table (DT), Routing Table (RT), Link-Cost Table (LCT) and Message Retransmission List (MRL) to make WRP capable to send data

messages to the destination by using the optimum path. WRP uses update messages regularly between neighbours that contain a list of update such as destination, distance to the destination, next-hop for each destination and list of mobile nodes that needs to send updates to them. Each node observes the communication links and in case one link goes down, the update would be generated and broadcasts to all neighbours. Any new discovered path to a destination relay back to the origin node to update its tables. Nodes in WRP check network constantly and keep tables up-to-date and it makes WRP benefits from instant convergence. Due to number of tables and number of nodes, it is requirement for WRP nodes to have enough memory and processing capacity to manage the network data. For this reason WRP is not a scalable routing protocol and is not a suitable routing for large number of nodes in the network [44][43].

In summary, WRP benefits from the avoidance of loops and fast route convergence in the case of link failure; it has limited scalability with limited mobility support. It uses shortest path as a routing metric and uses table exchange for maintaining topology. It is categorised as a low robust routing protocol. WRP is not suitable for highly dynamic and large-scale scenarios of wireless sensor networks and this is its drawback [24].

TBRPF

Topology Dissemination Based on Reverse-Path Forwarding Protocol (TBRPF) [45][46] is a pro-active routing protocol that sends updates when the state of the topology was changed from the previous state. TBRPF uses smaller routing update messages than other routing protocols. It uses spanning tree to form the topology by the minimum hop paths from all sensor nodes to the source node. TBRPF uses the concept of Reverse-Path Forwarding (RPF) to disseminate link-state updates in the reverse direction along the topology. TBRPF calculates the minimum hop paths to forms the tree by using the received topology information. Using the minimum hop trees instead of the shortest path trees based on link-cost makes TBRPF uses less frequent broadcast messages to maintain the tree and therefore less communication overhead and cost. Each node stores the topology information such as; a topology table, consisting of all links-states, neighbours list, parent's node, list of children and the sequence number of the recent link-state update. In TBRPF, each node has a complete view of topology; however, in the other hand, the convergence time in worst-case scenarios is double than flooding routing protocols [45][46][43].

In summary, TBRPF benefits from sending less frequent periodic topology updates compared with other routing protocols in this category. It has limited scalability with good mobility support. It uses the shortest path as the routing metric and uses HELLO message for maintaining topology. It is categorised as a good robust routing protocol.

TBRPF is not a suitable routing protocol for networks with low mobility [24].

TORA

Temporarily Ordered Routing Algorithm (TORA) [47, 48] is a reactive, highly adaptive, loop-free and distributed routing protocol based on link reversal. The main concept of TORA is to limit control-message dissemination in highly dynamic mobile computing scenarios. Each node has to initiate a query when it needs to send a data message to a specific destination. The main tasks of TORA are to discover a route to the destination, maintain it and then erase it when it is no longer valid. The main advantage of TORA is developed to minimize the communication overhead and then reduces energy consumption [47, 48][43].
In summary, TORA benefits from minimising communication overhead and also supports multiple routes. It has good scalability with good mobility support. It uses shortest path as a routing metric and uses IMEP control message for maintaining topology. It is categorised as a low robust routing protocol and TORA cannot be incorporated into multicast scenarios [24][47, 48][43].

Gossiping

Gossiping [49] is reactive routing protocol that uses gossiping instead of broadcasting. In broadcasting, one node sends its unique information to all neighbours; however, in Gossiping each node sends the incoming information to a randomly selected neighbour Gossiping uses less communication overhead and avoid having the same information on all nodes and in the other hand receiving the required information to all nodes needs longer time [49][43].
In summary, . Gossiping benefits from using less communication overhead. It has good scalability with good mobility support. It uses random selection to choose the path to a destination and does not use any message for maintaining topology. It is categorised as a good robust routing protocol. Gossiping suffers from long delivery times for messages to all nodes in the network [24][49][43].

Flooding

Flooding [50] is a traditional, reactive and simple routing protocol for WSNs. Each node retransmits any received message to all nodes except the node that the message came from. Flooding is a robust routing protocol that provides source-to-destination delivery guarantee; however, it generates an enormous amount of traffic within the network

[50][43]. Flooding is not a complex routing protocol and it also does not use any control message to maintain the topology. Flooding has some drawbacks such as broadcasting same message several times and a node may receive a message several times and also it is not an energy-aware routing protocol. The advantage of Flooding is a guarantee to receive the packet in the destination if at least one route does exist and the first packet which arrives in uses the fastest way to the destination. Flooding is a robust and suitable routing protocol for battlefield or path learning scenarios. Flooding consumes more energy than other protocols as each node in the network that receives the message should retransmit it to all its neighbours and it occurs more than one time for the same packet [50][43].

In summary, Flooding benefits from a simple and robust routing technique for WSNs. It has good support of scalability and mobility. It uses shortest path as the routing metric and does not use any message for maintaining topology. It is categorised as a good robust routing protocol. Flooding suffers from generating enormous amount of traffic within a given network and it may broadcast the same message several times as there is no mechanism to control duplicated messages for broadcasting [24].

Rumour Routing (RR)

Rumour Routing (RR) [51] is a reactive routing protocol that allows queries to be delivered to the nodes that sense the event. It is a tuneable routing protocol based on application requirements that are balanced between network overhead and data-packet reliability [51][43]. It is a suitable routing protocol when the geographical information is not available or is not accessible. RR is an algorithm between query flooding and event flooding. When reliability for delivering a message is not a requirement then RR can be tuned to work with less energy consumption to save energy in trade off with reliable delivery. Each query results consist of the event ID, distance and direction or next-hop neighbour. RR is a suitable routing for delivering queries to events region in large network scenarios in a wide range of application requirements. RR can manage node failure and degrading the delivery path by finding number of node failure [51][43].

In summary, RR benefits from handling node failure gracefully and keeping a record of routes with node failure. It has good scalability with low mobility. It uses shortest path as the routing metric and use HELLO messages for maintaining topology. It is categorised as a good robust routing protocol. RR suffers in that it may deliver duplicate messages to the same node [24].

E-TORA

Energy-aware Temporarily Ordered Routing Algorithm (E-TORA) [52] is a reactive and energy-aware version of TORA. The original TORA selects the best route with the least hops based on network topology. The nodes in the main route or in a route with heavy data delivery runs out their energy much earlier than other nodes. E-TORA considers energy level of each node in the path before selecting any route. It causes that the energy level in the network would be balanced and avoiding to selecting paths within nodes that drains their energy very soon. In case the node does not have a directed link to the destination nor has a record to the destination in its routing table with required a route to the destination flag then the node broadcast a query packet with route required flag. Any node that receives the query packet, checks its table and if it has a record for destination with route-required flag then it discard the packet otherwise re-broadcast it and updates its table [52][43].

In summary,E-TORA benefits from minimising energy consumption and creating a balance between nodes in the network. It has good scalability with good mobility support. It uses the best route as the routing metric and uses IMEP control messages for maintaining topology. It is categorised as a low robust routing protocol. E-TORA suffers when it is incorporated with multicast routing [24].

ZRP

Zone Routing Protocol (ZRP) [53] is a hybrid routing protocol and benefits from the advantages of proactive and reactive routing protocols. It finds loop-free routes to the destination by dividing the topology into zones. These zones use proactive techniques for locating local neighbours in the zone and dramatically reduce overhead costs. They use on-demand search for nodes outside the zone. ZRP sends query to a subset of the nodes in the border of each zone when nodes need to send message to the outside of the zone. The changes in the status of nodes or links have local effect only. Each node in ZRP creates and maintains its neighbours' table that it is called routing zone. Intra-Zone Routing Protocol (IARP) is a protocol that operates inside the zone and can use any link state or distance vector routing and maintains the topology only within a zone. The size of the zones is a trade-off between proactive and reactive behaviour. Bigger zones make bigger volume of overhead such as reactive protocols and very small zones makes ZRP operates such as a reactive routing protocol [53][43]. In summary, ZRP benefits from using low routing traffic. It has good scalability with good mobility support. It uses the best route as the routing metric and uses HELLO messages for maintaining topology. It is categorised as a good robust routing protocol. ZRP suffers from excessive delays in some complex scenarios [24].

B.0.1.2 Hierarchical Routing Protocols

These types of routing protocols are more energy-aware than flat routing protocols and are suitable for coverage of a large area without degrading the quality of services. They are more stable with capability of scalability. The topology structure is organised in clusters. In each cluster, one node with more capacity in residual energy, processing or radio module plays the role of cluster head. The cluster head coordinates activities within the cluster and communication between clusters. The clusters perform data aggregation and fusion tasks. Hierarchical protocols consume less energy and the network has more life-time than with flat routing protocols. High delivery ratio and scalability are characteristics of these routing protocols. The main disadvantages of this kind of routing protocol are that nodes are depleted around the base-station or cluster head faster than other nodes in the network and there is also non-connectivity of the part of network based on a single point of failure in the topology [43].

Figure 2.2 shows Cluster Based Routing Protocol and how nodes communicate until

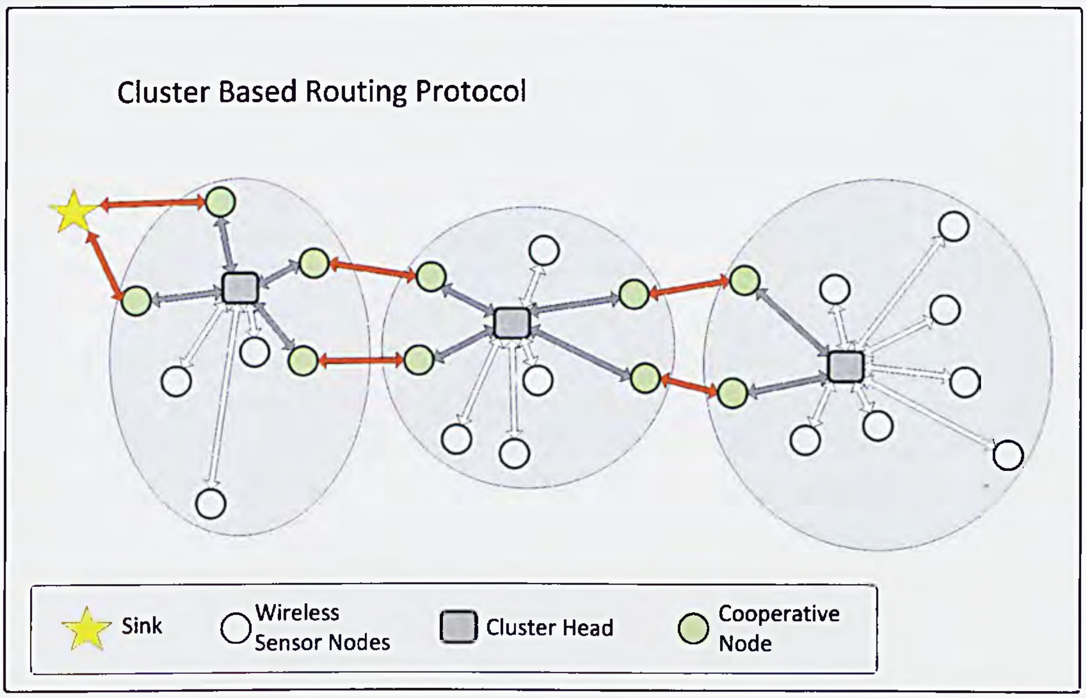

FIGURE B.2: Cluster Based Routing Protocol

the packets are sent to the destination or Sink.

LEACH

Low-Energy Adaptive Clustering Hierarchy (LEACH) routing protocol was introduced by Heinzelman, et al [54] and was the first hierarchical, self-organised and adaptive clustering routing protocol. It works in two phases; Setup Phase that organizing the clusters and runs election to select randomly Cluster Head (CH) and appointed the others in the cluster as Cluster Member (CM). Second phase is called Steady State Phase, in this phase that is longer than setup phase, each node selects closest CH to join the cluster and sends its data to the CH. CH is responsible to schedule a time for each CM to transmit CM's data and CH is responsible to aggregate data from CM, and then compresses and forwards them to the Base-station (BS).

LEACH forms clusters and CH dynamically and it avoids nodes to die quickly as it may was a CH for a long time. It selects CH based on residual energy level and has not been selected as CH in previous periods. It uses randomized concept to balance the energy level between nodes in a cluster. Leach allocates a time slot to each member to save energy and avoid inter-cluster and intra-cluster collision by using Time Division Multiple Access (TDMA) and Code-Division Multiple Access (CDMA) MAC. Each CM is in sleep mode to save energy except the time slot that is allocated by CH during the setup mode for transferring data. CM and CH communicate in a peer-to-peer mode during the dedicated time slot. LEACH uses single hop routing, CMs send data to CH and CH send data to BS and routing more than one hop does not implemented in this protocol and it is the reason that this protocol cannot cover big area and it is not scalable. LEACH is a proper protocol for constant monitoring, as it is a centralised data gathering protocol, which collect data in a certain periods. One of the setup parameters in LEACH is percentage of CH. In setup phase, each node chooses a random number between 0 and 1 and if the random number is less than percentage of CH then the node become a CH and if the chosen number bigger than percentage of CH the node become a CM. Then CH advertises its status to other nodes and CMs receive advertise message from different CH and then CMs decide to join to the best CH. The decision is based on signal strength that it is a factor of link-quality. After this decision, CM informs CH that this node is a member of this cluster and it should manage by this CH. After receiving CM joining packets, CH schedules a TDMA and assigns a time slot to each member and all nodes in the cluster are informed about their dedicated time slot that they can transmit data. During the steady state phase, each CM sends data to CH on its time slot and CH aggregates all data and compresses them and sends to the base-station. After a certain time that was defined in network parameters, the cluster ends the steady state phase and starts the setup phase and again selects CHs and CMs. During steady state phase, each cluster uses different CDMA codes to reduce collision and interference between clusters. Advantage of LEACH is its low-energy consumption level and it is an ad-hoc and distributed routing protocol. It has a good rate in scalability by using fixed base-station and use shortest path as the routing metric; however, it is not applicable to operates in large areas and creates more overhead by using dynamic clustering [54][43]. Leach has capability to increase network life-time; however, has some disadvantages in its properties. All nodes should have the capacity to communicate with BS to make the protocol be not feasible to cover a large area. The predetermined of percentage of CH cannot guarantee uniform distribution in the network. Some CM nodes may have too many CH option to join and in other side some CM nodes may not have a CH in their vicinity to join. Dynamic clustering such as CH election, advertisement and joining creates more overheads to the network and increases energy consumption in the system. Leach assumes the nodes have same energy level and this protocol cannot be a suitable protocol for scenarios that nodes have different level of energy [54][43].

In summary, The advantage of LEACH is its low-energy consumption level; it is distributed and has a good rate in scalability by using a fixed base-station and uses shortest path as a routing metric. It is not applicable to operation in large areas and creates more overhead by using dynamic clustering.

E-LEACH

Energy-Leach (E-LEACH) [55] is an energy-aware version of LEACH. The algorithm is similar to LEACH except the mechanism of CH's election is different after the first round. In the first round, the CH is chosen based on a probability function such as LEACH; however, in the next rounds the remaining energy level of each node accounts for choosing to become a CH. The nodes with a higher level of remaining energy have more chance to become a CH than nodes with low battery charge.

LEACH-C

Low-energy Adaptive Clustering Hierarchy Centralised (LEACH-C) [55] is a centralised version of LEACH. Base-station (BS) plays the role of a centralised cluster information centre in this algorithm and initially BS receives information regarding node location, their neighbours and energy levels of nodes in the network. After receiving data from all nodes in the network and analysing them, the number of cluster heads and topology of network based on predetermined clusters is defined. LEACH-C benefits by using BS with having the whole knowledge of the network to form clusters that can transmit data with less required energy. It also takes advantage of using the same predetermined of optimal value of cluster head in each round of CH election, where LEACH carries the disadvantage of selecting the varies number of CH in different rounds as the reason it does not have the global information about the whole network.

In summary,The advantage of LEACH-C is that it uses less energy to transmit message than LEACH and has a good rate in scalability with a fixed base-station. It uses the best route as the routing metric and also has a good rate of robustness; however, it generates more overhead [55][43].

TL-LEACH

Two-Level Hierarchy LEACH (TL-LEACH) [56] is designed to send data to the base-station in one hop. CH plays the role of hops in this protocol and the network is formed with two levels of cluster head, which are called primary and secondary. There is a reduction in energy consumption regarding data that is sent through a two-level structure to the Base-station.

M-LEACH

Multi-hop LEACH (M-LEACH) [43] uses others CH as relay in the network and data is sent to the Base-station through multi-hop networks which are CHs. This solves problem of distant CHs; however, it consumes more energy to transfer data through a far distance.

V-LEACH

Vice LEACH (V-LEACH) [43] is a version of LEACH that defines some Vice-CH. Vice-CH would be a CH in the case that a current CH dies and it then it takes its role. It solves the disconnection of cluster nodes regarding disappearing CH.

U-LEACH

U-LEACH [57] is a combination of I-LEACH and PEGASIS. It benefits energy-aware CH selection from I-LEACH and multi-hop transmission from PEGASIS. Master CH (MCH) sends the gathered data to the base-station and the clustering of nodes and electing the CH is based on a probabilistic approach such as LEACH.

PEGASIS

Power-Efficient Gathering in Sensor Information System (PEGASIS) is an enhanced version of routing protocol in WSN that was proposed after LEACH. It is a chain-based protocol that saves more energy in the system and increases network life-time because each node only needs to communicate to its closest neighbour. Then, nodes receiving data are responsible to make the replay to the base-station and this works such as a chain-based protocol [43]. The nodes are organised to dynamically form a chain-like connection to make all nodes connect to the base-station through some other nodes. This topology is formed based on using a greedy algorithm by base-station or some sensor nodes in the network. It makes the base-station be capable to broadcast to all nodes in the network. PEGASIS performs twice or more than LEACH [259]. The main advantage of PEGASIS is to reduce the transmission range that can save more energy. The disadvantage of PEGASIS is redundant data-transmission in case of one node in the chain was out of the reach. PEGASIS works with better performance in the bigger coverage area [43].

In summary, The advantages of PEGASIS are most of the nodes reduce the transmission radio range to save more energy and it has a good scalability rate with a fixed base-station. It uses greedy-route selection to choose the best routing path and has a good rate of robustness. However it does not consider the location of the base-station and also is not taken into account the residual energy level for nodes that become a cluster head [43].

Hierarchical PEGASIS

Hierarchical PEGASIS was proposed by [58] to reduce packet-delivery delay by avoiding collision between nodes that use the same spatial transmission. To avoid collision between close nodes, simultaneous data-transmission is considered and only nodes with a separate spatial data-transmission range are allowed to have simultaneous data-transmission[58][43].

TEEN

Threshold-Sensitive Energy Efficient Sensor Network Protocol (TEEN) [59] and Adaptive TEEN (APTEEN) [60] are two hierarchical routing protocols for wireless sensor networks. TEEN is designed for time-critical scenarios and although the nodes sense attributes continuously, they transmit data only on a few occasions. Wireless nodes sense the object uninterruptedly and nodes receive two parameters regarding the objects. Each object that the wireless nodes have to sense has two thresholds, hard threshold and soft threshold. If the object measurement passes the hard threshold or its changes are more than the soft threshold, this then triggers the node to turn on the radio module and transmit the data. The hard and soft thresholds are sent to nodes by the CH. Smaller value of soft threshold causes the nodes uses radio module to send data more frequently that obviously shows more accurate sensed data and in other side the nodes use more energy. There is a trade-off between accuracy and energy consumption in this system, any more accuracy needs more energy and less accuracy makes the system works in longer lift time period. The disadvantage of TEEN is if the update packet regarding hard and soft thresholds has not transmitted properly or if the node does not receive it, the data received in centre is then not as accurate as it should be [60][43].

APTEEN is a hybrid routing protocol that uses proactive and reactive attributes. It sends some properties to each node by CH. The parameters are: the physical parameters which nodes have to sense, Hard Threshold (HT) and Soft Threshold (ST); the TDMA schedule to let the nodes communicate with CH; and, Count Time (CT) (the maximum time period that nodes have to send data to the centre) [59][60][43]. APTEEN behaves such as TEEN regarding hard and soft thresholds and additionally nodes check the last update transmission time and if the counter of the maximum time period was expired then starts to transmit data to keep data updated at the centre. TDMA is used to dedicate a time slot to communicate with CH. It gives some flexibility to the user with ST, HT and CT to reach to a level of balance between level of accuracy and energy consumption level. The main downside of this protocol is adding more complexity into the system by adding more parameters. TEEN and APTEEN have performed better than LEACH. They show better performance in term of system life-time and energy dissipation. The main disadvantages of TEEN and APTEEN are their overhead and complexity. Communication overhead is included updating ST and HT in TEEN and ST, HT, CT and TDMA schedule in APTEEN. Executing process of the functions that deal with ST, HT and CT and how to process the attribute-base naming of queries increase complexity in these protocols [59][60][43].

In summary, the advantages of APTEEN are: its capability to handle sudden changes in sensing attributes; it has a good rate in scalability in a fixed base-station and choose the best route in routing; and, it has a good rate of robustness attribute. It is not an energy-aware protocol and creates more overhead to handle large networks [43].

CHIRON

CHIRON is a hierarchical chain-based and energy-efficient routing protocols for WSNs. CHIRON splits the sensing area into smaller areas to make several short chain-based paths to reduce packet delivery delay and also increases the redundant path to BS. It can save more energy and extend network life-time. Nodes in CHIRON are self-organised and dynamically form the network [61].

It uses fewer overhead in setup mode to inform nodes with their location information. Nodes report back to BS based on multi-hop method. CHIRON has four stage; Group

Construction, Chain Forming, Leader Election and the final stage is Data Collection and Transmission[61].

Small MECN

Small Minimum Energy Communication Network (MECN) [62] is an energy-aware routing protocol for WSNs. It computes the energy level of each sub network and chooses the best relay zone for each node based on neighbours' regions. The best neighbour's region is selected based on the transmission of data through the zone with less energy consumption compared with other regions. The regions with fewer nodes use less energy to relay data than regions with more number of nodes. MECN is a self-configuration protocol that can dynamically handle with joining new wireless sensor nodes or fading nodes. Small MECN (SMECN) [63] is a version of MECN which considers obstacles between two nodes. In MECN, all pairs have a communication link and obstacles do not come into account while it is assumed the network is fully connected.

SOP

Self-Organizing Protocol (SOP) was proposed by Subramanian et. al [64]. It is a proper routing protocol that can structure and support heterogeneous wireless sensors in stationary and mobile cases. In this protocol, some stationary wireless nodes work as routers and form the backbone of the network. Data is sent to routers by sensing nodes and then routers forward it to the base-station. All routers in this network have a unique address. Sensing nodes that are connected to each router use an identification mechanism. In some versions of SOP, all sensing nodes have a unique network address and are accessible by the base-station. Energy consumption for broadcasting a message in SOP is less than SPIN. The disadvantage of SOP is that when the network finds some hole in the topology, it increases the probability of reorganising the network as a cost-effective task and increases energy consumption in the system [64].

Virtual Grid Architecture

Virtual Grid Architecture (VGA) routing is an energy-aware routing protocol that benefits from data aggregation and in terms of network processing increases network life-time [65]. The process has two phases, clustering and routing-aggregated data. In clustering phase, the network divides to fixed, equal, adjacent and non-overlap and symmetric forms of clusters. Each cluster has some sensor nodes that collect data and they elect one node as Local Aggregator (LA) node which also is called CH that collects all data from nodes in the cluster. One node is selected as Master Aggregation (MA) node that is global aggregation point in the cluster that routes data toward outside of cluster and destination to the base-station.

In summary; VGA is a proper routing protocol in terms of achieving energy efficiency and maximising the life-time of a network. It has a good rate in term of scalability in fixed scenarios for nodes and base-station. It uses greedy-route selection in routing to choose the best path and has a good rate to be a robust routing protocol [43].

TTDD

Two-Tier Data Dissemination (TTDD) proposed by [66] as a capable routing protocol to deliver data to multiple mobile base-stations. In TTDD, sensing nodes are fixed and location-aware in this protocol although base-stations or Sinks are mobile. Regarding of data collection, all sensor nodes in the area sense the event and there is a predefined node that is responsible to prepare data and then transmit it to the base-station. To build the grid topology, one node sends a data announcement message to all its adjacent crossing point nodes using simple greedy geographical forwarding. Each node that receives the message stores the information of the source and then forwards it to its adjacent crossing point nodes until it reaches to border of network and then stop. After this process the grid structure is formed and the base-station can flood the network with its query. The path that query passes along to receive to the source is used when data flow back toward Sink. TTDD shows better performance than Directed Flooding regarding network life-time and packet delivery delay. TTDD is a routing protocol for scenarios that multiple mobile Sink are in the field. The main weakness of this protocol is each node should have enough capacity in case of processing and memory to maintain a virtual gird structure and cross points in topology that are used to send data source to the sink [43].

In summary; TTDD can be used in scenarios wherein fixed nodes are distributed in the field and there are multiple mobile Sinks to collect messages. It has a low rate in scalability and uses greedy-route selection in routing messages and has good rate of robustness routing. The drawback is all source nodes must have the essential capacity to build a virtual grid topology of dissemination nodes to make it capable to send message to mobile Sinks. [43].

WB-TEEN

WB-TEEN [67] uses distributed clustering and a time-driven model that was proposed to cover the weakness of an unequal number of nodes in different clusters in TEEN. Conceptually, it is the improved version of LEACH and TEEN. WB-TEEN forms the clusters with an equal number of nodes in each cluster. Each CH has two parameters, the number of nodes in a cluster and a degree. CH decides to accept or reject a new member based on the numbers already joined to the cluster and the degree of the cluster.

WNM-TEEN

WNM-TEEN [67] is an improved version of WB-TEEN that keeps all capability of WB-TEEN and also highlights multi-hop routing in the cluster by using performance-quality metrics. A performance-quality metric takes energy consumption of the process, number of live nodes, number of data-transmission rounds and network life-time into account to find the best route.

BCDCP

Base-station Controlled Dynamic Clustering Protocol (BCDCP) [68] is a centralised routing protocol that formed clusters in a balanced fashion. The base-station receives status information of all nodes in a topology before forming the clusters. This information is the current level of energy in each node, location and nodes' neighbours. After receiving information from nodes, the base-station calculates the average energy level in network and then chooses nodes with energy level above the average. Number of nodes in each cluster approximately is equal and BCDCP avoids making overhead on CHs and using a uniform method to replace CH and also make CH to be capable to communicate and using routing to send data to the sink by using CH to CH routing.

In summary; BCDCP benefits from being a low-energy consumption routing protocol and has limited scalability with no mobility support. It chooses the best route in routing protocol and has a limited rate to be a robust routing protocol. It also has a drawback in that performance decreases in scenarios in which the field areas of sensing become small [43].

HPAR

Hierarchical Power Aware Routing (HPAR) [69] is categorised as an energy-aware routing protocol in wireless sensor networks. It splits network into group of sensors that are called zones. The zones are formed by grouping nodes which are geographically close. All nodes in a zone have a unique identity. After the first stage that is forming zones, the second stage is finding the optimum path to send message from source to the sink through other zones by keeping the goal function on optimum level that is maximising nodes battery life. HPAR finds paths with maximum nodes battery life and also minimum energy consumption for transmitting the message that is called max-min path. The main advantage of HPAR is it takes into account both properties of nodes battery power level and energy consumption in transmission module. The weak point of HPAR is finding energy consumption and battery level for all nodes creates more overhead into the system. In summary; HPAR benefits from the advantage of taking transmission power into account as well as the residual energy level of nodes in the path. It also maintains a large number of nodes in zones; however, has low scalability and does not support mobility. It uses the shortest path with a view to total energy consumption as the routing metric. It is categorised as a robust routing protocol; however, its drawback is the requirement to create more overhead to find power consumption in the paths [43].

SWSP

Sleep/Wake Scheduling Protocol (SWSP) [70] is an energy-aware routing protocol that saves energy by switching off the radio module when not in use and turns it on only before transmitting or receiving a message. The sending and receiving time periods are scheduled by neighbouring nodes. Synchronisation is a big challenge in this protocol as both nodes which want to exchange the message should wake up at the same time otherwise the communication fail. Although the current synchronisation schemes can precisely synchronies both nodes instantly after exchanging synchronisation message, there still some random errors that can failure the process of synchronisation. [70] proposed an optimal sleep/wake scheduling algorithm that hold the captured message regarding consuming less energy and supporting multi-hop routing [43]. Sleep/wake scheduling is used in each cluster. Each node sends the message in a certain period of time based on a TDMA method. In this method CH has a unique time slot for each member node.

In summary; SWSP significantly increases network life-time and it is a suitable routing protocol for low-energy power systems. It has a satisfactory level in term of scalability; however, with no supporting mobility in base-stations or even in nodes. It selects the best route in routing metric and has a limited robustness rate. Its drawbacks are in the synchronisation mechanism and scheduling and these challenges affect the overall performance of the system [43].

GBDD

Grid Based Data Dissemination (GBDD) [71] is an energy-aware routing protocol for wireless sensor networks. In TTDD, nodes start to initiate the structure of a cluster;

however, in GBDD the Sink constructs the network and defines the clusters in the grid by sending and receiving the first messages. The first received messages from the Sink start to form the cluster by putting itself as crossing point (CP) and its geographical coordinates (x, y) as a starting point and it is the centre of cluster or grid cell. Maximum transmitting range (RH) and minimum transmitting range (RL) of wireless nodes was defined to take into account to determine the area of each square grid cells [43].
In summary; GBDD is a routing protocol that guarantees the sending of data from source to the sink continuously and has a good rate in scalability with supporting limited mobility. It uses the closest corner node in the case of an existing valid grid in term of routing metrics and has a good rate of robustness. Its drawback is that it consumes more energy when the frequency of data gathering increases [43].

ELCH

Extending Life-time of Cluster Head (ELCH) [72] is a hybrid routing protocol by combining cluster architecture and multi-hop routing that uses low-energy and increases the life-time of the network. In ELCH, wireless nodes elect the CH by using a voting system. ELCH operates in two phases; in the first phase or setup phase, clusters are formed and CH is selected based on an election. Each node votes to its neighbours and node with the most votes become a cluster head. In the second phase that is called steady-state; clusters are formed and CH was selected and all members of each cluster was joined to CH based on nodes' geographical location. Connecting to the Sink by passing through CHs in the path as multi hop was stablished for all CHs as a backbone. A TDMA schedule is defined for each node to declare the time slot that each node can communicate with its CH in each round. CHs maintain a table to keep all nodes energy level in each round. After completing the second stage, the network is ready to send the messages from nodes to the Sink[43].
In summary;ELCH can achieve minimum energy consumption in terms of data-transmission and benefits from balancing energy efficiency in the whole network. It has limited capability in term of scalability in fixed base-station scenarios. It uses paths with maximum residual energy nodes as a routing metric and has good rate of robustness [43].

NHRPA

Novel Hierarchical Routing Protocol Algorithm (NHRPA) [73] is a routing protocol for WSNs that takes into account network parameters such as distance of node to the base-station, the node distribution density the residual level of node energy. NHRPA can make a balance between energy efficiency and threshold value.

In summary; NHRPA benefits from low power consumption and has a good level of scalability in fixed base-station scenarios. It selects the best path in routing metrics and has good rate of robustness. Its drawback is packet-delivery latency in the whole system [43].

SHPER

Scaling Hierarchical Power Efficient Routing (SHPER) [74] was proposed for scenarios with a powerful base-station and a set of homogeneous wireless sensors nodes. The nodes are randomly distributed in a certain area. The base-station is normally out of sensing area and uses an unlimited power source it has enough power to transmit with high power. Nodes and base-station are supposed to be fixed and the protocol is not designed for mobile scenarios. SHPER operates in two phases; initialisation phase that base-station transmit a TDMA schedule to all nodes in the field and asks nodes to reply back with identification and distance with other parties. Base-station by receiving advertisement information from all nodes in the field, randomly elects a default number of the high probability of cluster heads. Then SHPER transmits cluster heads' IDs to all the nodes in the fields with the value of thresholds. In second phase that is called steady state phase, cluster heads find the best way to send messages to the base-station regarding low-energy consumption in the paths. The advantage of SHPER is it takes into account the energy level of node in each cluster and the system makes a balanced level of residual energy in clusters. The SHPER benefits from selecting the best path for sending messages to the base-station based on energy consumption in the path and also communication cost.

In summary; SHPER benefits from balanced energy distribution in the whole network and has good scalability with a fixed base-station. It selects the best path in routing metrics and has a good rate of robustness. Its drawback is that it does not support mobility [43].

DHAC

Distributed Hierarchical Agglomerative Clustering (DHAC)[75] is a routing protocol for WSN wherein the main concept is that each node forming a cluster need only have a neighbour node; with one neighbour's acknowledgment, one node can form a cluster. DHAC operate in 5 phases; in phase one: each node elects itself as cluster head and broadcast the status to its neighbours by a HELLO message. Nodes that receive a setup data builds a resemblance matrix. Phase two; each node executes the DHAC algorithm to find the minimum cluster head in the cluster and finds the minimum coefficient. Phase three; nodes reconsider the limitation of predefined the upper bond size of cluster and if the cluster reached to the limit, disconnects some nodes links. In phase four, the system controls the minimum cluster size and maybe uses merge clusters process to join other clusters with low members. In phase five, the cluster heads that are chosen, chooses the lower ID to select the cluster head between nodes. Each cluster member has an assigned role and after clusters are formed, they start to send messages to cluster heads to relay to the base-station[43].

In summary; DHAC benefits from longer network life-time and has a good rate of scalability. It selects the best path in routing metrics and has a limited rate of robustness. Its drawback is that it suffers from low performance in scenarios when traffic increases to a high level [43].

Summary of Hierarchical Routing

In summary, there are more types of hierarchical routing for wireless sensor networks such as [76–80]. To provide a view of hierarchical routing protocols, some are more scalable than others such as LEACH, PEGASIS, TEEN, VGA, SWRP, GBDD, NHRPA, SHIPER and DHAC. Regarding the use of greedy routing with the aim of reducing energy consumption in the system, routing such as PEGASIS, VGA, GBDD, ELCH and TIDD operate with better performance. Some routing protocols operate with more robustness such as LEACH, PEGASIS, TEEN, VGA, SWRP, GBDD, NHRPA, SHPER and DHAC [43].

B.0.2 Communication Model Scheme

The Communication Model Scheme refers to a group of communication-based routing protocols. They form a network based on data query and in some scenarios data processing passes to some sensing nodes or intermediate nodes. This category is divided into three sub-categories: query-based, coherent data processing based and negotiation-based routing protocols.

B.0.2.1 Query-based Routing Protocol

Query-based routing protocols work based on data queries that are broadcast by destination nodes. The sensing task is the first task in query-based routing protocols in that the data query disseminates through the entire network. The node that has collected data is matched with the query, the requested data is sent back to the destination node that initiated the query. The query can be in natural language, programming code or high-level query-based languages. For instance, a node may send a query to nodes in the network and ask, *"Is the temperature more than 50 in region A?"* and all nodes have a table that can translate the query to a data structure and respond or retransmit the query [43].

Directed Diffusion

Directed Diffusion (DD) [81] is a query-based routing protocol in which all nodes are query based and can respond to a series of predefined queries. DD has shown that it selects best paths and has the capability of saving and processing queries in the network in terms of using less energy. Figure B.3 shows different phases in DD routing protocol.

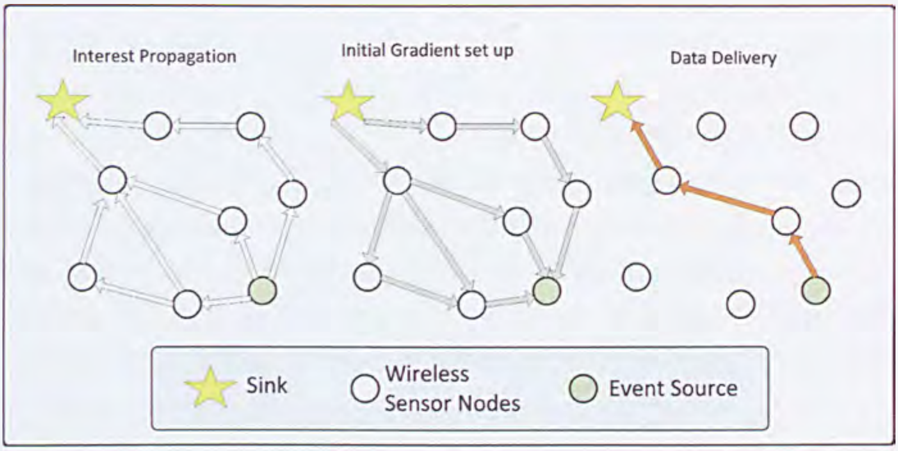

FIGURE B.3: Directed Diffusion Routing Protocol

DD operates based on four tasks: Naming. Interests and Gradients, Data Propagation and Reinforcement. The Naming task declares the name of event or other attributes such as data type, maximum or minimum thresholds, and the interval of data-transmission. They are formed as a list of attributes and values in Naming. Interests and gradients task describes the specification of matching the data with interests based on predefined attributes. The data is sent in respond to name as similar to the name is used in interest. Gradients describe the event and setup within the network. Nodes in the network keep records of interests and gradients. One interest can have different gradients for example gradients can be recodes of one interest from different neighbours. Data propagation task is the task in the case of nodes detects a target that is in the list of interests and then check with interest attribute, if the attributes imply with its attributes then it is sent to the highest gradient rate in cache. Reinforcement task supports a path or small number of possible paths toward the originator of interests in the network. [81] shows DD performs with better performance regarding decreasing energy consumption and increasing network life-time than traditional scheme such as omniscient multicast even if it does not choose the best path toward the destination.

In summary: DD benefits from extending network life-time and it has a good scalability rate with limited mobility support. It uses the best path for routing metrics and is categorised as a low robustness protocol. The weakness of DD is it cannot be used for continuous online data monitoring or event-driven applications [43].

COUGAR

COUGAR [82] is a query-based routing protocol for WSN. It is based on the concept of the data in the network nodes forming a huge distributed database. It uses declarative queries to distribute the processing task between nodes from network layer up to application layer. For example, in network layer, the function to find the relevant sensors can be done in network nodes. GOUGAR saves more energy by processing in-network data and use them for abstracting queries. GOUGAR uses an additional query layer that placed between network layer and application layer to provide the abstraction. Base-station generates and prepares the query plans. The query plan describes the necessary information regarding data flow and the computation that take place in-network and also how a leader be selected for a query. In-network computation defines for incoming queries, how to process and which relevant nodes should send to. GOUGAR performs with energy efficiency in scenarios that generate huge data. The drawback of GOUGAR is the amount of overhead to maintain in-network processing and also complexity of the synchronisation in the network and dynamically maintaining of leader selection to avoid failure nodes.

In summary: COUGAR performs with energy efficiency in scenarios with huge data generation. It supports limited scalability in fixed scenarios. It uses the best path for routing metrics and is categorised as a low robustness protocol. The weakness of COUGAR is its overhead and also the complexity of synchronisation in the network [43].

ACQUIRE

ACtive QUery forwarding In sensoR nEtworks (ACQUIRE) [83] is a query-based routing protocol similar to COUGAR and it considers the network as a huge distributed database. In ACQUIRE, a complex query splits into several sub queries that can handle by nodes. After base-station disseminate query to the network, each node forwards the receiving query. During the processing the query, each node checks the pre-cached memory for trying to respond to the query. If the pre-cached information is not up-to-date then it requests an update from its neighbours. ACQUIRE is a suitable routing protocol for one-shot and complex queries. It also is capable to collect the results of a query from responds is provided by some nodes.

In summary: ACQUIRE is an ideal routing protocol for one-shot and complex query-based scenarios wherein a query can be responded to by sub-query responses. It supports limited scalability with limited mobility. It uses shortest path for routing metrics and is categorised as a low robustness routing protocol. The weakness of ACQUIRE is its overhead, which can be compared with flooding [43].

Summary of Query-based Routing Protocols

In summary, DD and COUGAR select the path based on less energy consumption and can only support limited mobility. DD is more scalable than COUGAR. ACQUIRE selects the path based on short path to the destination to save more energy and it is less scalable than DD and COUGAR. Some other protocols can categorised as query-based routing protocols such as RR, SPIN-PP, SPIN-EC, SPIN-BN and SPIN-RL[43].

B.0.2.2 Coherent and Non-Coherent Data Processing-Based Routing Protocols

WSN as distributed data network in some scenarios is required to pass some data processing tasks to nodes to distribute the processing load and balance it within the network. [84] has proposed a routing mechanism for processing data in nodes. The mechanism can be categorised into two routing protocol groups; Coherent and Non-Coherent Data Processing-based Routing [85]. Coherent Data Processing based routings are energy-aware routing protocols for WSN which allow running minimum processing task by sensor nodes such as time stamping and checking duplicated message. The nodes run the tasks with minimum processing effort and then the message is forwarded to the aggregators [43]. Non-Coherent Data Processing based routings allow nodes to process data. Sensor nodes process the collected data locally and then forward them to other nodes for further process. Aggregator is the next node which runs the further process when receiving message from sensor nodes. The processing data takes place in three phases. Phase one is target detection, data collection and processing. In this phase, node detects the target and collects relative and predefined data and then process it based on dedicated task. Phase two is membership, in this phase node chooses and declares its membership and participates in a group task function and declares its task in this corporation to all its neighbours. Phase three is Central-node election that the central node which does more refine processing task in the final processing stage selects between eligible candidates [85].

SWE

Single Winner Algorithm (SWE)[86] is a routing protocol that selects an aggregator node as Central Node (CE). CE takes responsibility to do the complex processing tasks. CE is elect based on a comparison mechanism. In this election mechanism, the reserved energy level and computational capacity of nodes and many other properties take into account to find the best node in the network to run the complex data processing tasks. The election takes place in an one-to-one manner. Each node sends an election message to all its neighbours with announcing its CN candidacy and its capabilities. Each node by receiving the election message starts to compare the neighbour's capability with itself and if the sender of election message is more capable than itself then saves it in registry and forwards the message to the other neighbours in the radio range coverage to show the initial comparison of two nodes. If the capacity of the sender of election message is lower than received node then the message is discarded[86]. Figure B.4 shows

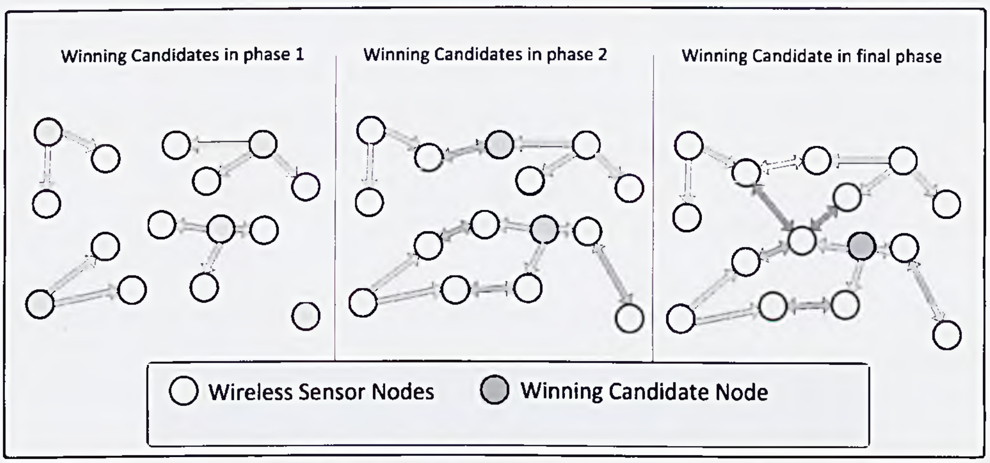

FIGURE B.4: SWE Routing Protocol - Election Mechanism

different phases of election mechanism in SWE. It shows how winning candidate is selected from small group of nodes toward whole network. SWE is a routing protocol that builds a minimum-hop spanning tree with reasonable level in scalability with no mobility support. It uses shortest path for routing metrics and categorised as a low robustness routing protocol. The weakness of SWE is its complexity in maintaining the network [43].

MWE

Multiple Winner Algorithm (MWE) [86] is a proposed routing protocol that in reality it is an extended version of SWE. SWE defines all nodes as source node and a node as a centre node (CN) and all nodes are allowed to send data to the centre node. This process in SWE uses energy and MWE proposed a mechanism that can save more energy and makes a balance in residual energy in the network. MWE limits the number of Source nodes which are allowed to send data to the centre node. All sensor nodes keep record of N best candidate nodes that are called Master Aggregator Node (MAN) and they are the source nodes that are allowed to send data to CN (N is a predefined number). MWE finds the best and low-energy consumption cost to the best MAN. Then the node with low-energy consumption and high level of capabilities is elected as CN between MANs. In summary;MWE is a routing protocol that each node discovers the best path to each source's node based on minimum energy consumption in each path. It supports low scalability with no mobility and uses shortest path for routing metrics. It is categorised as a low robustness routing protocol. The weakness of MWE is its long message delivery delay and it is not a scalable routing protocol [43].

Summary of Coherent and Non-Coherent Protocols

In Summary SWE and MWE are two routing protocols in this category. SWE is more scalable than MWE and MWE is a more sophisticated routing protocol that computes the paths to source node for each node based on minimum energy consumption.

B.0.2.3 Negotiation-based Routing Protocols

Negotiation-based Routing Protocol uses data centric routing mechanism that is also called Sensor Protocol for Information via Negotiation (SPIN).

SPIN

Sensor Protocol for Information via Negotiation (SPIN) [87] is a Negotiation-based Routing Protocol that designed based on data-centric routing mechanism. SPIN was proposed based on two concepts; first, operates with high performance and low-energy consumption and sensor nodes share data with each other regarding the data they have and the data they have to obtain. Second, nodes are responsible to monitor the energy level in the network to maintain the operability and extending the life-time in the system. SPIN uses high level descriptors or meta data exchanges to reduce redundant message retransmission in the network. Sensor nodes discover data by advertise it to all other nodes through sending an advertising message. The advertising message is checked with the list of interests and if it matches, then it sends a request message to the sensor node. The sensor node by receiving the request message sends the actual data to the node which has sent a request message in a data-packet. Figure B.5 shows different phases in SPIN routing protocol. It shows how the nodes receive and send ADV, REQ and Data-packets in the network. SPIN works based on three phases as ADV (advertisement), REQ (request) and DATA (the actual data). SPIN supports scalability as each node

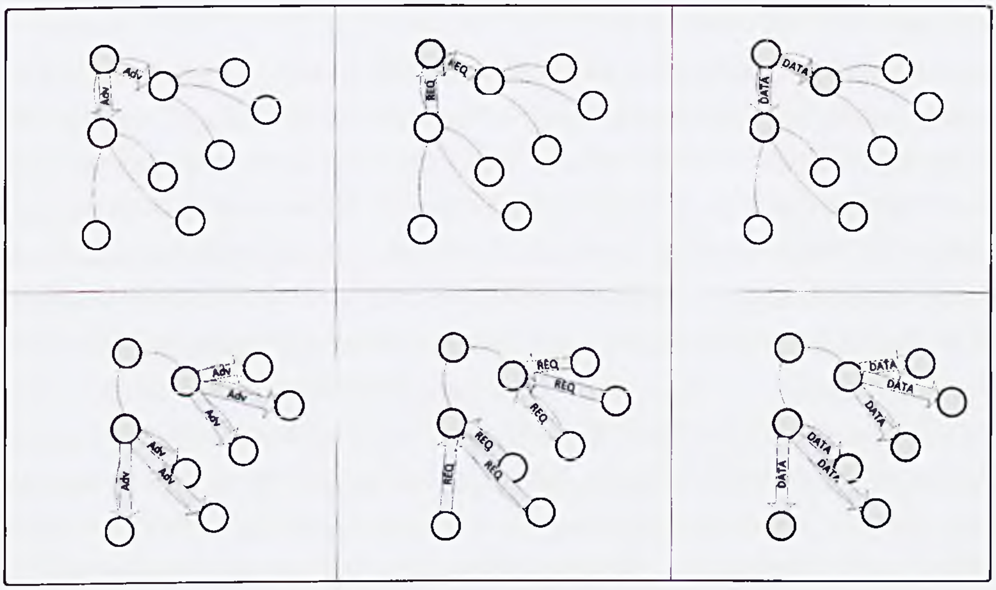

Figure B.5: SPIN Routing Protocol

does not know about the whole network and only operates with one hop node. The drawback of SPIN is there is no guarantee for data delivered to all nodes specially if the sensor node and interested node are far or the node between these two is not interested on the data [88].

SPIN-PP

SPIN for Point to Point Communication (SPIN-PP) [89] is from SPIN family routing protocol that focuses on one-to-one communication technique instead of one-to-many. Two nodes which are going to communicate select an exclusive time slot to communicate and avoiding making congestion to other nodes' communication. The phases in SPIN-PP is such as SPIN and the only changes is by receiving the ADV message, the receiving node checks whether it keeps the advertised data in its memory and if it doesnt then sends REQ message. SPIN-PP is not an energy-aware routing protocol and it operates based on there is no constrain in energy. SPIN-PP is a low cost setup routing protocol and it also categorised as a simple routing protocol that avoid implosion. The drawback of SPINN-PP is it does not provide packet delivery grantee mechanism and it uses more energy for operation.

In summary; SPIN-PP is a routing protocol that benefits from simplicity with minimal setup cost and also avoiding implosion. It is in good scalability rate and support mobility. It uses the direct connection to its neighbours in routing protocol and it doesnt use any routing metrics. It is categorised as a robustness routing protocol. The weakness of SPIN-PP is it does not guarantee the data delivery and consumes unnecessary energy[43].

SPIN-EC

SPIN with Energy Conservation (SPIN-EC) is an energy-aware version of SPIN-PP that takes the energy level into account when the node decides to send REQ message. SPIN-EC operates such as SPIN-PP in three stages for advertising, requesting and sending data. When the energy level in node is higher than threshold then SPIN-EC works such as SPIN-PP. When the energy level comes lower than threshold then the nodes does not send any REQ message even when it interests on data. SPIN-EC does not prevent nodes to receive ADV or REQ when they are in lower level of energy; however, it forces them to reduce participation into the protocol when the energy level is lower than threshold and even when by processing a task the energy level comes lower than threshold level[89].
In summary: SPIN-EC is a routing protocol that benefits to be used in the energy-aware scenarios. It reduces participation to the data-transmission if the energy level comes lower than threshold. It is scalable and it supports mobility and uses direct connection to its neighbours in routing procedures. It does not use any routing metrics and it categorised as a robustness routing protocol. The weakness of SPIN-EC is it does not support receiving ADV and REQ messages when the energy level of node is less than threshold [43].

SPIN-BC

SPIN for Broadcast Networks (SPIN-BC) [89] in a broadcast version of SPIN that use broadcast mechanism to send ADV message through the network that uses a shared channel for communication. In SPIN-BC, sensor node sends an ADV message in a broadcast manner and all nodes in radio coverage range receive the ADV message. Node by receiving the ADV message goes to a waiting time period and after passing this time period it sends REQ message. During the waiting time period, if node receives a REQ message, then it cancels its own REQ message to save energy and avoid redundant messages. The sensing node while receiving REQ message, broadcasts the data only once even it received multiple REQ message. SPIN-BC performs better than SPIN-PP as it uses broadcast facility and avoids redundant communication.
In summary; SPIN-BC is a routing protocol that performs better than SPIN-PP as using broadcast mechanism. It is in good level of scalability and supports mobility and uses direct connection to its neighbours in routing protocol. It does not use any routing metrics and categorised as a robust routing protocol. The weakness of SPIN-BC is it does not respond to REQ message instantly and it should passes a certain period of time to respond[43].

SPIN-RL

SPIN with Reliability (SPIN-RL) [89] is a reliable version of SPIN-BC that each node

keeps records of ADVs from each node and also REQ messages and traces each ADV message to receive at least one REQ message. If within certain period of time, the DATA message has not been received, then the node sends a REQ message again to be sure REQ message was delivered. SPIN-RL forces nodes to limit the frequent that node sends a same data. Nodes avoid resending data for less than a certain period of time. Node waits after sending data to a REQ for a certain time until it sends data again for another REQ message received. SPIN-RL performs better than SPIN-BC in case of reliability and even in cases a network faces packet-loss or network suffers from asymmetric link-quality between nodes.
In summary; SPIN-RL traces the ADV and sending data with avoiding to send redundant data; however, if it senses that REQ message has not been delivered, it sends it again to guarantee reliability. It is in a good rate in scalability and support mobility. It uses direct connection to its neighbours in routing protocol and it doesnt use any routing metrics. It categorised as good robustness rate. The weakness of SPIN-RL is it is time consuming and increases delay in end-to-end packet delivery[43].

Summary of Negotiation-based Routing Protocols
SPIN-PP, SPIN-EC, SPIN-BC and SPIN-RL are energy-aware routing protocols with mobility support. These protocols send message if the node has data to send and they minimize energy consumption in the system. The SPIN protocols are scalable and can maintain the network regardless of the size and its performance is not related to the size of the network. Finally they are categorised as robust routing protocols [43].

B.0.3 Technology Based Scheme

Technology Based Scheme is a category of routing protocols which using technologies such GPS to aid protocol to find the best path to the destination in an optimised manner. In this category location based routing protocols and mobile agent based routing protocols are studied.

B.0.3.1 Location Based Routing Protocols

In position-based or location aided routing protocols, it assumes that all nodes in the network know their location and also know about other nodes' location. This kind of routing protocols benefits from influence of physical distance and nodes' distribution into the field in network performance. Location based routing protocols based on two assumed concepts; first, each node knows about its neighbour position. Second, the source node before sending the data to the destination would be informed about position of the destination node. They use HELLO message to exchange neighbours' positions. They are not using a routing table and use positions to send data toward destination through direct neighbours. The drawback of this kind of routing protocols is the performance depends on distribution of nodes and the amount of traffic to exchange.

DREAM

Distance Routing Effect Algorithm for Mobility (DREAM) [90] is a proactive routing protocol that all nodes keep a table of nodes in the network with their positions. This protocol was designed to fully support mobility and wireless node called Mobile Node (MN). Nodes transmit location message to two sets of neighbours; nearby and faraway. The messages are sent frequently to keep the neighbour position tables up-to-date in the network. The frequent to update faraway nodes are lower than nearby nodes and those frequents are predefined. It is assumed the faraway mobile nodes move more slowly than nearby mobile nodes and it is not necessary to keep them up-to-date such as nearby mobile nodes. DREAM tries to limit the overhead of location packets by defining of nearby and faraway mobile nodes. If a node decides to send a data-packet to a destination node, it finds destination node in the position table to discover the position of the destination and also the neighbour nodes which are in the direction of the destination node position and then send data-packet to the neighbour node that is in the destination's direction. DREAM befits of availability of end-to-end rout to the destination and it decreases the packet delivery time delay.

In summary; DREAM benefits from efficient data-packet transmission and has limited scalability with good mobility support. It uses minimum power consumption in path as the routing metric and uses control message to maintain the topology. It is categorised as limited robust routing protocol. DREAM has a drawback as it wastes the network bandwidth [43].

GEAR

Geographic and Energy-aware Routing (GEAR) [91] is a position-based and also energy-aware routing protocol that uses greedy algorithms to forward the message. GEAR uses position and energy level information of neighbours to find the best route to a destination. All nodes know about the position and energy level of all nodes in the topology. They receive HELLO message that provide information about the neighbours's position and energy level. GEAR uses a technique to handle a hole in the network. When a node decides to send a message to the destination node and there is no node close to the destination in the radio communication rang then it selects a neighbour with a minimised cost mechanism as next-hop to deliver the message to it. In the normal situation, GEAR selects a closest node to the destination to deliver message to it as the next-hop. The advantage of GEAR is to balance the energy level within the network and try to increase the life-time of the network.

In summary: GEAR benefits from balancing energy level in the network to increase network life-time. It has limited scalability with limited mobility support. It uses the best path as the routing metric and uses HELLO message to maintain the neighbour exchange table and is categorised as a robust routing protocol. Its drawback is it needs to exchange the neighbour's tables periodically [43] and uses bandwidth.

Graph EMbedding for routing (GEM)

Graph EMbedding for routing (GEM)[92] is a position-based routing protocol for wireless sensor network that uses a Unique Identification Number (UIN) for each node in the network. A node in a routing path forwards the message based on the next UIN neighbour that was predefined by the sender. GEM instead of using physical coordination, it uses a virtual system that is formed in each node to have a view of the whole network and use a coordinator. GEM uses two elements for operation; Virtual Polar Coordinate Space (VPCS) and Virtual Polar Coordinate Routing (VPCR). VPCS is built in the first stage to form a loop-free spanning tree with route to the Sink based on node's position information and Sink in the network. The spanning tree is formed in parent and child manner. Each parent has some subtrees that each subtree has a centre-of-mass which shows the number of nodes in this subtree and also the average of node positions in each subtree that shows the position of subtree region. Then this subtree's information broadcasts it to all other nodes in the network. VPCR has a responsibility to route the message to the next hop to reach to the destination based on information from VPCS. GEM benefits from using the efficient routing in the network and each node routes the message by only knowing the UIN of the neighbour. It has also capability of operating in the dynamic scenarios with good scalability regarding the network size and node density. The drawback of GEM is load's overload and also drains of energy for nodes which are close to the Sink.

In summary; GEM benefits from running with efficient message delivery based on having only neighbours' table and have a good scalability rate with limited mobility support. It uses the shortest path as the routing metric and does not use periodic message to maintain the topology and is categorised as a robust routing protocol. Its drawback is the nodes with close distance to the base-station are overloaded and drain their energy earlier than others[43].

IGF

Implicit Geographic Forwarding (IGF)[93] is a state-free, location based and energy-aware routing protocol that uses distance and energy level to select next-hop as a valid receiver in radio transmission rang without having knowledge of nodes in the network. It uses an integrated Network/MAC solution to select the best forwarding node in the neighbours. It provides a robust message delivery protocol with stability. It uses lower control packets as overhead for operation. The energy level of nodes takes into account in time of selecting the next candidate node to avoid draining nodes and balance the energy level in the network. The packet's next-hop is selected in a real-time manner by sender node. The protocol supports fault tolerance and copes with shifting stats of neighbours in real-time for example switching nodes from sleep mode to awake mode to transit into the other regions. IGF does not need to use a highly cost overhead to maintain the topology of the network for routing protocol as the nodes decide instantly based on real-time information. IGF uses Increased Distance Toward the Destination (IDTD) and Energy Remaining (ER) methodes for selecting the best route toward the destination. IGF benefits from shorter end-to-end latency in comparison with other protocols and also load balancing across the network.

In summary; IGF benefits from robust performance and distributing the workload within the network and has limited scalability with good mobility support. It uses the best route as the routing metric and does not use periodic message to maintain the topology. It is categorised as a robust routing protocol. Its drawback is the performance is depend on local neighbour table that has to be up-to-date[43].

SELAR

Scalable Energy-efficient Location Aided Routing (SELAR)[94] is a position-based and energy-aware routing protocol for WSNs. It uses the location and also the energy level of neighbours to select the next-hop node. In the first stage, the Sink floods its position to the whole network and after that all nodes know about the Sink's location. Then all nodes broadcast their location to their neighbours and SELAR assumes that nodes are static. After initiate stage, only energy level sends to neighbour to keep the neighbours' table up-to-date. The control protocol travels only one hop and for this reason, SELAR consumes less energy and decreases the amount of overhead to maintain the neighbour table up-to-date. Minimum angle and maximum angle are parameters of SELAR that are predefined. Usually the minimum angle is 15 degree and the maximum angle is 90 degree. When a node decides to send a message toward the Sink, it searches between neighbours which are in minimum angle toward the destination. If SELAR cannot find any neighbour in this angle it increases angle up to the maximum angle. When SELAR finds some neighbours in certain angle then select the node with higher energy level to be the next-hop node. In case SELAR cannot find any neighbour in maximum angle then it uses gossiping to discover a root toward the destination. The advantage of SELAR is dissipation of energy in the network by selecting the higher level of energy between

candidates. The disadvantage of SELAR is it does not support mobility and works in fixed scenarios.
In summary; SELAR benefits from selecting the node with higher energy level and it provides uniform energy level dissipation. It supports limited scalability with no mobility support. It uses maximum energy level in neighbours as the routing metric and uses control message to maintain the topology. It is categorised as a robust routing protocol. The disadvantage of SELAR is it does not show good performance in case of nodes' mobility[43].

GDSTR

Greedy Distributed Spanning Tree Routing (GDSTR) [95] is a geographical routing algorithm that routes messages through shortest path by generating less overhead than CLDP. The normal geographical routing algorithms when facing to the holes or dead-end in topology, switch from greedy forwarding to planar network topology and then using the right-hand rule to pass the dead-end zone. GDSTR in case of facing dead-end zone, uses a spanning tree until the greedy forwarding again can make a progress in routing. In GDSTR, all nodes maintain a neighbour table that defines a summary of covered area by each neighbour's node. GDSTR provide two routes toward the tree's root to provide robustness and provide additional forwarding route. GDSTR uses hull tree concept. A hull tree is a spanning tree where each node has an associated convex hull that contains within the location of all its descendant nodes in the tree [95]. Aggregation location information is provided by hull tree which are built by aggregation convex hull information. This information is used in routing algorithm to avoid dead-end zones. GDSTR usually forwards packet using simple greedy forwarding. If it is not possible to use greedy forwarding then use forwarding based on hull tree to avoid dead-end zones then it switches back to greedy forwarding as soon as it has a progress in routing.
In summary; GDSTR benefits from finding the shortest routes and generates low traffic to maintain the topology. It supports limited scalability with no mobility support. It uses shortest path as the routing metric and uses HELLO message to maintain the topology. It is categorised as a robust routing protocol. The disadvantage of GDSTR is its overhead traffic in the network [43].

MERR

Minimum Energy Relay Routing (MERR) [96] is a position-based and energy-aware routing protocol. The basic concept of MERR is energy consumption in radio transmission module has the square relation to the distance between transponder and receiver. MERR uses the far node in radio communication coverage that is close to the destination and then based on the location of the next-hop node, it adjust the radio transmitter

power to only cover the respective node. This method decreases energy consumption in wireless communication. MERR is designed for scenarios that wireless sensors deployed in linear topology and they use a node as base-station or Sink.
In summary; MERR benefits from providing energy consumption distributed in the network and sensor nodes uniformly consume their energy. It supports limited scalability with low mobility support. It uses minimum energy consumption in the path as the routing metric and does not use control message to maintain the topology. It is categorised as a robust routing protocol. The disadvantage of MERR is it uses more energy in case the nodes are close to each other [43].

OGF

On-demand Geographic Forwarding (OGF) [97] is a purely on demand, energy-efficient and position-based routing protocol for delivering data in the large scales in static scenarios within unreliable sensors. OGF is a cross layer algorithm that uses an explicit contention scheme to find the next-hop node in a distributed wireless sensor network. It maintains a local forwarding table that keeps the neighbours information and is used in forwarding a message to the next-hop. OGF employs a partial source routing scheme to handle void communication. When a data-packet arrives, then the node looks up the forwarding table, if it finds an entry then checks whether the next hop is passive, if it is not passive, forward the data to the specific next-hop node. If the next-hop is passive, it uses void handle scheme to deal with this data-packet. If the entry does not exist in forwarding table then it initiates a contention to establish a next-hop node and if the next-hop node exists then it forward the data-packet to the next-hop and updates the forwarding table; however, if it does not exist, OGF pass it to void handling scheme to deal with it. OGF performs with low-energy consumption and it is a scalable protocol and has a good reliability in data delivery in targeted sensor scenarios.
In summary; OGF benefits from a superior performance in terms of scalability, energy consumption and void handling. It supports scalability with limited mobility support. It uses the best route as the routing metric and does not use any control message to maintain the topology. It is categorised as a robust routing protocol. Its drawback is its performance depends on up-to-date local neighbour table.

PAGER-M

Partial-partition Avoiding Geographical Routing-Mobile (PAGER-M)[98] is a geographical routing protocol for mobile sensor nodes that supports frequently mobility. The protocol uses the information of nodes and base-station to initiate a cost function that is similar to Euclidean length of shortest path. Whenever possible a packet is forwarded to the base-station by greedy forwarding. When a packet is received in a node that

greedy forwarding does not work after a number of hops then the packet is forwarded to the next hop based on low cost to high cost order. PAGER-M shows better performance in packet delivery ratio, routing overhead and energy consumption in comparison with AODV and GPSR.
In summary; PAGER-M benefits from a superior high delivery ratio, low routing overhead and low-energy consumption. It supports scalability with mobility support. It uses the shortest path and greedy algorithm as the routing metric and uses HELLO message to maintain the topology. It is categorised as a robust routing protocol[43].

HGR

Hybrid Geographic Routing (HGR) [99] is a geographical, hybrid and energy-aware routing protocol for wireless sensor network. The geographical routing protocols use distance-based or direction-based strategies to select the next-hop between neighbours. Distance-based is in favour of neighbours distance from source toward the base-station. Direction-based is in favour a neighbour with lowest angle toward the base-station. HGR combines both strategies and use them as a hybrid technique to select the next-hop. HGR uses a weight scheme of distance, direction of the next-hop neighbour with a wide array of application-specific parameters that adjust delay and energy consumption during the decision making process.
In summary; HGR benefits from using combination of distance and direction scheme to select the next-hop in a flexible manner. It supports scalability with mobility. It uses the paths with minimising the total power consumption and does not use control message to maintain the topology. It is categorised as a robust routing protocol. Its drawback is it does not guarantee end-to-end packet delivery time[43].

DHGR

Dynamic Hybrid Geographic Routing (DHGR) [99] is a dynamic version of HGR that supports quality of service by using more parameters from application layer. In DHGR, packet delivery's decision takes place locally and uses a parameter alpha to adjust decision to reach to QoS level. DHGR takes decision based on state at the node and it is independent of numbers of nodes in the network and for this reason it is scalable such as HGR. By selecting an optimal alpha, DHGR can minimize energy consumption while stay in QoS level of delay requirement in the application level.
In summary; DHGR benefits from using combination of distance and direction scheme to select the next-hop in a flexible manner and also guarantee the QoS level in application level. It supports scalability and mobility. It uses the paths with minimising the total power consumption and does not use control message to maintain the topology. It is categorised as a robust routing protocol.

Summary of Location-Based Routing Protocols:
In summary, DREAM, IGF, PAGER-M, HGR and DHGR uses lower energy consumption during the operation and also support nodes mobility. GEM and GDSTR uses shortest path for sending data-packet to minimize energy consumption. GEM, IGF, PAGER-M, HGR and DHGR avoid using periodic maintaining network message to minimize energy consumption in the system. GEM, OGF, PAGER-M, HGR and DHGR are more scalable than others protocols in this category. TTDD, COUGAR, ACQUIRE can categorised in this section; however, they are considered in other categories.

B.0.3.2 Mobile Agent Protocol

Mobile Agent Protocol (MAP) [100] is used for high-level interference and surveillance applications in WSNs where bandwidth and power consumption are the main concerns. MAP employs migrating code to provide re-tasking, local processing, collaborative signal and data processing. MAP adds more flexibility to WSN and makes it capable to operate the conventional tasks based on a client-server computing model. The main attribute of MAP is reducing significant amount of bandwidth by moving the data processing from base-station or a central Sink to sensor area where the main portion of energy consumption in the WSNs is in transmission of raw data. MAP provides a higher degree of re-tasking flexibility and collaborative information processing. MPS not only can work as single processing units; however, also it can form a distributed collection of components that can collaborate to achieve a given task. The core components of MAP are Architecture that can be flat or hierarchical, Agent Corporation that can be single agent or multiple agents, Itinerary planning that can be Static, Dynamic or Hybrid planning and finally Middleware system that can be fined or coarse grained[43].

Multi-agent Based Itinerary Planning (MIP)
The first generation of MAP is Single agent based Itinerary Planning (SIP) that cannot provide good performance in large scale network regarding long delay and unbalanced load distribution. Multi-agent based Itinerary Planning (MIP) [101] is a multi-agent based that cover drawbacks of SIP. MIP operates based on four algorithms; Visiting Central Location (VCL) selection algorithm, source-grouping algorithm, SIP algorithm and iterative algorithm. The main concept of MIP is a system that works based on impact factor. Each source node gives an impact factor to other source nodes and the source node with maximum accumulated impact factors would be selected as location of the agent. The simulation results show a significant energy consumption's saving by using MIP instead of SIP.
In summary; MIP benefits from using less energy in large number of nodes scenarios and

has limited scalability with good mobility support. It uses minimum power consumption in path as the routing metric and does not use any control message to maintain the topology. It is categorised as a robust routing protocol. MIP has a drawback as it has high delay in end-to-end packet delivery [43].

IEMF

Itinerary Energy Minimum for First-source-selection (IEMF) [102] considers data aggregation and energy efficiency in itinerary selection. Itinerary Energy Minimum Algorithm (IEMA) is iterative version of IEMF, during each iteration, IEMA selects the best node based on IEMF as the next source to visit between other source nodes. There is a trade-off between energy efficiency and computational complexity based on application requirements. IEMF selects the first source as the corresponding itinerary with smallest energy cost between other candidates. Then it uses IEMA to locate the optimised remaining itinerary to a certain degree. IEMA selects the first source node in an estimated energy cost based. The simulation results show MIP achieves better performance than SIP regarding delay and energy consumption.
In summary; IEMF and IEMA benefit from optimizing the remaining itinerary to a certain degree and has limited scalability with good mobility support. It uses minimum power consumption in path as the routing metric and does not use control message to maintain the topology. It is categorised as a robust routing protocol. IEMF and IEMA has a drawback as they are not scalable when a large number of source nodes to be visited[43].

B.0.4 Reliable Routing Scheme

Reliable Routing Scheme is a category of routing protocols that using techniques such as multi-path Routing or Quality-of-Service QoS parameters to guarantee packet delivery within certain properties. In this category, two sub-categories as multi-path routing and QoS-based routing are considered.

B.0.4.1 Multi-path Routing Protocols

Multi-path Routing Protocols as it is obvious from the title, they use several paths to send data toward the Sink or destination instead of trusting only one path. The protocols benefit from balancing load in whole network and show more resilient to node failures[103]. The routing protocol in this categories have advantage of lower routing overhead and also lower delay and avoiding congestion in comparison with single-path routing protocols.

ROAM

Routing On-demand Acyclic Multipath (ROAM) [104] is a distance-vector routing protocol that uses concept of feasible distance to maintain routes and avoids loop in the network. ROAM maintains the network topology be asking nodes to send an update to their neighbours whenever the distance is changed based on a certain threshold. ROAM forces each node to keep three tables; distance, routing and link-cost tables. The distance table is a matrix of neighbours distance and the routing table containing of the list of destination with the feasible distance and the successor for each router. The link-cost table keeps the records of each neighbour with their costs. Routers start to use a diffusing search in case of the destination is not in the routing table. Routing searches one by one hop and looking for message travels to reach to a node that knows about the destination. In case of the message travels to all nodes and no one knows about the destination, then the destination is labelled as unreachable. ROAM uses a periodic update message regarding routers to be update about active nodes.

In summary; ROAM benefits from avoiding sending packets to unreachable destinations that prevents routers to send unnecessary search packets. It has limited scalability with limited mobility support. It uses any path in routing messages and uses HELLO message to maintain the topology. It is categorised as a limited robust routing protocol. ROAM makes significant amount of overhead as sending HELLO messages to maintain the active nodes [43].

LMR

Label-based Multipath Routing (LMR) [105] is a routing protocol for WSNs that broadcasts a message to find the possible alternative path in form of a control message. The recent used paths that deliver the messages are labelled and then this label is used for finding the backup path in case of the best path is not achievable any more. LMR uses localisation information and flooding to discover the topology and reserves several segments to protect current paths. Label's message contains a value that is used to find the best backup path. Nodes keep labels and their values and also neighbours that associated in those labels. Routing overhead can reduce by using label information although finding an alternative path create overhead that contains flooded label, label reinforcement and backup exploratory messages.

In summary: LMR benefits from decreasing network overhead by using label information and also discovers the backup paths. It has good scalability with good mobility support. It uses any path in routing messages and does not use any message to maintain the topology and is categorised as a robust routing protocol. Disadvantage of LMR is it creates overhead for finding possible alternative paths[43].

GRAB

GRAdient Broadcast (GRAB) [106] is a routing protocol that was proposed for scenarios that need a robust data delivery guarantee within unreliable nodes and weak communication links. GRAB broadcasts advertisement message that contents cost of each node into the whole network. Each node by receiving an advertisement message, then it calculates link-cost and adds it to the advertised cost to find the total cost and then compares it with the previous saved cost and keeps the minimum one as the node cost. In case, the new cost smaller than the previous node cost, then after updating the table, the node advertises the new cost to the other nodes. GRAB controls the bandwidth by limiting the length of data message. The main advantage of GRAB is it relies on collective efforts of multi paths to deliver the message and not only trust to one path. It makes it a robust routing protocol although sending redundant data makes significant amount of overhead.

In summary: GRAB benefits from the collective efforts of multi path through multiple nodes to deliver data and not trusting only one route with specific nodes. It has a good scalability rate with mobility support. It uses the paths which satisfy the QoS requirements. It uses HELLO message to maintain the topology. It is categorised as a robust routing protocol. GRAB makes a significant amount of over-head for sending redundant data.

HMRP

Hierarchy-Based Multipath Routing Protocol (HMRP) [107] uses a Candidate Information Table (CIT) to keep topology up-to-date. Each node including Sink, broadcasts a layer construction packet and then nodes try to keep own CIT table up-to-date. Each nodes needs to know only the next parent node when decide to send a data-packet. HMRP does not need to know about whole network when nodes decide to send data-packet, they only need to know about their parents that can reduce the overhead in the network. HMRP can use multi path and it causes to distribute the energy level through the network and increase network life-time. HMRP can support scenarios with multi Sink and also with large number of sensor nodes. HMRP is scalable and can manage network with small and also large number of nodes in the fields and in the overall, overhead is very low. HMRP categorised as a simple routing protocol as the nodes do not need a high processing capacity and high memory. The long life-time in HMRP is one of the advantages of this protocol as it uses very low overhead.

In summary; HMRP benefits from scalability, simplicity and increasing system life-time. It is a scalable with low mobility support. It uses any path to rout messages and does not use any message to maintain the topology. It is categorised as limited robust routing protocol. HMRP makes significant over-head for sending construction packet once when the topology starts to form in initiation stage[43].

CBMPR

Cluster-Based Multi-Path Routing (CBMPR) [108] is a hierarchical routing protocol that benefits from both cluster based and multi-path attributes regarding delivering packets with high efficiency. CBMPR uses clustering to find independent multi path toward destination. It makes CBMPR to be more scalable with using low overhead. All nodes send a HELLO message regularly that nodes IP address are embedded. Cluster head nodes add the IP address of cluster member and the IP into the HELLO message. Cluster heads keeps track of all the IP addresses of the cluster in the routing tables. Cluster head also keeps a table of neighbours. CBMPR uses multipath to deliver the data message. The paths in the routing tables can be classified as optimal paths or shortest paths to help CBMPR select the best one. The advantage of CBMPR is it makes less interference and it is a simple protocol, the nodes need to send message to the cluster head only. Each node by receiving data message does not need to do a massive calculation and needs simply to pass it to the cluster head. The only disadvantage of CBMPR is fragmenting the data message and defragmenting in the destination makes it more complex and even causes increasing end-to-end delay.
In summary; CBMPR benefits from simplicity and low interference. It has good scalability with low mobility support. It uses the best path in routing messages and uses HELLO messages to maintain the topology. It is categorised as a limited robust routing protocol. CBMPR may suffer from path joining problems[43].

DGR

Directional Geographical Routing (DGR)[109] was proposed for delivering real-time video streaming packets through the bandwidth and energy limited networks. DGR delivers packets from a small number of distributed video sensor nodes to a Sink with forwarded error correction (FEC) coding. An active Video sensor Node (VN) broadcasts the video data-packets to its directed neighbours. Each neighbour based on its identifiers and the packet sequence number selects one part of the video packets and then sends the assigned packets to the Sink in a unicast manner.
In summary; DGR is a suitable routing protocol for real-time video streaming. It has high level of scalability with no mobility support. It uses paths with different initial direct neighbour in routing messages and does not use any message to maintain the topology. It is categorised as a high robustness routing protocol[43].

DFC

Directional Controlled Fusion (DFC) [110] is a multi-path, load balancing and also data fusion routing protocol for WSNs. DFC uses number of multi-path in the topology to achieve specific QoS requirements in various applications. DFS selects a source node as reference per round based on application attributes such as maximising the residual energy, distance to the source or distance to the Sink.

In summary; DFC uses multi-path in message delivery to achieve application requirements. It has properties of high scalability with high mobility support. It uses the best path in routing messages and does not use any message to maintain the topology. It is categorised as a robust routing protocol. DFC selects only one source node as reference source per round and it is its disadvantage regarding high risk of failure point[43].

RPL

Routing Protocol for Low power and Lossy Networks (RPL) [111] is an IPv6 routing protocol for WSNs that was proposed by ROLL (Routing working group in IETF). Directed Acyclic Graph (DAG) is a directed graph that all nodes in the path are terminated to one or more root nodes and they are loop-free. A Destination Oriented DAG (DODAG) root is a node within the DAG that has no outgoing edge which may act as a border router or aggregate routes. DODAG Information Object (DIO) message is the message that is delivered toward DODAG and using link-local multi-casting schemes. RPL uses a mechanism to distribute data messages over the dynamic formed network topology. It needs minimum node configuration and nodes simply operate in RPL.

In summary; RPL is a low-energy consumption routing protocol. It has good scalability rate with good mobility support. It uses shortest path in routing messages and uses DIO message to maintain the topology and is categorised as a robust routing protocol. RPL weakness is it only supports unicast traffic[43].

B.0.4.2 QoS-Based Routing Protocols

QoS-Based Routing Protocol balances between energy consumption in the network and QoS requirements at the application level [112, 113]. The network may need to achieve certain QoS metrics such as delay, energy level, bandwidth, etc. In best-effort routing protocols, increasing the throughput and decreasing end-to-end delay are the main concerns. Most of the proposed mechanisms for QoS-based routing for multimedia data in wired based networks are not applicable in wireless communication due to the nature of the media or limited energy sources in the nodes.

SRA

Sequential Assignment Routing (SRA)[114] is a QoS-based routing protocol that takes into account application level requirements when taking a decision to deliver a packet. Parameters such as energy resources, QoS on each path and packet properties are taken into account when SAR decides to send a packet. A multi-path scheme is used by SAR to avoid single path failure or nodes failure. The main task of SRA is to minimize the average weighted QoS metrics and increasing network life-time.

In summary; SAR benefits from low power consumption while maintaining multipath to the destination. It has limited scalability with no mobility support. It uses path with minimum average weighted QoS metric, uses HELLO message to maintain the topology and is categorised as a low robust routing protocol. SAR creates overhead in maintaining tables and states at each node and it may need a large memory capacity if the number of nodes goes high [43].

SPEED

SPEED[115] Protocol is a QoS routing protocol that provides end-to-end, real-time packet delivery guarantee. It also provides congestion avoidance when the network experiences the congestion. Stateless Geographic Non-Deterministic forwarding (SNFG) is the routing module in SPEED. It employs a delay-estimation scheme to inform protocol about delay as QoS requirement parameter. In congestion cases, SPEED uses slightly higher energy consumption as it delivers more packets toward the destination than other protocol to avoid congestion. SPEED is not an energy-aware routing protocol. The main advantage of SPEED is it has better performance in regarding end-to-end packet delivery delay.

In summary: SPEED benefits from good performance in terms of end-to-end delay. It has limited scalability with no mobility support. It uses a path which is geographical stateless, uses HELLO messages to maintain the topology and is categorszed as a low robustness routing protocol. SPEED cannot perform well in heavy congestion scenarios [43].

MMSPEED

Multi-Path and Multi-SPEED (MMSPEED) [116] is QoS-based routing protocol designed for probabilistic QoS guarantee in wireless sensor applications. The guarantee can be in two domains, time domain and reliability domain. In time domain, it guarantees end-to-end delay and in reliability domain, it guarantees various reliability requirements by probabilistic multipath forwarding. The QoS provisioning is estimated

based on localized information without relating on global network information. It uses localized geographic packet forwarding by considering dynamic information to take decision to forward the packet to the destination. The main advantage of MMSPEED is it guarantees end-to-end delay for packet delivery based on localized information to make it a robust routing protocol that can be scalable with reliability in large-scale and dynamic sensor networks.
In summary; MMSPEED benefits are QoS guarantees in terms of reliability and end-to-end delay. It has limited scalability with no mobility support. It uses a path that is geographical stateless, uses HELLO messages to maintain topology and is categorised as a low robustness routing protocol. MMSPEED cannot meet the end-to-end delay requirement in a high load network [43].

MGR

Multimedia Geographic Routing (MGR) [117] is an energy-aware routing protocol for Mobile Multimedia Sensor Networks (MMSN)s wheein Mobile Multimedia sensor Node (MMN) is exploited to enhance the capacity for event description. Its goal is to achieve expected end-to-end delay with giving top priority to QoS provisioning. It guarantees end-to-end packet delivery delay for specific applications. MGR tries to minimize energy consumption and respectfully increases network life-time.
In summary; MGR benefits from minimising energy consumption and guaranteeing end-to-end delay. It is a scalable protocol with good mobility support. It uses the path with minimum delay in routing messages and does not use any message to maintain the topology. It is categorised as a low robustness routing protocol [43].

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