Cognitive and Adaptive Routing Framework for Mobile Ad-hoc Networks

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Abstract

In this thesis, we investigate the field of distributed multi-hopped routing in Mobile Ad Hoc Networks (MANETs). MANETs are suitable for autonomous communication in remote areas lacking infrastructures or in situations where destruction of existing infrastructures prevail. One such important communication service domain is in the field of Public Protection and Disaster Relief (PPDR) services where rescuers require high bandwidth mobile communications in an ad hoc fashion.

The main objectives of this thesis is to investigate and propose a realistic framework for cognitive MANET routing that is able to adapt itself to the requirements of users while being constrained by the topological state. We propose to investigate the main proactive and reactive emerging standard MANET routing protocols at the Internet Engineering Task Force (IETF) and extend their functionalities to form a cognitive and adaptive routing approach. We thus propose a cognitive and adaptive routing framework that is better suited for diverse MANET scenarios than state-of-the art protocols mainly in terms of scalability. We also design our approach based on realistic assumptions and suitability for modern Android and iOS devices. In summary, we introduce the area of MANET routing and the state of the art in the field focussing on scalable routing approaches, derive QoS routing models for variable sized MANETs and validate these models using event based ns-2 simulations and analyse the scalable performance of current approaches. As a result we present and evaluate our novel converged cognitive and adaptive routing protocol called ChaMeLeon (CML) for PPDR scenarios. A realistic "Cognitive and Adaptive Module" is then presented that has been implemented in modern smart devices. Finally, we end the thesis with our conclusions and avenues for future work in the field.

To Isha for her unconditional support and my family for their lifelong guidance

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Glossary of Acronyms

ACO Ant Colony Optimisation

AntHocNet Adaptive Nature-Inspired Algorithm for Routing in MANET

AODV Ad-hoc On-demand Distance Vector

API Application Programming Interface

CA Critical Area

CAM Cognitive and Adaptive Module

CBRP Cluster Based Routing Protocol

CEDAR Core-Extraction Distributed ad hoc

CGSR Clusterhead-Gateway Switch Routing

CML ChaMeLeon

CP Change Phase

CSMA Carrier Sense Multiple Access

DiffServ Differentiated Service

dRSVP Dynamic QoS Concept

DSDV Destination Sequenced Distance Vector

DSR Dynamic Source Routing

DYMO Dynamic MANET On-demand

E2CML Energy-Efficient CML

E2E End-to-End delay

ECB Energy Consumption Balance

ELBW Estimated Link Bandwidth

ELD Estimated Link Delay

ELJ Estimated Link Delay jitter

ELTX Estimated Link Error before successful transmission

ETX Expected Transmission Count

FQMM Flexible QoS Model for Mobile ad hoc Networks

FSR Fisheye State Routing

GPS Global Positioning System

HC Hop Count

HOLSR Hierarchical OLSR

HSR Hierarchical State Routing

HUMO Human Mobility in Obstacle constrained environments

I-D Internet-Draft

IANA Internet Assigned Numbers Authority

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

IntServ Integrated Service

IP Internet Protocol

IPv6 IP version 6

L-NST Lower-NST

LAN Local Area Network

LANMAR Landmark Routing Protocol

LAR Location Aware Routing

MAC Medium Access Control

MANET Mobile Ad hoc Network

MDS Minimum Dominating Set

MIB Management Information Base

MPR Multipoint relay

MTU Maximum Transmission Units

NEN	Neighbour Node Energy Level
NFD	Node failure degree
NHDP	Neighbourhood Discovery Protocol
NP	Nondeterministic Polynomial
NST	Network Size Threshold
OSLR	Optimised Link State Routing
OSPF	Open Shortest Path First
P2P	Peer-to-Peer
PMP	Proactive MANET Protocol
PPDR	Public Protection and Disaster Relief
QoS	Quality of Service
RDMM	Random Direction Mobility Model
RERR	Route Error
RFC	Request for Comments
RMP	Reactive MANET Protocol
RPL	IPv6 Routing Protocol for Low power and Lossy Networks
RREP	Route Reply
RREQ	Route Request
RWP	Random Waypoint
S-D	Source-Destination
SBR	Statistic-Based Routing
SHARP	Sharp Hybrid Adaptive Routing Protocol
TBP	Ticket-Based Probing
TBRPF	Topol- ogy Dissemination Based on Reverse-Path Forwarding
TC	Topology Control
TD	Topology Discovery
TETRA	Terrestrial Trunked Radio
TIM	Topology Information Maintenance
TLV	Type-length-value
TORA	Temporally-Ordered Routing Algorithm
TTL	Time To Live
U-NST	Upper-NST
WG	Working Group
ZRP	Zone Routing Protocol

Chapter 1

Introduction

This thesis investigates issues related to scalability of mobile ad hoc routing protocols and proposes a novel cognitive and adaptive routing framework. A cognitive MANET routing protocol is able to analyse information from network packets in order to deduce the topological sate of the network and adapt its routing approach to improve its performance. The aim of this thesis is three-fold. We firstly investigate the efficiency and effectiveness of current routing approaches using derived mathematical models. These models are validated using event-based simulations in network simulator-2 (ns-2). Our model based investigations allows us to gain better understanding of the performance of the protocols under various Mobile Ad hoc Network (MANET) scenarios. Then, the thesis presents and evaluates the novel ChaMeLeon (CML) cognitive and adaptive routing protocol that we have developed for PPDR communications but that can also be used for multi-purpose MANETs. CML is designed based on aforementioned findings, derived models and simulation results in order to offer a scalable cognitive and adaptive routing approach. The thesis also aims to present our novel cognitive and adaptive framework that can implement converged hybrid and adaptive routing logics in a realistic manner. In the following sections of this chapter, we firstly present a general introduction to the investigated field of MANETs and MANET routing protocols. We then present our motivation, research objectives, list the thesis contributions and provide an outline the thesis content. We also include a thesis methodology plan that was derived as part of application of the research methodology from [1].

1.1 General introduction

The Internet has been evolving at great pace over the last few decades. Future Internet is embracing the Internet of Things (IoT) concept where smart devices should form fully distributed peripheral networks. The resulting architecture would consist of a two-level paradigm of the current infrastructure based internet platforms as well as a novel fully distributed peripheral network for IP based ubiquitous services. Such peripheral networks would then be interconnected to the Internet cloud using gateways or other backbone carriers. This will allow islands of autonomic smart devices to interchange data both with the Internet cloud and across remote fully distributed communication based "islands of things". Generally, there are different boundaries that are used to differentiate among forms of ad hoc networking in these "islands of things" namely single-hop or multi-hop communication as well as static or mobile ad hoc networking. Other boundaries that are also employed include data-centric or IP-centric routing paradigms or most recently, the nature and purpose of devices are used to classify such pervasive networks e.g. wireless sensor networks uses small low power sensors for monitoring ambient host conditions. These paradigms and boundaries of distributed ad hoc networks are described in Fig. 1.1. It can be hence foreseen that the future Internet paradigm is shifting from user operated devices that require network infrastructures for setup and communication towards autonomous distributed networks of smart devices that allows ubiquitous user-centric communication services.

The MANET flavour of cooperative distributed networks presents the highest level of research and engineering challenges as described by Conti and Giordano [2]. A MANET consists of a set of self-organized communicating devices that may assume the role of a data source, destination or router. Data can be sent directly from source to destination if these are both within the same communication range. This range is defined by the enabling technology e.g. Zigbee (IEEE 802.15.4), Bluetooth (IEEE 802.15.1), Wifi (IEEE 802.11) and bespoke experimental MANET medium access control (MAC) protocols. In the case where the source and destination nodes cannot directly connect to each other, intermediate nodes act as packet routers for multi-hopping data from a source to a destination. Hence, MANETs can be described as fully distributed, autonomous and cooperative communication networks that can be effectively setup and operated without the need for pre-established infrastructures where each node in the network can assume the role of data source, destination or router. These unique MANET characteristics makes such ubiquitous networks suitable for the deployment of several future pervasive applications, as presented in [2, 3, 4, 5, 6], such as pervasive applications that provides tactical military communication, intelligent transportation information, Public Protection and Disaster Relief (PPDR) response communication and broadband internet access in remote rural areas as shown in Fig. 1.2.

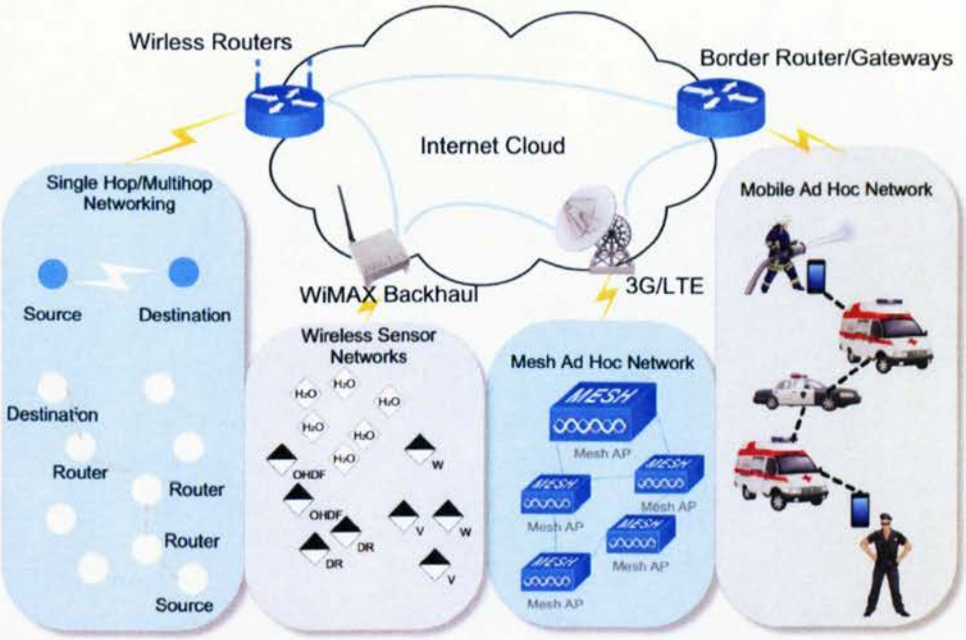


Figure 1.1: Forms of Ad hoc networks - The figure shows a probable infrastructure of future IoT with different forms of ad hoc networks

The pervasiveness of MANET enabled services will be mainly beneficial for users situated in areas with inadequate or no pre-existing communication infrastructures. For instance, emergency responders often have to carry out rescue missions in remote sites or disaster locations where infrastructures may be scarce, incapacitated or even non-existent. In such cases, MANETs will provide a new opportunity for an autonomous Internet Protocol (IP)-based multimedia communication platform to enhance mission critical coordination efforts as investigated in numerous large scale research projects [1]. MANETs can also be deployed as a tactical network in usually remote battlefields where

[1]http://www.ict-peace.eu/

ad hoc and autonomous communication setups are required. The DARPA project has developed a focus area for Communications, Networks and Electronic Warfare that deals with the "Advanced Wireless Networks for the Soldier" [1] program to study actionable implications for MANET design and deployment for ubiquitous rescuer communication. Moreover, ad hoc networking in a mesh topological paradigm can be potentially very useful for commercial applications.

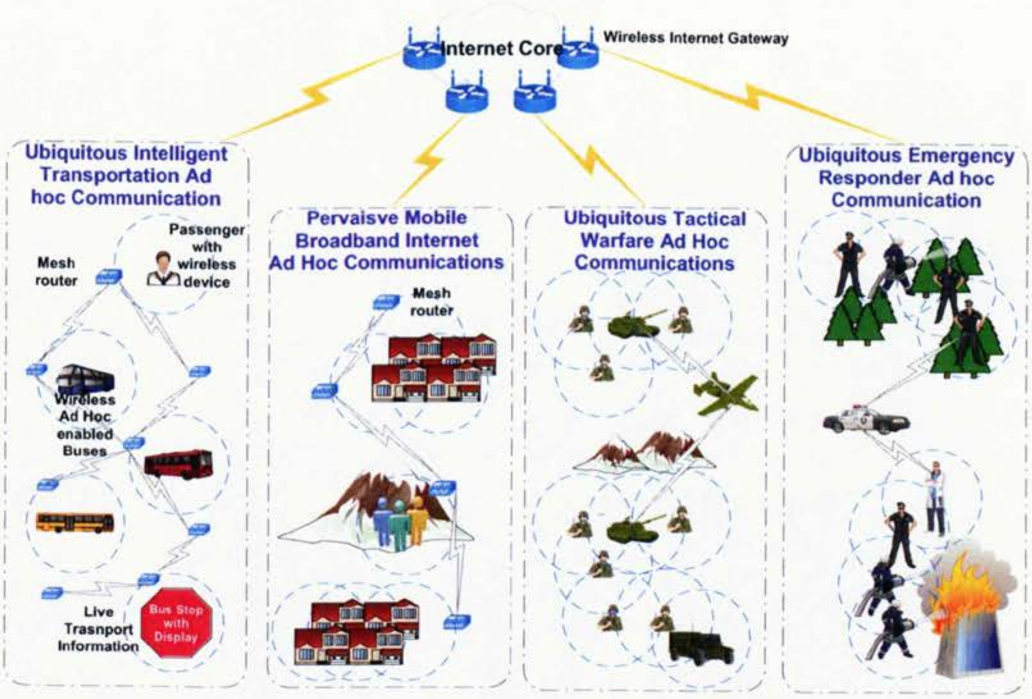


Figure 1.2: Ad hoc networking deployments - The figure illustrates the potential deployments of different forms of ad hoc networks for future smart ubiquitous services

For such deployments, wireless MANETs would enhance user mobility and remove any dependance on pre-existing infrastructures. At the same time such ubiquitous networks will maintain connectivity among users as well as between user devices and the internet to facilitate the deployment of pervasive applications such as described in [7]. The successful deployment of MANETs mainly depends upon establishing a suitable routing protocol satisfying application specific quality of service(QoS) requirements while being subject to constraints such as varying wireless link qualities along

[1] http://www.darpa.mil/Our_Work/STO/

routes, link breakage due to mobility of nodes and battery limitations of participating lightweight devices. Therefore, the added research interest on MANET routing stems from the fact that it requires a novel distributed cooperative multi-hopped routing approach to transmit data packets successfully among source-destination (S-D) node pairs in a dynamic topology.

The MANET Working Group (WG) of the Internet Engineering Task Force (IETF), formed in 1997, is currently leading the standardisation activities for a suitable IP based routing protocol functionality for both static and dynamic wireless MANET routing topologies. Emanating from the 2 chartered tracks of MANET WG are the proactive Optimised Link State Routing (OLSR) and reactive Ad-hoc On-demand Distance Vector (AODV) protocols deemed as pioneering work in the field of MANET routing standardisation [8]. However, one of the main challenges to be addressed before the widespread deployment of MANETs remains the scalability of the routing approaches discussed at the IETF and in literature [2, 9, 10, 11]. Also, recent research in the field of scalable MANET routing protocols [12, 13, 14] indicate that while OLSR and AODV approaches, also termed as flat routing approaches, do offer a strong MANET routing basis, they do not provide an appropriate solution to the problem. This is mainly because it has been found that both proactive and reactive approaches have been found to be more suited for different sets of MANET topological contexts. Thus, in order to benefit from the strengths of each approach, several hybrid approaches, including hybrid adaptive approaches are being proposed as a precursor towards enabling scalable MANET routing in the perspective of a future IoT. The protocols developed by the MANET WG are amongst the most adopted routing approaches towards implementation as discussed in more details in Chapter 2 of this thesis. One of the main objectives of work presented in this thesis aims at understanding flat MANET routing approaches and presenting a realistic solution for a cognitive and adaptive scalable routing approach that will encourage the deployment of MANET networks in real life applications such as ubiquitous communication for PPDR emergency services. One of the aspects of work in this thesis is enhancement of the most popular MANET routing protocols at the IETF in order to adhere by the standards guidelines to promote realistic protocols, thus our focus around improving OLSR and AODV protocols.

1.2 Motivation

The Future IoT is widely viewed as the interconnection of smart devices including the autonomic distributed networks [15, 16, 17]. The emergence of smart objects for everyday civilian use is already substantial e.g. smart PDAs, smart netbooks and smart "sensorised" devices. With the proliferation of wireless communication enabled smart objects, there is an emerging trend to exchange information pervasively and in a distributed manner among users and devices [18, 19, 20]. Therefore, future Internet applications and services will necessitate that smart objects should be able to communicate using ad hoc networks i.e. in an autonomous and distributed fashion. Such peripheral networks would then be connected to the internet core using IP gateways such as in the case of future emergency services as proposed in the European Union Framework Programme 7 ICT/SEC PEACE project. In this context, it is essential to consider the routing of information among such ad hoc networks of smart objects and their integration to the core Internet. For instance, PEACE project proposed the integration of rescuer ad hoc networks of smart objects to the IP Multimedia Subsystem.

Also, the significant worldwide increase in urban population has degraded the level of civilian protection provided by PPDR services. Thus, in recent times, both terrorist and natural disasters have had a higher impact as illustratable by the 7/11 New York attack, 2004 Madrid attack, 2005 London bombings and the 2011 London riots. With technological advances in the field of MANET wireless communications [3] and the evolvement of the Internet, there is now an opportunity to improve PPDR services using novel intelligent and ubiquitous PPDR communication platforms. Rescuer communications play a key role towards the coordination of response and rescue efforts in the event of extreme emergencies, such as terrorist attacks, earthquakes and riots [21]. Usually, these situations create a hostile communication landscape for rescuers where network infrastructures are either incapacitated or destroyed. In some rural extreme emergency scenarios, such as forest fires in remote touristic areas, communication infrastructures are non-existent. At the moment, most emergency rescuers have recourse to professional mobile radio technologies such as the well-known Terrestrial Trunked Radio (TETRA) technology. However, the limitations of PMR systems, established in 1995, with respect to modern IP-based wireless technologies are well documented [22]. Hence, wireless ad hoc networking is being proposed as the main candidate for a future PPDR communication platforms suitable for requirements of modern PPDR services [4].

Furthermore, future Internet services will comprise of pervasive HD media services, 3D services, user-centric personalised services and novel fully distributed applications. These will inject a substantial additional data load to the future core Internet. Therefore, next generation (NG)-Wireless network architectures [19] have to consider such service requirements. There is also an opportunity for NG-wireless networks to decentralise the provisioning of these future services so that the load on the core network is alleviated. In addition, the design of NG-wireless architectures has to consider the trends that will result from fulfilling requirements prevalent in the 2020. For instance, the wireless networks have to sustain the predicted throughput requirements of 1Mbps per user. There will also be a higher population and consequently user density in future societies. The penetration rate thus indicates that the high number of mobile users will require high throughput per area in the range of $(0.2Gbps/km^2 - 125Gbps/km^2)$. Also, it is important to respect the Base Station (BS) Transmission(Tx) Power (Powr) Constraints in order to preserve a green communication environment. Forecasts have shown that in dense regions, the BS density, in the range of $(112.6 - 22.5sites/km^2)$, will provide hurdles towards achieving this. Whilst in rural regions, the higher BS Tx Powr required coupled with the increased emitted radiation, may pose a challenge towards green communications.

MANETs are well-suited for the above scenarios as they do not require any centralised infrastructure for communication. As such, ad hoc networks can provide a localised autonomous network to provide location based or user-centric personalised services. One of the main issues to be addressed for the realistic deployment of MANETs is the development of a scalable routing approach that will provide the required QoS for data delivery in both small networks effectively, and in larger networks, in an efficient manner. This can be achieved by adaptively adopting the best suited standard routing protocol according to the network size. In order to enable such an adaptive behaviour, the routing protocol needs to be cognitive in order to monitor the state of a MANET. For instance, in the case of scalable routing, the cognitive feature requires that routing approaches are able to monitor the number nodes in a given network. This thesis mainly investigates a novel cognitive and adaptive framework to enable such a scalable routing approach. No significant work in literature could be found discussing cognitive and adaptive routing in MANETs.

1.3 Research Objectives

In this thesis, we can broadly identify 3 key research areas that will be investigated following the approach described in [1]. The approach towards research on MANETs in [1] specifies that the solution that are proposed in literature are too often based on unrealistic assumptions. Thus, a cycle of modelling, validating and implementing concepts and protocols have been adopted for our work in this thesis. Our research objectives and the rest of the thesis work has been structured accordingly. These research objectives are listed next with associated descriptions that are based on discussions presented in previous chapters and sections above:

- QoS MANET routing model: to investigate the operations of MANET routing protocols with respect to QoS actuators including the cost actuators defined above. In order to investigate further a routing protocol for MANETs that can be scalable for varied scenarios, it is important to understand the processes that are inherent in MANET routing approaches focussing on realistic standardised routing mechanisms. QoS models are derived for understanding and evaluating the performance of IETF MANET routing protocols from the RMP and PMP tracks in general. Further derivations are achieved to represent models for AODV and OLSR with repeat to QoS metrics. The suitability of these protocols are then examined for varied MANET scenarios. In summary, the following research topics will be addressed in this research area:

  - Derivation of generic mathematical models for end-to-end delay and routing overhead for IETF MANET WG tracks' routing approaches.

  - Further derivations using the aforementioned generic approach models to obtain specific corresponding models for AODV and OLSR respectively. The models include considerations for scenarios representing environments in free-space and with obstacles.

- Performance evaluation of AODV and OLSR in order to understand, validate and determine their suitability for various MANET scenarios. This is followed by corresponding discussions that lead to the next research area.

- Converged cognitive and hybrid adaptive routing protocol: to investigate the suitability of a converged cognitive and hybrid adaptive routing approach based on AODV and OLSR for scalable MANET deployment scenarios. Further to the models derived in the research area above, it is important to further use event-driven simulators in order to validate our findings within various mobility scenarios. We also evaluate the performance of flat routing protocols that are being promoted by the IETF for standardisation using such simulations. As a result, our converged cognitive and hybrid adaptive CML routing protocol will be presented. CML is a novel protocol designed and developed for dynamic topologies such as extreme emergency communication scenarios where there is a number of nodes joining and leaving the network at different time periods. The CML protocol development is particularly important for near future standardisation of hybrid protocols within a new IETF MANET WG track whereby it is generally accepted that a hybrid routing protocol is required for wide deployment of MANETs. CML will then be evaluated compared mainly to IETF endorsed flat routing protocols such as AODV, OLSR and DYMO but also against other competitor hybrid protocols, in order to determine its suitability for a wider range of network sizes. In a nutshell, the following research topics will be addressed in this research area:

  - A lightweight protocol design for a novel cognitive and adaptive protocol aimed at using a converged hybrid routing approach rather than the zonal approaches found in literature. The lightweight methods should include innovative cognitive methods for monitoring the size of MANETs, establishing a threshold for network size with regards to performance of flat routing protocols and adaptively converging the routing approach in the MANET if a switch in protocol is required.

  - Implement and evaluate novel energy-efficient mechanisms for CML protocol in order to improve QoS levels of flat routing protocols in scalable scenarios where prolonging network lifetime is essential.

- Provide appropriate effective mechanisms to tackle the problem of oscillation of nodes as identified in this thesis towards the design of non-zonal converged hybrid adaptive protocols.

- Cognitive and Adaptive Module for realistic routing frameworks: to design and present a realistic and implementable framework for future adaptive cognitive MANET routing approaches. In order to enable the implementation and deployment of the cognitive and hybrid adaptive routing approaches, it is important to provide a flexible, modular and re-usable realistic framework that will be able to provide the necessary features for MANET routing including cognitive, adaptive and routing modular components. In fact, we designed, implemented and have a patent pending Cognitive and Adaptive Module (CAM) for ubiquitous networking with appropriate routing components. An overview of the research topics to be addressed here are:

  - Design of the CAM and appropriate components in order to enable the realistic lightweight development of adaptive routing approaches in MANETs. Such approaches will include cognitive abilities to detect the state of the network such as traffic profile and size of network.

  - Description of CAM sub-components that are required to implement MANET routing protocols and services e.g. overlay structures and security.

  - Design and description of CML protocol using CAM and its sub-components as well as high level implementation details from experience over implementation in Android and iOS platforms.

  - Performance Evaluation of other routing components that are relevant for the CAM design and outlines of possible implementations within the CAM suite.

1.4 Contributions of this thesis

The contributions of this thesis are based on work that has been carried out in the field of scalable MANET routing approaches using cognitive and adaptive methods. One of the aspects of the contributions of this thesis relates to the derivation of models for MANET routing approaches in order to describe, understand and evaluate the operation of popular routing protocols. The other main contribution of this thesis consists of work carried towards engineering a novel hybrid and adaptive MANET routing protocol that is designed based on the derived models and associated investigations. The thesis also includes our innovative design of a patent pending concept for a cognitive and adaptive module for realistic and deployable MANET routing approaches. Thus, the overall contribution of our thesis is towards a cognitive and adaptive routing framework for MANETs.

From a network modelling point of view, we derive a mathematical model in order to gauge the performance of well-known MANET routing approaches that are endorsed by the IETF MANET WG and well-known in literature. The innovative model is used to analyse both efficiency and effectiveness of investigated routing protocols in this thesis. It is also utilised as a guidance to investigate and define our hybrid and adaptive routing protocol for PPDR communication in scalable MANETs. The mathematical model is derived considering a probabilistic approach for estimating the routing performance of protocols in multi-hopped data transmissions between mobile S-D pairs in dynamic MANET topologies. Our network model derivations are presented at two levels of granularity. Firstly, a proactive and reactive approach level derivation provides an avenue for reusing and applying our models for evaluating routing approaches in general rather than specific protocols. Then, we present a protocol level model derivation to explicitly investigate popular protocols including OLSR and AODV. The models are validated using the widely used event-driven ns-2 simulator.

From an engineering point of view, we investigate the design and performance of our adaptive and hybrid routing protocol called CML. We also present the design of our innovative CAM suite for the realistic implementation of multi-purpose MANET routing approaches. Findings from our network models, simulation results and real-time testbed implementations are then used in order to analyse the protocols proposed by other authors, demonstrate that an adaptive hybrid approach is more suited for scalable MANET routing and then define CML and CAM. Thus, in this thesis, we firstly present and evaluate CML as an adaptive hybrid routing protocol that is adequate for scalable routing. We then describe the concept and design of CAM suite that is a lightweight routing framework necessary to effectively implement complex protocol logics, such as in CML, over real-life mobile platforms such as Android and Apple iOS. Both CML and CAM have been presented and positively discussed at the MANET WG and they form part of the IETF meeting proceedings [23, 24].

1.5 Outline of this thesis

We have organised the structure of the rest of the work presented in this thesis in terms of the following chapters:

Chapter 2: Background and Literature Review - This chapter gives an overview of the area of MANET routing protocols as defined in the IETF MANET WG and extended in literature. We present the state-of-the-art approaches in IETF MANET WG as well as the broader classifications found in literature. The sub-categorisation of these approaches such as nature inspired, multi-path based and cluster-based routing are also introduced in this chapter. Additionally, this chapter specifies and describes the various popular open-source implementations of MANET routing protocols. These provide realistic guidelines to make our approach more realistic. We further consider actual user requirements during protocol design in addition to proposing a realistic implementable cross-platform framework.

Chapter 3: Scalable MANET Routing protocols - In this chapter we present, in more details, the various scalability issues and scalable protocols that are relevant for the work in this thesis. Therefore, one of the main focus of this chapter is to describe the underlying mechanisms that are part of the flat-routing protocols such that these mechanisms also form part of the presented hybrid and adaptive routing protocols. We also classify the various other scalable routing approaches from literature accordingly and propose prior analysis of protocol efficiency and effectiveness.

Chapter 4: Network Model for Realistic MANET Scenarios - In Chapter 4 of our thesis, we derive the various models that are required to define, understand and evaluate the various QoS routing performance of MANET routing approaches. We use appropriate notations to define various network models including network topology, end-to-end data delivery delay and routing overhead. We use realistic mobility models and simulations that consider the presence of obstacles in MANET scenes, in order to have accurate evaluations and validation of our derived models. Our performance evaluations emphasise the suitability of each routing approach for a particularly set of scalable network contexts.

Chapter 5: ChaMeLeon (CML): A Hybrid and Adaptive Routing Protocol - This chapter presents our novel hybrid and adaptive routing protocol for scalable MANET scenarios. Although the protocol is best suited for PPDR communication scenarios, it can also be used for general purpose MANETs. In this chapter, we describe detailed design of CML routing protocol as presented at the IETF and published in literature. The design of CML is instigated by the modelling and simulation work presented in Chapter 4. We also investigate the performance of CML as compared to other routing protocols so that its energy efficiency and effectiveness is compared over variable size networks. In this chapter, we also discuss the various challenges that arise when designing an adaptive converged hybrid routing approach as well as its essential constituents.

Chapter 6: A Cognitive and Adaptive Module for Routing - In this chapter we present and describe the CAM routing framework that we have developed at Kingston University and which is patent pending. The framework presents a new design concept whereby an adaptive and hybrid as well as other routing approaches presented in literature can be effectively implemented on real-life mobile platforms. The various flexible building blocks of such a framework are presented including the CAM Core, Components and Parts that are hierarchically more specific depending on the protocol to be implemented. The CAM design is aimed at promoting the standardisation of individual routing functionalities for specific MANET contexts rather than a routing protocol as a whole. This trend can already be observed by the standardisation of a neighbourhood discovery protocol and a flexible packet format that fits the ideology of the CAM suite.

Chapter 7: Conclusion and Future Work - This chapter concludes the thesis. In this chapter, we summarise our findings and highlight our main contributions with respect to the thesis objectives. We also deduce the main avenues for future work in the field of scalable MANET routing protocol.

We followed the methodology described in [1] in order to contribute to the 3 key research areas mentioned in the objectives. This methodology resulted in a looped investigation process presented across thesis chapters as illustrated in Fig. 1.3.

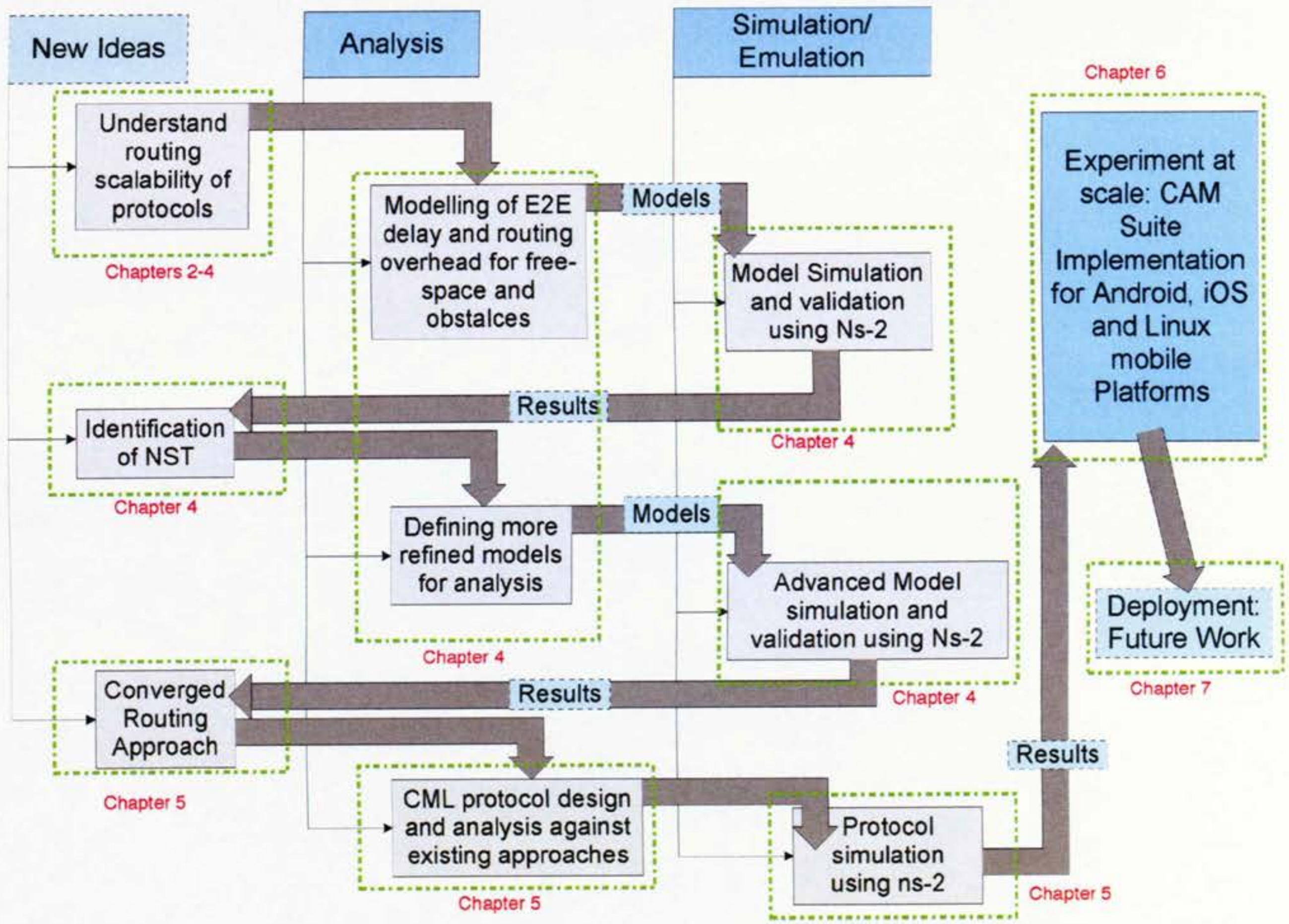


Figure 1.3: Overview of Research Methodology - The figure shows an overview of the research method that was applied for structuring of work within this thesis as recommended by Stojmenovic in [1]

Chapter 2

Background and Literature Review

In this thesis, our work is focussed on the area of routing for Mobile Ad-hoc NETworks (MANETs). In this chapter, we present an overview of the aforementioned focus area. Section 2.1 describes the background in MANET routing with emphasis on the main standardisation activities and guidelines for standard routing approaches. Guidelines from the IETF MANET WG provides the required boundaries for our work in this thesis so that our investigation contributes towards a realistic deployable solution. In Section 2.4, we present an extensive literature review of routing protocols that have been proposed both by standardisation activities in IETF and IEEE as well as MANET routing protocols and related work in literature. This section includes hybrid, adaptive, energy-efficient and scalable MANET routing protocols which is the main focus of our work while very few significant studies related to incorporating cognitive features to MANET routing protocols were found.

2.1 Introduction

In a wireless MANET, routing can be described as the multi-hop packet forwarding mechanism used by routers, that can adapt efficiently to changes in the network topology. In the context of IETF WGs, the charter limits the scope of work to be carried out. The IETF MANET WG has been chartered to standardise a lightweight distributed IP routing protocol functionality as further described in [8]. Towards this end, the MANET WG describes some important guidelines for the design of routing approaches. It is important to note that the two main work documents that are used by IETF WGs are the Internet-Drafts (IDs) for "work in progress" and the Request for Comments (RFC) to document mature work that are close to being standardised at the IETF.

These guidelines, as further detailed in literature [2, 3, 4, 5, 6, 8], recommend that designed MANET protocols have to exhibit some important fundamental characteristics. For instance, they have to be applicable to both peripheral pervasive networks attached to internet infrastructures and ubiquitous hybrid MANET-mesh fully autonomous infrastructures. Additionally, the developed protocols have to support both IP version 4 (IPv4) and IP version 6 (IPv6) while also considering routing security requirements and issues. Another goal of the WG is to develop a scoped forwarding protocol for efficient flooding of data packets to all cooperating MANET nodes as a simplified best effort multicast forwarding function by only considering routing layer design issues. The WG currently has two standards track routing protocol specifications namely the Reactive MANET Protocol (RMP) track and Proactive MANET Protocol (PMP) track. In the eventuality that RMP and PMP modules have significant commonalities, the WG may decide to converge these approaches into a hybrid protocol [8].

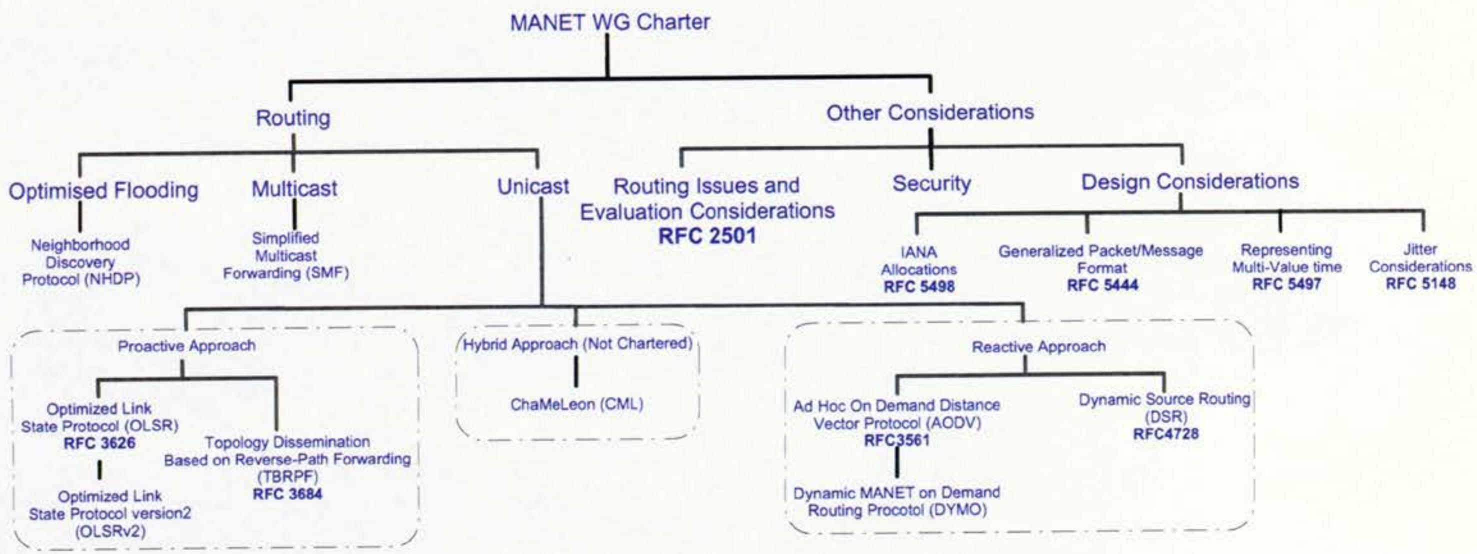


Figure 2.1: Overview of IETF MANET WG work - The figure illustrates an overview of active work being undertaken at the IETF MANET WG towards standardisation of MANET routing protocols

In addition to well-known wireless networking problems, wireless MANETs present researchers with several peculiar routing challenges as described in [2, 3, 4, 5, 6, 8, 9]. One key routing challenge resides in the fact that routing paths in both static and dynamic wireless MANETs are subject to regular changes. These variances are often consequences of both user mobility and changes in wireless link quality between nodes that may be due to varying antenna coverage patterns, channel interferences and fading effects. Here, a very low link quality can be regarded as a broken link and result in unreachable routers and destinations. Some other constraints that can often cause route breakages between source and destinations include failure of battery operated nodes and security attacks in such fully distributed wireless network environments [25]. The aforementioned occurrences are therefore important design issues that have to be addressed while designing a MANET routing protocol. A summary of the work being carried out at the IETF WG is shown in Fig. 2.1

2.2 Issues and Evaluation Considerations

MANET routing protocol evaluation should be based upon certain qualitative and quantitative performance metrics as explained in RFC 2501 [9] and literature [2, 3, 4, 5, 6, 8]. These metrics must be applicable to any routing protocol performance evaluation to indicate how well suited the protocol is for that particular investigated environment. According to aforementioned work in literature, a MANET routing protocol has to exhibit the following qualitative features.

Firstly, MANET routing algorithms must be fully distributed in nature. The protocols should have a loop-free routing mechanism to avoid same packets being repeatedly processed by set of nodes. The routing protocol to be proposed should be able to display a demand-based operation that can utilise network resources more efficiently. However, as mentioned in [9], the on-demand approaches can be used at the cost of increased route discovery delay that are initiated only when data sessions are required. MANET routing protocol should also present a proactive operation especially in the context of delay intolerant networks where relatively good levels of network resources are available. The routing approaches should also include security mechanisms to ensure network-level and link-layer security. Then, appropriate sleep period operation for energy conservation without any adverse consequences probably through link layer protocol coupling via a standardised interface should also be presented for the various approaches. Finally, the protocol should be able to include unidirectional link support in wireless environments where bidirectional links are often scarce or unavailable. Much work has been done in that respect in the MANET WG and the proposed routing protocols in the WG have mechanisms to implement the above qualitative features.

More interesting from a research perspective, the main quantitative performance evaluation metrics for MANET routing protocols are listed as:

- End-to-end data delivery throughput and delay: these are measurements of the protocol effectiveness.
- Route establishment time: time required to establish route(s) when requested as is often the case in on-demand approaches. This adds to overall end-to-end data delay.
- Routing overhead: a measure of efficiency of the protocol that may be expressed as the ratio of "Average number of control and data packets transmitted/data packet delivered".

Furthermore, emerging streaming applications that should form part of popular ubiquitous services [7], requires that the delay jitter, which is the variance in end-to-end data delivery delay, be constrained to a minimum [26]. Therefore, delay jitter should also be considered as an important performance evaluation metric for MANET routing protocols.

The networking context or test environment is another determining factor in measuring the performance of routing protocols as discussed in [8, 12, 27]. According to guidelines in [9], it is important to vary some of the contexts during the evaluation of the protocol including network size, average number of neighbours of each node, topological rate of change, effective link quality (in terms of capacity and fraction of unidirectional links) and traffic patterns (such as non-uniform or bursty traffic patterns and number of traffic connections). In our work presented in Chapters 5 and 6 of this thesis, we modify and extend AODV and OLSR protocols that have been reviewed at the IETF, implying that they at least satisfied the qualitative features listed above in this subsection. In the rest of the discussions in this thesis, we assume that protocols already have these qualitative characteristics, and focus investigations around the quantitative measurements of the efficiency and effectiveness of the protocols.

2.3 Realistic Design Recommendations and Considerations

As a result of over a decade experience gained through research, implementation and testing, the MANET WG has published several I-Ds and RFC to specify recommended protocol design guidelines that supplement the development of routing approaches which are:

- A generalized MANET Packet/Message format (RFC5444)
- Jitter considerations in MANETs (RFC5148)
- IANA allocations for MANET protocols (RFC5498)
- Representing multi-value time in MANETs (RFC5497)
- Management Considerations for MANETs

We provide a more detailed breakdown of the above recommendations and considerations next. The work in RFC 5444 [28] specifies the syntax of a packet format that is able to carry multiple messages required by MANET routing protocols. These messages are very useful for sharing routing information among MANET nodes. Each packet may consist of one or more messages, each in turn consisting of a message header, for message type identification and a message body, containing the actual route information. The authors in [28], only specify the syntax of such a packet and its messages as shown in Fig. 2.2 (a). The specification includes the packet format that may contain zero, in case that the packet header contains the route information, or more messages. The message header may, in turn, contain enough information for router nodes to perform processing and forwarding decisions. If required, the message body contains attributes corresponding to the message or message originator and address blocks or prefixes, with associated attributes. Here, an address block itself represents sets of addresses or address prefixes in a compact form with aggregated addresses.

In this optic, a generalised type-length-value (TLV) format is used to represent these attributes where a given TLV can be associated with a packet, a message, or a single address block containing one or more addresses or address prefixes. It is also possible to include multiple TLVs where each TLV is associated with a packet or a message. Otherwise, each of the TLVs can be associated with the same, different, or overlapping sets of addresses or address prefixes in address blocks. The standardised generalised packet and message formats should be suitable for any protocol parsing logic, extensible to include new messages and TLVs, efficient by compacting information and by allowing message header processing for forwarding without the need to process the message body. Interestingly, this specification was inspired and extended from the packet and message formatting used by the OLSR [29]. In a nutshell, a TLV allows the association of a value to either a packet or a message. While, in all cases, the data structure is identical, the position of the TLV within the packet determines its nature i.e. a "Packet TLV" is located in the packet header, a "Message TLV" in the TLV block, or an "Address Block TLV" in the TLV Block. In this thesis, our proposed work uses this standardised packet and TLV format to design our investigated solutions.

A general and flexible TLV for representing time-values is described in [30]. In MANET routing, time-values such as intervals or durations can be very useful in protocol operations. The RFC 5497 [30] uses the generalised MANET packet/ message format described above, to define two message TLVs and two Address Block TLVs. These TLVs may usefully represent validity and interval times for MANET routing protocols that need to express single time-values or a set of time-values where each time-value maybe associated with a range of hop counts. This general time TLV structure allows a receiving node to determine single time-values if the hop count from the message originator node is known or if the time TLV explicitly specifies a single time-value. The two message and address block TLV Types proposed in the document are "INTERVAL-TIME" and "VALIDITY-TIME". These messages and TLV types respectively specify the expected maximum time before another entity of the same type originating from the same node is received and the entity information validity period after receipt. These are used by the routing protocols to indicate, for each message type, the expected time period between successive transmissions so that transmission rate can be varied as desired. Another attractive feature of such representations is its ability to reduce computational complexity by decreasing the number of bits transmitted in bandwidth-limited wireless MANETs where time TLVs usages do not require high-precision values of time. The 8-bit field encoded time-values allows for a range from small to large values of 1/1024 second to 45 days respectively. MANET routing protocols are also allowed to parameterise this range by modifying a single parameter to change the compacted encoding.

RFC 5148 [31] includes recommendations for the time randomisation of control traffic transmissions for MANET routing protocols in order to reduce the probability of transmission collisions. This process is termed as jittering. Particularly in the case of wireless MANETs, simultaneous packet transmissions may cause collisions and loss of part, or all of the transmitted packets, over the wireless medium before they even join the receiver queue. In such cases, principally, the Medium Access Control (MAC) protocol determine the extent of the resulting impact. This can range from increased delay in packet delivery to the complete loss of the packet. The work in [31] assumes that the above problem cannot be solved by layers below the network layer in the TCP/IP stack, thus requiring a network layer mechanism. Consequently, the jitter mechanism is proposed as the recommended solution either as part of an IP protocol for wireless networks or complementing a lower-layer mechanism. The MANET routing protocols are especially prone to packet collisions because of regular scheduled transmission of routing messages by all nodes at equal time intervals, event-triggered messages by neighbourhood nodes and message forwarding during routing. The use of the Jitter mechanism aims to inject a voluntary random bounded timing variation before packets are transmitted in order to desynchronise transmitters. In this way, overloading of the transmission medium and receivers could be avoided, decreasing the risk of collisions. This mechanism is deemed particularly useful for broadcast transmissions in MANET protocols. However, a poorly designed jitter mechanism can also create undesired delay jitter for end-to-end packet delivery and thus degrade protocol performance [26] for ubiquitous streaming services [7].

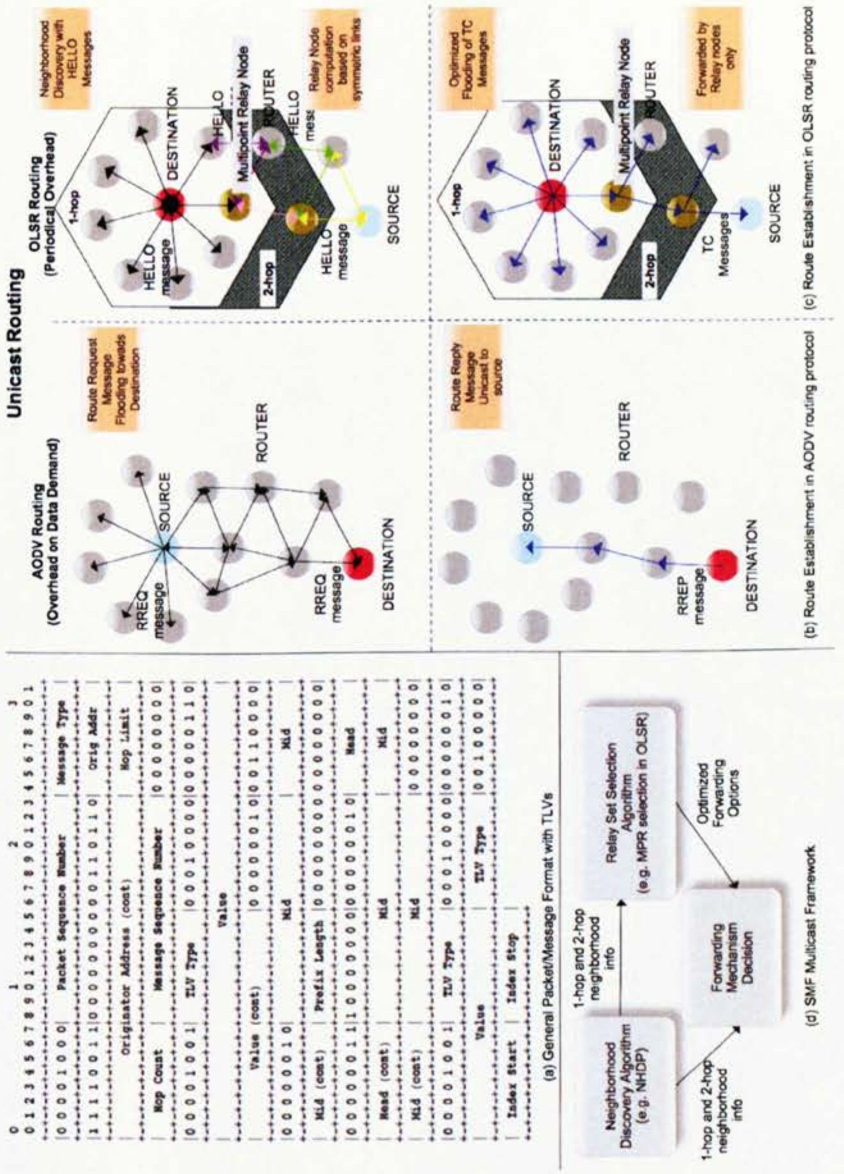


Figure 2.2: Standard MANET packet format - The figure shows the standardised MANET packet format and chartered routing protocols at IETF MANET WG

Furthermore, the RFC 5498 [32] mentions about several common Internet Assigned Numbers Authority (IANA) allocations to be used by MANET protocols. The interoperable MANET routing protocols using these IANA allocations have to conform to the RFC 5444 [28] in order to use a common format that enables the unambiguous sharing of these IANA allocations. To send and receive MANET routing packets, MANET protocols, from an IANA perspective, require:

- A UDP Port Number: the UDP port is entitled "manet" and allocated a value of 269.
- An IP Protocol Number: the IP protocol number is 138 and is referred to as "manet".
- A Link-Local Multicast Group Address: the multicast address to reach link-local (LL) MANET routers is termed "LL-MANET-Routers". These are 224.0.0.109 and $FF02:0:0:0:0:0:0:6D$ for IPv4 and IPv6 respectively.

Management considerations are important for MANET routing protocols as required by the IETF. Route change information is cooperatively obtained among MANET nodes and this is updated in the routing tables of each router. Though MANET routing protocols operate autonomously, it may be desirable to externally manage and monitor them in order to improve routing performance. The WG has work in progress based on management frameworks for relevant objects including several Management Information Bases (MIBs) modified from the Simple Network Management Protocol [33]. Several such I-Ds have been proposed for active WG protocols namely NHDP-MIB, OLSRv2-MIB, DYMO-MIB and SMF-MIB (see Table 2.1- 2.2 for the relevant I-D). Due to the bandwidth-limitations and variable delays within wireless MANET data exchanges, polling is not a desirable option to retrieve object value associated timings as is usually employed by Network Management Systems [33]. Instead, a proxy, physically located close to the managed nodes, is utilised as described in the REPORT-MIB (see Table 2.1 and 2.2 for the relevant I-D). In this way, performance reports can be generated remotely using a process similar to the Remote Monitoring [33] where the proxy would use local polling to obtain the required object values. In this thesis, the proposed framework for adaptive routing may be used as part of future work for network management.

I-D Title	Authors	Available online at:
The Optimized Link State Routing Protocol version 2 (OLSRv2) (Work in Progress)	T. Clausen et al.	http://tools.ietf.org/id/ draft-ietf-manet-olsrv2-11.tx
Simplified Multicast Forwarding (SMF) (Work in Progress)	J. Macker	http://tools.ietf.org/id/ draft-ietf-manet-smf-10.txt
Dynamic MANET On-demand (DYMO) Routing (Work in Progress)	I. Chakeres, C. Perkins	http://tools.ietf.org/id/ draft-ietf-manet-dymo-21.txt
Definition of Managed Objects for Performance Reporting (Work in Progress)	R. Cole et al.	http://tools.ietf.org/id/ draft-ietf-manet-report-mib-00.txt
Definition of Managed Objects for the Neighborhood Discovery Protocol (Work in Progress)	U. Herberg et al.	http://tools.ietf.org/id/ draft-ietf-manet-nhdp-mib-04.txt
Definition of Managed Objects for the Optimized Link State Routing Protocol version 2 (Work in Progress)	U. Herberg et al.	http://tools.ietf.org/id/ draft-ietf-manet-olsrv2-mib-02.txt
Definition of Managed Objects for the DYMO Manet Routing Protocol version 2 (Work in Progress)	S. Harnedy et al.	http://tools.ietf.org/id/ draft-ietf-manet-dymo-mib-03.txt

Table 2.1: Active I-Ds in IETF MANET WG - Summary of IETF MANET WG I-Ds that are actively being considered for standardisation.

I-D Title	Authors	Available online at:
Definition of Managed Objects for the Manet Simplified Multicast Framework Relay Set Process (Work in Progress)	R. Cole et al.	http://tools.ietf.org/id/ draft-ietf-manet-smf-mib-01.txt
MANET Cryptographical Signature TLV Definition (Work in Progress)	U. Herberg, T. Clausen	http://tools.ietf.org/id/ draft-ietf-manet-packetbb-sec-01.txt
Packet Sequence Number based ETX Metric for Mobile Ad Hoc Networks (Work in Progress)	H. Rogge et al.	http://tools.ietf.org/id/ draft-funkfeuer-manet-olsrv2-etx-01.txt
The ETX Objective Function for RPL (Work in Progress)	O. Gnawali, P. Levis	http://tools.ietf.org/id/ draft-gnawali-roll-etxof-01.txt
ChaMeLeon (CML): A hybrid and adaptive routing protocol for Emergency Situations (Work in Progress)	T. Ramrekha et al.	http://tools.ietf.org/id/ draft-ramrekha-manet-cml-01.txt
A Generic Cognitive Adaptive Module (CAM) for MANETs (Work in Progress)	T. Ramrekha et al.	http://tools.ietf.org/id/ draft-ramrekha-manet-cam-02.txt

Table 2.2: Active I-Ds in IETF MANET WG - Summary of IETF MANET WG I-Ds that are actively being considered for standardisation.

2.4 State-of-the-Art

In this section, we present the state-of-the-art for MANET routing protocols. There are tens if not hundreds of different routing protocols that have been developed for MANETs. In this thesis section, we focus on work that are either well-known in literature or part of the MANET WG activities along the RMP and PMP tracks. Within the context of MANET WG, it has been proposed in the charter that only if deemed appropriate, a hybrid track will be activated whereby a combination of the reactive and proactive protocol mechanisms will be standardised for MANET routing. Briefly, the first generation routing protocols were developed independently using the outlined design recommendations and guidelines in RFCs. However, through "lessons learnt" during development, a second generation protocol is currently awaiting for RFC status approval at the IETF. The second generation protocols propose to use and extend the Neighborhood Discovery Protocol (NHDP) [34] in order to obtain 2-hop network information whether in on-demand or proactive fashion. They also specify the usage of the new packet and message format from RFC 5444 [28]. The protocols are mainly based on modified versions of Dijkstra and BellmanFord algorithms as favoured in literature and within the IETF MANET WG activities.

The two main phases in traditional MANET routing protocols are:

- Topology Discovery (TD): involves processes, initiated by the source or relay nodes, to discover the topology and find an appropriate route to communicate with destination.

- Topology Information Maintenance (TIM): involves processes, initiated by the source node, to find the new route to destination or to a relay node leading to a destination.

The nature of processes in the TD stage and TIM phases define the type of approach being utilised for routing. Thus, reactive or source initiated on-demand routing protocols use the flooding technique in the TD phase to get route information to a destination. Once the route is established, the TIM phase is carried out for a limited period of time or to a given event so that route information is discovered every time the TIM phase is over.

2.4.1 Protocols under Standardisation

2.4.1.1 IETF MANET WG Standards track

NHDP [34], recently approved as RFC 6130, is a symmetric 1-hop and 2-hop neighbourhood discovery protocol for MANETs. This protocol requires each node to locally exchange HELLO messages so that each MANET router can detect the presence of bi-directional 1-hop and 2-hop connected neighbours. These messages are disseminated through packets as defined in [28]. The symmetric 1-hop neighbourhood information is stored to determine direct connectivity to nodes while 2-hop symmetric neighbourhood information is necessary for optimising flooding techniques. An example of a reduced flooding technique is the selection of relay sets to minimise the flooding of network wide link state advertisements as in OLSR [29]. Thus, the NHDP records symmetric 1-hop and 2-hop neighbourhood information in repositories so that these are available for use by other routing protocols.

Besides, NHDP is designed to use link layer information if available as well as applicable and is based on the neighbourhood discovery process utilised by OLSR. The NHDP protocol has added importance due to the fact that communication between two neighbouring nodes may be uni-directional. Additionally, the dynamic nature of wireless communication implies that neighbouring nodes even when sharing the same channel, may still have different broadcast domains. Due to the dynamic nature of wireless MANET links discussed above, IP protocols need to gather such neighbourhood information rapidly as generally no such information can be obtained from lower layers. The NHDP therefore updates each node with neighbourhood changes, link bi-directionality and local topological information spanning up to 2-hops. It is important to note that the exchange of HELLO messages can be carried out proactively after a time interval or reactively when a change has taken place in a node's neighbourhood table. The NHDP has gained wide acceptance in the WG and has been recently declared as RFC 6130 [34].

The proactive routing approach proposed in the MANET WG PMP track, also known as table driven routing, consists of maintaining consistent and updated route information between all possible source-destination (S-D) pairs in the routing tables. Thus, routes between S-D pairs are always available reducing the latency in route establishment. Since a large amount of routing information is periodically disseminated and stored, the downside to such an approach is the high overhead of control packets and power consumption even when no data is being transmitted. There are several published work and work in progress for such an approach within the WG. The Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [35], last updated in 2004, is a proactive, link-state MANET routing protocol that was considered as an improvement over Open Shortest Path First (OSPF) routing protocol.

OLSR [29] is one of the most popular protocols currently found in literature and experimental testbeds. It is a modified version of classical link state algorithm based on the requirements for MANET routing. The main optimisation introduced by OLSR is the flooding message reduction technique using multipoint relays (MPRs). MPRs for each node are the set of minimum symmetrically connected 1-hop nodes that can symmetrically connect the source node to all 2-hop neighbours. Each node periodically issues HELLO messages to establish the MPR sets while periodic Topology Control (TC) messages are used to flood route information network wide. However, these TC messages are only forwarded by the MPRs in the network thus optimising the flooding procedure. Each node receives these routing data at regular intervals of time to update neighbourhood information and compute routes to all possible destinations. In addition, only MPRs generate link state messages further reducing routing overhead. OLSR had been designed to work independently from other protocols including underlying link-layer protocols. OLSR is particularly well suited for MANETs with random traffic sources and sporadic data traffic as well as for deployments where the S-D pair regularly changes with time as no additional control traffic is required in such cases.

Also, the WG is currently working on a version 2 of OLSR called OLSRv2. OLSRv2 operates using the same basic algorithms and mechanisms as in OLSR. However, OLSRv2 uses a more efficient and flexible framework for control packet distribution and more simplified messages are exchanged. More specifically, OLSRv2 uses and extends NHDP for neighbourhood discovery and uses the generalised packet/message format [28] as improvements over OLSR. The NHDP is extended by adding MPR Address Block TLV(s) that contains MPR selection of nodes and degree of willingness of nodes to be MPRs. A node can use this willingness value to decline to be a MPR while still participating as a router, source or destination. It is important to note that both OLSRv2 and OLSR, inherit its forwarding and relaying concept from the High

Performance Radio LAN MAC layer protocol standardised by the European Telecommunications Standards Institute.

On the other hand, a reactive routing approach from the MANET WG RMP track, also known as on-demand routing, establishes and maintains routes between S-D pairs when requested by the data source node. Although such an approach generates routing overhead on an on-demand basis only, it nevertheless requires added latency for route discovery before routes are established. The Dynamic Source Routing Protocol (DSR) [36] is a well-known reactive protocol that utilises route discovery and route maintenance on-demand to route data from source to destinations. The particularity of DSR is that it allows the source to maintain several routes to specific destinations and select its preferred route that can be useful for load balancing and improved robustness.

The AODV [37] routing protocol is one of the most well-known reactive protocols in literature. AODV uses an on-demand route discovery and maintenance algorithm for route establishment in unicast routing and is based on modified Bellman-Ford algorithm. The source node initiates route discovery by broadcasting Route Requests (RREQs). Intermediate nodes check if they have a route for the required destination before storing packet information in their routing table for reaching the source and flooding the RREQ further. If the routers have a valid route to the required destination, a Route Reply (RREP) is sent back to the source. Otherwise the destination eventually receives the RREQ, stores the source information in a routing table and sends a RREP through the reverse path. The source receives this reply message and data transmission occurs through the RREQ and RREP established paths. These messages are received via UDP, and the IP header are processed normally. A Time To Live (TTL) value within the packets is used to limit the dissemination radius of messages to a specific number of hops. The stored route information is valid for a timeout period after which the route discovery has to be re-initiated. The validity of a route is extended by the timeout period each time data is sent over that route. The route discovery process is repeated after a preset *ROUTE_TIMEOUT* time interval for a given connection between a S-D pair and a Route Error (RERR) message is used to notify nodes that a link has been lost and that destinations are unreachable. DSR protocol [36] specifies that each node should have a route cache to store topology information where each possible destination is associated with a usage timeout. The main difference between AODV and DSR is that AODV uses hop-by-hop routing while DSR uses source routing i.e. AODV utilises only next hop information for routing while DSR uses the complete node record for the route used.

Dynamic MANET On-demand (DYMO) routing protocol(see Table 2.1 for relevant I-D) is regarded as the second generation AODV and is a work in progress in the WG. The basic route discovery and route maintenance processes are similar to AODV. The DYMO protocol can be suitable for use in MANETs exhibiting a variety of mobility and traffic patterns by establishing routes on-demand and is more suitable for sparse networks. It also requires little processing from CPUs. The DYMO protocol differs from the AODV protocol in the sense that it considers the use of NHDP(see Table 2.1- 2.2) to detect bidirectional links in the neighbourhood ensuring establishment of bidirectional routes. This is a major improvement over AODV. These links are exclusively used for route discovery and route maintenance. DYMO also uses TLV(s) from the packet/message format described in [28] for generating and disseminating RREQ, RREP and RERR messages. As compared to AODV, DYMO allows for support of MIB, local route repairs, unicast links and accepts new improved routes even after routes establishment.

Furthermore, apart from unicast routing techniques which is the focus of work presented in this thesis, the MANET WG is also working on a multicast routing approach. While the unicast routing can be described as a point-to-point i.e. source to destination data routing mechanism, the multicast routing protocol needs to carry out point-to-multipoint routing i.e. source to multiple destinations routing. Multicasting is useful for a group communication paradigm for various classes of applications within a MANET. Some examples of such applications include multimedia streaming, discovery or registration services and interactive group messaging. The Simplified Multicast Forwarding (SMF) (see Table 2.1- 2.2 for the relevant I-D) is a matured work in progress within the WG that attempt to satisfy the multicast MANET routing requirements using optimised flooding mechanisms as in OLSR. SMF also uses techniques for multicast duplicate packet detection in its forwarding process.

The NHDP is particularly useful in the absence of an existing MANET unicast protocol or lower layer interface information. The SMF draft also specifies alternative processes that can provide the necessary neighbourhood information to support relay set selection. In particular, it emphasises on the requirements for neighbourhood discovery with respect to the forwarding process and it finally discusses the relay set selection algorithms. The basic idea behind SMF is to provide a simple best-effort data forwarding mechanism based on optimised flooding. This is achieved using relay sets for local data routing. The latest version of the SMF I-D specifies the use of the NHDP to gather information so that a relay set selection algorithm can compute the required relays. SMF then uses this neighbourhood information and the relays to efficiently multicast data packets to the required nodes. Here, Classical Flooding can be regarded as the simplest case of SMF multicasting and the use of neighbourhood discovery (e.g. using NHDP) and relay set selection algorithms are recommended but not required in that case. If used together with NHDP, it is recommended that the NHDP HELLO messages should include the "SMF RELAY ALG" TLV type for the explicit identification of SMF enabled nodes and their corresponding relay sets that are participating in the MANET.

A summary of the IETF chartered MANET routing approaches and the generalised packet format is illustrated in Fig. 2.2.

2.4.1.2 IEEE 802.11s Standards track

IEEE 802.11s [38] is an IEEE 802.11 amendment for mesh networking within a WLAN and thus deemed suitable for static topologies of ad-hoc networks. Unlike work in IEEE 802.11s, there is no corresponding work in MANET WG that provide means for admitting only trusted peers as part of the routing process. The MANET WG has started to work on assuring network integrity by developing security extensions of the routing protocols, based on digital signatures but this work is still at a work in progress stage. The amendments proposed by the IEEE considering the wireless ad hoc mesh networking peculiarities, as part of the IEEE 802.11s standard, is a work in progress carried out by the IEEE P802.11. It mainly defines a secure password-based authentication and key establishment protocol called Simultaneous Authentication of Equals based on a zero knowledge proof and it is resistant to active, passive, and dictionary attacks.

However, from a networking point of view, IEEE 802.11s modifies the IEEE 802.11 MAC standard by including an architecture and protocol for multicast, unicast and broadcast transmissions based on radio metric awareness in multi-hop mesh topologies. IEEE 802.11s also defines a default routing protocol called the Hybrid Wireless

Mesh Protocol (HWMP) [38] but also define generic interfaces for routing protocols so that any other suitable protocols could be used in conjunction with the standard. The HWMP is mainly a form of AODV [37] with tree-based routing alterations. Therefore, as it can be deduced from the above discussions, the work in IEEE 802.11s task group is oriented towards providing adequate security and MAC protocols for mesh networks while the IETF MANET WG offers more relevant standardisation work towards MANET routing protocols that is investigated in this thesis.

2.4.2 Routing Protocols in Literature

In literature, there are variations to the MANET WG RMP and PMP tracks that are presented under several categories as described in [2, 3, 6, 13]. The routing approaches found in literature and described below, stem from alterations of link-sate, distance-vector or hybrid mechanisms for shortest first path calculations. These routing alterations are used to add intelligence to the routing paradigm in view of improving QoS and scalability. A classification of the various protocols found in literature, further to alterations of proactive and reactive protocols are:

- Hybrid protocols: are protocols that use a combination of proactive and reactive routing mechanisms. Most hybrid protocols consist of AODV and OLSR protocols.

- Adaptive protocols: are routing protocols that can adapt at either grain level, by changing their parameters such as signalling intervals, or at coarse level, by changing their approach such as shifting from OLSR to AODV in CML [14]. These changes are instigated a result of the conditions in the network. The challenges reside in monitoring and determining appropriate threshold values at which changes should take place. In Chapter 5 of this thesis, we describe CML [14, 23, 39] routing protocol that we have developed and published.

- QoS-aware protocols: are protocols that use QoS metrics instead of hop count based shortest path in order to compute the best routing path in order to improve the routing QoS in MANETs. Such protocols include load-balanced algorithms that are used to optimise the energy-efficiency of routing approaches and improve network lifetime.

- Geographical routing protocols: are proactive, reactive or hybrid routing approaches that use absolute or relative location information in order to optimise the routing QoS of protocols.
- Clustered protocols: a routing approach carried out using a hierarchical classification or intermediate routers based on the prioritisation of resources.
- Nature-inspired cognitive protocols: protocols are designed in such a way that the sequences of signalling and data routing mimic a pre-determined natural system such as systems of swarm intelligence. The well-known Ant Colony Optimisation (ACO) method is utilised by several work [40, 41, 42, 43, 44, 45] in order to carry out routing in a hybrid manner. Epidemic routing is another approach that is gaining much research interest [46].
- Multipath routing protocols: a category of routing protocols that store a prioritised list of shortest paths in the topology in order to revert to the best path if the precedent best path is broken through mobility. This approach can improve the QoS in certain dynamic scenarios at the expense of much higher routing overhead.

2.4.2.1 QoS-aware Routing

The routing of multimedia data packets in MANETs is key towards its deployment in critical emergency and tactical military communication scenarios. Thus, there is a requirement for routing approaches to provide the required QoS guarantees that are usually measured in terms of throughput, end-to-end delay, delay jitter and packet loss rate, as described above and found in [9]. However, due to the highly dynamic wireless network state, the task of ensuring hard QoS routing guarantees is nondeterministic polynomial time (NP)-Complete problem for MANETs [47]. Therefore, most of the techniques designed for traditional networks are not applicable to MANETs due to the unique challenges imposed by such networks [2, 3, 4, 48, 49]. Integrated Service (IntServ) and Differentiated Service (DiffServ) are two QoS models used for traditional networks forming the Internet.

IntServ provides QoS for each flow of data in the network creating a virtual connection-oriented path where specific state information has to be maintained for every flow in all intermediate nodes including bandwidth requirements and other QoS measurements. The DiffServ model aims to provide scalable service differentiation, without maintaining per-flow state information and signal-ling at every intermediate node so that a service model for aggregated traffic classes supporting QoS is provided. There is no explicit signalling in the network (i.e. the routers) before data transmission. Instead, the network tries to deliver a specific service based on the QoS specified by each packet. For the dynamic MANET, either these QoS models have to be modified or new QoS model con-cepts have to be introduced. There are some solutions proposed in literature for QoS provisioning in MANETs where soft QoS routing using inaccurate statistical information points towards a more realistic solution. In this subsection, we present an overview of selected routing protocols from work in [50, 51] that use QoS-aware methods for routing based on aforementioned metrics to measure routing effectiveness and energy-efficiency of protocols.

The Core-Extraction Distributed ad hoc (CEDAR) [50] was designed for small to medium size mobile ad hoc networks and consists of 3 main components which are the core extraction which uses a minimum dominating set (MDS), link state propagation which is a core broadcast mechanism and route computation in an on-demand source routing algorithm basis. Ticket-Based Probing (TBP) is a hop-by-hop, multi path QoS routing scheme [51]. Imprecise state information can be tolerated and multiple paths are searched simultaneously to find the most feasible path. It has the advantage of not using the flooding-based route discovery technique. Instead it attempts to search only the best possible routes considering different QoS constraints (i.e. bandwidth, delay, packet loss and jitter). Ticket-based QoS routing solutions for the bandwidth and delay-constrained routing issues. TBP utilises tickets to limit the number of paths searched during route discovery by permitting ticket-holders to search a single path. A source uses a probe (routing message) to the destination carrying at least one ticket. At an intermediate node, a probe with more than one ticket is allowed to split into multiple ones, each searching a different downstream sub-path. The Bandwidth Routing (BWR) is a QoS routing protocol for throughput based QoS support in MANETs. It is based on the destination sequenced distance vector (DSDV) routing scheme. The routing protocol provides QoS support via separate end-to-end bandwidth calculation and allocation mechanisms, thus called bandwidth routing. The proposed bandwidth routing scheme depends on the use of a CDMA over TDMA medium access scheme and thus can be regarded as a cross layer solution for QoS routing.

INSIGNIA [50], an IP-based QoS framework, is among the first signalling protocols for MANET. Its primary goal is to support adaptive services aiming to provide minimum bandwidth guarantees to real-time applications. INSIGNIA describes strict separation of routing, QoS signalling and forwarding functions. It uses in-band signalling (i.e. piggybacks control and signal data into data packets). The INSIGNIA signalling protocol uses per-flow service granularity and is responsible for multiple operations: setting up, restoring, adapting and closing down of real-time connections. Flow restoration and adaptation algorithms respond to topology changes and changes in available bandwidth, respectively. Destination nodes actively monitor ongoing flows, checking metric values (e.g. packet loss, delay and throughput) and measuring the QoS of data delivery. The commands are encoded in the IP option field, which avoids the need for supporting packet encapsulation. INSIGNIA is only one component of the QoS architecture and assumes the availability of routing. INSIGNIA may face scalability problems similar to RSVP. The Dynamic QoS Concept (dRSVP) is a resource reservation-based approach that fits into the IntServ model. To provide the flexibility needed in dynamic environments such as MANETs, the reservation requests are specified as a range of values (e.g. data rates). The network makes a commitment to provide service at a point in this range. The Dynamic QoS concept is based on the dRSVP protocol, extending the basic RSVP protocol to support dynamic QoS in mobile ad hoc networks. Flexible QoS Model for Mobile ad hoc Networks (FQMM) proposes a hybrid QoS model and has 3 main characteristics which are:

- Dynamic roles of nodes: there are 3 types of nodes defined. These are the ingress node that sends data, interior node which forwards data and the egress node that receives data. Any node in MANET can assume one of these roles.

- Hybrid provisioning: It is the process of determining and allocating resources at various mobile nodes in the network. A hybrid method implies providing both per-flow (IntServ) and per-class (DiffServ) scheme in which traffic of high priority is given per flow treatment as compared to general per-class treatment.

- Adaptive conditioning: The adaptive traffic conditioner contains the following components: a traffic profile, meter, marker and dropper. The traffic conditioner, placed at the ingress node, polices the traffic according to the traffic profile and is also responsible for marking the traffic streams.

In FQMM, bandwidth allocation is used as the relative service differentiation parameter. FQMM assumes that the larger proportion of traffic does not belong to the highest-priority class. The per-flow granularity is preserved for a small portion of traffic in MANETs and the scalability problem of IntServ is expected to improve. The QoS over AODV (QAODV) is an enhancement over the best effort AODV routing described in [37]. To provide QoS support, a minimal set of QoS extensions has been proposed as explained in [51]. The RREQ message formats are modified to specify Maximum Delay and Minimum Bandwidth as well as other optional metrics. The relay nodes specify through the RREP packet whether a route with such constraints could be provided. If a node determines that the requested QoS can no longer be maintained, a node must send an Internet control message protocol QoS LOST message back to the source so that other routes could be established.

Similarly, QoS over OLSR (QOLSR) enhances the variant of Dijkstras shortest path algorithm in [29]. OLSR provide optimal routes considering the number of hops. QOLSR enhancements over OLSR include using a multiple-metric routing criteria. Each path is assigned a number representing its bandwidth, delay or jitter value determined using aggregation of metrics at each link obtained through HELLO and TC messages. The path provided aims at having the highest bandwidth as well as the lowest delay and jitter values. Since the problem with two additive and one concave metrics is NP-Complete [47], a solution using the Lagrange Relaxation method was proposed to resolve this issue. If no paths exit satisfying the constraints, the best effort method is applied. The incoming packets are mapped into specific traffic classes based on the contents of the flows requesting weaker QoS or best-effort services until the passive reservations become active. It is important to note that the QoS-aware protocols described here are not good candidates for standardisation due to the high overhead produced in order to provide the required effectiveness. A better approach is to use an adaptive approach based on flat routing protocols as discussed in the next Chapter.

2.4.2.2 Load-Balanced Energy Efficient Protocols

Route selection mechanisms used in MANET routing protocols rarely consider node residual energy as a criterion while making their decision. Consequently, routing approaches may lead to particular nodes (critical nodes) being unfairly burdened to support routing if popular data paths exist during transmission. Such a mechanism will therefore lead to a high node failure rate due to battery exhaustion of nodes. Here, it is important to emphasise that unbalanced power consumption may not only result in earlier node failure of overloaded nodes, but can also lead to network partitioning, and a reduction in network lifetime (especially in small networks) and in route reliability [52]. So, there is a need to both improve energy efficiency and balance battery consumption among nodes in MANETs to reduce the number of critical nodes in the network.

There are few protocols that use various approaches to achieve energy efficiency or battery consumption balancing. However most of these protocols try to find some network layer mechanism to avoid flooding and unnecessary packet forwarding. Nonetheless one major drawback of most of these ad hoc routing protocols is that they do not have provisions for conveying the load and/or quality of a path during the route setup. There is a considerable number of studies that try to improve these issues, but they usually suffer from particular drawbacks such as requiring prior-knowledge of global topology information, increasing data delivery delay or even creating a blocking issue [52], [53], [54], and [55]. The blocking issue happens for example, when a source node is impeded by a timeout timer for starting data transmission before receiving all replies for a route request message. In the context of MANETs, these energy efficient algorithms also do not contain considerations for routing protocol scalability and QoS.

Besides, current ad hoc routing protocols do not have a proper mechanism to handle and save critical node failure. As previously mentioned there is a high probability that some nodes turn into critical nodes due to their favourable routing location in network topology. Consequently, more battery power is consumed for routing which often leads to node failure. We have proposed a new mechanism over the CML protocol called Energy-Efficient CML (E2CML) that detects such critical nodes and decrease their load as presented in [56]. Also most of the energy-efficient protocols try to find the optimised routing mechanism in terms of energy efficiency, but they usually cause more delay or create additional routing load. E2CML [56] not only aims to find the best energy balanced route, but also provides energy efficiency and delay improvements as presented in Chapter 5.

2.4.2.3 Scalable Routing approaches

There are various scalable routing approaches such as hybrid, adaptive and cluster-based, nature-inspired and geographical routing protocols. These will be described in more detail in the next chapter of this thesis. In summary, hybrid routing approaches use a combination of proactive and reactive routing mechanisms in order to improve routing performance. Some examples of scalable routing approaches are Statistic-Based Routing (SBR) [57] protocol, Temporally-Ordered Routing Algorithm (TORA) [51], An Adaptive Nature-Inspired Algorithm for Routing in MANET (AntHocNet) is presented in [51], inspired from ACO framework where paths are learnt through guided Mont Carlo sampling with ant-like agents communicating in a stigmergic manner. Also various well-known hybrid, adaptive and geographical routing approaches such as Location Aware Routing (LAR), Landmark Routing Protocol (LANMAR), Cluster Based Routing Protocol (CBRP), Hierarchical OLSR (HOLSR), Zone Routing Protocol (ZRP), Fisheye State Routing (FSR) Protocol, SHARP and DREAM will be further explained in more details in Chapter 3 as they are the protocols that most relate to our contributions in this thesis.

2.4.3 Mobility Models

A mobility model describes patterns adopted by mobile nodes over a period of time and thus mobility models are important factors affecting routing in MANETs. The use of mobility models in MANET routing research is further justified as they help to model and simulate the movement of real-life mobile nodes where it is reasonable to assume that there is a possibility for nodes to change in speed and direction. In [58], a number of mobility models are described that could be used for simulation purposes in MANET research. A list of mobility models is Random Walk Mobility Model, Random Waypoint Mobility Model, Random Direction Mobility Model, Boundless Simulation Area Mobility Model, Gauss-Markov Mobility Model, Probabilistic version of the Random Walk

Mobility Model, City Section Mobility Model, Exponential Correlated Random Mobility Model, Column Mobility Model, Nomadic Community Mobility Model, Pursue Mobility Model and Reference Point Group Mobility Model.

Node mobility is prominent in MANET applications such as PPDR communication scenarios. In that respect, it is important to consider its impact on the performance of routing protocols. There are several studies that have been carried out in the realm of mobility and QoS routing in MANETs e.g. [59] and [60]. The two defining properties of mobility are the mobility model and the degree of mobility as mentioned in [61] where the degree of node mobility can be defined in terms of average node speed and pause time. Higher mobility implies higher node speed and lower pause time. MANET mobility models are described in more detail in [62, 63]. Here, we present a categorised short description of entity and group mobility models. Firstly, the entity models are summarised below for convenience:

- Random Walk Mobility Model: node mobility patterns are based on random directions and speeds.
- Random Waypoint Mobility Model: mobility model which includes pause times between changes in destination point and speed. The Random waypoint model is a mobility model that is based on the random model describing the movement pattern of nodes moving freely and randomly without restrictions. The destination and velocity of any particular node is chosen randomly and independently of other participating MANET nodes.
- Random Direction Mobility Model: mobile nodes in this model have to travel to the limit of the boundary of simulated area before changing direction and speed.
- A Boundless Simulation Area Mobility Model: in this instance, the 2D rectangular simulation area is converted into a torus-shaped simulation area.
- Gauss-Markov Mobility Model: this model uses a specific tuning parameter to vary the degree of randomness in the mobility pattern.
- A Probabilistic Version of the Random Walk Mobility Model: it utilises a set of probabilities to determine the destination points of each mobile node.

- City Section Mobility Model: this model represents the simulation area as streets in a city.

Then, in group mobility models, individual nodes move randomly within node groups. For MANETs, these can be summarised as:

- Exponential Correlated Random Mobility Model: mobility pattern is created using a motion function.
- Column Mobility Model: the mobile nodes form a line and uniformly move forward in a specific direction.
- Nomadic Community Mobility Model: mobile nodes move together from initial location to destination location.
- Pursue Mobility Model: the mobile nodes of a given group follow a given target.
- Reference Point Group Mobility Model: the mobile group mobility is defined using the path traveled by a logical centre.

Since MANETs consist of autonomous nodes and distributed routers, the node mobility characteristics dictate the creation and destruction of the routes within the network. However, the aforementioned mobility models do not consider important features such as the effect of obstacles that might be present in the investigated area. These features are especially important for the case of emergency cases and could greatly affect the routing performance of protocols. Research has rarely considered the obstacles that may change mobility models but an extension to these concepts have been made in order to introduce the concept of human mobility in obstacle constrained environments (HUMO) [64], considering mobility of nodes such as firemen, policemen and medics in MANETs that are deployed in mission critical situations like earthquakes, forest fires, floods and military operations. In this thesis, we use the HUMO model, Random Waypoint (RWP) Mobility Model and the Random Direction Mobility Model (RDMM) in order to analyse the various scenarios for realistic MANET deployments. The RDMM mobility model [25] is particularly interesting as it addresses the issue of density waves creation with average number of neighbours as produced by the RWP Mobility Model. RWP mobility does not replicate a realistic mobility model, but is useful for our evaluations as it creates "worst case" random mobility scenarios. Therefore, if protocols perform adequately for RWP scenarios, they should be adequate for real-life scenarios as well.

2.5 Real-life Protocol Implementations

There are a few real-life MANET deployments on experimental basis including the wireless ad hoc community networks [1] where it was concluded that the use of hop-count as routing metric leads to unsatisfactory network performance. Therefore, there is a need to devise a new metric for route selection that is easy to implement and results in satisfactory network performance. Hence, experiments with the Expected Transmission Count (ETX) metric [65] were undertaken on the aforementioned networks few years ago. The ETX metric of a link is the estimated number of transmissions required to successfully send a packet (each packet smaller than the preset Maximum Transmission Unit (MTU)) over that link, until an acknowledgement is received confirming that the packet has indeed been correctly transmitted. It should be noted that the ETX metric is additive. The result of these experiments was that ETX was found to be sufficiently easy to implement, while providing sufficiently good performance, and this metric has thus been used for daily operation on these wireless ad hoc community networks ever since, alongside OLSR [29]. Subsequently, some interest in standardising the use of ETX for OLSRv2 has been shown, and work in progress such as the ETX I-D (see Table 2.1- 2.2 for the relevant I-D) might be the first steps in this direction, notably, within numerous IETF WGs. Preliminary work has also taken place within the ROLL working group to standardise the use of ETX within the "IPv6 Routing Protocol for Low power and Lossy Networks" (RPL) routing protocol for wireless sensor networks (see Table 2.1- 2.2). A summary of freely available open-source implementations of protocols is shown in Fig. 2.3. However, other proprietary implementations can also be found but they are not freely available and some are mostly being used for commercial ends.

[1] Berlin and Vienna Wireless Community Networks (http://www.freifunk.net), Athens Wireless Community Network (http://awmn.net), Roma Wireless Community Network (http://www.ninux.org), Barcelona Wireless Community Network (http://www.guifi.net), Boston Wireless Community Network (http://openairboston.net)

Implementation	Features	Source
AODV		
Ad-hoc Support Library and AODV-UIU	API to implement ad-hoc routing protocols. Operating System (OS)	http://aslib.sourceforge.net/
Embedded AODV & TORA.	Embedded in the commercial NovaRoam mobile router	http://www.nova-eng.com/novaroam.html
AODV-UU	Implemented by Uppsala University for linux and crosscompiling for ARM/Mips based devices	http://core.it.uu.se/core/index.php/Main_Page
UoB-JAdhoc	Java based multi-platform implementation for Windows and Linux.	http://www.aodv.org/
OLSR		
OLSR daemon	Implementation for Nokia 770, iPhone (8GB model), Mac OS X Tiger, Debian Linux, Ubuntu Linux, Windows 2k/XP/Vista and Android HTC.	http://www.olsr.org/
OOLSR	C++ Implementation by INRIA for Linux and Windows.	http://hipercom.inria.fr/OOLSR/
NRL-OLSR	Naval Research Laboratory olsr implementation in C++ for Linux	http://cs.itd.nrl.navy.mil/work/olsr/index.php
Qolyester	OLSR implementation without any QoS feature by the QOLSR team.	http://qolsr.lri.fr/code/
DYMO		
NIST DYMO	Implementation of by National Institute of Standards and Technology (NIST) for Linux.	http://sourceforge.net/projects/nist-dymo/
DYMOUM	C++ implementation by MASIMUM for Linux.	http://masimum.dif.um.es/?Software:DYMOUM
DSR		
DSR-UU	DSR implementation for Linux and LinkSys WRT54G by Uppsala University.	http://core.it.uu.se/core/index.php/DSR-UU
SMF		
NRL-SMF	Naval Research Laboratory (NRL) PROTocol Engineering Advanced Networking (PROTEAN) Research Group for Linux, MacOS, BSD, Win32, and WinCE.	http://downloads.pf.itd.nrl.navy.mil/smf/

Figure 2.3: List of routing protocol implementations - The figure shows a detailed list of MANET routing protocol implementations and links to their respective sources

Chapter 3

Scalable MANET Routing Protocols

In this chapter, we present, in more details than in Chapter 2, work in the area of scalable routing protocols for MANETs including cognitive and adaptive features. One of the main contributions of work in our thesis is the proposition of a scalable cognitive adaptive routing approach as will be investigated in the next three core chapters of the thesis. Thus, we dedicate this whole chapter to reviewing closely related routing approaches and protocols, found in literature, analysing and classifying these in terms of their overhead complexity. In the next chapter, we present our proposed network model that we have derived in order to provide in depth analysis and better understanding of the scalability properties of flat MANET routing protocols that are being proposed for standardisation. In the following sections, we provide a more detailed description of the scalability of flat routing protocols in terms of the various routing parameters that affect QoS provisioning. We also introduce our Chameleon (CML) protocol that provides one of the most significant work in the field of cognitive and adaptive scalable MANET routing.

3.1 Introduction

One of the main challenges towards deploying MANETs is providing a scalable routing protocol that also guarantees the required QoS in terms of quantitative metrics described in [9, 10, 11]. Routing scalability in the case of MANETs implies that the routing protocol needs to be able to sustain data routing with high throughput, low delay, jitter and packet loss as well as low routing overhead for various network sizes. There are several scalable MANET solutions proposed in literature as presented in [10, 11]. As described in Chapter 2, it was observed that scalable routing protocols found in literature can be broadly classified as illustrated in Fig. 3.1. The flat or traditional routing approaches that have been introduced by the IETF MANET WG activities mainly, and they have recently proposed a second generation of routing protocols in order to provide more flexibility to the proposed protocols. Other protocols proposed in literature are modified forms of the flat routing protocols that use a combination of the basic Topology Discovery (TD) and Topology Information Maintenance (TIM) mechanisms in order to maximise the QoS of the protocols.

The nature-inspired routing protocols use phenomenons in natural systems in order to translate such natural behaviours into routing processes. Some examples of such behaviours include swarm intelligence, epidemic ant colony behaviours that have inspired the design of routing protocols. Geographical approaches propose routing protocols that use the absolute or relative location of nodes in order to direct TD and TIM messages in an efficient manner. Hierarchical or cluster-based protocols modifies proactive flat routing protocol where all nodes can equally act as a source, destination and router. In this approach, nodes form part of distinct groups whereby inter-group routing is allowed only through elected nodes. Lastly, Hybrid routing protocols use zonal or converged routing approaches in order to make use of both proactive and reactive routing mechanisms. In a zonal approach, proactive and reactive zones are demarcated whereas in a converged approach adaptivity mechanisms are required to shift protocol operation from one mode to the other.

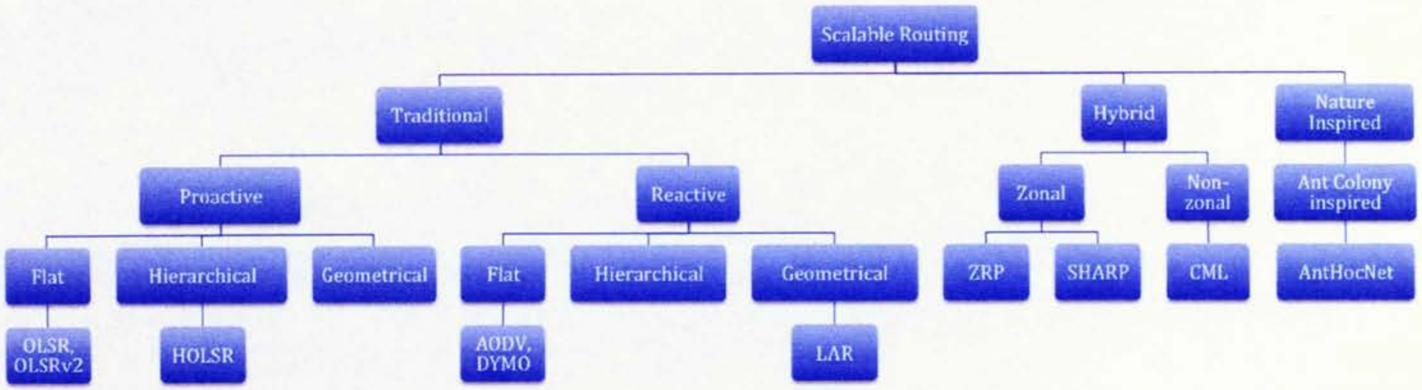


Figure 3.1: Classification of scalable routing protocols - The figure illustrates a classification of scalable routing approaches and protocols as found in literature

One of the main objectives at this stage is to provide a high level routing overhead complexity analysis of the discussed protocols in order to get some insight into scalability properties in terms of routing efficiency (or routing cost) [9]. In order to achieve this target, we need to identify and discuss the cost actuators (i.e. routing parameters directly affecting how energy is required for the routing process) that are attached with the various routing approaches. A list of these actuators with corresponding descriptions is listed in Table 3.1.

Cost actuator	Description
N	Total number of nodes in the network
T_{op}, T_{con}	Total time of network operation and Average time of a data connection respectively
I_{HELLO}	Time interval between successive HELLO message emissions in OLSRv2
ROUTE_TIMEOUT	Time duration for validity of a given AODV or DYMO established route
P	Number of established paths by multipath routing approaches such as AntHocNet
L	Rate of change of links as a result of node mobility from the set of n nodes
n	Average number of nodes reachable in 1-hop transmission
W	Willingness of a node to act as an MPR node in proactive approaches
I_{TC}	Time interval between successive TC message emissions in OLSRv2
Con	Total number of data connections between all S-D pairs during T_{op}
C	Number of clusters formed from N nodes by hierarchical routing approaches such as LAR
Z_{radius}	Number of hops for which proactive routes are maintained from a given node

Table 3.1: List of cost actuators - Table of MANET routing protocol cost actuator abbreviations with corresponding descriptions.

3.2 Traditional or Flat Ad-hoc Networking approaches

Flat routing protocols are traditional ad hoc routing protocols that have been discussed in literature and being actively promoted at the IETF MANET WG for standardisation. Although simple in design and satisfying the qualitative metrics that are listed in literature [9, 10, 11], each of the flat reactive and proactive approaches, introduced in Chapter 2, is better suited for a subset of MANET scenarios as discussed in literature [8, 9, 12, 14, 25, 66] and investigated in more details in Chapters 4 and 5. There are 2 generations of flat-routing approaches that have been proposed in literature that differ from each other mainly in terms of the introduction of standardised packet structures including TLVs. In this section we mainly discuss about the active RMP and PMP track protocols which are AODV and OLSR respectively.

3.2.1 First Generation Flat Routing Protocols

The well-known reactive AODV protocol [2, 37] uses RREQ broadcast packets to locate destinations when required on-demand by the data source with a RREP sent back to the source from the destination to establish a unicast route for data transmission. It is expected that AODV generates routing overhead on an on-demand basis at the cost of added end-to-end delay due to reactive route discovery latency. This route discovery process is repeated after a preset $ROUTE\_TIMEOUT$ time interval which denotes the time period after which an established route is invalidated if not utilised. Hence, the cost actuators in the case of AODV are the number of nodes N that have to forward the RREQ message, the number of hops for which RREQ and RREP have to travel to reach intended recipients derived from n, the number of discrete data connections Con for which TD has to be re-initiated and the rate of route changes due to mobility L [8]. An overview of the AODV routing process is illustrated in Fig. 3.2.

The proactive OLSR protocol [2, 29] is one of the most researched protocol in literature. It uses a table driven routing approach whereby each node in the MANET maintains route information to all possible nodes in the network. This is done using a periodic two-level routing process [8] where HELLO messages are used to compute routes to upto 2-hop neighbour nodes. Then MPR node set selection permits the optimisation of TC message flooding to propagate global routing information to all reachable recipient nodes in the MANET. Thus, OLSR proposes an approach that provides low

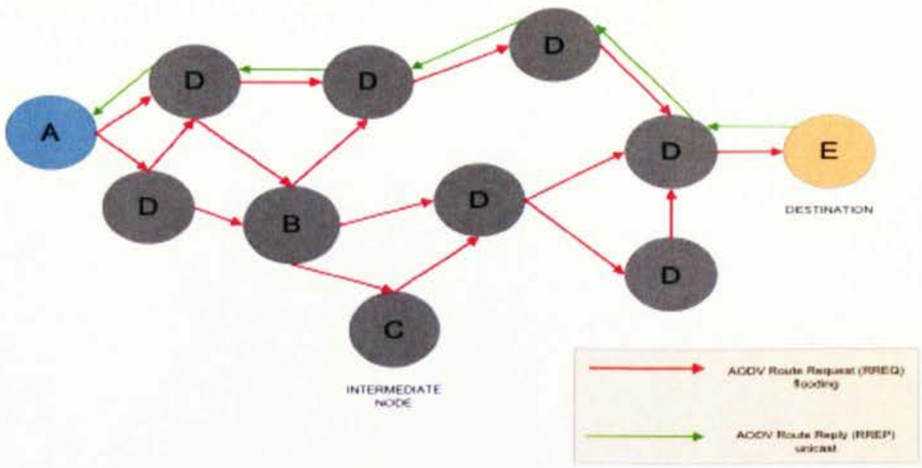


Figure 3.2: AODV routing approach - The figure illustrates an overview of the AODV routing approach in general purpose MANETs

latency for data delivery as TD latency is not a factor in the end-to-end data delivery delay. However, there is the added cost of periodic routing message overhead for the duration of the network lifetime. Since the MPRs are nodes elected on the basis of being the minimum set of symmetrically connected 1-hop nodes that can symmetrically connect the source node to all 2-hop neighbours. The number of nodes N in the network will periodically create and flood HELLO messages for every I_{HELLO} seconds and TC messages for every I_{TC} seconds. This process will be periodically repeated for the duration of the network lifetime of T_{op}. Here, each node has the option to indicate its willingness to participate as MPR node in the network by providing a value of "Willingness" W that ranges from $0.0 - 1.0$ where 0.0 implies that the node will not participate as MPR node and 1.0 means that the node will definitely participate as MPR node if selected. An overview of the OLSR routing process is illustrated in Fig. 3.2 where we illustrate the use of HELLO messages for nodes of up to 2-hops. Thus, it can be observed that node A should act as MPR node for node A so that it can communicate with node E.

TBRF [35] is a proactive routing protocol for MANETs which uses a shortest path hop by hop routing algorithm to each destination. It computes a source tree using partial topological information from its routing table using a modified version of Dijkstras algorithm. Only part of this tree information is disseminated to the neighbour

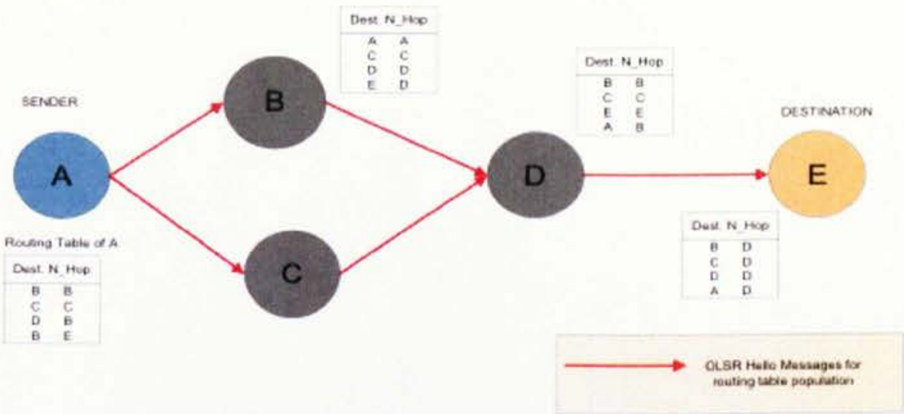


Figure 3.3: OLSR routing approach - The figure illustrates an overview of the OLSR routing approach of up to 2 hops using HELLO messages

node to minimise overhead. TBRF uses periodic update to update information stored in each node table and a differential update to increase the responsiveness to change in topology.

3.2.2 Second Generation Flat Routing Protocols

The authors of OLSRv2 and DYMO have described these protocols as the second generation MANET routing protocols based on OLSR and AODV respectively [2, 8]. The use of TLVs by these new generation protocols offers the possibility to efficiently add routing features so that the routing approaches are more scalable. OLSRv2 proposes the use of Fisheye State Routing features (FSR) [67] through TLVs in order to exchange TC messages only with $k-hop$ neighbours instead of flooding it over the entire network. The value of k helps each given node to form a zone so that TC messages to faraway nodes are propagated with lower frequency than those of nearby destinations. This will result in OLSRv2 producing accurate paths information for $k - hop$ neighbourhood of a node, and imprecise knowledge of paths to distant destinations. This imprecision is compensated by the packet route becoming more accurate as the packet approaches the destination. OLSRv2 also recommends Fuzzy Sighted Link State [68] routing feature additions for similar ends using in particular the Hazy Sighted Link State [69] optimisations. Thus, such approaches proposes to limit the TC message dissemination of

OLSRv2 in space over time in order to achieve potential scalability.

In the case of DYMO [2, 8], it is proposed that NHDP should be used as active link monitoring tool in order to determine the correct $ROUTE\_TIMEOUT$ value. This value will indicate the link duration of neighbour nodes and thus give a maximum value for $ROUTE\_TIMEOUT$. Consequently, the initiation of RREQ based route discovery mechanism of DYMO can be limited by this time interval and should result in a less costly, more scalable routing approach. In Chapter 4, we investigate the performance of OLSRv2 and DYMO based on derived models for MANET scenarios. In the case of the aforementioned second generation routing protocols, there is no proposed enhancements to the core routing mechanisms of OLSR and AODV respectively.

3.3 Non-traditional MANET Routing protocols

Apart from the flat traditional routing protocols found in literature and part of developments at the IETF MANET WG, there are various other scalable unicast routing approaches that have been proposed. An overview of well-known approaches has been presented in Chapter 2. In this section, we present in more details the various categories of scalable routing protocols. A simulated performance evaluation of these various protocols will be presented in Chapters 4, 5 and 6. Here, we focus on the routing overhead and the various parameters that affect it (or cost actuators of routing protocols). These will then be used to have an initial analysis of the scalability feature of non-traditional routing protocols.

3.3.1 Nature Inspired Routing Approaches

Moving away from traditional purely proactive and reactive approaches, there are several nature inspired algorithms that are being proposed as possible routing solutions to scalable MANETs such as ant colony optimisation, genetic zone routing and epidemic routing [46]. One of the most well-known MANET nature inspired routing approach is the adaptive nature-inspired algorithm for routing in mobile ad hoc networks (AntHocNet) [70]. AntHocNet is designed based on self-organising behaviour of ant colonies with respect to shortest paths discovery as well as the related framework of ACO [70]. The routing is achieved following ants approach of depositing a volatile chemical substance called pheromone moving between the nest and a food source, with higher pheromone intensity indicating shorter paths. These paths will then attract more ants and ultimately converge the majority of the ant agents onto a shortest path. This phase of global coordination of the agent actions is called stigmergy which is one of the key features of self-organised behaviours across various natural social systems including humans [70]. A good stigmergic model is believed to provide global robustness and scalability to the system, in our case, this should result in a robust and scalable distributed self-organised routing system.

AntHocNet is designed as a hybrid multi-path algorithm consisting of both reactive and proactive components. It does not maintain paths to all destinations proactively, but sets up paths reactively where reactive forward ants (agents) are flooded by the source in order to find multiple paths to the destination, and backward ants (agents) return to establish these paths. The established paths are then represented in pheromone tables in terms of path quality. After reactive route establishment, data packets are routed stochastically over the different paths according to the path qualities. For a given data session, these routes are maintained and improved proactively using proactive forward ants (agents). Link failures are either repaired locally or by warning preceding route nodes of such an occurrence.

3.3.2 Hierarchical cluster-based Routing Approaches

In cluster based hierarchical approaches, such as Clusterhead-Gateway Switch Routing (CGSR) [71], a stable clustering algorithm, is used to form node clusters with one node elected as cluster-head for each cluster. A gateway node belongs to at least two clusters thus inter-connecting the clusters. Routing of data packets is achieved using the paradigm of "$sourcenode \rightarrow sourceclusterhead \rightarrow gateway \rightarrow destinationclusterhead \rightarrow destination$". Each CGSR node maintains a distance vector (DV) routing algorithm with a cluster member table, that is broadcast periodically, and a DV routing table, containing the next hop towards its clusterhead, that in turns routes the packet to the destination clusterhead through gateway nodes as shown in its routing table. This approach greatly reduces the routing table size compared to traditional DV protocols thus allowing for scaling to large network size. There are other multilevel clustering algorithms such as Hierarchical State Routing (HSR) [72] that maintains a logical hierarchical topology using the clustering algorithms recursively to create multilevel clusterheads. HSR reduces the overhead for route storage and establishment for scalable networks. However, the corresponding cost of frequent updates of the cluster hierarchy is substantial especially in the case of high node mobility.

Recently, the Hierarchical OLSR model (HOLSR) [11] based on OLSR algorithm was proposed where node cluster levels are dynamically formed. This cluster structure supports random node mobility. HOLSR protocol thus reduces the amount of topology control information required at different hierarchical network topology levels, and the efficient use of existing high capacity nodes. In HOLSR, low-power nodes with only one interface are at Level 1, while nodes at the topology Level 2, are equipped with two interfaces, one of which communicates with Level 1 nodes. These longer range mobile nodes can also relay packets to other Level 2 simultaneously using different frequency band or MAC protocol. The Level 3 nodes, are equipped with three wireless interfaces capable of communicating in turn with Level 1, Level 2 and other Level 3 nodes at high-speed. There are clusters for each topology level, where MPRs are selected and TC messages exchanged. However, in HOLSR each interface sends out TC messages relating only to its own level and run HOLSR independently. Thus, hierarchal routing protocols tend to cluster mobile nodes to reduce area of flooding of topology messages using cluster head to manage routing in each virtual group of nodes.

Finally, the Cluster Based Routing Protocol (CBRP) [73] requires that nodes elect cluster heads to route messages in the network. In large networks, the simultaneous operation of both reactive and proactive routing creates substantial routing overhead and the process of electing cluster heads might not be appropriate in MANETs with high mobility because member nodes and neighbour nodes might change frequently. The main deficiency of hierarchical routing in MANET scenarios is that cluster heads have to be regularly elected in dynamic environments with high node mobility and node failure rate.

3.3.3 Geographic location based Routing Approaches

The Geographic approaches use the physical position of nodes whether absolute or relative, as additional information for routing. The information can be obtained through a location service such as Global Positioning System (GPS). The sender uses this position information of the intermediate and destination nodes to determine the route to be utilised to reach the destination. In this approach, routing information in tables are not required thus decreasing overhead and increasing scalability.

The Location Aware Routing (LAR) [11] uses GPS information to determine location of nodes and consequently attempts to reduce the TD related message flooding overhead. In LAR, this TD flooding limitation strategy constrains the RREQ flooding for nodes found in specific geographical areas based on coordinates stored from previous TD cycles. However, this also implies that each node should be equipped with GPS and incur the additional cost of calculating and updating its geographic location periodically. Thus data routing is achieved through Geographic Addressing and Routing (GeoCast). Further examples of geographic routing are LANMAR, DREAM and SLURP [10, 11]. However, a high cost is incurred due to the node localisation process that is used to identify nodes in the network. These identifiers also have to be propagated or queried making location based routing protocols efficiently scalable for only very specific scenarios. Additionally, there is a need for reactive approaches to gather and store coordinate information of nodes in the network using flooding techniques. In case of high node mobility in the network involved, the coordinates of nodes may change rapidly and subsequent refresh of information may cause significant delay as well as routing overhead. This is an important cost as routes have to be updated and flooding can only be efficiently optimised once these updates take place.

3.3.4 Hybrid and Adaptive Routing approach

It has been demonstrated that considering the "best effort" routing protocols, OLSR is more suited to particular network contexts (e.g. smaller networks, high mobility, higher number of data connections), as compared to AODV while AODV performs better for other network contexts (e.g. larger networks, low resource MANETs, delay tolerant applications), as discussed in [8, 12, 14, 27, 66]. The family of hybrid protocols combine both reactive and proactive features of flat routing protocols such as OLSR and AODV. In literature, the proactive mechanisms are used to discover and maintain routes nearer to source nodes within $k-hops$ while reactive routing features are utilised for establishing routes with destination nodes located further away.

Consequently, most of the hybrid approaches presented below attempt to minimise the overhead introduced by proactive routing for the global routing process, limiting proactive routing to local neighbourhood nodes only, at the cost of added delay of on-demand TD processes. Thus, most of the zonal routing techniques proposed show a balance between the proactive zones and reactive zones for optimised routing protocols. Thus, pre-defined hybrid routing approaches uses reactive and proactive features of routing in a fixed manner i.e. the proactive route maintenance extent of the network, also called zones, are pre-defined and consequently the reactive features are implicitly required to route data to destinations outside these zones. A novel approach that is further investigated as part of our work in this thesis,'is the utilisation of a converged proactive or reactive technique based on the network context. This will be explained in more depth in Chapters 4, 5 and 6 of this thesis. In the latter approach, a hybrid adaptive protocol is proposed in order to provide the optimal QoS depending on the network conditions. Thus, the proactive or reactive routing behaviour of the protocol changes dynamically with network conditions. In this case, it is essential to define adaptive processes for setting an adequate threshold value for a critical network parameter (e.g. network size), monitoring such network parameters, detecting if the threshold value is exceeded and finally changing the behaviour of the protocol as a result. Another challenge that we address is the automation of the adaptive processes of such a converged hybrid approach as compared to zonal approaches i.e. the protocol can cognitively adapt to the environmental and topological constraints in order to route packets in an optimised manner. We next describe and analyse the most popular hybrid and adaptive scalable routing protocols in literature.

The Zone Routing Protocol (ZRP) [11] is among the first and most well-known hybrid MANET routing protocol. It is based on a routing zone concept where the minimum hop distance from a given node for proactive route maintenance is defined by the zone radius value, k. A value of k equal to 1 refers to 1-hop neighbourhood proactive route maintenance; while if k is equal to the network diameter implies that the whole network will be covered proactively. ZRP was further enhanced into a zone routing framework using the independent zone routing (IZR) [12] where each node configures its zone radius in a distributed manner using local measurements only. This zone radius is then determined and updated in a distributed and adaptive manner. The FSR protocol [74] is a table-driven routing protocol which uses a hierarchical routing structure. FSR updates the link state information at different frequencies depending on its scope distance. Source nodes have inaccurate information when remote link states change due to node mobility. However, as the packet approaches the remote destination, it can obtain more accurate information from remote nodes. The level of flexibility of FSR depends on the scope level chosen and the radius size as described above.

Then, the Sharp Hybrid Adaptive Routing Protocol (SHARP) [75] claims to adapt efficiently and seamlessly between proactive and reactive routing strategies based on network characteristics. It can be configured to optimise user-defined performance metrics, such as loss rate, routing overhead, or delay jitter. A proactive zone is defined around some nodes with a node-specific zone radius determining the number of nodes within a proactive zone. All other destination nodes outside the proactive zone of a node is routed to, using reactive routing approaches. Nodes found within a proactive zone maintain routes proactively only to a central node. It is important to note that SHARP creates proactive zones around popular destinations with data connections. Hence, SHARP reduces network wide overhead by focussing proactive routing overhead cost around popular destinations by dynamically adapting the zone radius of a node according to incoming data traffic and network mobility. However, by reducing this radius value, SHARP decreases routing overhead at the cost of more delay jitter and higher packet loss rates. Thus, SHARP behaviour ranges from being completely reactive protocol when the zone radius of nodes is zero to being completely proactive if all nodes have zone radius equal to network diameter. As in most adaptive protocols, the optimal threshold value definition is a complex challenge. SHARP thus has to find the value for zone radius where the balance between proactive and reactive approaches overhead is optimal depending on some threshold values for the monitored network characteristics i.e. node mobility and incoming traffic.

The novel CML [14], that will be described in details in Chapter 5, is an adaptive hybrid routing approach that differs from the above described hybrid protocols in that it does not maintain routing zones. Instead, CML operates in a converged approach that is optimally maintained using three distinct phases of operation which are Oscillation (O)-phase, Proactive (P)-phase and Reactive (R)-phase. Each phase has augmented cognitive features on top of the utilised flat routing approach that operate in parallel to the traditional routing protocol. The CML design is focussed towards providing a solution for adaptive routing protocol that is scalable whereby the associated adaptive routing mechanisms are supported within an adaptive module. The cognitive feature of CML implies that it can monitor the number of nodes in the network by using phase specific mechanisms that are described in Chapter 5. A threshold value for the size of the network is determined through experimentation as explained in the next chapter of this thesis. This is specific to deployment scenarios and has been found to be in the range of 10-15nodes depending on the scenarios utilised as explained in Chapters 4 and 5. This threshold value indicates the network size point beyond which a reactive approach such as AODV is more efficient that the proactive OLSR protocol in terms of routing overhead, delay and delay jitter metric considerations.

Unlike ZRP and SHARP where zones delimit the proactive and reactive routing reaches for each node, CML dictates a converged network wide routing approach according to the size of the network in order to optimise routing overhead cost and improve QoS performance of the MANET routing process. Briefly, the default mode of operation is the P-phase whereby OLSR disseminates HELLO and TC messages. Each time such messages are received and the routing table updated, the adaptive module checks the number of reachable nodes in the network from the routing table, and compares it with the threshold value established. If the threshold is exceeded the O-phase is initiated. The O-phase checks the oscillation timer and group oscillation limits before allowing or rejecting a phase shift initiation whereby the R-Phase is started with AODV routing and a CML alert message is flooded to converge the network to the required routing approach. The O-phase checks for the occurrence of oscillations i.e. if there are periodic group movement of nodes that causes network size to repetitively exceed the threshold. In such a case, repetitive phase shifts are deemed inappropriate. CML also defines a cognitive network size estimation algorithm utilised by the adaptive module in the R-phase. If the network size shrink back beyond the threshold, the O-phase can be re-instated. Thus, CML caters for dynamic scalable networks with temporal network size changes. CML was originally designed for realistic scenarios in rescuer mission-critical communications but that should also be suitable for other scalable general purpose MANET scenarios.

The various approaches discussed above in this section can be summarised as shown in Fig. 3.4. Due to the varied characteristics of applying nature inspired routing methods, it was not possible to illustrate this in this figure.

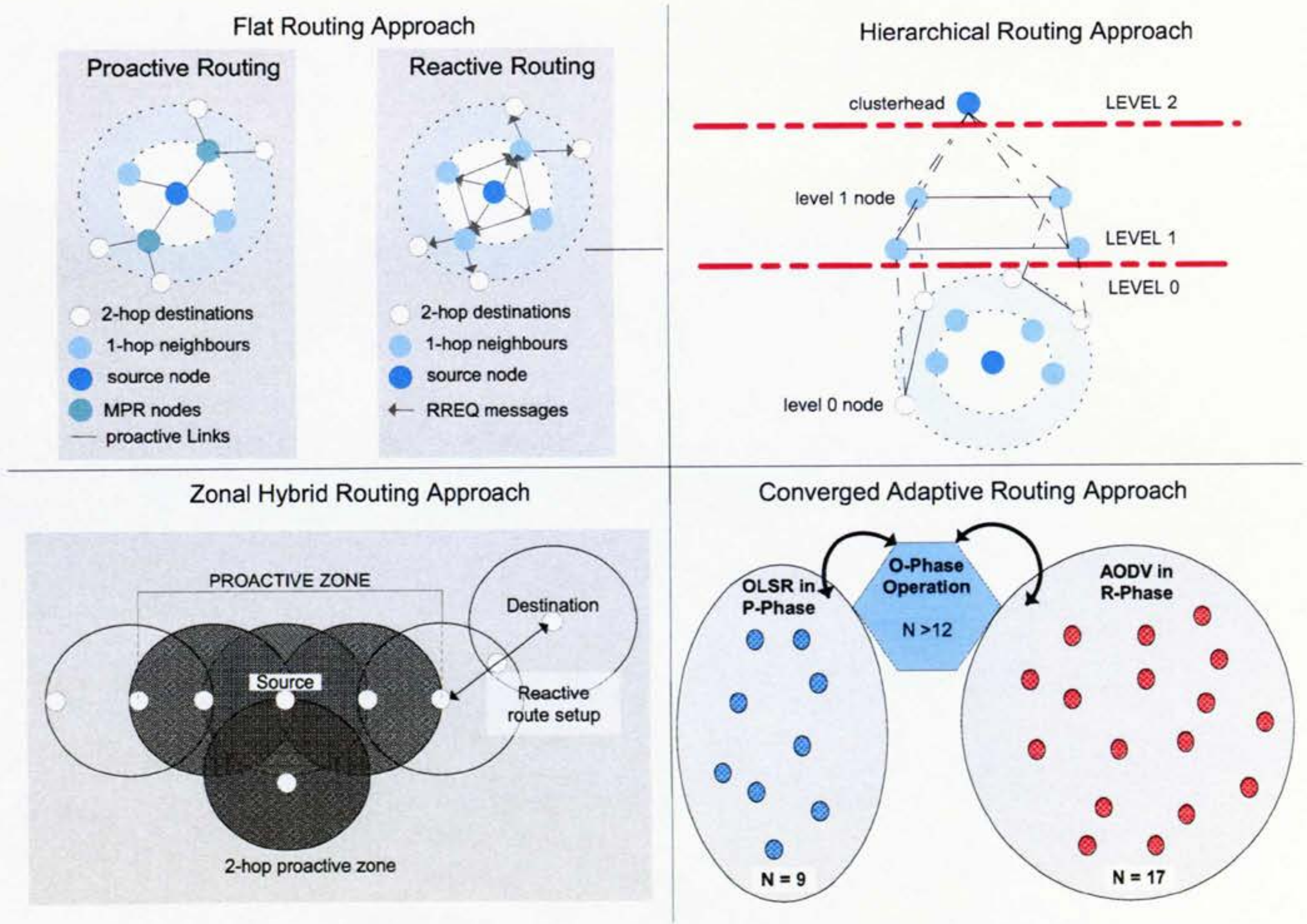


Figure 3.4: Overview of scalable routing approaches - The figure illustrates an overview of the scalable routing approaches as found in literature

3.4 Initial analysis of overhead complexity

In this section, we provide an initial analysis of the routing overhead complexity of some of the scalable approaches discussed above. The OLSR protocol issues HELLO and TC messages at regular intervals of time. Thus, if there are N nodes in the network each node needs to generate its own messages as well as forward messages from other nodes. This is restricted by only a fraction of MPR nodes in the network and thus the overhead incurred is of the magnitude of $O(N * N)$. In the case of DYMO routing, the routing is carried out in an on-demand basis rather than on a periodic basis. The flooding is source-initiated and requires in the worst case that all N nodes in the network forward the packet to the destination resulting in an overhead complexity of $O(N)$. Further components that affect the QoS level of flat routing protocols that will be further investigated in Chapter 4.

The AntHocNet routing protocol uses proactive HELLO and TC mechanism to keep track of neighbour nodes while at the global network routing level, it uses a reactive approach as inspired by ACO methods. Thus, it can be approximated that the complexity of routing overhead for this protocol is $O(N * N)$ for nodes that are close to each other or in small networks but this scales on the basis of $O(N)$ for larger network routing. The HOLSR routing protocol uses a hierarchical approach to segment the proactive message flooding space. However, although only a fraction of the routing message overhead will be issued as a result of using such an approach, the overall worst case complexity still follows the same trend as a proactive approach and can be approximated to $O(N^2)$ where N in this case represents the number of nodes in a given cluster.

The LAR and geographical routing protocols have at least the same level of overhead complexity as the underlying flat routing approach utilised. The main drawback of using such an approach is that it uses significant GPS or such localisation overhead in order to operate. These messages in turn add up to the overall routing message complexity so that geographical approaches although providing better QoS in terms of latency can be a costly alternative for MANET routing. ZRP utilises a hybrid approach similar to AntHocNet and is therefore subject to the same level of complexity which is $O(N^2)$ for large scale routing and $O(N)$ for neighbourhood or small scale networks. In the case of ZRP, the benefit of using a zonal approach is that the value of $k - hops$ zone can be defined, although in a fixed manner, in order to specify the size of the network for which a proactive zone associated overhead complexity will be applicable. On the other hand, SHARP offers an adaptive form of setting zonal size. The different "hot-spots" or popular destinations develop a proactive zone around itself so that messages can be readily transmitted to it. However, it can be deduced from the above discussions that as a proactive zone is being used, the protocols will have an overhead complexity of $O(N^2)$ in any case.

We have summarised the above discussions in the Table 3.2 below which includes the approximate complexity of the analysed protocols and the cost actuators that will affect the determination of such routing overhead complexity. Thus the number of nodes N in the network is one of the main factors that causes scalable routing protocol degradation. In the next chapter, we will investigate in more depth about the effect that actuators have towards the degradation of QoS routing.

3.5 Summary

In this chapter, we have presented the various scalable routing approaches that are well-known in literature. We present an initial analysis of estimated routing overhead complexity for each of these protocols. In general, the initial analysis showed that a proactive approach for routing that uses HELLO and TC messaging in order to discover and maintain routes, will have complexity of $O(N^2)$ as compared to a reactive approach using the flooding of RREQ messages from the source only in which case an overhead complexity of $O(N)$ can be expected. However, the TID process which is on-demand in reactive protocols introduces more end-to-end delay in the network. We have presented a review of scalable MANET routing protocols found in literature. The CML protocol that we have developed uses a novel converged cognitive approach towards adaptive routing that can effectively and efficiently route packets in scalable network scenarios whereby nodes regularly leave and join the network. In the next chapter, we present our work that has been carried out for the investigation of QoS models for realistic MANET scenarios.

Protocol	Routing Approach	Features	Cost Actuators	Overhead Complexity
OLSRv2	Flat Proactive	Uses local Hello and Global TC messages	N, T_{op}, I_{HELLO},I_{TC}, n	$O(N^2)$ for all networks
DYMO	Flat Reactive	Floods RREQ and unicasts RREP messages	ROUTE_TIMEOUT,N, n, L, Con	O (N) for all networks
AntHocNet	Nature Inspired	Uses ACO swarm intelligence to create multipath routes reactively and maintains these proactively	N, P, n, Con, I_{HELLO}	$O(N^2)$ for neighbourhood, O(N) for global
HOLSR	Hierarchical	Uses 3 level hierarchical clusters with clusterheads at each level for inter-level communication. Inter-cluster communication achieved though level 3 clusterheads	N, I_{HELLO}, C, L	$O(N^2)$ for all networks
LAR	Location Based	Uses GPS position to limit overhead	ROUTE_TIMEOUT,GPS, Localisation cost, N, n,T_{con}, Con	$O(N^2)$ for all networks, $O(N)$ for global
ZRP	Hybrid Zonal	Uses predefined zone radius k-hops for proactive routing and reactive discovery for inter-zone routing	ROUTE_TIMEOUT,k, I_{HELLO},I_{TC}	$O(N^2)$ for all networks
SHARP	Hybrid Adaptive Zonal	Adaptively forms proactive zones around popular destinations and uses reactive routing to find destinations outside zones	ROUTE_TIMEOUT,N, T_{op}, I_{HELLO},I_{TC},T_{con}, Con,N, n	$O(N^2)$ for all networks
CML	Hybrid Adaptive Converged	Switches from proactive to reactive routing based on the network size threshold	N, T_{op}, I_{HELLO},I_{TC}, N, n, $ROUTE\_TIMEOUT$, T_{con}, Con	$O(N^2)$ for all networks, O(N) for global

Table 3.2: Initial overhead analysis - Table of initial overhead complexity analysis of well-known scalable MANET routing protocol from literature.

Chapter 4

Network Model for Realistic MANET Scenarios

In this chapter, we investigate the routing models that include processes and metrics that affect the QoS routing levels of MANET routing protocols. Two important metrics that have to be considered while designing a routing approach are the end-to-end data delivery delay and the energy efficiency of the routing approach used. In both cases, network models have to be derived and utilised in order to define and understand the routing mechanisms that affect these QoS metrics and subsequently provide an enhancement of existing routing mechanisms in order to improve QoS performance of protocols. Here, we focus on routing protocols that are being proposed for standardisation as one of the objectives of this thesis is to work towards deployable routing approaches. Hence, our work in this chapter for deriving network models for end-to-end delay and routing overhead that are associated with AODV and OLSR protocols. We also present performance evaluations of the investigated routing protocols that were modelled using our mathematical derivations and associated discussions. These discussions confirm the hypothesis that there is a network size threshold (NST) beyond which it is preferable to use AODV instead of OLSR and thus provides a guideline towards the development of the CML protocol in Chapter 5.

4.1 Introduction

End-to-end packet delivery delay and routing overhead are two very important measures of the efficiency and effectiveness of MANET routing protocols i.e. routing metrics that determine the QoS of MANET routing protocols [9]. Other QoS metrics include throughput, packet loss rate and delay jitter. Although we do consider the latter metrics in our thesis, mainly in Chapter 5, these MANET QoS routing metrics have been widely investigated in literature and various solutions have been proposed whereby these did not explicitly make use of the routing parameters we considered in our thesis, in order to improve QoS.

For instance, the throughput in [76] uses a load-balancing approach for route discovery similar to our work in presented in Chapter 5 without actually considering energy efficiency, work in [77] proposes a MAC rather than routing enhancement, in [78] authors propose a scheduling cross-layer strategy while discussions in [79] present an approach to use the multi-user diversity in MANETs in order to improve the throughput in networks. While various other works in literature [26, 80, 81, 82, 83] tackle the issues of packet loss and delay jitter by either proposing cross-layer frameworks or discussing scalable video coding and adaptive buffering techniques respectively.

Our work on the derivation of end-to-end packet delivery delay [27] and energy efficiency [56] stems from well-known work presented in literature. We have extended such work proposed in literature to include considerations of MANET routing parameters that affect QoS in IETF endorsed proactive and reactive approaches. The assumptions, model derivations and performance evaluations relative to our work are presented in the following sections.

4.2 MANET model description

The variable size of MANETs as in the case of various real-life applications such as PPDR emergency communications, requires that employed protocols should be efficient and scalable while remaining effective in such dynamic scenarios. In fact, the number of MANET nodes in disaster rescuer communication scenarios may vary rapidly depending on the severity of the rescue operations. Thus, the employed protocol should have the ability to efficiently route data in small, large as well as variable sized MANETs operating in a delimited disaster area called the Critical Area (CA) both with and without the presence of obstacles that impede line of sight communications and rescuer mobility. In the following sections, we present novel models for proactive as well as reactive routing for such CAs, in terms of routing cost and E2E delay. We also present corresponding evaluations using model simulation results as applied to AODV and OLSR. We then determine NST values for hybrid adaptive routing approaches as our proposed CML protocol in Chapter 5.

Thus, we aim to analyse the end-to-end delay and routing overhead costs associated with MANET routing protocols through a probabilistic approach that is related to the dimensions of the CA of operation by extending work from [84]. We also investigate for realistic emergency scenarios, the way the presence of obstacles will affect such a model. Then, we derive a delay model that use a probabilistic model that also considers MAC cross-layer implications as derived in [85].

4.2.1 Notation and Assumptions

It is important to note that we assume a MANET deployment for rescuer PPDR communication where the rescue operation takes place within a pre-defined CA. The nodes forming the MANET in that CA can be represented by a graph, $G = \{V, E\}$. Let the set of nodes, n, in the network be denoted by the set of vertices $V = \{1....n\}$ and the links between nodes be represented by the set of edges $E = \{(i, j) : i, j \epsilon V\}$. A distance function $\Delta(i, j)$ gives the distance between vertices i and j in terms of number of hops required by a packet originating at node i to reach node j. Therefore, for $\forall(i, j)$ that are *h-hops* away from each other, $\Delta(i, j) = h$ where if $h = 1$, it implies that i, j are immediate or 1-*hop* neighbours. We also assume that all the packet sizes in the network have common headers and are of the same size as recommended in [34].

4.2.2 Topology

To define our network topology, we consider extreme emergencies where the two important topological aspects to be considered are the distribution of nodes and the nature of obstacles. For this model, we consider that the number of nodes in the network at a given time t is n within the CA of A m^2 that can be regarded as a rectangular 2−D space with length l and width w where $n \geq 2$ and $l \geq w$. The MANET is made up of a set of homogenous nodes and that each device has a transmission radius of r m. The n nodes are assumed to be always uniformly distributed within the network, as also assumed in [86], so that in the worst case scenario of a fully connected network, the number of nodes in an obstacle free CA can be estimated as $n = (l/r) \times (w/r) = A/r^2$. The maximum achievable number of hops, h_{max}, in such a network is derived from nodes that can be placed along the diagonal of the CA. This can be calculated as $h_{max} = (\sqrt{l^2 + w^2}/r)$.

We characterise the possible number of hops, h, as a binomially distributed random variable where $1 \leq h \leq h_{max}$ since the topology consists of a uniformly distributed collection of nodes. Therefore, we assume a symmetric probability distribution function where the mean value of H can be calculated as $h_{av} = h_{max}/2 = \sqrt{l^2 + w^2}/2r$. Then, assuming that the nodes will arrange themselves in a grid formation, average number of neighbours, 1_hop_{av}, for a given MANET of size n in a CA of A m^2, is estimated as $1\_hop_{av} = \lceil (n/A) \times \pi r^2 \rceil = \lceil n\pi r^2/(lw) \rceil$ where 1_hop_{av} is the upper bound average number of nodes likely to be found within the coverage area of a given node. Hence, if the assumed rescuer formation and specifications for the CA are known, the values for the above variables can be estimated for a particular rescue operation.

4.2.3 End-to-End Delay

In our derived models we consider work in literature where the end-to-end delivery delay is a cumulative additive function of queuing delay in buffers, D_{queue}, packet computation delay at nodes D_{proc} and transmission delay between nodes at each hop, D_{trans}. For the sake of discussions here, we simplify the more elaborate model presented in Section 4.3, assuming the use of CSMA/CA link access protocol and that queuing, D_{queue} and route computation delays, D_{proc}, are negligible. Thus, considering that the collision avoidance mechanism in CSMA requires that only one node can transmit at a time, the average delay, D_{access}, imposed on packet transmission across a given link, is directly proportional to the number of routing packets exchanged as supported in [87] and further examined in [88]. The cumulative sum of such link delays result in an overall increase in end-to-end data packet delivery delay, $Dtotal$. Therefore, in such a model, using less routing packets will improve QoS of the protocol while also reducing routing cost. We consider a packet transmission over a route R_i connected by links L_i

where $i \in \{1, ..., H\}$. H is the number of hops along the route and is bounded by the maximum number of hops achievable in a given operation area when transmission radius of each node is equal to R. We denote packet delay due to packet transmissions across the jth link along a path between a given S-D pair as D_{trans_j}.

In the case of proactive protocols such as OLSR, where the routes are pre-established, the total data end-to-end delay, $OLSR\_D_{total}$, is the sum of cumulative link layer transmission delays and backoff delays, $D_{backoff}$ due to a busy link along the route:

$$OLSR\_ D_{total} = \sum_{j=1}^{H}(D_{trans_j} + D_{backoff_j}) \tag{4.1}$$

where D_{trans_j} and $D_{backoff_j}$ are the transmission and back-off delays respectively, at the jth hop along that route.

Then, in the worst case, reactive protocols such as AODV requires establishing a route before transmitting. This includes flooding the network followed by 2 unicast transmissions. Therefore total end-to-end delay in data packet delivery, $AODV\_D_{total}$, is given by

$$AODV\_ D_{total} = \sum_{j=1}^{H}(3 * (D_{trans_j} + D_{backoff_j})) \tag{4.2}$$

It can observed using such a simplified model that the routing overhead is a determining factor in end-to-end delay performance of routing protocols and a lower routing overhead should provide better delay performance of protocols. The simplified model above is further investigated in more details with respect to proactive and reactive approaches in general as well as OLSR and AODV more specifically in Section 4.3.

4.2.4 Energy Consumption

In our MANET energy consumption model, nodal energy consumption is a result of packet transmission, processing and idle operation costs as shown in Fig. 4.1. Since energy consumed for idle operation and algorithmic processing are considered negligible compared to data packet transmission and data packet processing energy consumption [89], our protocol design focuses on reducing the latter two factors. These two factors are in turn both linked to the routing packet overhead for using TD and TIM

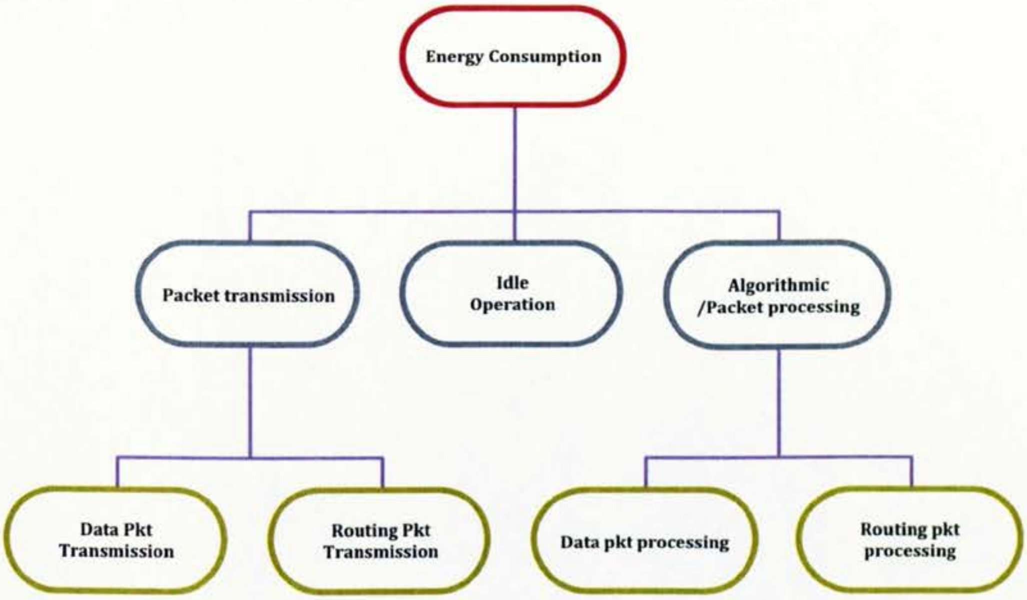


Figure 4.1: Energy Consumption Model - The figure shows the model for energy consumption for MANET routing scenarios as considered in this thesis

messages as well as processing and transmission for data packets as shown in Fig. 4.1.

Therefore, we define our model using three main definitions below for energy that form the basis for our model derivations. It is important to note that we do not consider propagation models in our investigations as we only observe residual energy levels in each node. Consequently, this implicitly includes considerations of energy spent due to signal propagation and any extra routing overhead due to node mobility. In a MANET each node can operate in a role-dependent (source, destination or router) state that changes temporarily. These states include one of the following:

1. Send packet: node sends data and control packets.

2. Receive packet: node receives data, control and any overheard packets.

3. Forward packets: node receives and sends a particular packet.

4. Idle state: node does not receive or send any packets. This is a rare state in MANETs where routing packets are regularly flooded and overheard by most of

the nodes in the network. However, if some nodes spend energy in the idle state, this will be implicitly considered while observing the residual energy of nodes at different times.

In Section 4.3 below, we derive a more detailed mathematical model based on the above considerations for energy. The energy model that we develop includes both routing overhead and data packet routing costs.

4.3 Derived packet overhead and end-to-end delay models

The model we derived for the routing overhead in [27] is based upon the topological specifications of the network as presented next. Therefore the afore derivations will be used to estimate the routing overhead for each IETF MANET WG track routing approach. It is important to note that we consider the "worst case" communication event where node i and j are located at extreme corners of the CA so that $\Delta(i,j) = h_{max}$ so that h_{max} hops separate destination node j from source node i.

The end-to-end (E2E) data packet delivery delay model that is used in this paper is inspired from [85], [90] and [91] and is thus an extension of the simplified model presented in Section 4.2, for the sake of discussions. In summary, E2E packet delay along a route between a given S-D pair i, j, D_{total} comprises of several delay constituent parts that can be expressed as:

$$D_{total} = D_{route} + \sum_{h=1}^{H}(D_{queue_h} + D_{tran_h}) \tag{4.3}$$

where D_{queue_h} and D_{tran_h} are the queuing and transmission delays respectively, at the hth hop along that route. Here,D_{route} is the route computation delay at source and H is the number of hops between the S-D pair. It is also assumed that the underlying layer consist of IEEE 802.11 CSMA/CA MAC that requires a back off time in for collision avoidance. An analytical model that explicitly considers such main features of MANETs such as transmission range, mobility pattern, and wireless link quality would be mathematically intractable [90]. Instead, our model assumes that these features are on an average homogenous for all the nodes in the network.

Thus, we define D_{route} as the latency between the time data is obtained from upper layer agents to the time a route is found so that the packet is placed in the outbound queue. Then, since D_{queue} depends on dynamic variables related to ad hoc wireless environments, its definition requires the use of advanced analytical models as described in [85]. Briefly, the model accounts for random access MAC that includes considerations for back off and collision avoidance mechanisms of IEEE 802.11 MAC. Therefore, main actors in this model include interfering 1-hop neighbours where a successful transmission at source occurs only if no other 1-hop node transmits concurrently. 2 nodes (i, j) may transmit successfully and concurrently if $\Delta(i, j) \geq 2$ [92].

The neighbours maintain a back-off timer that is frozen when other nodes transmit in the same medium space. Packets are only sent when the timer expires. The detection and clearance for transmission is achieved by exchanging Request To Send, Clear To Send and ACKnowledgement packets within time T_0 so that the time required to transmit a packet is $L/W + T_0$ where L is the size of the packet and W is the achievable transmission rate of the channel. It is assumed that T_0 is negligible compared to L/W, so that $D_{tran} = L/W$. Then, the queueing and transmission delays can be combined to D_{MAC} such that D_{MAC_1} is the 1-hop value for such a delay and

$$\begin{aligned} D_{MAC} &= \sum_{h=1}^{H} (D_{queue_h} + D_{tran_h}) \\ &= H \times D_{MAC_1} \end{aligned} \tag{4.4}$$

For a uniformly distributed topology, using Little's law and equation $\bar{K}_i = \rho/(1 - \hat{\rho})$ [85], then queueing and MAC access delay is given by $D_{MAC_1} = \bar{K}_i/\lambda_i$ where $\bar{K}_i$ represents the mean number of packets at node i and λ_i is the effective packet arrival rate at each source node i characterised as a poisson distribution function. Also, ρ is the utilisation factor at each node so that probability that node i has a packet to transmit is $P(Y_i = 1) = \rho$ and $\hat{\rho}$ is obtained by assuming diffusion approximation [93] used to indicate the probability that the number of packets at station $i = k$. By symmetry we assume that average delay is the same at each node. Thus, $D_{MAC} = (\bar{K}_i/\lambda_i) \times H$, implying that the values of D_{MAC} are dependant on the volume of packets (both data and control) in the network and generated by the node itself. This equation also implies that D_{MAC} depends on the ability of the nodes to transmit queued packets in busy channels shared by neighbours.

In our model, D_{MAC} can be derived based on the assumption that we normalise its value by considering that the data traffic transmitted is equal for all investigated routing protocols. We also apply this form of normalisation for all routing and E2E delay observations in the thesis. Thus, this connotes that λ_i can be approximated by the routing overhead for each protocol per unit time t, $Cost_{total}(t)$, (defined below) and an estimation of $\bar{K}_i$ can be made using the probabilistic approach from [85] so that this value approximates to the ratio of packets unsent by the node at time t. This is related to the availability of the free channel as compared to probability that neighbours are using it. To this end, we assume that the average routing overhead generated by each node at time t to be $Cost_{node}(t)$ and the number of neighbours sharing the same medium as 1_hop_{av}. Therefore,

$$\begin{aligned}\bar{K}_i &= (1 - (\frac{Cost_{node}(t)}{\sum_{node=1}^{1\_hop_{av}} Cost_{node}(t)})) \times Cost_{total}(t) \\ &= (1 - (1/1\_hop_{av})) \times Cost_{node}(t) \qquad (4.5)\end{aligned}$$

then D_{MAC} can be expressed as

$$D_{MAC} = \frac{(1 - (1/1\_hop_{av})) \times Cost_{node}(t)}{Cost_{node}(t)} \times H \qquad (4.6)$$

$$D_{MAC} = \begin{cases} 0 & \text{if } 1\_hop_{av} = 1 \\ (1 - (1/1\_hop_{av}) \times H & \text{if } 1 < 1\_hop_{av} \leq n - 1 \end{cases}$$

where n = total number of nodes in the network so that in the first case there is just one node which is the destination within the one hop neighbourhood. In the second case the number of nodes in the neighbourhood can be in the range of two nodes to all remaining nodes being in the neighbourhood. A value of $1\_hop_{av} = 1$ is not valid as this would mean that the source node is not connected with any other node in our assumed fully connected network.

4.3.1 Analytical models for Proactive Approaches

For proactive approaches, routing cost is associated with control packets that are used to establish routes to all possible nodes in the network. This is usually achieved by disseminating link information to 1_hop neighbours as described in [34]. Therefore, this routing overhead, $Cost_{neigh}$ at time t is given by $Cost_{neigh}(t) = 1\_hop_i$ where 1_hop_i denotes the number of 1 hop neighbours for node i. For n nodes in the network, this equation becomes $Cost_{neigh}(t) = \sum_{i=1}^{n} 1\_hop_i$. Since $1\_hop_{av} = \lceil n\pi r^2/(lw) \rceil$, the $Cost_{neigh}$ can be approximated to $Cost_{neigh}(t) = n \times 1\_hop_{av} = n \times \lceil n\pi r^2/(lw) \rceil$. Each node then shares this information network wide so that each node can compute a route to all possible nodes in the network. For a node i, this routing overhead $Cost_{netw}$ at time t is given by the sum of number of neighbours of each node, $Cost_{netw}(t) = \sum_{i=1}^{n} 1\_hop_i$. If the flooding undertaken by all n nodes are considered, the equation for routing cost becomes $Cost_{netw}(t) = \sum_{i=1}^{n}\sum_{i=1}^{n} 1\_hop_i$. Then using $1\_hop_{av} = \lceil n\pi r^2/(lw) \rceil$, this equation can be approximated as $Cost_{netw}(t) = n \times n \times 1\_hop_{av} = n^2 \times \lceil n\pi r^2/(lw) \rceil$.

These two processes are then repeated at intervals of, t_{int}s, for the time duration, Ts,of the rescue operation. Then, the total overhead for the whole duration of the operation can be expressed as

$$\begin{aligned} Cost_{pro} &= \sum_{t=0}^{T}(Cost_{neigh}(t) + Cost_{netw}(t)) \\ &= ((n \times \lceil n\pi r^2/(lw) \rceil) + (n^2 \times \lceil n\pi r^2/(lw) \rceil)) \\ &\times \frac{T}{t_int} \end{aligned} \tag{4.7}$$

Since routes are pre-computed in proactive approaches, D_{route} is assumed to be zero and $D_{total} = D_{pro} = D_{MAC}$ replacing D_{MAC} and H by h_{max} we derive $D_{pro} = (1 - (1/1\_hop_{av}) \times (\sqrt{l^2 + w^2}/r)$.

4.3.1.1 Application of models to OLSR

Each OLSR node uses HELLO messages at every t_{Hello} interval of time to share neighbourhood information and TC messages every t_{TC} s to flood the network with global route information. However, only a fraction of the neighbours, equal to the MPR_{ratio}, that receive the TC messages actually forward them as they form part of the source node's MPR set. Therefore, $Cost_{neigh} = Cost_{Hello} = (n \times \lceil n\pi r^2/(lw) \rceil) \times T/t_{Hello}$ and

$$\begin{aligned} Cost_{netw} &= Cost_{TC} \\ &= n^2 \times MPR_{ratio} \times (\lceil n\pi r^2/(lw) \rceil) \times \frac{T}{t_{TC}} \end{aligned} \tag{4.8}$$

finally adding both costs together we derive the total routing cost for OLSR,

$$\begin{aligned} Cost_{OLSR} &= Cost_{Hello} + Cost_{TC} \\ &= (nT \times \lceil n\pi r^2/(lw)\rceil) \\ &\times (1/t_{Hello} + (n/t_{TC} \times MPR_{ratio})) \end{aligned} \tag{4.9}$$

In the case of OLSR, the cost complexity $Cost_{OLSR}$ is $O(n^3)$ as observed above. Thus for a period t_{int} s, this should be considered for as compared to [85] where a homogenous packet rate was considered, our comparative based approach requires that we normalise delay relative to AODV. Therefore, the estimated normalised delay for OLSR D_{OLSR} can be expressed as

$$\begin{aligned} D_{OLSR} &= D_{pro} \times n^3 \\ &= (1 - (1/\lceil n\pi r^2/(lw)\rceil) \times (\frac{\sqrt{l^2 + w^2}}{r}) \times n^3 \end{aligned} \tag{4.10}$$

4.3.2 Analytical model for Reactive Approaches

In the case of reactive routing protocols, the routing cost is incurred on a reactive basis whenever data is ready to be transmitted. The route establishment mechanism generally require the protocol to flood the network with route discovery packets and therefore the cost of route discovery at time t, $Cost_{disc}(t)$ is given by $Cost_{disc}(t) = \sum_{i=1}^{n} 1\_hop_i$ where $i = 1$ denotes the source node that initiates the TD and $i = n$ represents the intended destination. Using $1\_hop_{av} = \lceil n\pi r^2/(lw)\rceil$ the equation can be approximated to $Cost_{disc}(t) = n \times 1\_hop_{av} = n \times \lceil n\pi r^2/(lw)\rceil$. The destination then proceeds to establish the route by unicasting a route confirmation packet along the reverse path from which the TD was received. The route confirmation overhead at that time t for S-D pair i, j is $Cost_{conf}(t) = \Delta(i,j) = h_{max} = \frac{\sqrt{l^2+w^2}}{r}$.

Since we focus on worse case scenarios, assuming that subsequent data transmissions take place after the route validity timeout, t_{out} s, the TD has to be re-initiated each time for the whole duration of the rescue operation for each connection period of the total duration Con s of all connections in the network. Assuming $Con = T$, therefore, total routing overhead for reactive approaches can be expressed as

$$\begin{aligned} Cost_{re} &= \sum_{t=0}^{T}(Cost_{disc}(t) + Cost_{conf}(t)) \\ &= ((n \times \lceil n\pi r^2/(lw)\rceil) + (\frac{\sqrt{l^2+w^2}}{r})) \times \frac{T}{t_{out}} \end{aligned} \tag{4.11}$$

In reactive approaches, source nodes have to initiate TD before transmission. This process results in the packet travelling a distance of $2\Delta(i,j) = 2 \times h_{max}$ for a connection between source i to destination implying that $D_{route_{re}} = 2 \times D_{MAC}$. Given that the E2E delay is the summation of both establishing a route and then the multi hop MAC delays,

$$\begin{aligned} D_{re} &= D_{route_{re}} + D_{MAC_{re}} \\ &= 3 \times (1 - (1/1\_hop_{av}) \times (\frac{\sqrt{l^2+w^2}}{r}) \end{aligned} \tag{4.12}$$

4.3.2.1 Application of models to AODV

In the case of AODV routing, source nodes use RREQ packets for route discovery while RREPs are sent back from destinations to confirm and establish routes that remain valid for t_{out} s such that the respective costs are $Cost_{disc} = Cost_{RREQ} = n \times (\lceil n\pi r^2/(lw)\rceil) \times T/t_{out}$ and $Cost_{conf} = Cost_{RREP} = (\sqrt{l^2+w^2}/r) \times \frac{T}{t_{out}}$. As a result the total cost for AODV routing can be expressed as

$$\begin{aligned} Cost_{AODV} &= Cost_{RREQ} + Cost_{RREP} \\ &= ((n \times \lceil n\pi r^2/(lw)\rceil) + (\frac{\sqrt{l^2+w^2}}{r})) \\ &\times T/t_{out} \end{aligned} \tag{4.13}$$

In the case of AODV, the complexity of cost $Cost_{AODV}$ is $O(n^2)$. Thus an estimated normalised expression for E2E delay, D_{AODV}, considering the complexity of the overhead is $D_{AODV} = 3 \times (1 - (1/(\lceil n\pi r^2/(lw)\rceil)) \times (\frac{\sqrt{l^2+w^2}}{r}) \times n^2$.

4.4 Models for realistic environments with obstacles

In this section, obstacles are represented by large blocks in the centre of the scene emulating damaged buildings in urban PPDR communication scenarios. In this context,

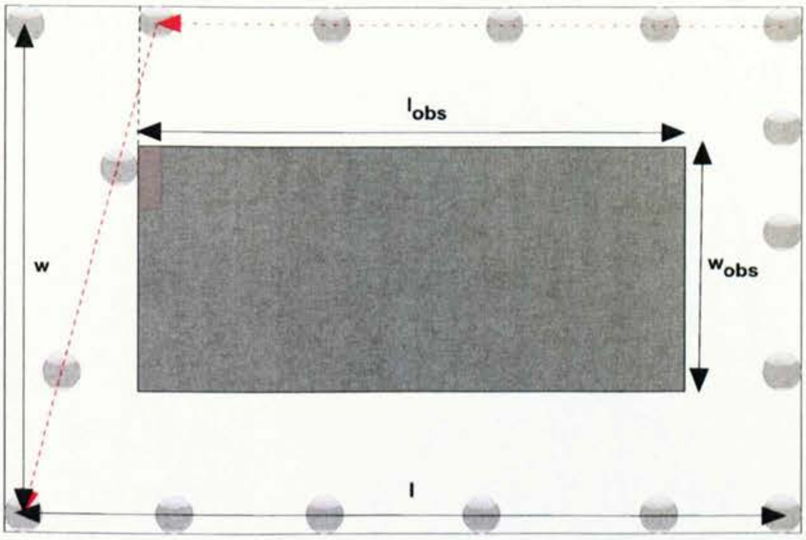


Figure 4.2: Urban Scenario - The figure shows the topological distribution of nodes in the event where environments have obstacles

there will be subsequent expected changes in the topology of the network due to l_{obs} and w_{obs} the length and width of obstacles respectively that has an area of A_{obs}. These changes are depicted in Fig. 4.2.

4.4.1 Topological changes with obstacles

In this urban emergency scenario, the centrally located obstacle in the CA is expected to have a direct effect on LoS and location of the n mobile nodes so that the nodal density i.e. average number of 1-hop neighbours $1 - hopu_{av}$ is increased as a consequence of usable free area A_{free}. Consequently, the CA can be considered as having subdomains of LOS with, in the worst case, one node linking the domains. This is illustrated in

Fig. 4.2. It can be consequently deduced that:

$$
\begin{aligned}
l_{free} &= (l - l_{obs})/2 \\
hu_{max} &= ((l - l_{free})/r) + (\frac{\sqrt{l_{free}^2 + w^2}}{r}) \\
hu_{av} &= h_{max}/2 = ((l - l_{free})/2r) \\
&+ (\frac{\sqrt{l_{free}^2 + w^2}}{2r}) \qquad (4.14) \\
A_{free} &= A - A_{obs} = lw - l_{obs}w_{obs} \\
\Rightarrow 1 - hopu_{av} &= (n/A_{free}) \times \pi r^2 \\
&= \lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil \qquad (4.15)
\end{aligned}
$$

where l_{free} is the length of free spaces between the obstacle and the vertical CA borders, hu_{max} is the maximum number of hops and hu_{av} is the average number of hops for this scenario.

4.4.2 Routing Overhead and Delay with obstacles

Our models for both OLSR and AODV cost and delay estimation make use of the changed variables above. We have new bounds for routing cost. In the case of OLSR, the revised urban obstacle routing cost $Costu_{OLSR}$ can be defined as:

$$
\begin{aligned}
Costu_{Hello} &= (n \times \lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil) \\
&\times \frac{T}{t_{Hello}} \\
Costu_{TC} &= \sum_{i=1}^{n}\sum_{i=1}^{n} 1\_hopu_i \times MPR_{ratio} \times \frac{T}{t_{TC}} \\
&= n^2 \times MPR_{ratio} \\
&\times (\lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil) \times \frac{T}{t_{TC}} \\
\Rightarrow Costu_{OLSR} &= Costu_{Hello} + Costu_{TC} \\
&= (nT \times \lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil) \\
&\times (1/t_{Hello} + (n_u/t_{TC} \times MPR_{ratio})) \qquad (4.16)
\end{aligned}
$$

Similarly, the expression for normalised delay Du_{OLSR} can be expressed as

$$\begin{aligned}
Du_{OLSR} = & (1 - (1/\lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil) \\
& \times ((l - l_{free})/r) + (\frac{\sqrt{l_{free}^2 + w^2}}{r})) \\
& \times n^3
\end{aligned} \tag{4.17}$$

Then, the urban scenario routing overhead for AODV $Costu_{AODV}$ can de derived using $Costu_{RREQ} = n \times (\lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil) \times T/t_{out}$ as

$$\begin{aligned}
Costu_{RREP} = & ((l - l_{free})/2r) \\
& + (\frac{\sqrt{l_{free}^2 + w^2}}{2r}) \times T/t_{out} \\
\Rightarrow Costu_{AODV} = & Costu_{RREQ} + Costu_{RREP} \\
= & ((n \times (\lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil)) \\
& + ((l - l_{free})/2r) + (\frac{\sqrt{l_{free}^2 + w^2}}{2r})) \\
& \times T/t_{out}
\end{aligned} \tag{4.18}$$

And the normalised delay for AODV can be expressed as Du_{AODV} below

$$\begin{aligned}
Du_{AODV} = & 3 \times (1 - (1/(\lceil (n/(lw - l_{obs}w_{obs})) \times \pi r^2 \rceil)) \\
& \times ((l - l_{free})/r) + (\frac{\sqrt{l_{free}^2 + w^2}}{r})) \times n^2
\end{aligned} \tag{4.19}$$

4.4.3 Energy Model for routing data packets

We assume that a multi-path routing mechanism is to be used for extending network lifetime such as in the energy-efficient, E2, mechanism that we have proposed in [56] and we introduce in Chapter 5. Therefore, to achieve a more energy efficient mechanism via load-balancing using such a multi-path method, we should focus on further analysing the energy required for states 1-4 described in Section 4.2.4 above.We assume that a MANET node mainly utilises energy for receiving and sending packet from its wireless network interface as indicated in [89]. It is also assumed that the node does not spend significant energy while in idle state and does not switch to sleep mode. We assume that the link capacity of all links in the network is equal to C. Therefore the same time

T is necessary to send a packet from node u to node v in the network. Let E_{init} be the initial battery level in each node and E_{total} be the total energy of all the N nodes in the network where energy input from external sources is not possible,

$$E_{total} = \sum_{j=1}^{N} E_{init,j} \tag{4.20}$$

Also, each transmitted packet requires energy E_t while a received packet obliges a node to consume energy E_r. If E_{fw} represents the energy required by a node to forward a packet, it can be deduced that energy required to forward a packet is given by

$$E_{fw} = E_r + E_t \tag{4.21}$$

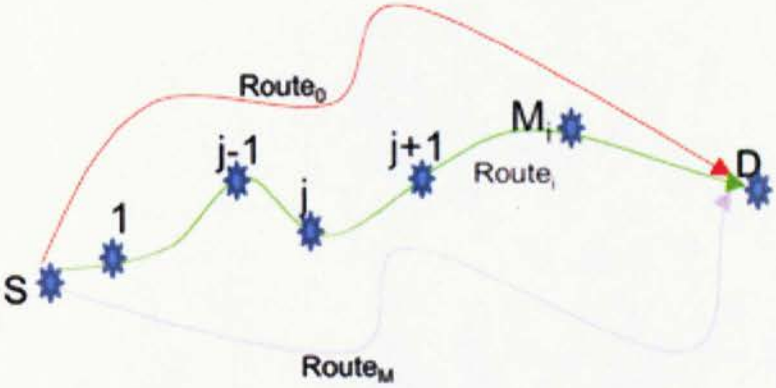


Figure 4.3: Multi-path scenario - The figure illustrates that for each S-D pair there is M routes which each of them such as Ri has Mi nodes excluding S and D

With respect to discussions related to the E2 mechanism, we consider the case where multiple paths exist from source node S to destination node D as shown in Fig. 4.3. Then, the set R_{SD} of M possible routes from source node S to destination node D is given by $R_{SD} = \{R_i : 0 \leq i \leq M - 1\}$ where R_i is the ith route connecting node S to node D. Given that route $R_i = \{S, ..., D\}$ is a set of nodes found along route i, the length of a route is defined as $|R_i|$

$$|R_i| = (N - 1) = H \tag{4.22}$$

where N is the number of nodes in R_i and H represents the number of hops along that route. The energy required to send a packet along route R_i can be expressed as

$$E_{R_i} = (H * E_{fw}) \tag{4.23}$$

4.5 Performance Evaluation

In this section, we present our simulation results of the above derived models in order to investigate the performance of routing protocols in varied MANET scenarios. We use simulations to evaluate the models related to our scenarios based on free LOS environment and an urban emergency scenario as described above. Moreover, discussions and results focus on the range of values of the total number of nodes in the network, n, such that $2 \leq n \leq 50$ in order to determine the threshold region for MANET routing. However, discussions are also applicable to larger values of n on the evidence of the models. We use the normalised E2E data delivery delay from the source node to the destination node as the main metric for QoS and the routing packet overhead as the main metric to measure the efficiency of the routing approaches as recommended by the IETF through document [9].

4.5.1 Evaluations: Scenario1

In the first scenario, we investigate the primal models that are proposed in Sections 4.2.4 and 4.2.3. Therefore, we setup a simulation environment for different network size N starting at 6 nodes with increments of 2 nodes in each scenario set up, up to a maximum network size of 20 nodes. AODV and OLSR were then utilised to investigate the actual traffic generated compared to a theoretical plot of the MANET routing overhead. The packet delivery delay was also investigated by plotting a graph of network scales against the delays experienced by AODV and OLSR in changing MANET sizes. One of the objectives of scenario1 is to verify that the assumptions made for our energy and delay models are in line with initial simulation results and to identify whether a network size threshold between AODV and OLSR exists as suspected in Chapter 3.

From Section 4.2.4, it can be deduced that for each data connection in the network, given that $ROUTE\_TIMEOUT$, I_{HELLO} and I_{TC} have comparable magnitudes (as proposed in [29] and [37]), the routing packet overhead required by OLSR is more

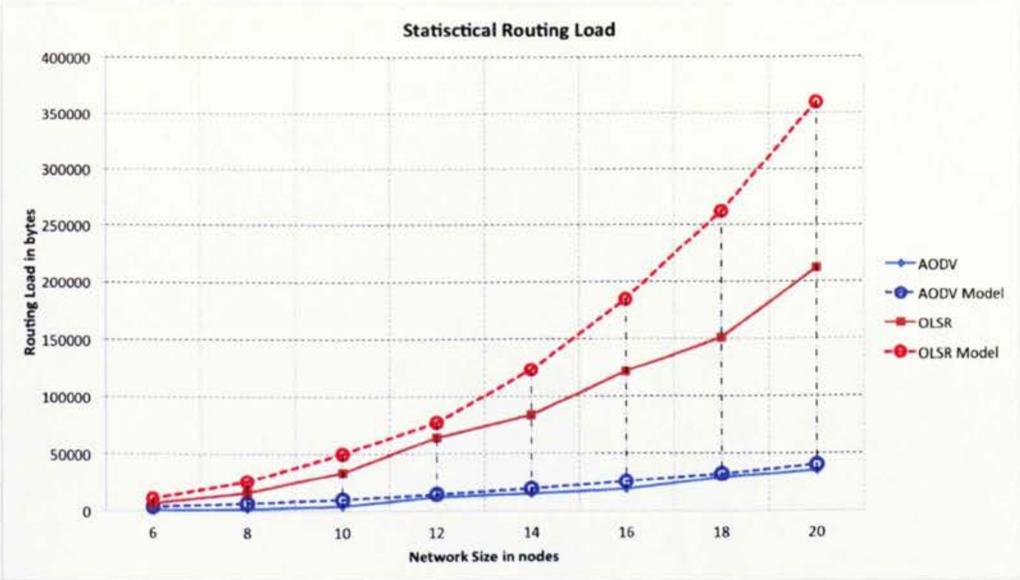


Figure 4.4: Overhead model evaluation and validation - Illustration of modelled packet overhead from our mathematical model and simulations for AODV and OLSR routing

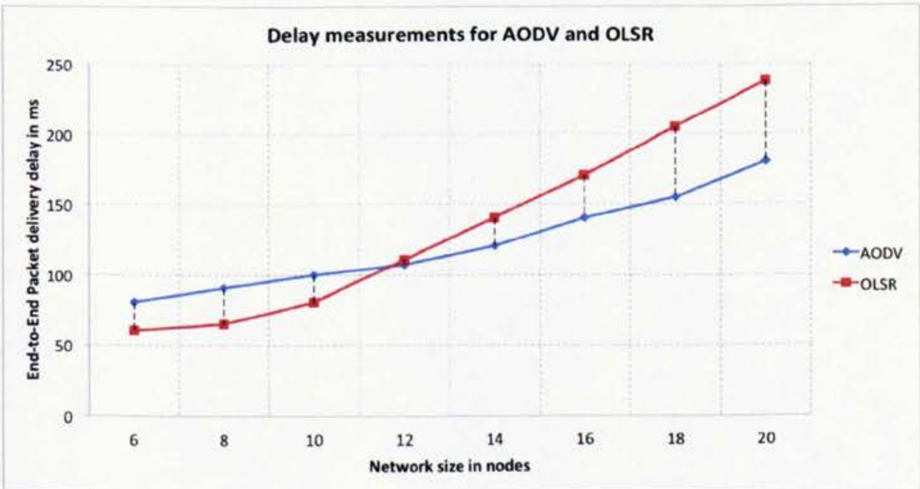


Figure 4.5: End-to-end delay simulated evaluation - End-to-end data packet delay measurements using AODV and OLSR

significant than that of AODV routing as the network size N increases. More particularly, the OLSR routing cost increases exponentially as opposed to a linear increase for AODV overhead packets with increasing number of N nodes as shown in 4.4. As further illustrated in the figure, our simulated results using the event-driven packet level simulator ns-2, support the aforementioned model claims that the routing overhead $R\_Pkt_{OLSR} \approx R\_Pkt_{AODV}$ for smaller networks, but $R\_Pkt_{OLSR} >> R\_Pkt_{AODV}$ for larger networks above a certain network size that we describe as the network size threshold (NST) value in our work in this thesis. In addition, from the delay models defined in Section 4.3, a higher number of overhead packets will increase the total packet delivery delay D_{total} due to higher values of $D_{backoff}$ [87]. This is illustrated in Fig. 4.5 where for smaller networks OLSR outperforms AODV while in larger networks AODV protocol performs better than OLSR. In this initial scenario, the NST value can be estimated to be approximately equal to 12.

4.5.2 Evaluations: Scenario2

In Scenario2, we simulate our more extensive derived models presented in Section 4.3 and evaluate the corresponding normalised E2E delay and routing cost, followed by comparative discussions of the results. In this scenario, we use in-depth evaluation of the AODV and OLSR routing protocol with emphasis on how the presence of obstacles in a realistic scenario can affect the performance of such protocols. Thus our evaluations use the models for both free space and an urban obstacle at the centre of the scene and measures the E2E delay and packet routing overhead performance of the AODV and OLSR protocols.

Fig. 4.6 and 4.7 compare the normalised (as explained in Section 4.3) for E2E delay of AODV and OLSR for our 2 scenarios respectively. It can be deduced from these figures that $D_{OLSR} \approx D_{AODV}$ for smaller networks of size n such that $n \leq NST$. For the range $NST \leq n$ the $D_{OLSR} >> D_{AODV}$. This trend is not affected by the presence of obstacles within the CA. However, the obstacles affect the magnitude of the normalised delay. Fig. 4.8 and 4.9 compare the routing cost of AODV and OLSR for our different scenarios. In Fig. 4.8, for the obstacle free scenario, it can be clearly observed that there is a threshold value NST_{free} for routing cost when $n = 15$ where $Cost_{OLSR} = Cost_{AODV}$. For $n < NST_{free}$, the OLSR protocol has a more efficient cost

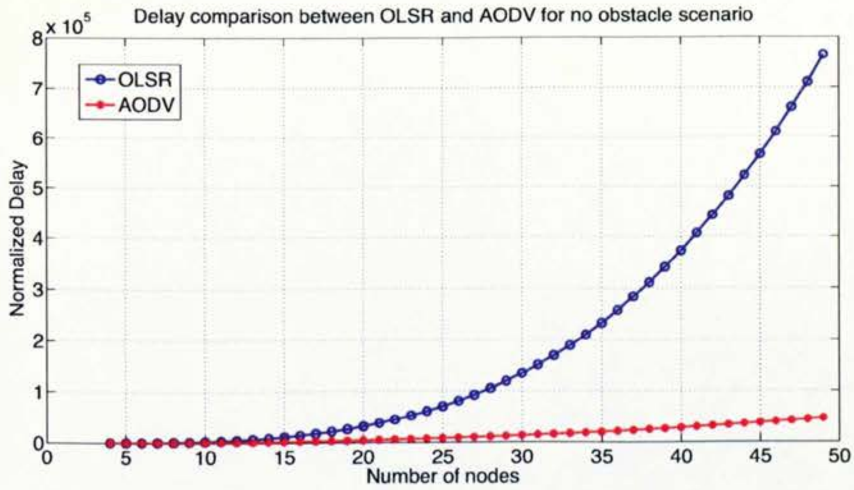


Figure 4.6: Delay model evaluation, free space - Comparison of normalised E2E delay between AODV and OLSR for obstacle free disaster scenarios

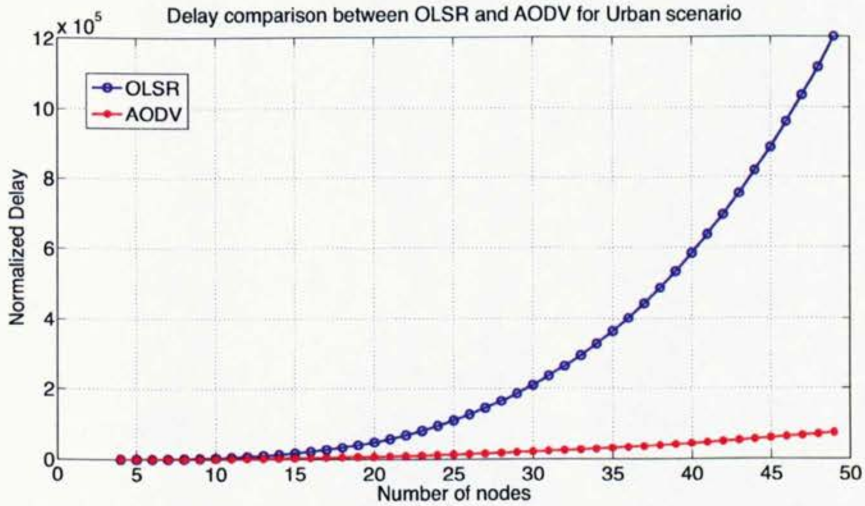


Figure 4.7: Delay model evaluation, urban obstacle - Comparison of normalised E2E delay between AODV and OLSR for urban disaster scenarios

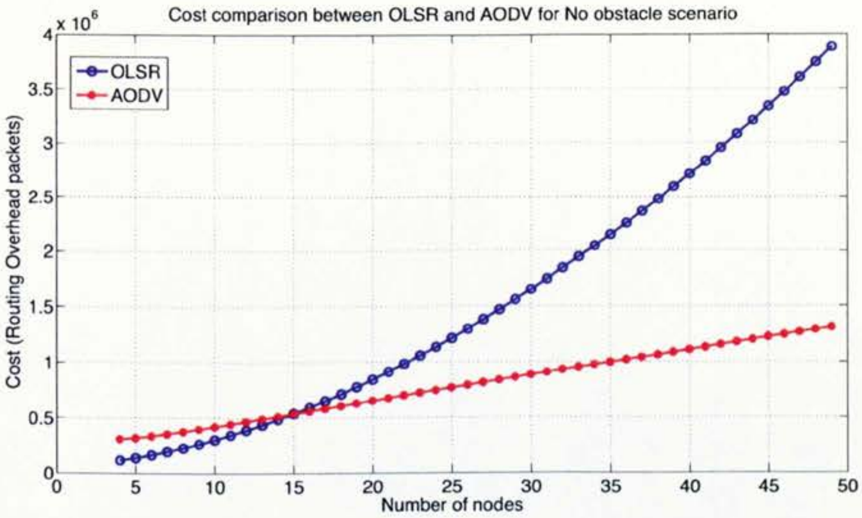


Figure 4.8: Overhead model evaluation, free space - Comparison of routing cost between AODV and OLSR for obstacle free disaster scenarios in terms of routing packet overhead

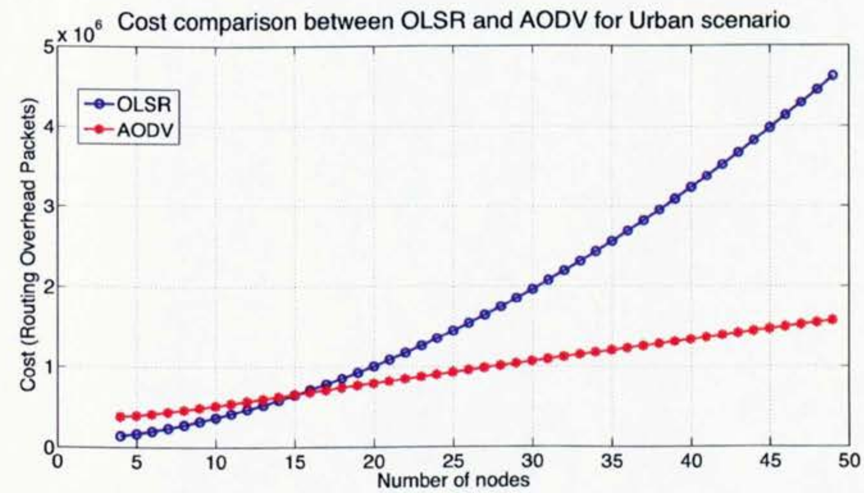


Figure 4.9: Overhead model evaluation, urban obstacle - Comparison of routing cost between AODV and OLSR for urban disaster scenarios in terms of routing packet overhead

wise routing mechanism than AODV while AODV proves to be more cost efficient for the range $n > NST_{free}$. In Fig. 4.9, exactly the same trend can be observed for urban scenarios where the threshold value is $NST_{urban} = 15$.

4.6 Summary

In this chapter, we have presented our derived models for E2E packet delivery delay and routing overhead cost for free-space and urban obstacle scenario. In our scenarios and topological model we assume that an obstacle is present at the centre of the scene for urban scenarios. We have developed models for both proactive and reactive approaches in general as well as OLSR and AODV protocols more specifically to evaluate their suitability for PPDR communication emergency scenarios. These models were then evaluated to observe that there is a NST as being stipulated near the 10-12 nodes topology range of network size whereby the routing overhead and E2E delay performances of both AODV and OLSR are approximately equal. Moreover, AODV has better performance for larger MANET scenarios and OLSR should be preferred for smaller networks that the NST. It is also shown in this section that the presence of obstacles in our urban scenarios do not affect the trend in protocol performances but they do degrade the QoS levels of protocols. We have simulated some of the modelled scenarios to confirm that the same trends occur using ns-2 results. In the next chapter, we use the above findings to design and evaluate our proposed CML routing approach for such variable size MANETs in emergency situations.

Chapter 5

ChaMeLeon (CML): A Cognitive and Hybrid Adaptive Routing Protocol

In this chapter, we present and investigate our proposed cognitive and hybrid adaptive routing protocol for scalable MANET scenarios. Our proposed protocol, called ChaMeLeon (CML) due to its adaptive nature, is designed to work as a cognitive and hybrid adaptive routing protocol for MANETs in general but is more suited for ad hoc communication in highly dynamic scalable MANETs where nodes join and leave the network frequently. The normal mode of operation is under one of the stable phases where flat routing protocol operation is assumed. The default stable operating phase is the Proactive (P)-phase. This chapter describes the design of CML with constituent processes and structures and also presents performance evaluation of CML as a comparison to some of the popular routing protocols discussed in previous chapters. In the next sections, we present an overview of CML routing protocol, the constituent structures and processes of CML, the operation of CML including the energy-efficient (E2) mechanism, its performance evaluations followed by analytical discussions. In Chapter 6, we present a realistic framework that we have designed and developed for the efficient lightweight development and deployment of adaptive routing protocols such as CML.

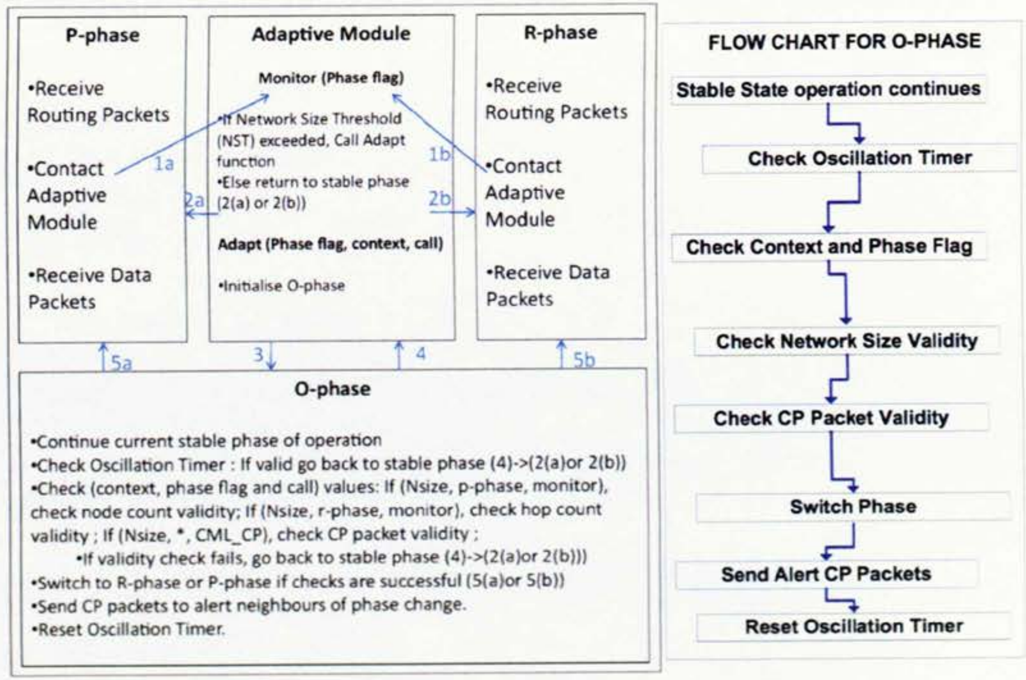


Figure 5.1: Overview of CML routing protocols design - The figure shows the various constituent structures and links that are enclosed within the CML protocol design

5.1 Introduction

CML is a cognitive and adaptive routing protocol that has been designed specifically for scalable PPDR emergency scenarios in mind, where rescuers are equipped with lightweight communication devices, but can be used for ad hoc communications in general purpose MANETs. The autonomous nature of MANETs is very suitable for extreme emergency communications within the Critical Area (CA) because communication infrastructures in such disaster sites are usually incapacitated. Also, as investigated in Chapter 4, there is a Network Size Threshold (NST) point whereby it is beneficial to use proactive routing approach for smaller networks and a reactive approach for larger networks.

CML has the ability to adapt its routing behaviour using its cognitive ability to monitor changes in MANET size. Such a hybrid approach is supported by findings in Chapter 4. Hence, it is a more suitable routing alternative than flat or traditional routing approaches for small, large as well as variable sized MANETs operating in a defined CA. The main concept behind CML is the adaptability of its routing mechanisms towards changes in the physical and logical state of an emergency MANET for PPDR communications. For autonomous emergency communications, there is a likelihood that the network size will vary whenever more rescuers join or leave the network. In addition, battery exhaustion of lightweight mobile communication devices used by rescuers could stipulate another reason for changes in the network size.

CML operation consists of 3 phases of operation namely Proactive, Oscillation and Reactive. The P- and Reactive (R-) phases operate in the same way as the core functions of OLSR [29] and AODV [37] respectively and are discrete from each other. The Oscillation phase (O-phase), therefore, acts as an intermediate between P- and R-phases and decides on whether a shift from P-phase to R-phase is appropriate based on the network size criteria. The main purpose of the O-phase is to avoid the oscillation problem as described further in this chapter and explained in [14, 94]. The O-phase also ensures the convergent nature of CML operation whereby all nodes in the network operate using the same flat routing protocol homogeneously as opposed to a zonal hybrid routing approach in literature. In addition, CML introduces an Adaptive module which runs in parallel to and is accessible by all phases of operation. The Adaptive module is designed to monitor relevant MANET characteristics, detect a certain quantitative threshold exhibited by specific monitored characteristics and in such an event, transfer the control to the O-phase.

Hence, our proposed version of CML adapts its routing behaviour according to changes in the network size within a pre-defined CA. For small networks, CML routes data proactively using the OLSR protocol [29] whereas for larger networks it utilises the reactive AODV Routing protocol [37] so that overall routing performance is improved. These transitions occur via the CML O-phase so that the oscillation of nodes problem, that is identified and explained in more details in the next section, does not affect the efficiency of CML. This chapter focuses on the description of the processes involved in the CML Adaptive module, CML O-phase and transition between phases. An overview of the CML routing protocol design is shown in Fig. 5.1 below. As it can be observed, such a design may require more computational complexity as compared to traditional approaches. However, with the emergence of highly resourceful devices it is deemed more important to decrement the communication complexity at the cost of increased computational complexity.

5.2 CML Protocol Overview

CML operates in three distinct phases of operation which are O-phase, P-phase and R-phase. Each phase of operation comprises of an augmented version of a flat routing protocol so that it interacts with the CML Adaptive Module. In the event that the routing protocol receives a routing control packet in the stable phase of operation, it contacts the "Monitor function of the Adaptive Module ($1a_{\rightarrow}$ or $1b_{\rightarrow}$ in Fig. 5.1) by passing the current routing phase information. The latter function checks if the NST is exceeded and calls the "Adapt" function in that case. Otherwise the normal routing processing defined in that operation phase is resumed ($2a_{\rightarrow}$ or $2b_{\rightarrow}$ in Fig. 5.1).

The "Adapt" function initiates the O-phase of operation by passing on information about the current routing phase and the nature of the method whereby a threshold breach was detected ($3_{\rightarrow}$ in Fig. 5.1). In the O-phase of operation, the routing processes as defined by the current operation phase continues while the O-phase uses routing specific CML mechanisms to confirm whether the size of the network actually necessitates a change in phase. A change in phase is only allowed after a pre-defined time interval referred to as the oscillation interval (*Osc_Interval*) which is reset each time a phase shift occurs. The O-phase is used to both confirm the actual size of the network and to prevent node oscillation as defined below. Therefore, any change from one stable phase to the other, called a phase shift, has to be made through the O-phase. If it is confirmed that the network threshold has been exceeded, the O-phase allows a phase shift ($5a_{\rightarrow}$ or $5b_{\rightarrow}$ in Fig. 5.1). Otherwise, the O-phase signals the Adaptive Module that an oscillation has taken place ($4_{\rightarrow}$ in Fig. 5.1) and stable routing operation is resumed. This process is illustrated in Fig. 5.1.

5.2.1 Challenges

There are numerous new challenges that emerge while designing CML. For instance, oscillation of nodes in a network is one such challenge. This occurs when nodes join and leave the CA repeatedly so that the total number of nodes fluctuates, thus exceeding and returning below the pre-established threshold for phase shifts. Such events would result in performance degradation for CML where each phase shift will be accompanied by unnecessary routing overhead for network routing protocol convergence. In order to minimise the effect of oscillation, we devise a solution based on the identified characteristics of such an event that are the number of nodes that oscillates and the frequency of oscillation. These will be tackled in the following subsections.

5.2.2 Operation

CML requires topological cognition to find out the number of nodes and subsequently adapt its routing behaviour if necessary. We devise a monitoring and adaptive module to tackle this. Since the stable phases operate using different protocols, it is important that there is interoperability among nodes in the event of a phase shift for a given convergent period. We use a generalised packet format [28] to ensure that packets are not dropped irrespective of the operating phase at a given node. In addition, it is assumed that "good practice" processes such as routing loop freedom using sequence numbering as described in [9] are part of the CML algorithms as inherited from AODV [37] and OLSR [29]. In case the network has different routing domains for the convergent period, any well formatted data packet received may be processed as customary employing the routing process in the node.

In the P-phase, routing is carried out in the same ways as in OLSR [29]. Any well formatted but non-OLSR packets are flooded back in the network so that routing of data packets is affected to a minimum. In addition, the adaptive module is alerted each time a TC packet is received. In the R-phase, each node routes packet as described in AODV [37]. Any well formatted but non-AODV packets are flooded back in the network to minimise disruptions of data packet routing. Also, the adaptive module monitors any received RREP packet. The O-phase is an augmented version of the stable phases. This phase is initiated by the adaptive module when a MANET threshold is exceeded. The O-phase augments the current stable phase operations by using mechanisms to confirm the validity of a phase shift-condition as opposed to conditions due to oscillation. The following measures have been designed for detecting and preventing oscillations:

- Use of an oscillation timer: the timer is reset to "Osc_Interval" each time a phase shift occurs. The O-phase returns to stable phase operation unconditionally if the oscillation timer has not expired so that no phase shift is allowed. This prevents excessive phase shift cost due to periodic oscillations in the network.
- Network state confirmation through sampling: the decision to shift from one stable phase to the other is based on 3 sampled network size information.
- Use of threshold margins: instead of using a fixed threshold value for the size of the MANET, a margin is used with a lower threshold (L-NST) and an upper threshold (U-NST) so that oscillation effects due to group mobility away and into the CAs, are reduced.

As the O-phase is responsible for shifting stable phases and thus changing the routing approach at a given node, it should also alert the network of such a situation so that all the nodes converge to a common routing approach. Consequently, the O-phase floods a CML Change phase (CP) packet in the network for that purpose. The CP packet is formatted in the same manner as HELLO packets but also contains added information about the new routing phase. If the phase of operation at the time of flooding is the P-phase, MPR based flooding reduction can be applied to minimise overhead.

The O-phase conducts sampling in different ways depending on the current stable phase. For a "P-phase" $\rightarrow$ "O-phase" transition, sampling is done by monitoring the network size for 2 TC Intervals i.e. $2 \times t_{TC}$ s. Thus, 2 more network size samples should be obtained. A phase shift is allowed if the network size is found to exceed the threshold in any one of these samples. If the transition is "R-phase" $\rightarrow$ "O-phase", the source node gathers two more network size samples by flooding Hop Count Request (HCREQ) packets. The HCREQ is similar to the AODV RREQ packets but has a Time To Live (TTL) equal to network hop threshold (NHT) which is the reactive approach interpretation of the NST value. Within a timeout period of, t_{HC} s, every node receiving such a packet has to check the packet TTL value. If $TTL = 0$, the node must send a Hop Count Reply (HCREP) packet to the source so that it can forward a gratuitous HCREP to the source, if one is received. Otherwise, the node decreases the packet TTL value by one and forwards the HCREQ in the network. It also generates and floods its own HCREQ (called gratuitous HCREQ) while also storing the source node that instigated this. It is proven in [37] that it is sufficient for a packet to receive a RREP from the most distant node in the network within $2 \times NET\_Traversal\_Time$. Therefore, such a wait time window should suffice:

1. For the node i to send its HCREQ packet so that it reaches the relatively most distant node j (1st $NET\_Traversal\_Time$).
2. For that distant node j to send its own HCREQ to all nodes in the network (2nd $NET\_Traversal\_Time$).
3. For the most distant node from node j to send an HCREP to node j (3rd $NET\_Traversal\_Time$).
4. For node j to send an HCREP to node i (4th $NET\_Traversal\_Time$).

Therefore, a source node should wait for a HCREP for $4 \times NET\_Traversal\_Time$ after sending each HCREQ. If in at least one occurrence, no HCREP is obtained for the HCREQ with $TTL = NHT$, it is implied that the network size is smaller than the threshold. In this case, the O-phase switches to P-phase. Finally, if the O-phase is initiated (after checking the validity of the oscillation timer) as a result of CP packet signalling, it is assumed that the sampling process has already been conducted by the CP source node and therefore as being redundant. Hence, the O-phase conducts a phase shift and forwards the CP packet to its neighbours.

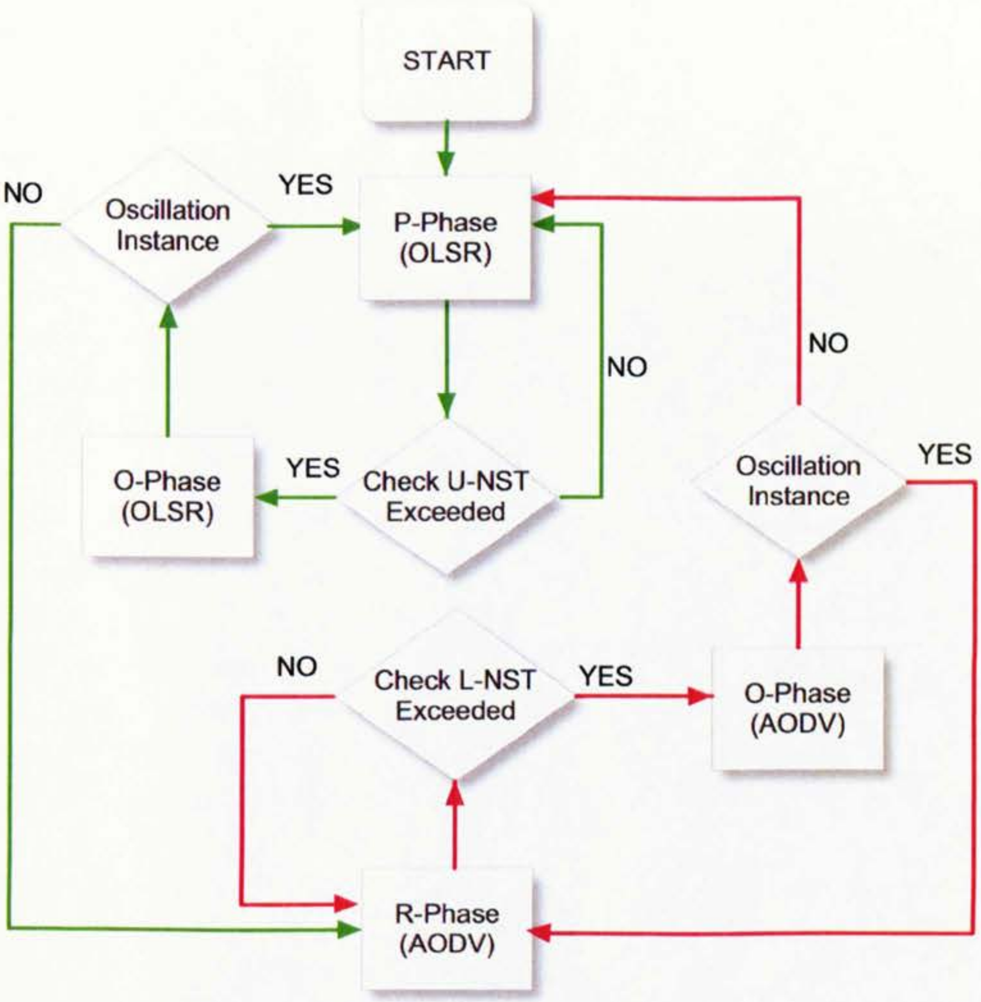


Figure 5.2: Overview of CML routing protocol operation - The figure shows the logical flow of control in CML during operation

The default mode of operation for a node is the P-phase and the normal mode of operation for CML nodes are under stable phases. Under a stable phase, the adaptive module monitors the network to check if the threshold has been exceeded or checks if a CP packet has been received. If that is the case, the O-phase is initiated. The O-phase checks the validity of the adaptive module alert by notably using a sampling process among others. If the alert is deemed invalid, the current stable phase of operation is resumed. Otherwise, the routing approach is changed and the oscillation timer is reset. Furthermore, a CP packet is flooded into the network. The operation is summarised in the flow chart of Fig. 5.2.

Since the generalised packet format [9] is used to format all packets in the network, well formatted packets are not dropped even in the convergent period when the network switches its routing approach. Any well-formatted unrecognised routing packets are simply forwarded to neighbours while data packets are routed according to the routing approach currently being used.

5.2.3 Threshold definition

The NST can be considered as the main routing threshold for uniformly distributed MANET in disaster environments as identified by the model in Chapter 4. This threshold indicates the point beyond which the network size makes AODV routing more effective than OLSR. Thus, this threshold point is denoted by NST. In addition, as implied by the O-phase, Upper (U-NST) and Lower NST (L-NST) values are required to reduce the effect of group oscillation and these are all defined in these 3 equations:

$$\begin{aligned} \sigma_{NST} &= NST \pm G \\ U - NST &= NST + G \\ L - NST &= NST - G \end{aligned} \tag{5.1}$$

where σ_{NST} represents the threshold tolerance in order to address group node oscillation and G defines the group size moving in/out of the CA so that $NST + G \leq N_{total}$. Here, N_{total} is the total number of nodes in the MANET. This is often characterised by emergency teams comprising of G rescuers working together. The value of G depends therefore, on the mission scenario.

In the P-phase, the threshold is set as the U-NST value so as to prevent phase shifts whenever G rescuers leave/join the network whereas in the R-phase, this value is set to L-NST for the same aforementioned reasons. The adaptive module determines that the NST has been exceeded in the following cases:

1. If in the P-phase, the monitored network size is greater than U-NST.

2. If in the R-phase, the monitored network size is less than L-NST.

In addition, the O-phase requires that a value for NHT should be defined as used in the sampling process. This value of NHT should be calculated by using the expression $NHT \approx \lfloor(\sqrt{NST}-1)\rfloor$ derived from $n \approx (h+1)^2$ where n is the number of nodes in a uniformly distributed in a square grid topology that we consider and h is the maximum number of loop free hops that can be traversed diagonally by a unique routing packet.

5.3 CML Adaptive Module

In our proposed CML protocol we present a novel adaptive module that is designed to monitor the size of the MANET, detect if the network size threshold (NST) as observed in Chapter 4 has been exceeded and in such an event, transfer the control of operation to the O-phase. There are two possible routing scenarios, which can result in such an event as discussed further in this section. Therefore, the two main functions in the designed adaptive module are the "Monitor Function" and the "Adapt Function".

The CML adaptive module runs concurrently to all operating phases to monitors the network state and initiates the O-phase if the network threshold is exceeded. The monitor function consists of checking a node's neighbourhood density (this is optionally used to confirm that we have an equally spaced node distribution for a known CA), $\rho_{neighbourhood}$ and total number of nodes, N_{total} in the network every time a control packet has been processed. It then compares these values to pre-set network size threshold (NST). The calculation of $\rho_{neighbourhood}$ and N_{total} are phase specific. In the P-phase, OLSR proactively maintains tables containing number of 2-hop nodes and routes to all possible nodes in the network. Therefore, $\rho_{neighbourhood}$ = number of rows in 2-hop neighbour table and N_{total} = Number of rows in the routing table respectively. However, in the R-phase, $\rho_{neighbourhood}$ can be calculated in several ways. The use of the NeighbourHood Discovery Protocol (NHDP) [34] can provide this value. However, in order to minimise routing overhead, a MAC Layer Neighbour Discovery protocol such as the one proposed in RFC 5942 [95], could be used to populate a table for 1-hop neighbours.

On the other hand the value for N_{total} can be estimated using the value of h_{max}. The monitor function in the source node must use the Hop count field in the RREP message to obtain the value of Hop Count (h) towards the destination node. The function that maps the hop count, h to n is derived from $h_{max} = (\frac{\sqrt{l^2+w^2}}{r}) - 1$ and is given by $N_{total} \approx (h_{max}+1)^2$ or $n \approx (h+1)^2$. The derived mapping space for such a function $f(h) \rightarrow n$ is described below:

$$f(h) \rightarrow \begin{cases} n_j & \text{if } h = h_i; \\ N_{total} & \text{if } h = h_{max}; \\ NST & \text{if } h = NHT. \end{cases}$$

where h_j is the hop count from node j to the current node i and n_j is the number of neighbourhood nodes found between nodes i and j. Hence, the approximated value of number of nodes in the network can be compared with the threshold to check whether it has been exceeded. This technique of network size estimation via hop count information is also applied during the "R-phase"$\rightarrow$ "O-phase" transitions for sampling purposes as described above.

If the adaptive module detects that the threshold has been exceeded or a CP packet has been received, it initiates the O-phase. The O-phase then has to continue routing using the current stable phase and additionally decide whether to change the routing approach through a phase shift. Most notably, the sampling process in the O-phase requires that two more samples of network size are considered before a confirmed decision is made.

5.3.1 Monitor function

When a control message is received at a CML interface, the node must call the monitor function of the Adaptive module after regular control message processing by the stable phase, as described in [29] and [37] depending on the current mode of operation. This mode of operation is indicated by passing a phase specific flag to the function, i.e. a "Pphase" flag for P-phase operation and "Rphase" flag for R-phase operation. The monitor function, when called, must check the number of nodes in the network.

This is accomplished differently depending on the current stable phase of operation as summarised in Section 5.2.2 above.

In the P-phase, this task consists of calculating the number of reachable hosts from the routing table that is defined in [29]. This calculation is done by counting the number of rows in the routing table. Each row includes fields of possible destination nodes, the next hop to reach the destination as specified in the possible destination field and its distance from the current source node. These field values are computed using periodical TC and HELLO message broadcasts by each node in the network. If the number of nodes is found to exceed the U-NST, the monitor function must call the Adapt function with the phase flag set as "Pphase" and the context flag set as "Nsize" (for Network Size). The last argument passed is the call flag and denotes the source of the call. In this case the call flag is set as "Monitor".

In the R-phase, the number of nodes in the network is estimated using the maximum value of the hop count from a source node to a destination. As defined in [37], a source finds a route to a destination 'on-demand' by flooding RREQ messages throughout the network using an expanding ring approach until destination receives the RREQ and issues a unicast RREP. The monitor function in the source node must use this RREP message to obtain the value of Hop Count (HC) towards the destination node. It then compares this with the NHT, which is calculated according to the relationship defined in the previous subsection. The monitor function must act as follows:

1. If HC in RREP is greater or equal to NHT, it decides that the L-NST is not exceeded.

2. If HC in RREP is less than the NHT, the data packets are transmitted through the established route. After data transmission, the CML Hop Count Request (HCREQ) packet described will be generated and flooded in the network to probe for the network HC (as opposed to destination HC). The HC is said to be less than the NHT, if after $4 * NET\_TRAVERSAL\_TIME$, no HCREP has been received. If the HC is less than the NHT, the monitor function decides that the R-phase L-NST has been exceeded and calls the Adapt function with the phase flag set as "Rphase", the context flag set as "Nsize" and the call flag set as "Monitor".

3. If a node receives HCREQ, it must first make sure that the sequence number of the packet is greater than that stored in the Change phase (CP) table for the

same originator address. Then, it checks if the TTL = 0. If the latter is true, it must store HCREQ originator IP and packet sequence number information in the CP table and send back an HCREP to the originator. Otherwise, it decreases the TTL value and floods back the HCREQ packet in the network. It then generates and floods its own HCREQ to probe for the HC with TTL value set to NHT. The value of the originator address of the original HCREQ packet (triggering the probing locally) is stored in the CP table along with the sequence number. The message type field is set equal to the value of message type "HCREQ" as which is equal to 9 as mentioned in Section 5.5. If for that particular HCREQ, an HCREP is received, the node must send an additional HCREP to that HCREQ originator address.

4. If a node receives a CML CP Packet described in Section 5.5, it must flood the packet in the network after decreasing its TTL count. Then, the node MUST call the adapt function from its Adaptive module with the current phase flag, the context flag set as "Nsize" and the call flag set as "CML_CM".

5.3.2 Adapt function

The Adapt function, when called by the monitor function makes sure one of the following is valid:

1. The phase flag is set to "Pphase", the context flag is set to "Nsize" and the call flag set as "Monitor".

2. The phase flag is set to "Rphase", the context flag is set to "Nsize" and the call flag set as "Monitor".

3. The phase flag is set as either "Pphase" or "Rphase", the context flag is set as "Nsize" and the call flag is set as "CML_CM".

If any one of the above cases is true, the Adapt function changes operation to O-phase by maintaining the current values of the phase flag, context flag and call flag which will be accessed by O-phase processes. In any other situation, the Adapt function terminates and the appropriate stable phase operation is resumed.

5.4 Oscillation phase (O-phase)

In the O-phase, the O-phase validity time, "Osc_Interval" of the oscillation timer is first checked. If the timer is still valid, the call for O-phase is ignored and the stable phase of routing denoted by the phase flag is resumed. If the timer has expired, the O-phase checks the flag values:

1. If the phase flag is set to "Pphase", the context flag is set to "Nsize" and the call flag set as "Monitor": The routing mechanism of P-phase will continue to operate. At the same time, the node will check the number of nodes in the network as described in Section 5.3 for $2 * TC\_Intervals$ [29]. If the number of nodes is then found to be greater than NST at least once, the O-phase switches to R-phase and resets the oscillation timer. It also generates and floods a CML CP Packet. The CP packet includes its address as originator address and its incremented sequence number. The CP field value of the CML packet is set as "Rphase". Otherwise, the node returns to operating in the P-phase.

2. If the phase flag is set to "Rphase", the context flag is set to "Nsize" and the call flag is set as "Monitor": The routing mechanism of R-phase will continue to operate. At the same time, the node will check the HC of the network using two more HCREQ packets, as described in Section 5.3, waiting for $4 * NET\_TRAVERSAL\_TIME$ [37] each time. If in at least one occurrence, no HCREP is obtained for the HCREQ with $TTL = NHT$, it is implied that the network size is smaller than the L-NST. In this case, the O-phasehase switches to P-phase and resets the oscillation timer. It also generates and floods a CML CP packet. The CP packet includes its address as originator address and its incremented sequence number. The value of the CP field in the packet is set to "Rphase". Otherwise, stable R-phase routing is resumed.

3. If the phase flag is set as either "Pphase" or "Rphase'", the context flag is set as "Nsize" and the call flag is set as "CML_CP": The node MUST check the value of the sequence number in the packet and compare it to any stored sequence number having the same originator address in the CP table. If no match is found in the CP table, a new entry is created with the aforementioned values obtained from the CP packet before further processing. Otherwise, if a match is found and the

packet sequence number is less than the sequence number stored in the table, the message is silently discarded and the node returns to the stable phase specified by the phase flag.

For non-discarded packets, the node must check the CP field value in the CP packets and compare it with the phase flag:

1. If they are equal, the CP packet is silently discarded and the node returns to the phase specified by the phase flag.
2. If they are not equal, the O-phase changes the operation phase to the value specified in the CP field of the CP message and resets the oscillation timer.

In both cases, the CP packets are flooded back in the network.

5.5 CML packet/message formats, table and timer

The basic layout of a CML packet is shown in Fig. 5.3 (IP and UDP headers are omitted). The packet format is such that Packet Length is the length of the CML packet in bytes. The Packet Sequence Number is the Packet Sequence Number and it must be incremented by one each time a new CML packet is transmitted. The Message Type indicates the type of message found in the "MESSAGE" section. This could be a CML message or messages from [29] or [37] . The rest of the packet fields are standard and are defined in [29].

5.5.1 Change phase (CP) Message

The Change phase message format is shown in the Fig. 5.4 below. A summary of the fields and possible values are:

- CP: The CP field represents the phase to which the originator node has shifted to and subsequently requests neighbor nodes to shift to where a value of 01 represents "Rphase" and 10 represents "Pphase".
- Reserved: This field is filled with 0 and ignored at reception.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Packet Length         |    Packet Sequence Number     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Message Type |     Vtime     |         Message Size          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Originator Address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time To Live |   Hop Count   |    Message Sequence Number    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
:                            MESSAGE                            :
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Message Type |     Vtime     |         Message Size          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Originator Address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time To Live |   Hop Count   |    Message Sequence Number    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
:                            MESSAGE                            :
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
:                                                               :
        (etc.)
```

Figure 5.3: Packet format of CML protocol - The figure shows the CML packet format with the number of bits allocated to each field listed at the top

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Reserved                             |CP |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 5.4: CP Message format of CML protocol - The figure shows the CML CP message format with the number of bits allocated to each field listed at the top

5.5.2 Hop Count Request (HCREQ) Message

The HCREQ message has an empty message body. It can be identified as a CML packet with:

- Message Type: The value of message type is set to 9.
- TTL: The TTL value is set to NHT.

5.5.3 Hop Count Reply (HCREP) Message

The message format for the HCRep message is as shown inFig. 5.5. The fields that are required are:

- Destination IP address: Originator IP address in corresponding HCREQ packet.
- Destination Sequence Number: Originator Sequence Number of corresponding HCREQ packet.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Destination IP address                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 5.5: HCREP Message format of CML protocol - The figure shows the CML HCREP message format with the number of bits allocated to each field listed at the top

5.5.4 CML Change phase table

The CML CP Table fields are listed below:

- Originator IP Address: The IP address of the node which generated the packet.
- Originator Sequence Number - The Sequence number of the message that was sent by the node which generated the packet. This is incremented monolithically for each message generated by a node.
- Message Type - The message type value of the message through which the table row was populated.

5.5.5 CML Timers

The CML Oscillation timer is used in the O-phase to prevent phase shifts within the time period of *Osc_Interval*. This timer prevents inefficient phase shifts due to frequent oscillations.

5.6 Constants

There are various constants that have to be specified for the operation of the CML protocols. These are in addition to the constants specified for the stable routing protocols that are listed in [29] and [37]. The Network threshold values for CML are described here:

- NST - The theoretical Network size threshold "Nt" of a network depends on the number of nodes N in the network, the critical area A of the network and the radio coverage area of each node. NST marks the point after which a reactive routing approach will be more effective and efficient compared to a reactive routing approach. Below the NST point, proactive routing approaches outperform reactive routing approaches. Appropriate values for NST have been proposed in Chapter 4 using derived models and event-driven simulations.
- U-NST: The Upper limit network size threshold "Nu" is given by $Nu = Nt + Nosc$ where "Nosc" is the number of nodes in the network which are expected to oscillate. When operating in the P-phase the actual value of NST is equal to "Nu".
- L-NST: The Lower limit network size threshold "Nl" is given by $Nl = Nt - Nosc$. When operating in the R-phase the actual value of NST is equal to "Nl".
- NHT: The network hop threshold value "Nht" is directly proportional to the square root value of the NST $Nht = Function(sqrt(Nt))$

5.6.1 Oscillation Interval (Osc_Interval)

The Osc_Interval is a time period for which no phase shift is allowed. While the U-NST and L-NST values cater for group oscillations, the Osc_Interval prevents unnecessary phase shift overheads due to regular oscillations. Thus, the Osc_Interval should be set according to the time period of node oscillations. The optimal value for Osc_Interval can be derived through experimentation and mathematical modelling for a given critical area, A and node coverage radius R.

5.6.2 Parameter Values

Parameter values used by the CML protocol are adopted from the recommendations of OLSR [29]and AODV [37] RFCs which were themselves derived after experimentation. These values are:

- NET_DIAMETER: 35
- NET_TRAVERSAL_TIME: 2 * NODE_TRAVERSAL_TIME * NET_DIAMETER
- NODE_TRAVERSAL_TIME: 40 milliseconds
- PATH_DISCOVERY_TIME: 2 * NET_TRAVERSAL_TIME
- HELLO_INTERVAL: 2 seconds
- TC_INTERVAL: 5 seconds

5.7 Energy Efficient (E2) CML mechanism

One of the main objectives of this thesis is providing an energy-efficient mechanism that will compliment the CML routing protocol. While the reduction of routing overhead improves the energy efficiency of protocols to a certain degree, further improvements can be achieved by extending network lifetime. The E2 mechanism that we proposed in [56] and present here aims at reducing energy consumption due to data packet transmission and processing at critical nodes that are frequently solicited for data forwarding. This is achieved by modifying the route selection process so that a more balanced route utilisation mechanism based on the sum of residual nodal energy along delivery paths is used, whenever possible. The number of data packets sent from the source cannot be reduced at the network layer and the routes available are constrained by the physical proximity of nodes. Thus, the E2 mechanism only focuses on "fairly" distributing the forwarding load of data packets whenever possible.

5.7.1 Route Selection Scheme

We assume that for the (source, destination) pair $S - D$ nodes in the network, the routing table of node S has a set of routes $R_{SD} = \{R_i : 0 \leq i \leq M - 1\}$ and as illustrated in Fig. 4.3, each route R_i consist of M_i nodes excluding S and D. From a routing protocol point-of-view, a MANET can be represented as a set of nodes forming several alternative routes prioritised using a routing metric. Thus, as shown in Fig. 4.3, a S-D communication pair can be connected via several routes from the set $\{Route_0, ..., Route_M\}$ where each of the routes, $Route_i$, is composed of at least two nodes from the fully connected. For instance, Fig. 4.3, we have M routes for (S, D) pair and the ith route is composed of M nodes excluding S and D.

E2 defines a two phase checking process to choose the best route Ri such that the variance between average residual energy of nodes in RSD and actual residual energy of nodes along route R_i is minimum. Importantly, routes that contain nodes having critical battery levels are avoided if possible. Therefore, route selection process consists of two phases as described below.

First phase check: Critical Nodes

Despite the fact that the summation of remaining energy for nodes in a route may be high, the route may still consist of nodes with very low energy levels (termed as critical nodes). There is a high probability of route breakage due to the presence of critical nodes. Hence, these routes should be avoided. For the purpose of E2 mechanism, we represent the energy values of nodes in a $4bit$ string so that we quantify $16(= 2^4)$ different energy levels where each level shows nearly 6% of battery charge. The Min Level implies that the node is off ($MinL = 0$) and Max Level shows a fully charged battery ($MaxL = 15$) with energy E_{init}.

Also we use the notation of $E_{min}(R_i)$ to designate the minimum residual energy level of a node from all nodes along route R_i. Furthermore, a critical node n is defined as a node with energy E_n such that $E_n \leq 2$. As a first step, all M routes will be checked so that routes R_i with condition $E_{min}(R_i) \leq 2$ are not considered for routing as long as other "non-critical" routes exist. We suppose that from an initial set of M candidate routes, $N(N \leq M)$ routes pass the first phase check.

Second phase check: Route Priority

First step: For a given $S-D$ pair, the number of candidate routes for the second phase is N. Each route has two parameters: (i) length and (ii) sum of energy level of each node. Length and energy level parameters are normalised in range [0 ... 1] to make them comparable. The route R_i that has a better *Length* and *Energy* parameter will be best route for communication. These input parameters are defined next:

Length of route R_i: from Chapter 4, we deduce that longer routes produces more delay and additionally may lead to a higher probability of route breakage. Here, $L(R_i)$ indicates the route length factor that defines the priority of route R_i:

$$L(i) = \frac{|R_i|}{Max\_Length} = \frac{H}{Max\_Length} \tag{5.2}$$

where $|R_i|$ is the actual length of route R_i (i.e number of hops, H, along R_i) and Max_Length is the maximum length that a route can have i.e $NS-1$ where NS is the network size. From equation 5.2, it can be deduced that $0 < L(R_i) \leq 1 \; for \; i \in \{1, ..., N\}$.

Residual Energy Level of Route: the remaining energy level of nodes in route R_i is of central importance to the E2 mechanism. Thus routes with higher summation value of nodal residual energy levels are favoured. The energy factor, $E(R_i)$, indicating the preferred routes due to favourable energy levels, is defined below:

$$E(R_i) = \frac{\sum_{j=1}^{n_i} E_{ji}}{n_i * E_{init}} = \frac{E_{sum}(R_i)}{n_i * E_{init}} \tag{5.3}$$

where n_i is the number of nodes along route R_i, E_{ji} denotes the remaining energy level of the jth node along the route, $E_{sum}(R_i)$ is the summation of battery levels of all nodes in route R_i, and E_{init} is the nodes battery level at the beginning of simulation. It can be inferred from equation 5.3 that $0 < E(Ri) < 1 \; for \; any \; i \in 1, ..., n_i$.

Therefore, in the first step of the second phase, for all N routes of a given S-D pair, we calculate the lengths and the energy parameters of all N routes. Then Ri, which has the best L(Ri) and E(Ri) simultaneously, will be chosen for communication and the second step of the second phase will be skipped but if no such a route exists, then we proceed to the second step.

Second step: The factor termed as the Route Priority Factor (RPF) will be computed for all N routes to destination D and the route with maximum RPF will be selected. RPF is given by:

$$RPF(R_i) = K_E * E(R_i) + K_L * \frac{1}{L(R_i)} \tag{5.4}$$

where K_E and K_L are coefficients for factors of energy level and route length respectively. As formerly discussed, small length routes are preferable so RPF is inversely proportional to $L(R_i)$. Also since we require routes with high residual energy levels, the RPF of route R_i is defined to be proportional to $E(R_i)$.The desired coefficient values obtained through simulation are set to 2 and 1 respectively, thus giving a higher priority to balanced energy consumption across routes over route length. The processes involved in the E2 route selection mechanism is summarised in the algorithm below.

```
E2 algorithm (index of Ri)
For(i=1 to M) //M = number of routes for S-D
   {
     //First phase Check
     N=0; //N = routes passing first phase check
     Esum(Ri)=0;
     For (j=1 to ni)
          {
            E_sum(Ri)= Esum(Ri) + Eji;
            If (Eji < Emin(Ri) )
             Emin(Ri)= Eji;
          }

   //Second phase Check
     If (Emin(Ri) > 2 )
          {
```

```
        N++;
        L(Ri) = |Ri| / Max_Length;
        E(Ri) = Esum(Ri) / (n*Einit);
        //n is the number of nodes of Ri th route

        //first Step of second phase
        If(L(Ri)>maxL)
           {
    MaxL = L(Ri);
    IndexL = i;
   }
        If(E(Ri) > maxE)
   {
    MaxE = E(Ri);
    IndexE = i;
   }

       //Second Step of second phase
       RPF(Ri) = KE * E(Ri) + KL*1/L(Ri);
       If ( MaxRPF < RPF(Ri) )
           {
            MaxRPF = RPF(Ri);
            BestRouteIndex=i;
           }
      }
  }

If(IndexL==IndexE)
  BestRouteIndex=IndexL;
```

```
Return(i) as the index of best route;
```

5.7.2 Energy Field

Each node in a MANET using E2 mechanism requires to extend its routing table to include an "Energy" field which preserves the value of the remaining energy of nodes in network. By extracting required data from this field we can determine the energy level of whole path and also we can know about the topology of the network. For the reactive mechanism of E2CML, the RREQ and RREP control packets have a section called energy packet field. When an intermediate node wants to forward a RREQ coming from a source node, it writes its residual battery power value at the end of energy packet field of RREQ. Finally the destination node will receive this RREQ and creates a related RREP. The destination node also will fill in the energy packet field of RREP by extracting the values of energy packet field of RREQ and send it back to the source node. Each intermediate node which receives this RREP will extract all values of energy packet field of RREP and write them in its "Energy" table field, or updates the old values. With time, each node in the network will receive more control packets and will be informed about more nodes (and consequently their battery power) subsequently the Energy field of the table of a node will have information about all or most of the network nodes.

5.7.3 Integrating E2 with CML (E2CML)

The E2 mechanism is designed so that it can be integrated with any route selection mechanism that can collect information of node residual energy levels. In this subsection we describe two such instances where this mechanism is integrated with AODV and OLSR respectively as part of the CML protocol. It consists of gathering node energy level information and transferring this to the source node.

AODV Integration: The integration with AODV consists of extending the route discovery mechanism so that multiple RREQ packets are processed at the destination, resulting in multiple RREP packets being sent back to the source. The RREP is extended to include a minimum energy field, and a cumulative energy field where information for the minimum nodal residual energy recorded along the route and the sum of the energy levels at each node along the path are stored respectively. The source then uses the information gathered through the RREPs to generate an RPF value for each route so that the appropriate route can be selected.

OLSR Integration: The E2 mechanism can be merged with the OLSR protocol by first extending the Hello and TC packets so that they can send the required energy information of each node to the source. These energy values are then use to compute the minimum as well as the sum of energy levels of the routes. The RPF of each route is then calculated and stored in the node repositories so that the node can use the pre-established route information to send data in an energy efficient manner.

An overview of the E2 mechanism and its integration with proactive and reactive approaches of CML is shown in Fig. 5.6.

5.8 Protocol Evaluation

Our protocol evaluation in this section is two-fold. In the first instance, we present different scenarios where the CML protocol was evaluated and compared to different routing protocols found in literature under different network conditions. Then, we evaluate the E2 mechanism that is proposed in this chapter after integration as the E2CML protocol and compare its benefits in terms of improving network lifetime and avoiding network segmentation.

5.8.1 Evaluation of CML

5.8.1.1 Evaluations: Scenariol

In this scenario, we propose to investigate the scalable performance of well-known routing approaches presented in Chapter 3 and subsequently determine the relative suitability of each approach as compared to CML. We present simulation results from our derived models for the evaluated protocols, corresponding to the routing overhead and normalised data delivery delay between S-D pairs as more devices join an ad hoc collaborative network in real-time as will often be the case in the PPDR communication scenarios. The various parameters used for simulations and discussions are listed and described in Table 3.1 of Chapter 3. It is important to mention that a random waypoint

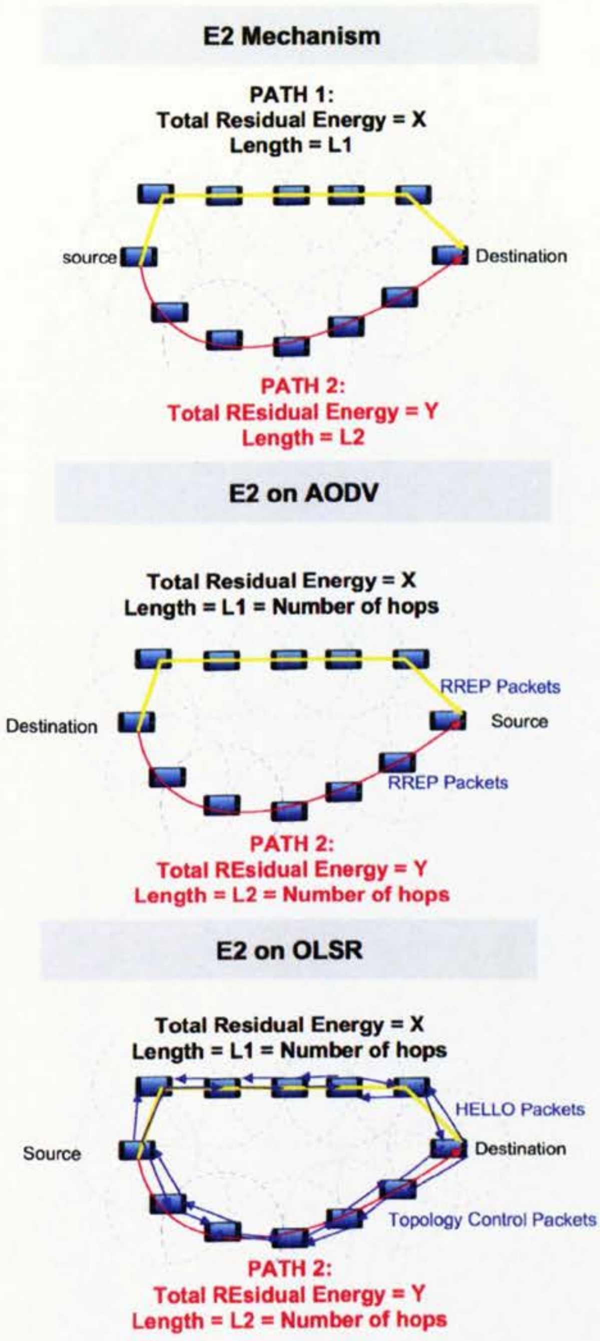


Figure 5.6: Overview of E2CML mechanism - The figure shows an overview of the E2 mechanism and its integration with the proactive and reactive parts of the CML protocol

mobility model was considered with average low mobility of 0.5m/s and high mobility of 1.5m/s for simulating on-foot rescuers moving in the disaster scene. Also, 10 discretely sourced UDP data connections over 802.11 MAC are used for these simulations while the default parameter values recommended from respective MANET WG RFCs and literature are implemented.

It was observed in Table 3.2 of Chapter 3, that the investigated complexity is not only related to the number of nodes in the network but to other parameters such as $ROUTE\_TIMEOUT$, T_{con} and Con. In general, all the approaches scale to $O(N^2)$ except in the case of reactive protocol that are more suited for larger networks. In small network sizes, the complexity of $O(N^2)$ is imposed on reactive routing approaches due to the significance of $ROUTE\_TIMEOUT$, T_{con} and Con multiplicatively weigh in with overhead in the magnitude of N. As the value of N increases however, the cost due to these parameters are less significant and the complexity is reduced to $O(N)$. It can therefore be deduced from the descriptions in Table 3.2 that proactive and reactive protocols have similar cost overhead for smaller networks, but at a certain point where the value of N is large enough as compared to $ROUTE\_TIMEOUT$, T_{con} and Con, reactive protocols become more efficient than proactive approaches. CML identifies this network size point and use it as a threshold value for proactive networking, beyond which the network is converged to a reactive routing approach. Hybrid zonal routing use the same principle to optimise the overall routing by limiting proactive routing to zonal limits, using reactive route establishment beyond zones. However, due to the parallel operation of both flat routing mechanisms, the routing overhead reduction is non-optimal as compared to CML.

Furthermore, we propose a simulation based delay and routing cost evaluation, in Fig. 5.7 and Fig. 5.8, to more analytically compare the presented approaches as most have similar routing complexities but propose different optimisations to reduce cost. In Fig. 5.7, we illustrate a normalised measure of overhead for each approach for comparative ends. It can be seen that, for small network sizes of up to 10-12nodes, all the approaches have similar scaling complexity of $O(N^2)$ and produce comparable routing costs. However, for larger networks each approach varies. Mainly, we have two trends emerging, one for proactive based protocols with optimisations (hybrid) and the second for reactive based trends. As it can be observed, OLSR has the highest cost because of its pure proactive approach scaling at $O(N^2)$. LAR has second worst cost because of the extra signalling required for geographical addressing, although some optimisation is achieved by targeted geographical flooding. ZRP uses predefined zones to limit proactive overhead, instead of geolocation, which further reduces cost compared to LAR. Then, AntHocNet uses mostly reactive routing to establish routes but has some elements of proactive route maintenance that add minimal costs as compared to ZRP. SHARP saves some costs as compared to ZRP given that it defines its proactive zones only around popular destinations. Interestingly, the optimisations provided by hierarchical routing paradigms based on OLSR has better performances that zonal hybrid approach. The segmentation of the proactive flooding domain significantly reduces the routing overhead and is only bettered by pure reactive DYMO routing in larger networks. Nevertheless, HOLSR type approaches requires node election in case of high mobility networks and can render it to be much more costly. As the network size grows the specified extra cost of proactive routing is further emphasised.

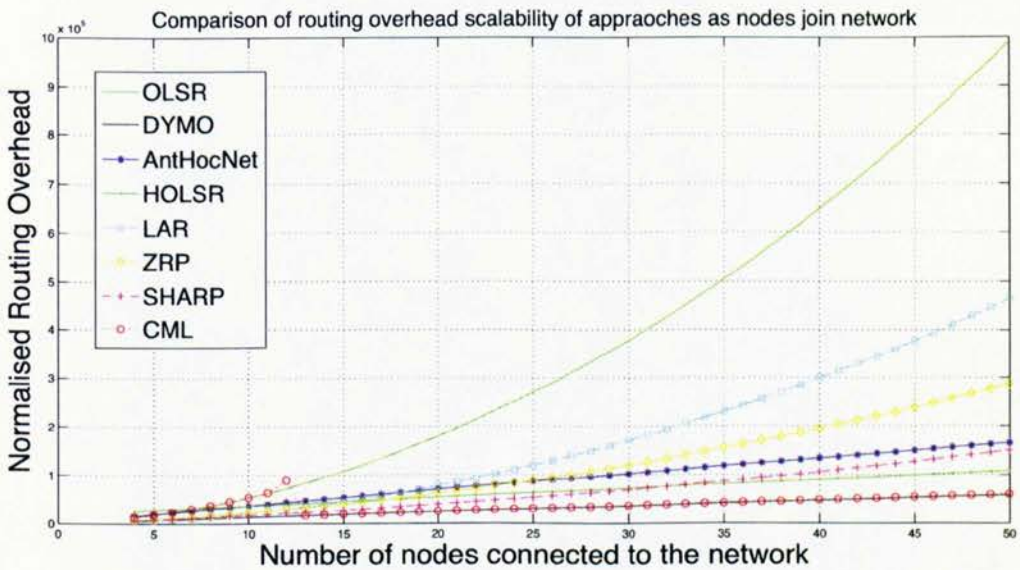


Figure 5.7: Low mobility overhead evaluation - Normalised routing overhead comparison as 30 nodes join the network with low mobility of 0.5m/s

In Fig. 5.9, it can be observed that the same trend persists for higher mobility in the network and for the range of nodes of up to 100 nodes. In general more routing overhead are generated by all approaches in order to keep updated routes providing the

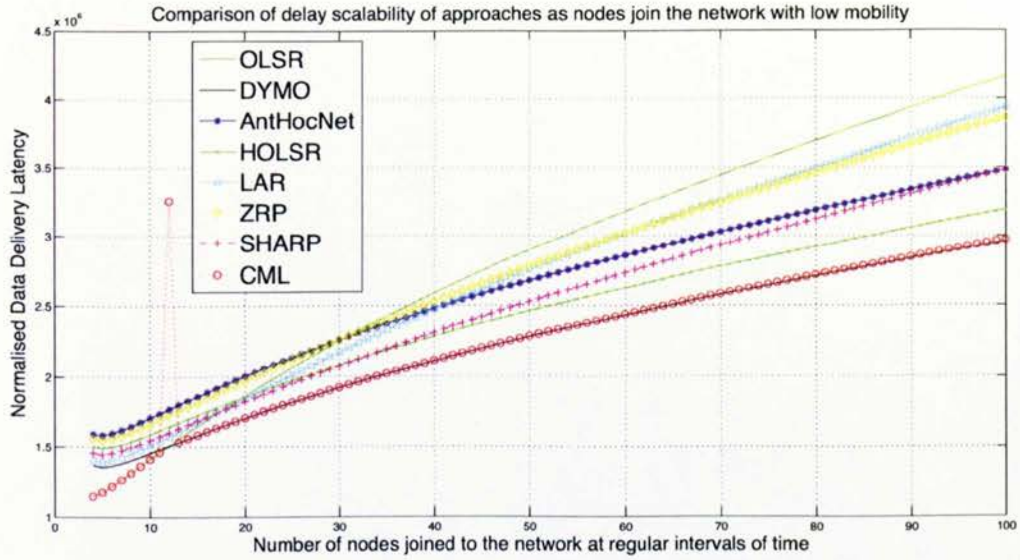


Figure 5.8: Low mobility end-to-end delay evaluation - Normalised routing delay comparison as 100 nodes join the network with low mobility of 0.5m/s

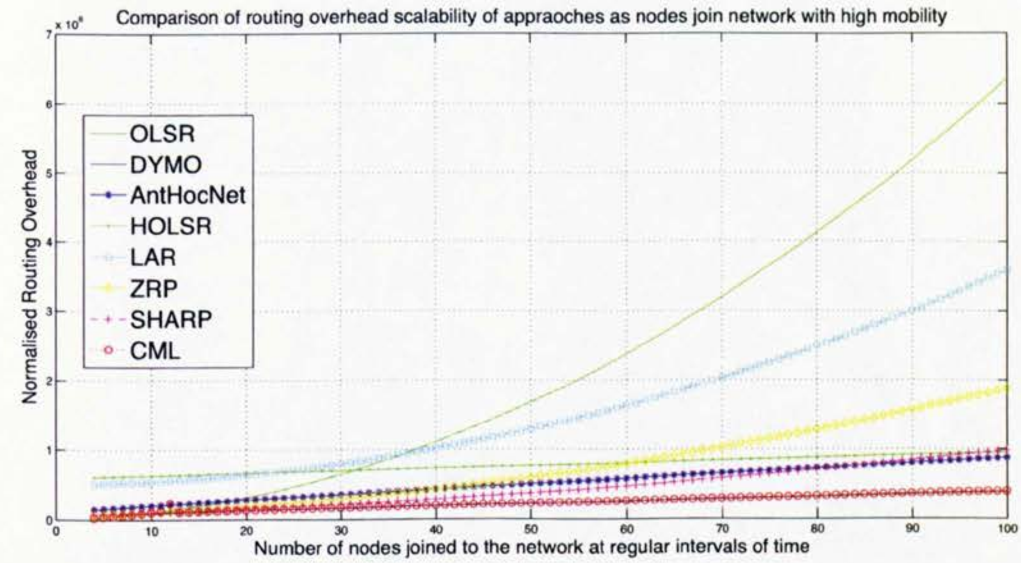


Figure 5.9: High mobility overhead evaluation - Normalised routing overhead comparison as 100 nodes join the network with high mobility of 1.5m/s

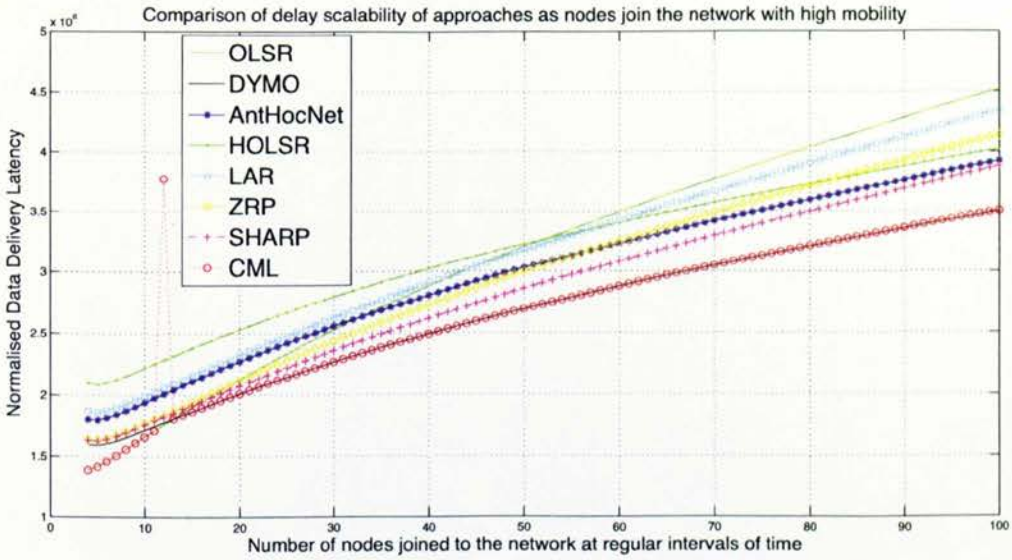


Figure 5.10: High mobility end-to-end delay evaluation - Normalised routing delay comparison as 100 nodes join the network with high mobility of 1.5m/s

same level of QoS. Particularly, LAR and HOLSR produce much more overhead as a result of higher mobility network as a result of higher geographical and cluster based information maintenance respectively. Thus, CML tries to have an optimal reduction of routing overhead based on OLSR routing for smaller networks of less than 12 nodes and DYMO routing for larger networks. However, as observed in Fig. 5.7 and Fig. 5.9, there is a slight overhead that occurs during the switching period from P-phase to R-phase or vice-versa due to network wide CML packet flooding to converge network routing.

Moreover, in Fig. 5.8, for larger networks (more than 12 nodes), it can be observed that OLSR, LAR and AntHocNet can only guarantee higher delay than reactive, hierarchical, zonal hybrid and hybrid adaptive approaches. However, proactive HOLSR has the delay performance comparable to DYMO with the drawback of having higher overhead especially for high mobility network as shown in Fig. 5.7 and Fig. 5.9. As the network size is increased, ZRP and SHARP reduces the delay caused by the proactive approaches by confining those to zones and using less delay prone reactive routing for inter-zonal communication. However, in smaller networks of less than 12 nodes, it is clear that since the same level of overhead is required by all approaches, the OLSR proactive route establishment causes decrease overall end-to-end delay as compared to reactive and hybrid approaches that induces on-demand route establishment latency. The same trend occurs in higher mobility network, as results demonstrate in Fig. 5.10. Nonetheless, it can be observed that the overall delay increases as compared to results for low mobility in Fig. 5.8. CML capitalises on this routing behaviour by using OLSR routing for networks smaller than 12 nodes and DYMO routing for larger networks. However, when CML detects 12nodes in the network and switches from P-phase to R-phase routing, a high data delivery delay is experienced at the time of the switching as shown in Fig. 5.8 and Fig. 5.10.

Thus, proactive routing approaches are vulnerable to higher delays in larger networks due to the high volume of packets it requires thus increasing medium access backoff wait times and queueing delays in addition to the multi-hop transmission delays. While for reactive approaches, the route discovery delay is reduced significantly because user diversity results in updated route information being available closer to the source. Therefore, a RREQ packet does not have to actually reach the destination to find the required route. Interestingly, for smaller networks, the proactivity of route establishments is more efficient than the DYMO on-demand based RREQ-RREP process. Thus, CML justifiably uses the OLSR approach for smaller networks while shifting to AODV or DYMO based routing for larger networks. However, as in the case of routing overhead, there is an increased delay experienced at the time the switch between phases occurs. This is due to the added delay at that particular point of convergence of network routing approaches.

5.8.1.2 Evaluations: Scenario2

In this scenario, we use a discrete event-based packet level simulator to validate our model based evaluations presented above and in Chapter 4. In addition, the performance of CML relative to AODV, OLSR and DYMO routing protocols is also compared. Here, DYMO is included for comparative discussion as a state of the art (still a "work in progress") MANET protocol. We use the HUMO [64] mobility model to simulate the urban disaster scenario from Chapter 4 as shown illustrated in Fig. 4.2. The number of nodes in the network in the range of $4 \leq n \leq 49$ with the mobile nodes being on an average equally spaced but moving using the Random Waypoint Mobility (RWP) model with an average speed of 2m/s. The simulation time was set to 1000s and the number of connections to 10 with each connection being a CBR of 128 kbps UDP based data. In addition, the NST value was set at 16 nodes for CML set up purposes. Although the area was set to 1500 m by 1500 m, the CA is variable and is equal to the effective coverage of the deployed nodes where as the obstacle was considered to be symmetrical with $l_{obs} = 0.4 * l$.

The simulation results are shown in Fig. 5.11 and Fig. 5.12. It can be observed that the results validate the result trends and discussions presented in Fig. 4.5- 4.7. Although, there are some randomness associated the respected general trends set by our model due to the RWP mobility model adopted and channel propagation properties that were out of the scope of our particular research work in this thesis. Briefly, CML shares approximately the same routing cost properties with OLSR for $n < NST$ and then with AODV for $n \geq NST$. This is advantageous because CML adopts the routing mechanisms of the most energy efficient routing protocol for a particular network size. The benefits of CML are further emphasised in Fig. 5.12 where the CML routing protocol adapts its behaviour at NST value in variable size MANETs so that it provides the lower delay bound for delay QoS of the investigated approaches for these network situations. However, CML induces slightly higher packet processing delay that the operating flat routing approach due to its adaptive module processes. Also, there is a hike in performance around the NST region as a result of the O-phase operation and phase shift. It is worth mentioning that DYMO uses explicit path error signalling, Route Error (RERR) packets, to repair broken routes. Hence, it has a slightly better delay performance but at a much higher routing cost compared to both AODV (its predecessor) and CML.

5.8.1.3 Evaluations: Scenario3

This scenario evaluation aims to evaluate the CML protocol in more varied network contexts in order to compare its performance against OLSR, AODV and DYMO. The performance results of the DSR protocol described in [36] is also included purely for the sake of comparison. The simulation scenario is described next. The simulation area is 1000m*1000m, the average network node speed 0.5 m/s and the value of average node

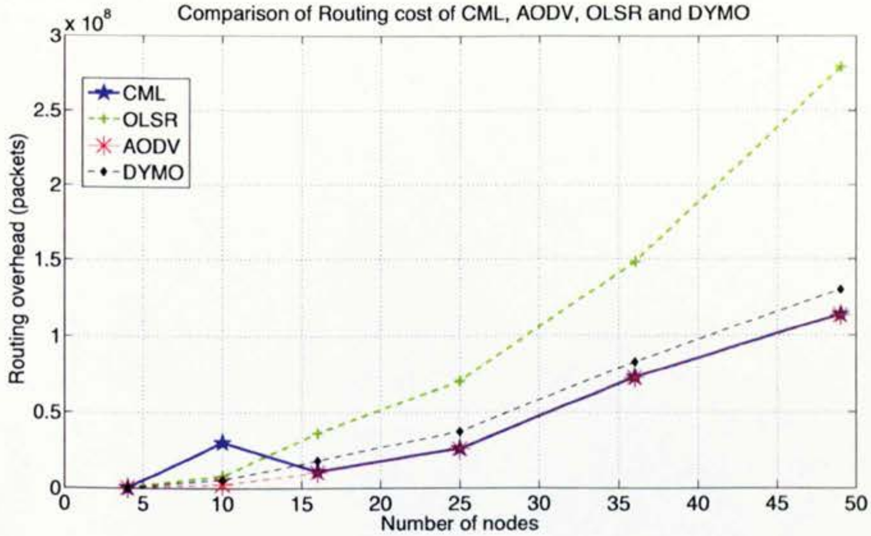


Figure 5.11: Event based routing overhead simulation results - Comparison of routing cost for CML, AODV, OLSR and DYMO under urban scenarios

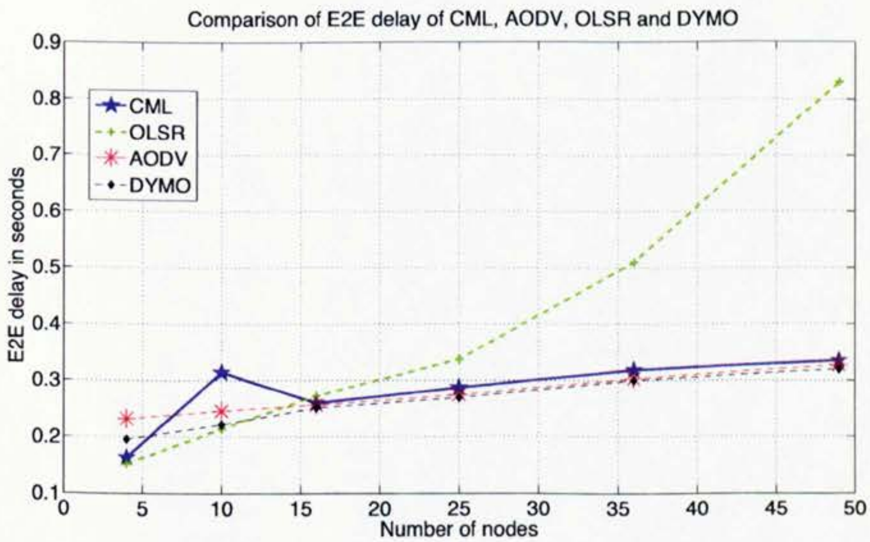
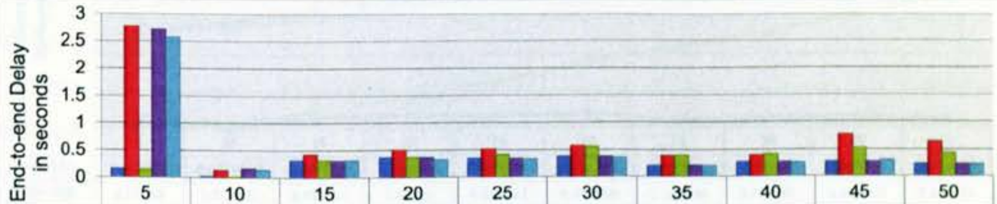


Figure 5.12: Event based E2E simulation results - Comparison of E2E delay for CML, AODV, OLSR and DYMO under urban scenarios

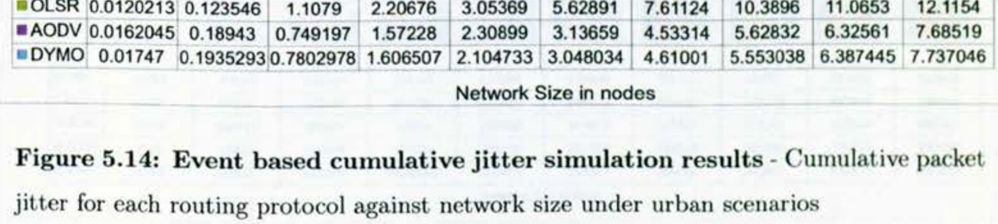
pause time of 10 seconds using the emergency HUMO Mobility Model as presented in [64]. We use a CBR traffic of 64 kbps to simulate the use of voice data transmission over the network with 10 CBR connections. The number of nodes for which the simulation scenario was run are 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 nodes. The Fig. 5.13-5.16 show the simulation results from the above scenarios.



	5	10	15	20	25	30	35	40	45	50
CML	0.155376	0.027087	0.308904	0.357967	0.336344	0.372783	0.197011	0.26843	0.269315	0.228047
DSR	2.77068	0.139621	0.425463	0.505816	0.523277	0.577201	0.387228	0.399775	0.769935	0.647567
OLSR	0.152184	0.021338	0.312801	0.358851	0.410214	0.56449	0.392517	0.418757	0.530194	0.440852
AODV	2.70938	0.166203	0.305771	0.357098	0.334221	0.372783	0.207011	0.267446	0.269315	0.228047
DYMO	2.5673	0.1452	0.313031	0.318904	0.324716	0.35569	0.200765	0.250735	0.300734	0.228392

Network Size in nodes

Figure 5.13: Event based E2E simulation results - End-to-end delay for each routing protocol against network size in urban scenario

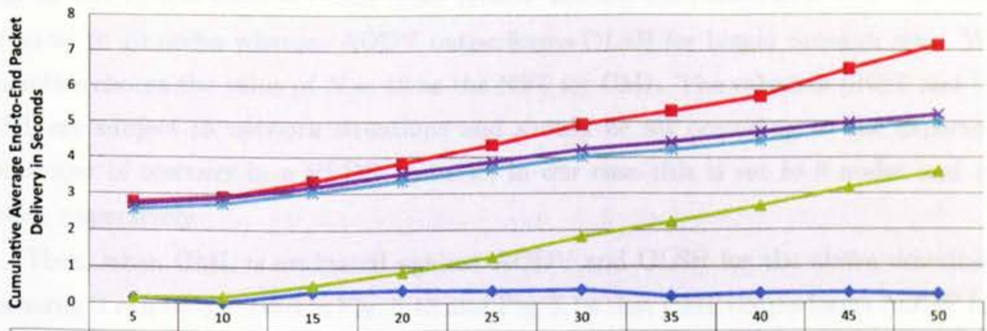


	5	10	15	20	25	30	35	40	45	50
CML	0.0120213	0.142829	0.694719	1.51544	2.25423	3.08183	4.47838	5.58247	6.27976	7.63934
DSR	0.0190892	1.65616	2.32066	3.23729	4.53008	5.24003	6.51881	8.77179	9.57226	10.5361
OLSR	0.0120213	0.123546	1.1079	2.20676	3.05369	5.62891	7.61124	10.3896	11.0653	12.1154
AODV	0.0162045	0.18943	0.749197	1.57228	2.30899	3.13659	4.53314	5.62832	6.32561	7.68519
DYMO	0.01747	0.1935293	0.7802978	1.606507	2.104733	3.048034	4.61001	5.553038	6.387445	7.737046

Network Size in nodes

Figure 5.14: Event based cumulative jitter simulation results - Cumulative packet jitter for each routing protocol against network size under urban scenarios

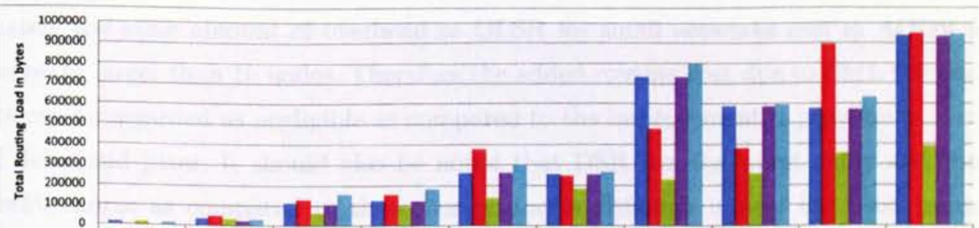
Firstly, it can be seen from Fig. 5.13 that the end-to-end delay performance of OLSR is better than AODV for network sizes of less than or equal to 10 nodes and that AODV performs better for networks greater than 10 nodes for this scenario. Additionally, in



	5	10	15	20	25	30	35	40	45	50
CML	0.155376	0.0270867	0.308904	0.357967	0.336344	0.372783	0.197011	0.26843	0.269315	0.228047
DSR	2.77068	2.910301	3.335764	3.84158	4.364857	4.942058	5.329286	5.729061	6.498996	7.146563
OLSR	0.152184	0.173522	0.486323	0.845174	1.255388	1.819878	2.212395	2.631152	3.161346	3.602198
AODV	2.70938	2.875583	3.181354	3.538452	3.872673	4.245456	4.452467	4.719913	4.989228	5.217275
DYMO	2.5673	2.7125	3.025531	3.344435	3.6691507	4.0248407	4.2256057	4.4763407	4.7770747	5.0054662

Network Size in nodes

Figure 5.15: Event based cumulative delay simulation results - Average cumulative packet end-to-end delay for each routing protocol against network size under urban scenarios



	5	10	15	20	25	30	35	40	45	50
CML	16963	36198	112980	124385	262034	254806	732424	585925	574462	938816
DSR	2503	47284	128516	151718	376889	246228	475150	379475	892444	948931
OLSR	16963	35633.5	64284	92512	138038	183972	227918	258762	352557	390646
AODV	1915	23383	106005	121686	261176	251693	729036	583632	570117	934245
DYMO	16095	32052	155095	183414.5	300275	264532	796846	592865	632625	945694

Network Size in Nodes

Figure 5.16: Event based routing overhead simulation results - Total routing load for each routing protocol against network size under urban scenarios

Fig. 5.14 the same situation can be observed where the end-to-end data delivery jitter due to OLSR operation is better than AODV routing for networks of size less than or equal to 10 nodes whereas AODV outperforms OLSR for bigger network sizes. We therefore choose the value of $N = 10$ as the NST for CML. The values of LNST and U-NST are subject to network situations and should be set according to the expected behaviour of rescuers in a PPDR scenario, in our case this is set to 8 nodes and 12 nodes respectively.

Then, when CML is evaluated against AODV and OLSR for the above described scenario, it can be observed in Fig. 5.13 and Fig. 5.14 that CML outperforms AODV for small sized networks of up to 10 nodes and outperforms OLSR for bigger networks of up to 50 nodes in terms of both data end-to-end delivery delay and jitter. Also it can be observed that the delay performance for nodes of less than or equal to 10 nodes is slightly higher than OLSR. Then, for bigger networks, CML performs slightly worse than AODV because of transmission and processing delay of CML CP packets. However, Fig. 5.15 illustrates that CML will provide a better performance than both AODV and OLSR for varying size networks and that it is a better alternative than both these protocols for such growing or shrinking networks based on the cumulative delay of such variable size networks.

The Figure 5.16 shows the cost of using the protocols in terms of the routing control packets that they utilise to function. It is clearly noticeable that CML uses approximately the same amount of overhead as OLSR for small networks and as AODV for networks larger than 10 nodes. Therefore the added routing cost due to CML CP packets can be regarded as negligible as compared to the improvement it provides in terms of delay and jitter. It should also be noted that DSR has the worst delay and jitter performances as compared to the other protocols although it uses the least routing overhead. There is a sudden increase in routing overhead for reactive routing protocols in Fig. 5.16 for our simulation with 35 nodes in the network which is mainly due to a random positioning of S-D node pairs. In that particular case, route discoveries were frequently required in order to compensate for frequent route timeouts and route breakage.

Therefore, using delay and jitter performance metrics, we can deduce that the proactive OLSR routing approach is better for small networks whereas for larger networks the reactive AODV protocol will provide a better routing alternative in eMANET scenarios such as the one described above. CML outperforms the protocols because it adaptively uses proactive or reactive approaches which best suits the size of the network. Additionally, the performance of DYMO is similar to that of AODV based on the metrics and over the range of network sizes considered. From the above figures, it can be noticed that DYMO only uses slightly higher routing overhead than AODV while also having approximately the same delay and jitter performance as AODV for this low mobility network. However, DYMO does propose a faster approach towards route failure detection and reparation than AODV. This can in turn help in the reduction of packet loss and data retransmission overhead in higher mobility networks.

5.8.2 Evaluation of E2 mechanism

The main aim of this subsection is to evaluate the performance of the E2 mechanism. For this scenario, we assume and set simulation parameters such that the energy required for packet transmission, et and for packet reception, er, within the simulator were set at $0.28J$. The initial energy in each node was set at $40000J$ so that the node battery could last for the simulation period which was set at $2000s$. The traffic was generated using 5 UDP based CBR connections set at $64kbps$. The simulation area was set to $1000m * 1000m$ with nodes moving at 0.5m/s on a RWP model with a pause time of 10seconds. We use the HUMO [64] mobility model to simulate the urban disaster scenario with number of nodes in the network in the range of $4 \leq n \leq 49$. The simulation time was set to $1000s$ and the number of connections to 10 with each connection being a CBR of 128 kbps UDP based data. Thus, we implemented and simulated the E2CML protocol to investigate its performance compared to the performance of both AODV and OLSR by using the performance metrics defined below. The simulation was run for a fixed network of size 20nodes with the same configurations as above.

5.8.2.1 Evaluation Metrics

Energy Consumption Balance (ECB): We define the balanced energy consumption metric to determine the effectiveness of the energy balancing algorithm used by E2 mechanism. If the ECB for each node n is En, the relationship between the ECB of node n and the total consumed energy in all the networks nodes is:

$$E_n(ECB) = \frac{E_{n\_consumed}}{E_{total\_consumed}} \tag{5.5}$$

The obtained value will be the metric for balanced energy consumption of the protocol. A smaller deviation value implies better energy balance in the network.

Node failure degree (NFD) : The node failure degree is, for a time window T, the percentage of nodes in the topology that have failed because of low battery power. This value can be computed by using the following formula:

$$NodesFailureDegree(NFD) = \frac{Num\_Nodes_{failed}}{Num\_Nodes_{total}} \tag{5.6}$$

5.8.2.2 Simulation results and discussion

Fig. 5.17 shows the average value for the ECB of each node over the duration of the simulation. The ECB indicates the variation in Energy consumption of nodes as a fraction of total energy consumed in the network. Therefore, the fraction denotes the energy consumption load per node compared to total energy load and demonstrates the ratio of energy that each node has consumed during its operation. It can be seen from this fig. 5.17 that in the case of E2CML, the energy consumption is spread more evenly across the nodes of the network as compared to both AODV and OLSR. The latter protocols select nodes based on the best hop-count path and therefore have a tendency to use the same best nodes whenever possible. Thus there a high variances in ECB for the case where nodes used the "best hop-count" routing approach as compared to the results for E2CML where there is a much smaller variance among ECB values of nodes.

Additionally, Fig. 5.18 uses the NFD to show the merits of the E2 mechanism when applied to AODV and OLSR operating within the CML protocol. The value of NFD indicates the number of nodes that have failed as a proportion of the total number of nodes. As mentioned before, high number of node failures can lead to partitioning of the network and reducing the overall lifetime of the network. In the Fig. 5.18 above, it can be observed that the NFD of the E2CML protocol is less than both AODV and OLSR over the simulation period. This is because E2CML balances energy consumption load more evenly as supported by results in Fig. 5.18. In addition, the OLSR protocol

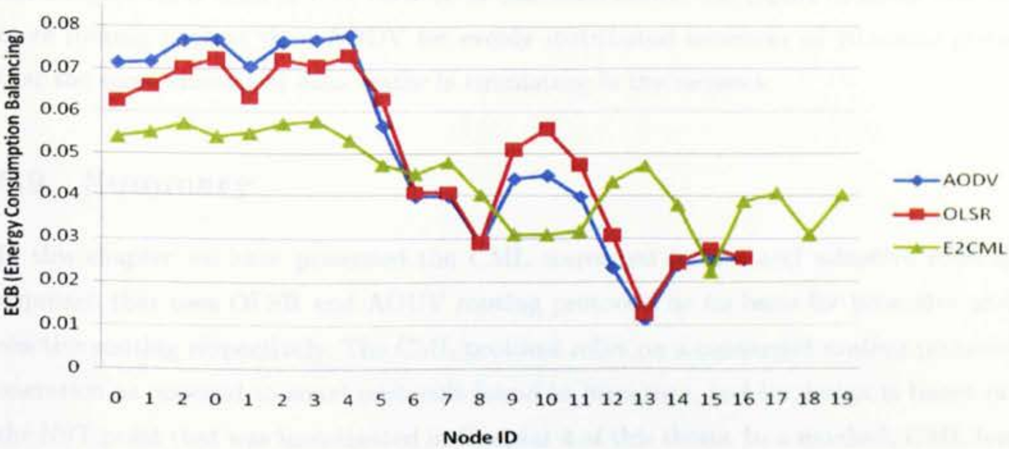


Figure 5.17: Event based ECB simulation results - The figure shows the simulation results for the average value of ECB (Energy Consumption Balancing) metric for each node connected in a MANET with 20 nodes

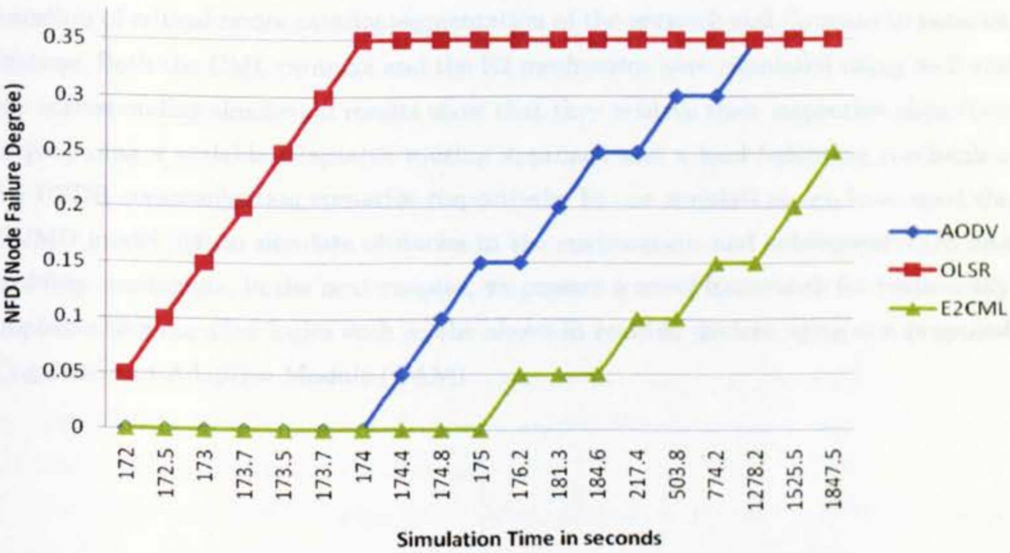


Figure 5.18: Event based NFD simulation results - The figure shows the graph of node failure degree as taken over the simulation time period in seconds for the 20 nodes MANET simulated using event based simulator

has a higher NFD than AODV because as discussed above, the OLSR protocol utilises more routing packets than AODV for evenly distributed networks of 20 nodes given that the same amount of data traffic is circulating in the network.

5.9 Summary

In this chapter we have presented the CML converged hybrid and adaptive routing approach that uses OLSR and AODV routing protocols as its basis for proactive and reactive routing respectively. The CML protocol relies on a converged routing protocol operation as opposed to zonal protocols found in literature, and its design is based on the NST point that was investigated in Chapter 4 of this thesis. In a nutshell, CML has a 3-phase operation logic whereby a P-phase operates the OLSR protocol, the R-phase operates the AODV protocol and the O-phase is used to shift from one protocol to the other while making sure that there is no oscillation taking place in the network. We also present our E2 mechanism that was designed as a load-balancing method in order to avoid over-use of critical nodes in the network. Such over usage will result in battery exhaustion of critical nodes causing segmentation of the network and decrease in network lifetime. Both the CML protocol and the E2 mechanism were simulated using ns-2 and the corresponding simulation results show that they achieve their respective objectives of proposing a scalable adaptable routing approach and a load-balancing mechanism for PPDR communication scenarios respectively. In our simulations we have used the HUMO model [64] to simulate obstacles in the environment and subsequent LOS and mobility constraints. In the next chapter, we present a novel framework for realistically implementing complex logics such as the above in real-life devices using our proposed Cognitive and Adaptive Module (CAM).

Chapter 6

Cognitive and Adaptive Module (CAM)

In this chapter, we present our innovative design of a Cognitive and Adaptive Module (CAM) for the lightweight implementation of routing approaches. The CAM suite is particularly useful for MANET routing in realistic MANET scenarios including flat, cognitive and both zonal as well as converged forms of hybrid adaptive approaches. Our proposed CAM concepts, design and developments which are patent pending [96]. The main concept behind CAM is the fact that the provisioning of multimedia communications traditionally requires routing Quality of Service (QoS) guarantees [47]. Such a task is NP Complete in MANETs when QoS optimisation is subject to more than one parameter [91]. Hence, the provisioning of soft QoS guarantees for effective and efficient routing in dynamic environments, as specified in [9], is the best alternative. However, the latter cannot be optimally achieved by using a single metric based path selection process or routing approach due to variations in both upper layer service QoS requirements and situational constraints.

The CAM suite provides application programmable interfaces or APIs, to routing components such that protocol logics can be segmented into components and can be flexibly implemented, configured and adapted to a researcher's or developer's need. For instance, the route selection process can be done in an adaptive manner to satisfy the requirements for dynamic topological contexts. This can be implemented efficiently using the CAM suite such that the centrepiece of the suite, the CAM Core provides APIs for various user configurable or definable Components (e.g. Repositories Component and Monitor Component.). These Components implement essential functionalities required by a routing approach. These in turn provide interfaces to Component Parts (e.g. tables Part and Network size monitor Part) that implement the actual logics of functionalities. All the Parts can inter-communicate to share information as appropriate. The afore described modularity of CAM suite implies that the Components and Parts that are not essential for routing can be omitted in less resourceful devices while implementing the same approach over a heterogeneous MANET. In the following sections, we describe the main concepts behind CAM, the design of the CAM suite and high level implementation details of the developments that have been carried out within our research group for cross-layer Android and Apple iOS mobile platforms. We also extend our investigations of routing performance of reactive and proactive approaches, in order to determine their suitability for various network conditions. We thus vary mobility and routing timeout, interval and MPR ratio timeout values to determine its effect on the QoS of the different approaches. We then use two examples of design guidelines to demonstrate how the CAM suite can be used to facilitate the implementation of CML as well as our further routing logics based on our extended simulation evaluations. In the next chapter, Chapter 7, we provide a summary of the achievements of this thesis and avenues for future work in the field of cognitive and hybrid adaptive MANET routing.

6.1 Introduction

The CAM suite is a flexible framework to enable lightweight, interoperable, adaptive and hybrid routing protocol implementation in real-life MANETs. The autonomous nature of MANETs makes them suitable for deployment in various scenarios. In such scenarios, the routing QoS is defined by the service requirements but the achievable QoS is limited by network and scenario constraints. A detailed list of these requirements and constraints is presented in [9]. It can be deduced that rigid routing protocols based on a fixed route selection process that only consider single path metrics shall not perform optimally in such dynamically varying environments. A small list of such identified environments and corresponding specificities are:

- Emergency rescuer and military ad hoc communication: Rescuers and military participants will require multimedia communications (requiring low delay and delay jitter as well as high throughput routing QoS) in terrains where obstacles are common. Devices will have limited battery resources and the network topology (in terms of both network size and node distribution) will change regularly as participating nodes join or leave the network.
- Mesh-based wireless community networks: Community users are likely to access multimedia services. Since the topology consists of static rechargeable routers, energy spent for routing is not a limitation towards QoS provisioning. However, users might prefer more efficient energy utilisation for greener and cheaper solutions while also maintaining the required QoS routing levels.
- Mesh-based wireless enterprise networks: Enterprise users (i.e. office users) are likely to access email and file transfer services (requiring low packet loss routing QoS). Since the nodes are rechargeable, energy limitation is not an issue but users might prefer more efficient energy utilisation for greener and cheaper solutions.
- Smart home ad hoc networks: Home users may want to distribute content among home devices such as TV, IP-radios, laptops and PCs. Here "bursty" communication would be desired and proactive maintenance of route information may be inefficient and expensive in idle periods between bursts.

Although the network performance using flat and inflexible protocols may be satisfactory for specific scenarios, the routing approach performs sub-optimally for wider context usages as proved in Chapter 4. An adaptive approach using routing logics from well tested protocols such as OLSR [29] and AODV [37] will provide a more flexible routing solution for the widespread use of MANETs. CAM is a generic module that provides interfaces for user defined routing components e.g. "Routing algorithms", "Repositories" and "Route quality" determination so that these are easily configurable and reusable for different scenarios. In addition, CAM offers interfaces to the "Monitor" and "Adaptive" components that allow protocols to cognitively adapt its routing process in dynamic environments. This should enhance overall routing QoS levels such as efficiency and effectiveness as defined in OLSR [9] and explained in Chapters 2 and 4. The current version of developed CAM suite defines the appropriate module, interfaces and components that are necessary to enable this.

Furthermore, this chapter describes the operation of an instance of components and parts usage that implements the CML protocol as described in Chapter 5. Thus the implemented instances of the components and parts of CAM embodies the CML processes that are required. The implementation of CML logic is thus achievable in a lightweight fashion such that adapting to various network sizes and node distributions by utilising required adaptive and cognitive features are possible in real-life devices.

The concept behind CAM design can be regarded as representing hierarchically, in decreasing order of importance, the essential constituents of a MANET routing protocol e.g. the structure of CAM consists of the central CAM core, the logical processes implemented in CAM components and then the enabling algorithms developed using the CAM parts as shown in Fig. 6.1. For the purpose of clarity, this figure includes only a subset of the components and parts that will be required by the CAM Core. CAM offers several improvements over the only well-known routing framework for MANET that is described in [12] which presents a simple rigid structure for hybrid routing. CAM is also beneficial as it encourages the development of standard components for different MANET contexts due to the need to fulfil scenario specific requirements. In this way, researchers or engineers will be able to create their own routing module and configure the adaptivity of their routing protocol up to a certain level of granularity as restricted by the standard components.

In particular, the generalised packet format [28] and NHDP are good candidates for such standard components for defining MANET packets and neighbourhood discovery methods respectively. Then, researchers and engineers will have high level interfaces that can be used to configure the behaviour of routing protocols using tuneable parameters such as HELLO intervals, TC intervals, network context limits and network thresholds according to their desired scenarios. Moreover, the CAM design should be especially useful for communication devices with multithreading capabilities such as new generation PDAs. One of the main aim of CAM is to provide researchers with a flexible and modular framework that can be used as a linchpin to experiment on a particular area of interest in MANET routing without having to implement a complete working solution. Instead, the particular CAM Component or Part can be easily defined or configured to carry out investigations or developments.

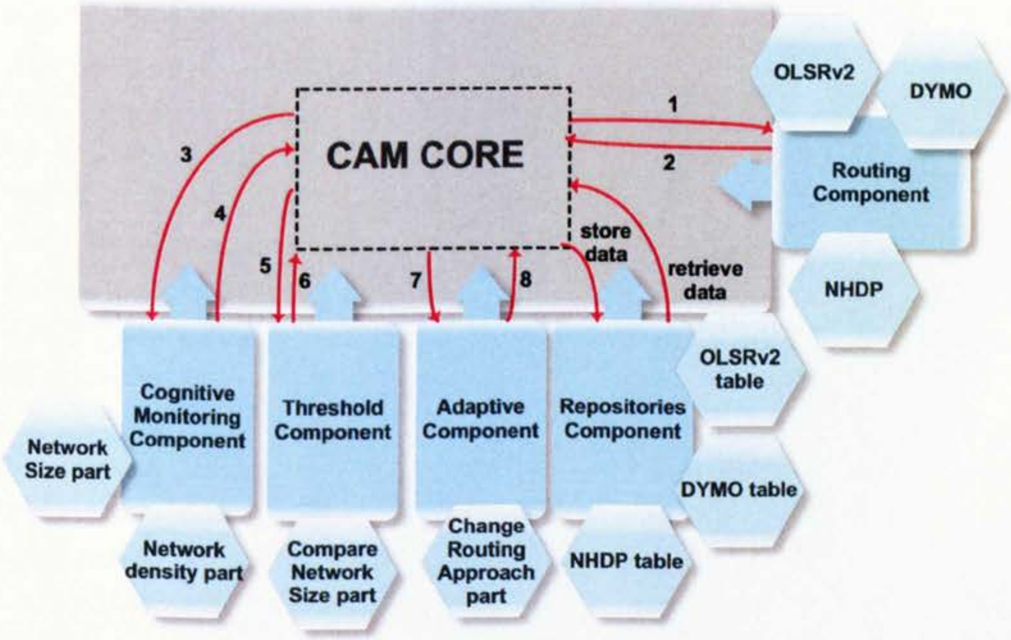


Figure 6.1: Overview of CAM suite - The figure shows an overview of the CAM suite with its constituent core, components and parts for realistic lightweight MANET routing implementations

6.2 Overview of CAM suite

The CAM suite defines a CAM Core that acts as a "controller" to direct routing efforts for MANETs. The CAM Core mainly provides interfaces (in the form of Application Programming Interfaces (APIs)) to "CAM Components" (developed based on fixed guidelines) that implement MANET routing functionalities. The components in turn have to provide APIs to "CAM Parts" (also developed based on fixed guidelines) that implement the actual logics of routing functionalities. These components and parts should be easily pluggable into the CAM Core. The CAM Core also defines the required interface for receiving and sending packets from lower layers (MAC) and upper layers (Transport). The adaptive features implementable in the CAM suite will allow for monitoring certain network state parameters obtained from packets and other cross-layer information, comparing these network state parameter values with defined thresholds and if the thresholds are exceeded, the required adaptive action has to be initiated to change the routing behaviour accordingly. The hybrid features of CAM suite will allow different routing protocol approaches to be utilised according to the change in the network state. This change from one protocol to the other is one of the possible actions as part of the adaptive actions taken by the protocol suite. However, the design of CAM is such that one can choose not to have adaptive and/or hybrid features by altering the CAM core sequence list and actively using only the required Components and Parts implementing flat routing approaches for instance.

The CAM Component is a structure containing definitions and implementations of routing logics and structures whereas the CAM Parts actually implements the algorithms and logics to be used for certain functions. Also, CAM uses "Coarse variables" to identify the component that needs to be activated during operation. The value of the coarse variable may be equal to the ID of the component for convenience. The CAM "Fine variables" are used to identify the parameters that needs to be modified within a CAM part. The variable value should uniquely identify variable parameters within each CAM Part. A CAM Trigger is defined which is an implemented logic in the CAM Core that is used by Monitors to activate specific Adaptive Component Parts when a threshold is exceeded.

6.2.1 CAM Core

The module Core contains the essential variables, data structures and algorithms that are required for the operation of a MANET routing protocol. In addition, it contains APIs for "CAM Components" that is used to plugin the essential components for adaptive and hybrid routing as well as optional or user defined "CAM Components". The CAM Core will also contain interfaces and functions for inputting received packets and outputting broadcast, unicast or forwarded packets (e.g. the socket parser, packet parser and scheduler). The CAM Core should act as a "central controller" for all data exchange among components . Essentially, it contains a "Sequence list" that dictates the flow of control of operations as packets are received or in case of periodical events.

The CAM Core will contain identifiers that will identify the components and the parts of each component. In addition, it is important to declare and assign values for routing variables in the CAM Core, such as time periods for route discoveries (e.g. HELLO messages every 3seconds) within components and parts. These values affect the routing protocol behaviour. Each declared variable will have to be associated with its component and part. Then, the "sequential list" will contain the identifiers of those parts and components used to process packets and route data packets in the right order so that the proper flow of operation as required by users. The CAM Core APIs will provide an interface to the essential CAM Components described below along with any user-defined CAM Components. In addition, APIs will facilitate interaction between CAM Suite Core and Graphical User Interfaces, MAC layer and Overlays.

6.2.2 CAM Components

There are 2 types of CAM Components which are "required" CAM Components and user defined pluggable CAM Components. These will be connected to the CAM Core via appropriate APIs. The CAM Components will be activated according to the sequential list in the CAM Core in order to carry out the desired processing in order. The CAM Component will define and assign appropriate values that are compulsory for parts that logically belong to that component. It is important to note that the "required" Components exist in the following forms: "compulsory", "replaceable", "optional". A list of compulsory components for adaptive converged hybrid routing approaches include:

- Repositories component: The repositories component will define the routing table fields that are required by each essential tables that are implemented in the CAM table parts. It provides APIs for the routing table parts.

- Monitor component: The monitor component defines the network parameters that will be monitored by its parts and provides the required APIs for these.

- Threshold component: The threshold component defines the thresholds that will be defined by its parts and provide the required APIs for these. The threshold component also contain the adaptive component parts to be activated in case a threshold has been breached.

- Adaptive component: The adaptive component implements the actions to be taken when activated by the threshold component. It provides APIs to the parts that implement adaptive actions.

- Link Metric component: The link metric component defines link metrics and APIs to Link Metric parts that implement the link metric definition equation.

- Routing component: The routing component defines APIs to routing parts that are required to route packets from source to destination. Some of the functionalities of the parts that are implemented and interfaced through the routing component are described next. The neighbourhood routing protocol part discovers one-hop and 2-hop neighbours. New standards require this as a compulsory component in CAM suite. Therefore, components should define the API for basic logics and parameters that are used to interface with the parts where the NHDP is implemented. An API (required parameters) that are used to interface with parts implementing the proactive routing algorithm is also required. Additionally, the reactive routing logic requires an API (required parameters) that are used to interface with parts implementing the reactive routing algorithm.

- Packet and TLV component: The MANET packet format has been defined by the IETF and will be fixed in the component. The component will specify the TLVs (components for carrying extra information such as energy of device and security keys). The APIs will then provide an interface to parts to define these TLVs.

The optional (user defined) component will have to be declared in the CAM Core and the essential parameters and logics that are required for its parts have to be specified as coarse and fine variables. The parts will then implement the actual algorithms or logics for the component to fulfil its routing functionality.

6.2.3 CAM Parts

There are 2 types of "CAM Parts" for each component, which are "required" parts or optional user defined plugin parts. While the component defines the APIs and compulsory logics that are required for a particular routing function, the CAM Parts implement the actual logics that are used to carry out these functions. The parts are designed so that they are pluggable and re-usable. It is recommended that the Parts be developed in code that can be used across mobile platforms for widespread acceptance. The "required" CAM Parts can be further sub classified as "compulsory", "replaceable" and "optional". Some examples of CAM Parts that are relevant for our thesis work are:

- Repositories parts: The repositories parts will consist of tables necessary by the CAM Core, CAM Components and CAM Parts to carry out routing. For instance, a routing table for NHDP, a routing table for proactive component, a routing table for reactive part are necessary to store routes computed by the Routing Components. In addition, the parts for these tables will slightly differ across operating systems e.g. the NHDP table part for Apple iOS platforms will have slightly different logic to interact with the OS routing tables as compared to the part of NHDP table for Android platforms. These parts need to implement the APIs for its component so that it can interact with the CAM suite.

- Monitor parts: The monitor parts that are compulsory include the processing of packets and cross layer information in order to calculate the network parameter as specified by the CAM monitor component. The parts have to follow the API specification of the Core. The monitor part need to indicate the CAM threshold part where parameters will be compared to their thresholds implemented.

- Threshold parts: The threshold parts implement the logic for comparing the values for the thresholds with the monitored values. They indicate the adaptive part that has to be activated as a result of a threshold being exceeded.

- Adaptive parts: The adaptive part implements the actions to be taken when activated by the threshold component or parts. The actions consist of changing the parameters in the CAM core or CAM components or change active CAM components in the Core sequential list in order to change the behaviour of the routing process.

- Link Metric parts: The link metric parts define equations that are used to calculate the link metrics for routing paths e.g. if we want to select a route with good reliability we choose the equation for link metric to calculate least packet loss links and use this to sort the routing tables in the repositories path.

- Routing Part of Neighbourhood Discovery Component: This will consist of routing logic of Neighbourhood Discovery Protocol (NHDP) as established by the IETF.

- Routing Part of Proactive Routing Component: This will consist of routing logic OLSRv2 which is a work in progress being developed by the IETF.

- Routing Part of Reactive Routing Component: This will consist of routing logic of DYMO which is a work in progress being developed by the IETF.

- TLV parts: The TLV parts will implement the creation of TLVs in routing packets and filling them with values of Link Metric parts when routing packets are used in the network.

User-defined CAM Parts can also be used to implement emerging functionalities that are being researched and developed as long as it follows the guidelines for design as established above.

6.3 Structure of CAM Suite

In this section, we describe in more depth about the various structures of CAM Core, Component and Parts. In addition to the actual implementation of routing logics, the

CAM suite should include other interfaces and identification mechanisms in order to allow unambiguous intra-communication among various structures in the apparatus. The Core must implement interfaces for each defined component. Thus, the core can communicate with the components through these interfaces. Component-to-Component communication must only be possible via the core. Each interface is associated with a component ID. The core can then pass messages to the required component using its stored ID within CAM Core data structures and as directed using the flow implemented in a "sequence list". Furthermore, each component and each component part is identified through a unique ID. This ID may be coded as a 'x' bit string using a logic such as $x = x\_component||x\_part$ where x_component and x_part are combinations of binary IDs required to represent a Component and Part respectively. The number of bits required to compute an ID for Components or Parts is $|x_component|$or $|x\_part|$ $= (log_2(Numberofcomponents))$ or $(log_2(Numberofparts))$.

6.3.1 Thresholds and Triggers

The CAM Core must define triggers for all the contexts being monitored in the Monitor component parts. To achieve this, an upper and lower threshold must be defined for each monitored context. The trigger is used to contact the Adaptive module if for a context C:

1. $(Previous\_C\_Value < Lower\_Threshold\_C) and$
   $(Current\_C\_Value >= Lower\_Threshold\_C)$ or
2. $(Previous\_C\_Value > Upper\_Threshold\_C) and$
   $(Current\_C\_Value <= Upper\_Threshold\_C)$

The trigger must contact the appropriate component by using the required IDs in order to change the routing approach.

6.3.2 Component Coarse and Fine variables

The CAM Core must define both coarse and fine variables for component parts. This will allow the core to change routing behaviour according to context changes. For each active component part, a coarse variable may be assigned the component part ID. Then, for each defined coarse variable specifying a part, associated parameter names and values are stored. These values are set by the Adaptive component parts and are used to change the routing behaviour of protocols.

6.3.3 Monitor Component

The Monitor component aims at providing cognitive capabilities to routing protocols. The parts of this component should contain logic that processes incoming packets or data in the Repositories component or both, in order to derive network state information. These parts, also called monitors, checks the appropriate threshold according to the current operating band. It then alerts the CAM core if a threshold is exceeded. This should be done using the appropriate threshold trigger.

From the scenarios described above, important CAM Parts that may be defined in this component are monitors for:

- Number of neighbours monitor: it collects and maintains information for number of neighbours of the node. This will give an indication of the density of the local network.

- Rate of change in neighbours monitor: it regularly compares current neighbourhood information to calculate neighbourhood changes. Neighbourhood changes include changes in the total number of neighbours and neighbour nodes leaving or joining the neighbourhood. It then, computes and stores the value for the rate of change. This information is then stored in the Repositories component. This will give an indication of network mobility.

- Total number of nodes monitor: this monitors the total number of nodes at regular intervals of time within the network. This function is specific to the routing algorithm being used. In proactive approaches such as OLSR [29], this function only consists of counting the number of rows in the routing table. In the case of AODV [37], an estimation of the number of nodes in the network can be obtained by using probe packets as defined in Chapter 5.

- Traffic profile monitor: this monitor checks for the traffic profile of current data packets received at the node. It stores this profile along with the number of connections that are supported by this node and the number of packets received for each profile type within a timeout period. This should be stored in the Repositories component. This also specifies the metrics that should be recorded by the metric statistics monitor and determines the coefficient values for metrics used in the path selection process.

- Metric Statistics: it processes the received routing control packets containing metric TLVs (similar to R_etx TLV as indicted in [65]) and stores the metric value of nodes in the Repositories component indexed to the appropriate node or path in a routing table. A few important metrics that can be stored in packet TLVs are estimated link error before successful transmission (ELTX), estimated link delay (ELD), estimated link bandwidth (ELBW), estimated link delay jitter (ELJ), and neighbour node energy level (NEN). The values for route quality can be calculated as follows:

  - ETX: The ELTX is the estimated number of transmissions required to successfully send a packet over a link as defined in [65]. ETX is defined as the sum of the ELTX values of links that form a given path.

  - ED: It is assumed that the clocks in all the participating nodes are synchronised. The ELD value can then be calculated using a timestamp message TLV that is written by each sender. The receiver node on the end of the link then has to use the current clock value. The difference between the two clock values gives the ELD value. Since delay is an additive metric, the ED value of a path is equal to the sum of all ELD values of links within that path.

  - EBW: The ELBW value may be calculated using the ELD value of a link as estimated above. $ELBW = ReceivedPacketsize/LinkELD$. Since bandwidth of a path is constrained by the minimum ELBW along the path, the EBW value is equal to the minimum ELBW value. Another alternative for calculating EBW is described in [47].

  - EJ: The EJ value is additive in nature. It is the sum of ELJ values where each ELJ value is the variance in consecutive ELD values for that link.

  - NEN: The NEN value can be included by each node in a TLV when it sends control packet messages to neighbour nodes. If the energy level of a route is required, the sum of NEN can be sent in node TLVs that are incremented at each node along that route.

- Hop Count (HC): The HC value can be obtained from the message header $< msg - hop - count >$ field defined in [28].

6.3.4 Adaptive Component

The Adapt Component must check the validity of a trigger. Furthermore, they must change coarse and fine variables in the CAM Core so that adaptive actions are enabled. The parts of this component should contain implementations of actions that change the routing behaviour of nodes. Therefore, the triggers should target one or more adaptive parts as required by the utilised adaptive concept. Hence, the parts here should allow users to specify their desired adaptive actions.

As mentioned above, the required module part must first check if the trigger is valid by confirming whether the threshold has been exceeded. This is done by consulting the Repositories module (for a given time period) or by initiating a confirmation process. Then, if the trigger is valid, some Adaptive Parts and their possible roles may be:

- Switching routing logic: the adaptive module may decide to switch from proactive routing to reactive routing when triggers such as the one for the number of nodes or number of neighbours thresholds are exceeded.
- Tuning route discovery and maintenance intervals: the logic in such a part may change the interval for route discovery and maintenance such as HELLO intervals and route timeouts. This may be as a result of a confirmed mobility threshold trigger.
- Determining coefficient values for routing metrics: the coefficient values established here determines the importance of each routing metric as a result of traffic requirements and scenario specific constraints (user may input these manually).
- Other self defined parts: other similar logics can be used in parts to define actions required to adapt to changes in context as detected by the monitors and alerted through confirmed triggers.

6.3.5 Routing Component

For the purposes of CAM, this component must have at least one part defined whereby all the essential routing heuristics necessary for routing packets in MANETs are defined. The routing component contains algorithms as Parts of protocols defined in [29, 34, 37]. Hybrid approaches may therefore be enabled by defining a hybrid routing logic within a single part for a zonal approach. In the case of hybrid converged approaches, routing logics of different approaches may be defined several parts. These separate parts should be then triggered when deemed necessary. The processes of route discovery, route maintenance and route selection should be defined within at least one part.

6.3.6 Route Quality Component

This component is used to define the logic for quantifying route qualities using defined metrics. Here, the CAM Parts define metrics that are required by the "Metric Statistics" part of the "Monitor Component". This should allow for a multiple metric based path selection process. Several techniques may be utilised for metric quantisation. Firstly, hierarchical based metric quantisation may be implemented where route selection is based on comparing high priority metrics of routes (that should be above a certain defined quality level) followed by comparison of lower quality route metric values as required by supported services:

```
if (ETX > ETX_min_quality)
{
  if (Metric2 > m2_min_quality)
 . . .
      if (Metric(m-1) >m(m-1)_min_quality)
      set Route_quality = Value_m
}
```

Moreover, a utility score,U(Rt), for each route R_t may be used to make route selections based on the metrics that are defined:

$$U(R_t) = (\alpha * ETX) + (\beta * ED) + (\gamma * EBW) + (\delta * EJ) + (\zeta * NEN) + (\eta * HC) \tag{6.1}$$

where $\alpha, \beta, \gamma, \delta, \zeta and\ \eta$ are the coefficients that dictate the importance of each metric in the route establishment decision. In the event that a metric has to be ignored, its corresponding coefficient is set to zero. Then, a hybrid approach combining both hierarchical and utility score techniques can be used for route quality determination. The route quality information must be stored in the repositories component and indexed to the appropriate routes.

A generic implementation instance is illustrated in Fig. 6.1 where the CAM Core initiates the Routing Component which starts the routing algorithms. The Cognitive Component then implements network monitoring so that any defined threshold is verified. If an adaptive action is defined and required the Adaptive Component implements this logic. The Repositories Component is accessed whenever necessary to store and retrieve data such as route information. Other CAM Components not described above include generalised packet format must be used so that all parts and components can access information within packets. Also, a Repositories Component is used to store data that is useful for other components of the CAM module. The Security Component contains logic that enables security measures against attacks launched by malicious nodes in the network. Additionally, the CAM Core must be able to accommodate user defined Components and Parts that can implement novel functionalities and logics based on emerging research as long as the above guidelines are followed.

6.4 Performance Evaluations and Implementation Guidelines

6.4.1 Evaluations: Scenariol

In this section, we extend our investigations from Chapter 5 of MANET protocol evaluations to investigate further factors that influence QoS metrics such as routing protocol parameters and network contexts. Consequently, we design the appropriate CAM suite

Components and Parts to for implementing optimised routing QoS metric based algorithms based on our findings. Since it is very complex to properly understand effects of various network contexts on the routing performance in real life test environments, we have used simulation based evaluations of protocol models derived from their definitions in the RFCs and Chapter 4. For the scope of this scenario, we choose to simulate the most popular researched protocol RFCs in literature that are the most promising candidates for standardisation only. Therefore, we compare the performance of NHDP, AODV and OLSR using our custom built simulators. Our simulator was developed using MATLAB and ns2 simulation platforms. We also use a "normalisation process" where the results obtained through our simulations are benchmarked against scenario results where routing operations are absent. In that manner, we aim at comparing protocol performance strictly related to routing processes.

As a possible CAM Part for neighbourhood routing, the performance evaluation of NHDP for local scoped routing or route maintenance is important. Fig. 6.2 and Fig. 6.3 shows the performance evaluation results of OLSR and AODV based on the routing overhead [1] and average normalised average end-to-end data delivery delay [2]. Thus, the simulated scenario considers the qualitative and quantitative performance of these routing approaches for different network sizes with a uniformly distributed topology. In our scenarios, we investigate the effect of varying required number of route discoveries by AODV as a result of link breakages or need for different data connections. In that case, we assume that the source and destination nodes are located at the furthest possible points from each other while remaining connected in the aforementioned topology. Then, we also compare the overhead incurred by the investigated protocols when the HELLO_INTERVAL, TC_INTERVAL and TIMEOUT_INTERVAL are decreased in order to maintain the same level of delay guarantees. We simulate such a scenario based on the need to update routes at a higher rate due to rapidly changing network topologies.

An overview of the model, that was considered for our evaluations is described next. We assume that all the nodes forming the modelled MANET are uniformly distributed over a space of area A. The nodes are represented by a graph, $G = \{V, E\}$ and all nodes, n, in the network are denoted by the set of vertices $V = \{1....n\}$ and

[1] in terms of control packets only i.e. excluding data packets

[2] including route establishment time delay

the links between nodes be represented by the set of edges $E = \{(i,j) : i, j \epsilon V\}$. A distance function $\Delta(i,j)$ gives the distance between vertices i and j in terms of number of hops required by a packet originating at node i to reach node j. Therefore, for $\forall(i,j)$ that are *h-hops* away from each other, $\Delta(i,j) = h$ where if $h = 1$, it implies that i,j are immediate or 1-*hop* neighbours. We also assume that all the packet sizes in the network have common headers and are of the same size as recommended in [28]. Thus, the normalised protocol overhead are derived based on the 1-hop neighbour nodes and the value of n nodes for a given area A. In addition, a maximum normalised bound for end-to-end packet delivery delay can be approximated based on [27, 85, 90, 91]. We use values reproduced in Table 6.1 for our simulations based on recommendations from RFC 3626 [29] and RFC 3561 [37].

Parameter	Value
Simulated Protocol Usage Time	1 hour
Duration of discrete data connection	5 minutes
Default HELLO_ INTERVAL	2 seconds
Default TC_ INTERVAL	5 seconds
Default TIMEOUT	3 seconds
Default MPR ratio	0.75
Number of nodes	for n in [4; n++; 55]
Number of Connections	2; 4; 6; 8; 10
Reduced HELLO_ INTERVAL	1 second
Reduced TC_ INTERVAL	3 seconds
Reduced TIMEOUT	1 second
MPR ratio	0.25; 0.5; 0.9

Table 6.1: Simulation parameter values - The Table shows parameter values used for our simulation based evaluation of protocols

6.4.1.1 Results and Discussion

In this subsection, we describe and discuss simulated evaluation results that provides further insight on the merits of having an adaptive approach. It is important to note that the results of NHDP is based on a 2-hop data delivery scenario for delay and a 1-hop evaluation of the overhead cost for each node. Thus it has a lower normalised end-to-end delay value as compared to other evaluated protocols that are examined over more than 2-hops. It can be observed in Fig. 6.2, that AODV overall produces lower normalised overhead (in terms of relative routing control data used by each protocol)

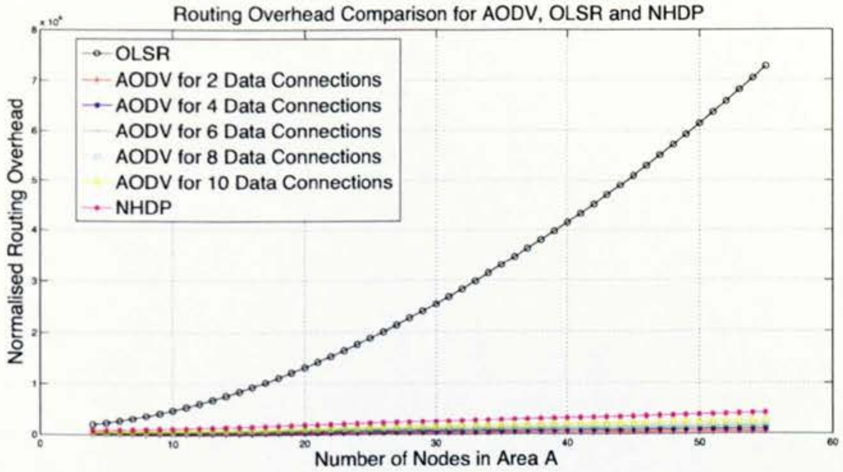


Figure 6.2: Normalised routing overhead comparison - The figure shows the performance evaluation of OLSR, AODV (with different number of data connections) and NHDP using routing packet overhead

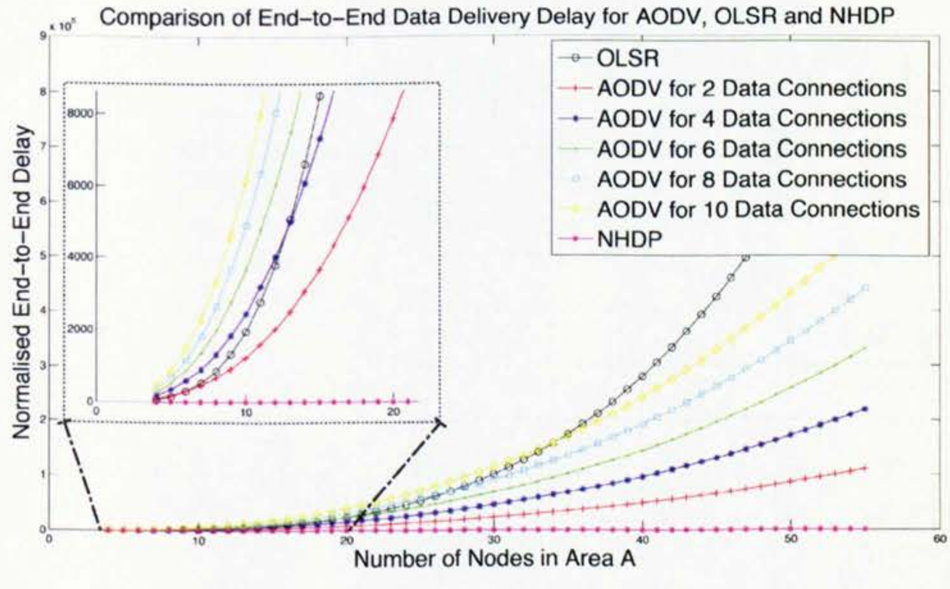


Figure 6.3: Normalised end to end data delivery delay - The figure shows the performance evaluation of OLSR, AODV (with different number of data connections) and NHDP using E2E data delivery delay

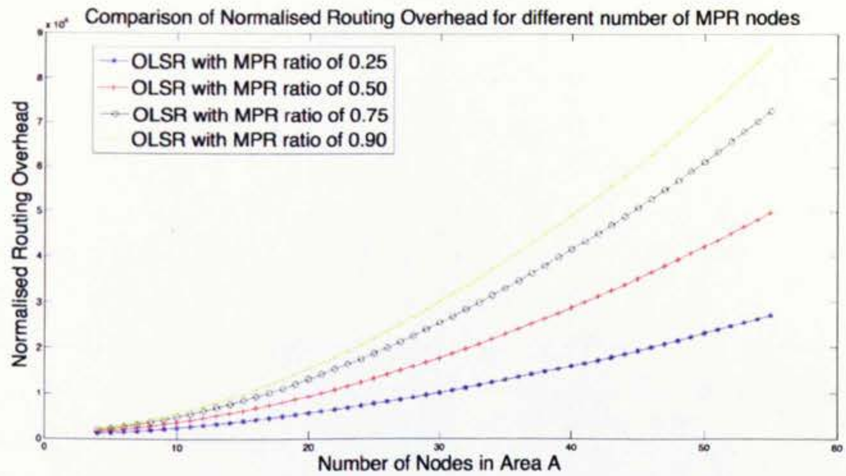


Figure 6.4: Normalised routing overhead comparison for OLSR - The figure shows the performance evaluation of OLSR with different MPR ratios using routing packet overhead

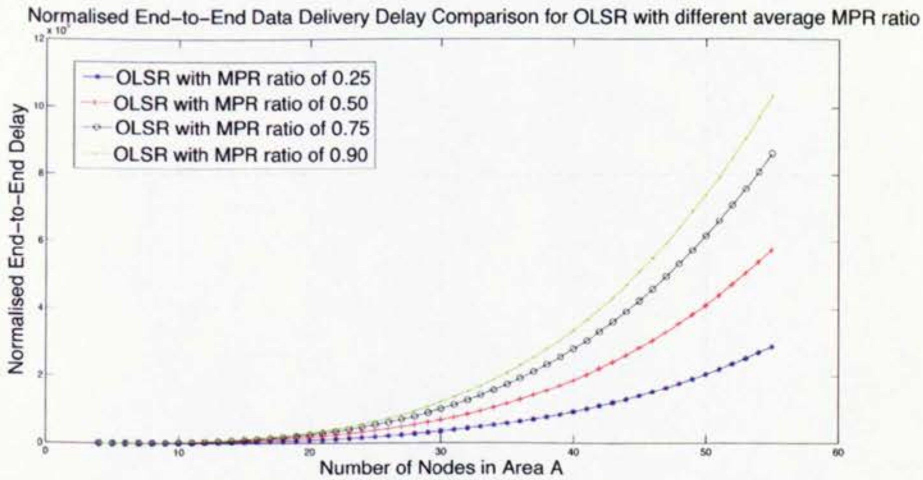


Figure 6.5: Normalised end to end data delivery delay for OLSR - The figure shows the performance evaluation of OLSR with different MPR ratios using E2E data delivery delay

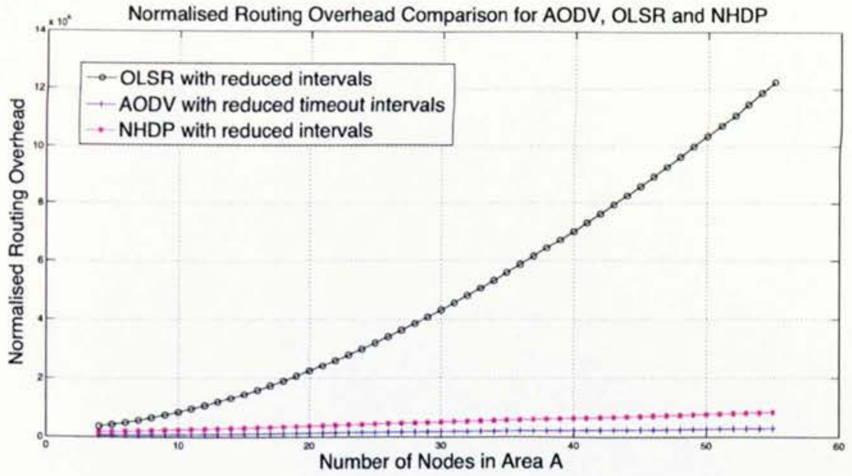


Figure 6.6: Normalised routing overhead comparison - The figure shows the performance evaluation of OLSR, AODV, and NHDP based on reduced route validity intervals using routing packet overhead

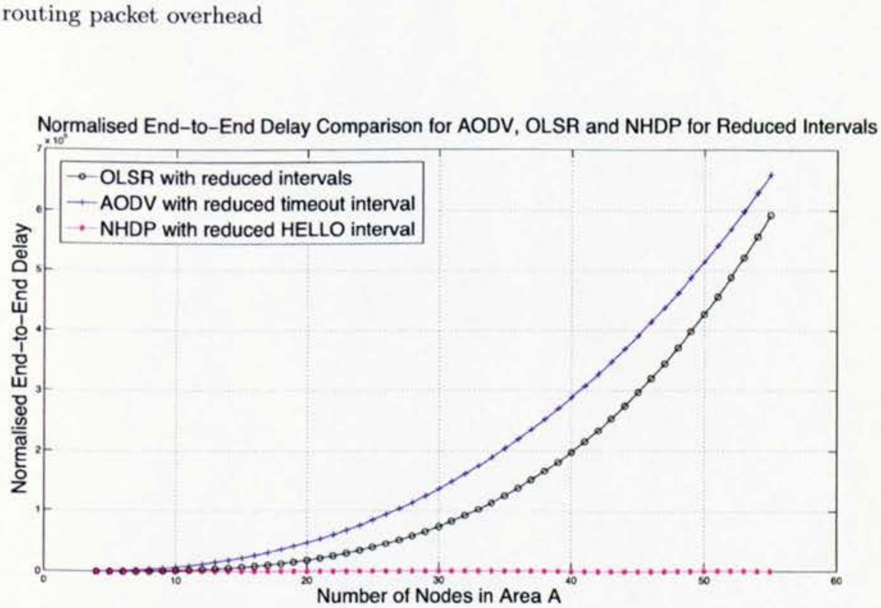


Figure 6.7: Normalised end to end data delivery delay - Performance Evaluation of OLSR, AODV, and NHDP based on reduced route validity intervals using E2E data delivery delay

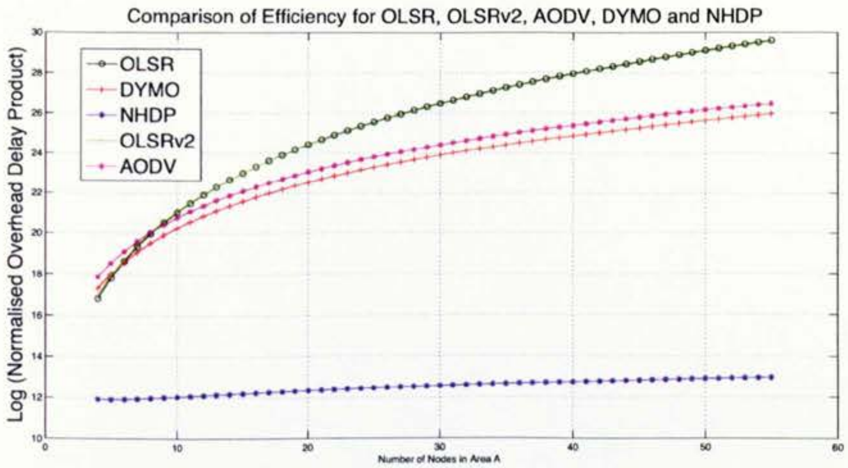


Figure 6.8: Efficiency in terms of log (Overhead x Delay product) - The figure shows the evaluation of efficiency for OLSR, DYMO, OLSRv2, NHDP and AODV

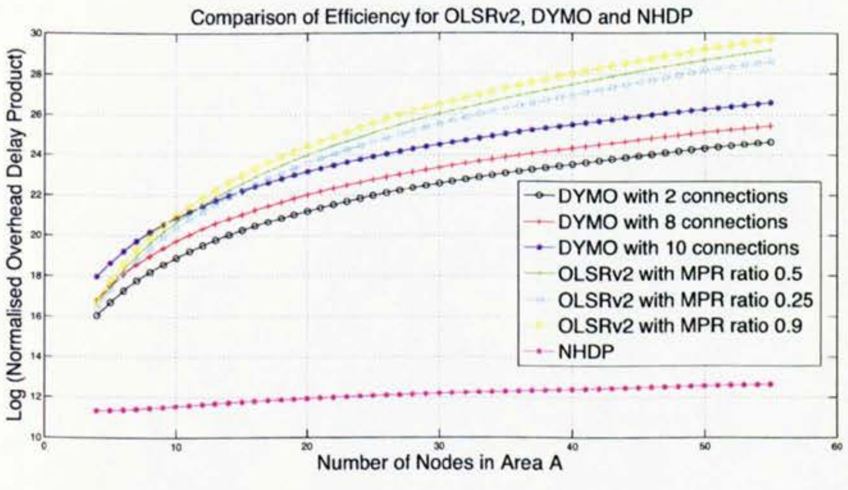


Figure 6.9: Efficiency in terms of log (Overhead x Delay product) - The figure shows the evaluation of efficiency for DYMO, OLSRv2 and NHDP using varying routing parameters

than NHDP and OLSR. The overhead of AODV depends on the number of connections and increases proportionally to the latter parameter. Here, NHDP results can be regarded as the local overhead cost for each OLSR node and thus NHDP has less overhead than OLSR indicating that the TC messages used by OLSR produces exponential overhead. Additionally, the normalised overhead for all protocols increases as the size of the network increases, with the routing cost for OLSR increases exponentially in that case. From Fig. 6.3, it can be seen that the normalised average delay for NHDP increases insignificantly as the network size increases as compared to both AODV and OLSR. The increase of normalised delay as a function of network size depends on the number of connections used, with a higher increasing gradient for higher number of connections. The increase in normalised delay for OLSR is independent of the number of data connections used. It is important to note that in this scenario as well the existence of a *NST* beyond which AODV produces less delay than OLSR. This NSt, as observed in Fig. 6.3, is dependent on the number of connections used in the networks and consequently the rate of increase of the AODV delay gradient.

In Fig. 6.4 and Fig. 6.5, we investigate the effect of having different proportions of neighbour nodes as MPR nodes in the case of OLSR. MPR nodes are important for the optimisation of flooding mechanism that is prominent in OLSR for TC message dissemination. In cases where the link qualities in the network are poor or for sparsely distributed networks, a high ratio of MPR nodes will be required to form fully connected networks with reduced flooding using MPR. It can be seen that both the normalised overhead and normalised delay are dependent on the MPR ratio. A higher ratio results in higher overhead and delay. Furthermore these values increase exponentially for OLSR as the network size is increased. It is also observable that for smaller networks, the OLSR protocol has approximately the same performance irrespective of the MPR ratio. This small network size value is of the order of 10 nodes when the normalised overhead is considered and 20 nodes for normalised delay considerations.

Moreover, Fig. 6.6 and Fig. 6.7 consider the case of changing routes where a high route change of a second is considered. In such a case, in order to update routes in a timely manner, the intervals have to be decreased in order to have faster route update periods as described in Table 6.1. It is observed that although the order of normalised routing overhead remains, in decreasing order, OLSR, NHDP and AODV, the normalised end-to-end delay performances change. NHDP deliver data to 2-hop neighbours and has the lowest average delay value. However, AODV has a higher delay for data delivery as compared to OLSR due to the increased TIMEOUT value. While in the case of OLSR, the delay is only due to medium access backoff time and queue wait time at each intermediate node, for AODV the route discovery time is significant. A lower timeout forces the source node to re-initiate route discoveries at a higher rate and thus injects a higher delay value to the network. This degradation in performance as compared to OLSR is even more noticeable for larger networks where the average number of intermediate hops towards potential destinations increase.

We finally analyse the efficiency of the protocols in Fig. 6.8 and Fig. 6.9. Thus we evaluate the directions taken by the MANET WG i.e. the justification in the design of OLSRv2 and DYMO. We use the logarithm of the normalised delay-overhead product in order to estimate the efficiency of a protocol. This is because a relatively higher delay may be acceptable if the overhead is low but at the same time, higher overhead may be tolerated for relatively lower delay performance. Hence, a lower product indicates a better efficiency of the routing protocol and thus better performance as recommended in RFC 2501 [9].

It can be observed in Fig. 6.8 that OLSR is more efficient than AODV for smaller networks of less than 10 nodes whereas AODV is the preferred protocol for larger networks based on the IETF RFC recommended parameter values in Table 6.1. Here, it is clearly noticeable that NHDP is most efficient for 2-hop route information maintenance and data routing throughout the investigated range of network sizes. Hence, as supported by our above discussions, the MANET WG has proceeded in the right direction by integrating NHDP as the basis of OLSRv2 and DYMO as a second generation OLSR and AODV respectively. It can be seen that OLSRv2 has slightly better efficiency than OLSR with the benefit of having variable parameters of HELLO_INTERVAL and TC_INTERVAL as well as a more flexible packet format. In the case of DYMO, a significant improvement in efficiency can be observed by using NHDP instead of re-initiating route discoveries at TIMEOUT intervals. Although it produces more overhead than AODV, DYMO benefits from much improved delay performance as it no longer endures delays due to route discoveries unless routes are changed during transmission as indicated by the reactive mode NHDP component.

In Fig. 6.9, we confirm the fact that even though DYMO and OLSRv2 have improved efficiencies, DYMO still perform better for larger network size than OLSRv2. The NST beyond which this occurs depends on the number of connections and MPR ratio. For a reasonable scenario, where 10 connections are used and the MPR ratio of neighbours is 0.25, the network size threshold resides in the order of 15 nodes. Hence, it is not effective to utilise different protocols depending on the changing context of the network and also not efficient to use one given protocol approach for all network contexts. A logical solution is to use the different mechanisms of the underlying approaches into a hybrid routing framework such as the CAM suite that will adaptively use the most efficient routing mechanism based on the network conditions and traffic requirements.

6.4.2 Evaluations: Scenario2

In Scenario2, we focus on the effect of mobility on the well-known IETF routing protocol so that they can provide us with an insight of the possibilities of using the CAM Suite to configure and design appropriate Components and Parts in order to consider the effect of mobility on different environments that are described next and simulated using the HUMO [64] ns-2 extension.

Firstly, we plan to vary node mobility speed and pause time while using the RWP mobility model in an obstacle free environment. Then, we aim to study the effect of varying average node speed and pause time in extreme environments where obstacles are prevalent. In addition, in these extreme scenarios, the obstacle coverage area, size and distributions vary according to simulation scenarios as illustrated in Fig. 6.10 and Fig. 6.11 respectively. The former can be regarded as a case of forest fire emergency where the small and scattered obstacles act as trees whereas the latter scenario includes an urban setting with the main obstacle acting as a building being damaged by fire or a terrorist attack in an urban scenario similar to the scenario investigated in Chapters 4 and 5. For these purposes, we simulate a MANET comprising of 25 nodes and the following values for average node pause time are used 5, 10, 15, 20, 25, 30, 40, 50, 60, 70 and 90 seconds. This simulation set up is repeated for varying average node speeds of 0.2, 1.0 and 2.0 m/s for RWP mobility case while the speed is fixed at 1.0 m/s for PPDR emergency scenarios simulated. The low speeds simulate the mobility of on-foot rescuers in an emergency scenario.

To investigate the QoS performance of routing protocols, we simulate AODV, OLSR and DYMO routing protocols under a constant bit rate traffic of 256kbps. It is im-

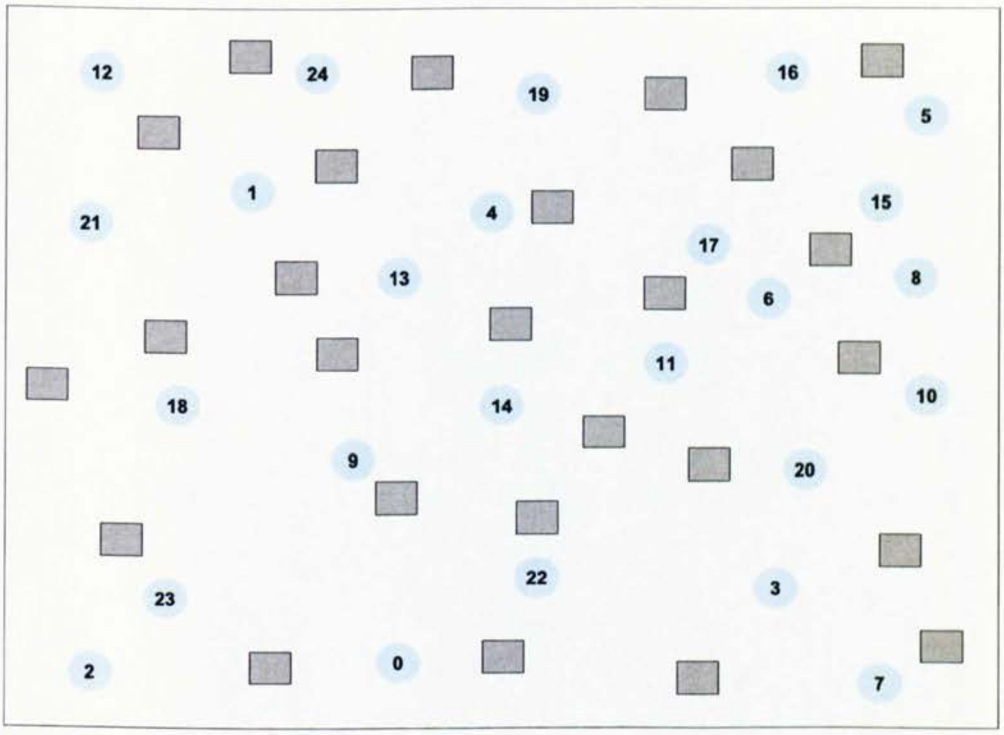


Figure 6.10: MANET topology within a forest fire context - The figure shows the topology of nodes moving in a forest fire context with smaller distributed obstacles

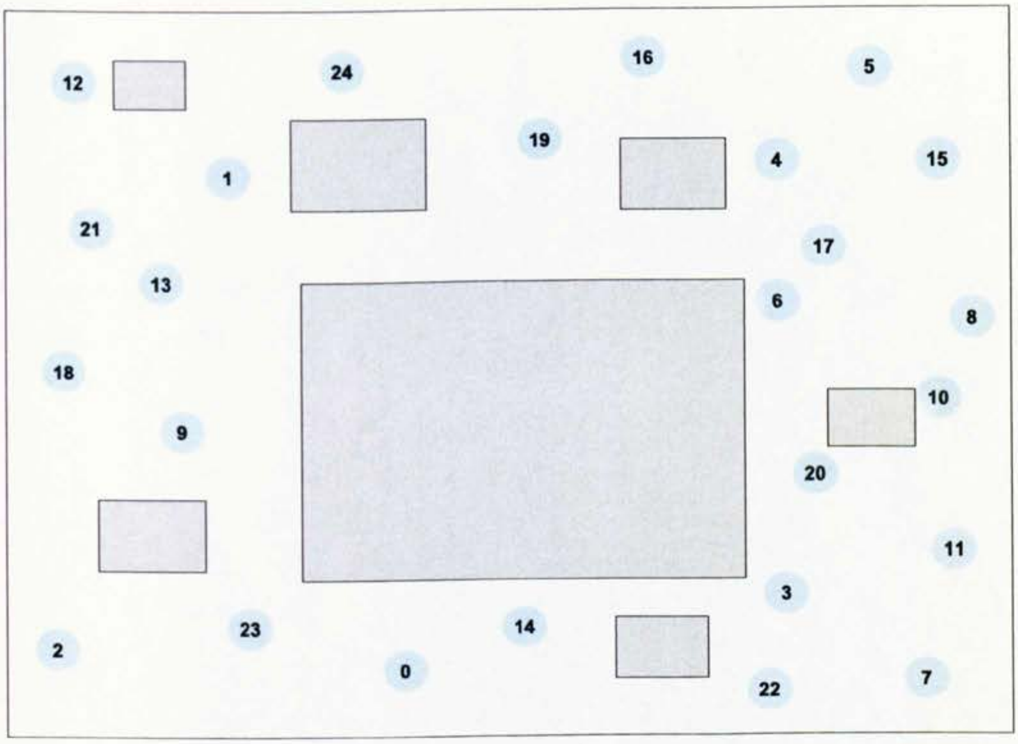


Figure 6.11: MANET mobility within an urban emergency context - The figure shows the topology of nodes moving in an urban emergency context with large obstacles

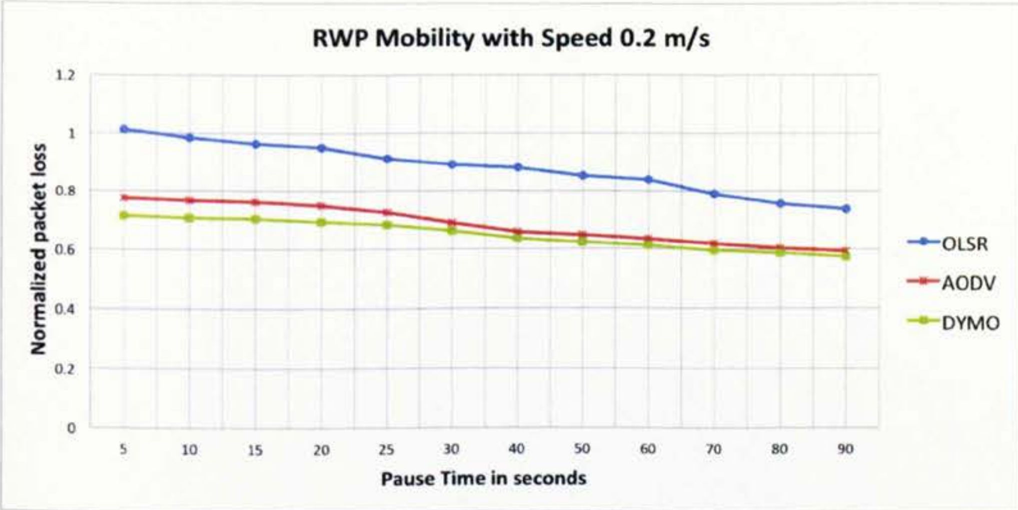


Figure 6.12: Packet loss for RWP mobility at 0.2 m/s - The figure shows the performance evaluation of normalised packet loss for RWP mobility model with speed of 0.2 m/s

Figure 6.13: Packet loss for RWP mobility at 1.0 m/s - The figure shows the performance evaluation of normalised packet loss for RWP mobility model with speed of 1.0 m/s

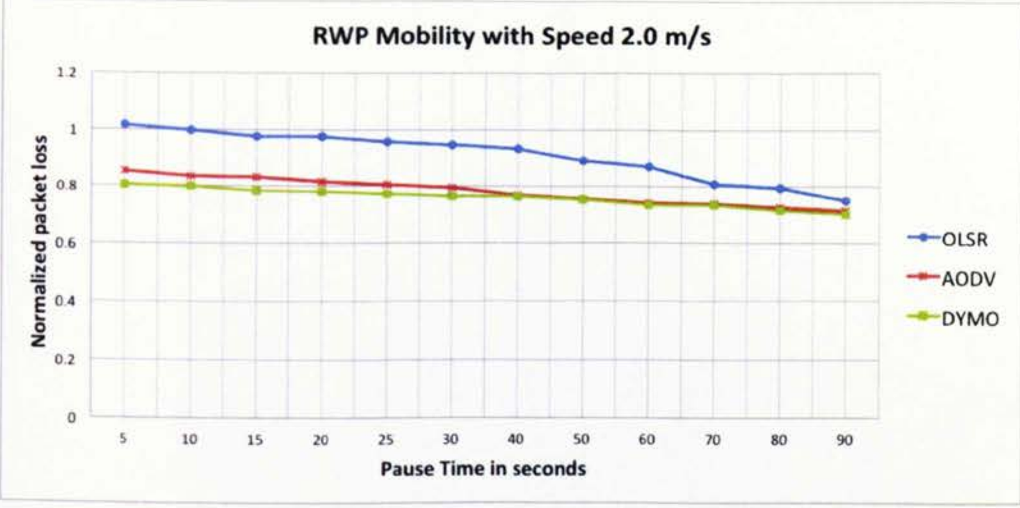


Figure 6.14: Packet loss for RWP mobility at 2.0 m/s - The figure shows the performance evaluation of normalised packet loss for RWP mobility model with speed of 2.0 m/s

Figure 6.15: Packet loss for forest fire scenario - The figure shows the performance evaluation of normalised packet loss for forest fire scenario

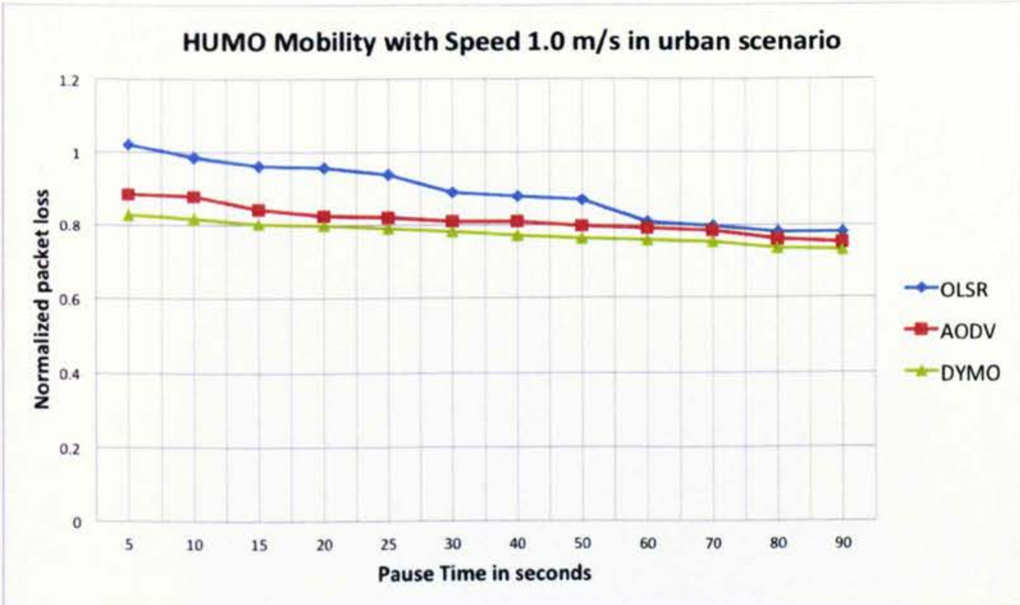


Figure 6.16: Packet loss for urban scenario - The figure shows the performance evaluation of normalised packet loss for urban scenario

portant to note that the HUMO model [64], also explained above, is used in all our simulations. In addition, the simulation area used is set to $1000m * 1000m$. We base our routing performance evaluation upon the data packet loss during the simulation. In this paper, we consider the ratio of number of packets lost per packet sent as a normalised value of lost packet rate which can be used as a metric to fairly compare protocol performances.

Fig. 6.12-6.16 illustrate the normalised packet loss results for the various simulation scenarios described above. In Fig. 6.12-6.14, we clearly observe that as the average pause time is increased (node mobility decreased), the packet loss ratio is decreased. This is mainly due to the fact that lower mobility results in less route changes and thus the validity period of discovered routes increases. Moreover, OLSR updates route information at fixed intervals during which routes can become invalid due to route changes and packets are dropped as a result of this proactive mechanism. The difference in packet drop rate between OLSR and the reactive approaches is reduced as the mobility of the network decreases. Furthermore, DYMO has a better routing performance than AODV because it uses the RERR packet to immediately signal a route change to

DYMO routers so that the source node can initiate route discovery for a valid route. In the case of AODV, the source node has to wait until the changed route is timed out for it to rediscover a valid route. In addition to the pause time, the average node speed is also varied. It can be noticed that the packet loss rate slightly increases when speed is increased. Nonetheless, for the range of investigated pause times and speeds, it can be deduced that pause time has a more pronounced effect on packet loss rate than changing speed.

Results of performance evaluations from the use of the HUMO mobility model is shown in Fig. 6.15 and Fig. 6.16. It can be observed that the same trend in packet loss rate exists when the average pause time of nodes in the network is varied. Furthermore, there is a slight increase in packet loss rate for all the protocols because of the presence of obstacles in the environment. The presence of obstacles limits direct connectivity among nodes which have to use multi-hopping for data packet delivery. This increases the likelihood of a route change with increased node mobility thus increasing packet loss rate. This is further supported by the fact that the packet loss rate in the urban scenario is slightly lower than in the case of the forest fire scenario where the presence of numerous obstacles creates longer and more dynamic routes. Hence, it can be concluded that both average node pause time and the presence of obstacles in the environment affect the packet loss rate more than the variation of the average node speed for speeds up to 2.0 m/s.

6.4.3 Protocol Implementation Guidelines for CAM Suite

In this subsection, one of our main aims is to illustrate how the CAM suite can be utilised to facilitate the implementation of complex algorithms including converged cognitive and hybrid adaptive routing approaches based on research and experimental findings. It is important to note in that respect that a sequence list is defined in the CAM Core and contains an updated list of Components and Parts that are active. It also specifies the data and control flow among the components and parts. The CAM Core defines appropriate data structures and algorithms that will help to accommodate additions in the sequence list before the CAM Core starts operating in order to enable the defined Components and Parts.

A researcher or engineer who uses the CAM suite to implement a protocol should be able to define a consistent control flow and data flow within the CAM Core as described next. If a control packet is received from another node, the packet is duplicated. One copy is used to extract context information in the monitor component while the other is used by the routing algorithm for processing route information. The active routing component is identified using the coarse variable that identifies the "Routing Component". Any associated fine variable values should be used to identify CAM Parts and to update the routing parameters such as that of route discovery intervals. The monitor gathers information in the Repositories component. It also compares the network context against defined thresholds according to methods described above and in Chapter 5.

If a threshold is exceeded, the associated trigger is used to pass the message to the relevant Adaptive component part using its associated ID. Then, the Adaptive Component must check whether the trigger is valid and may subsequently change values for coarse and fine variables if trigger is valid. In the case that a control packet needs to be sent to another node, the routing algorithm sends the packet to the CAM Core "packet send interface". The core then sends the packet to the outgoing queue. In the event that a data packet is received from another node, the core sends the data to the Routing algorithm component. The Routing algorithm component checks the packets according to the active routing logic. If the current node was the intended recipient of the packet, data packet is sent to the core send interface.The data packet is placed in the incoming queue and then sent to upper OSI layers. Otherwise, the data packet is forwarded as specified by the routing logic. If a data packet needs to be sent to another node, the core sends the packet to the relevant part of the Routing Component. The data packet is forwarded as specified by the routing logic.

6.4.3.1 CML Protocol

We illustrate here the CAM Suite design guidelines for implementing a converged hybrid routing protocol using CML, described in Chapter 5, as a use case. This version of CML should provide more flexibility as compared to OLSR and AODV individually. Consequently, it may be more appropriate for usage in a wider range of scenarios such as where battery limitations and packet delay are important routing factors. In such a context, this version of CML may provide better performances. CAM allows for easier protocol configuration and thus add-ons can be readily integrated to proposed protocols while routing parameters may be either manually or automatically tuned. The Routing component of CML consists of various parts that include a proactive part based on OLSR, a reactive AODV part and a neighbour discovery part using NHDP. Initially, routing is carried out as described in OLSR [29] using the Routing Component, OLSR Part logics. The Monitor component monitors the network size and network density. The NHDP part in the Routing Part is always operational in parallel updating neighbourhood information as described in [34].

The coarse and fine variables indicate the mode of operation and the default mode of operation for this use case is as described in [29]. The CAM suite operations in each node can be described as follows. The Monitor Component monitors network size by counting the number of nodes in the network in the routing table found in the Repositories Component. It also monitors the network density by counting number of neighbours in the 2-hop neighbourhood table used by NHDP. These values are compared with the corresponding threshold values that may be stored in the CAM Core or ideally in the Repositories Component. These threshold values may be lower or upper bound threshold values for density and network size depending on the operation band of the node. The corresponding defined triggers found in the CAM Core are then used to access the relevant part of the adaptive module. The adaptive component uses the core to set the TC_HOP_LIMIT value to $H1$ hops if the ratio of (Network density/Total number of nodes) is greater than a pre-set threshold value R, uses the core to set the TC_HOP_LIMIT value to $H2$ hops if the value of node density and number of nodes thresholds are greater than $D1$ and N respectively, uses the core to set the TC_HOP_LIMIT value to 2 hops if the value of node density is less than D1 and number of nodes greater than N or finally uses the core to increment the TC_HOP_LIMIT value by 1 if the value of node density is greater than D2 and number of nodes is less than N. The aforementioned checks are carried out to make sure that the node distribution in the network and the total number of nodes in the network have values are expected via research in Chapter 4.

The Routing Component consists of Parts that are described in [29, 34, 37] respectively. The CAM suite uses routing logic as described in OLSR [29] by default to calculate routes and store them in routing tables proactively using HELLO and TC messages, forward data to destinations found in the proactive routing tables and process control packets. If RREQ and RREP packets are received while the current active part is the OLSR part, CAM suite will process packets as defined in [37]. RREQ packets are unicast to destinations found in the proactive routing table and RREQ are flooded through MPR nodes if destination is not in proactive routing table. Corresponding relevant information of RREQ packets are stored in the reactive routing table as specified in [37]. A RREP is then unicast towards the source node using the stored reactive table RREQ information if the proactive table does not contain an entry for such a source. In case that the proactive table has such an entry, it sends the packet through that route updating the reactive table with relevant entries. In the event that the Adaptive Component activates the AODV Routing part, the CAM Suite uses routing logic as described in [37] generate reactive routing packets when routes to destinations are not found in the proactive table and forward data to such destinations not found in the proactive routing tables but listed in the reactive table as a result of the previous step. It also generates and flood RREQ packets if the node acts as a data source. The Repositories component defines and implements the reactive, proactive, neighbourhood routing tables as well as other tables as required by the Routing Component. It also defines and implements data structures to store different parameter values required by the other specified components. Finally, the Packet and TLV specification component defines and produces packets and messages using the formats specified by the routing logics such as in [29, 34].

6.4.3.2 Integration of further research findings

Here, we describe design guidelines for the CAM suite to demonstrate how its modular features. From the results illustrated in Fig. 6.2-6.16, it can be observed that various other contexts and routing parameters can be considered to optimise the routing approach in MANETs as an extension of our investigations from Chapter 5. One such parameter is the monitoring of data traffic in the network and determining the number of connections. It can be observed from the results that the potential NST value varies according to the number of data connections in the network. Therefore, it the monitored number of connections in a Monitoring Component is equal to a corresponding threshold value in the Threshold Component, a different NST threshold value in the NST part of the same Component is utilised. Another component that can be monitored in the network is the MPR willingness of nodes that use a proactive approach. The lower the level of willingness of nodes to form part of MPR sets or the the higher the value of the MPR ratio, the higher number of routing overhead will be present in the network and the higher delay that will be observed. Hence, in such cases, there may be requirement of decreasing the NST value if necessary. Such a study of finding a balance by using experimenting with a combination of the different factors in real-life situation can be a very useful path for future work in the area, especially using the CAM suite. These are further emphasised in Fig. 6.8 and Fig. 6.9 where the efficiency of proactive and reactive routing approaches are compared based on varying number of data connections and MPR ratios.

Another very important parameter to monitor in the network is the mobility of nodes. As deduced above, the pause time of mobile nodes has a more pronounced effect on routing performance that the actual magnitude of the speed in the network. Hence, it is important to deduce a mechanism such as described in [25], that monitors the link lifetime among nodes and accumulates a statistical database. The CAM suite could be used to store a historical data set of link durations in the Repositories Component and then compute the necessary statistical mean values as required using the Monitoring Component based on a timer driven process. This evolving statistical monitoring and storage process will allow for a novel Adaptive Component Part that will deal with mobility in the network. As shown in the results from Fig. 6.12-Fig. 6.16, the main objective in such a routing approach would be to minimise packet loss at the cost of added overhead using routing packets more regularly. Thus, as indicated in the above results, the ROUTE_TIMEOUT for reactive approaches or HELLO interval for proactive approaches can be increased or decreased respectively using the Adaptive Component according to the mobility level as monitored by the Monitoring Component. A higher mobility level would require higher HELLO interval values and lower ROUTE_TIMEOUT values in order to decrease the packet loss rate to an acceptable level as well as illustrated in Fig. 6.6 and Fig. 6.7.

6.4.3.3 Testbed Implementation

We have implemented an alpha prototype version of the CAM suite at Kingston University using objected oriented C++ code. Thus, we have implemented and deployed the

CAM Core, Routing Component, Repositories Component, Cognitive Component with ETX value monitoring Part, Packet format Component and Threshold Component with ETX Part over Android HTC phones, Motorola Zoom tablets, Apple iPads and Apple iPhones. The native C++ code for developing core functionalities were similar across mobile platforms with the chief difference between codes being the interfacing required by CAM suite with respect to the operating system routing tables. Also, the way of implementing such an interface were different in Android platforms as compared to iOS platforms. In Android devices, we created an interface between the C++ source code and the Java based Android Runtime libraries using the inbuilt Java Native Interface through Eclipse. In the iOS devices the same interface was created using Objective-C with embedded C++ sockets to access the BSD stack and routing tables. The observations obtained from initial tests from a testbed of 6 heterogeneous Android and iOS devices have shown that the deployment of CAM suite for MANET communication is realistic.

6.5 Summary

In this chapter, we presented the CAM suite and extended our research from the previous chapter to investigate other parameters that affect QoS MANET routing metrics. We have also shown that complex cognitive and adaptive routing approaches can be implemented in a lightweight fashion using the flexible and modular design of CAM. The framework is unique in the way it defines the Core, Components and Parts as a sequence of containers that implement routing processes in an increasing order of configurability and decreasing order of essentiality in terms of MANET routing. Thus these modular containers can be readily isolated and experimented with in order to design innovative approaches for routing. In particular, we have demonstrated how the CML protocol can be implemented in the CAM suite to cognitively and adaptively converge network routing approaches for variable size MANETs. Additionally, we extended our research to evaluate some other network contexts and protocols to give an insight on the way further investigations can be carried out for various MANET scenarios and adaptive features implemented to improve the performance of routing approaches. In the next chapter we present our conclusions and future work.

Chapter 7

Conclusion and Future Work

This chapter concludes the work that has been presented, in previous chapters, as part of our contributions in this thesis. It presents the achievements of this thesis with respect to the research objectives that were listed in Chapter 1. We then present possibilities of future work in the area of cognitive and adaptive approaches for scalable MANET routing including the utilisation of CAM suite to implement such approaches. We also include a complete list of our publications related to our work in the broader field of ad hoc routing including those cited in this thesis as part of work in the area of cognitive and adaptive approaches.

7.1 Major Achievements

In this thesis, we have achieved contributions to 3 key research areas in the field of MANET routing following the approach described in [1]. This methodology resulted in a iterative investigation process as illustrated in Fig. 1.3 from Chapter 1. Our investigations have resulted in:

1. Derived QoS models: We have modelled the end-to-end delay, routing overhead and energy consumption characteristics of MANET routing approaches including AODV and OLSR over IEEE 802.11 interfaces assuming a Distributed coordination function CSMA/CA MAC protocol in Chapter 4. We have used these models to understand the behaviour of routing processes especially related to the changing sizes of MANETs for scalable scenarios. One version of the model considers

free-space environments whereas an obstacle prone environment model was also derived and presented. We have evaluated the performance of AODV and OLSR based on these models and have deduced that for both situations, there exist a theoretical NST (found to be between 10-15 nodes depending on scenarios), beyond which reactive approaches should be more suitable than proactive approaches assuming the default approach is a proactive one. We have also validated this approach using ns-2 simulator to show that these models are valid within margins of error due to other real-life parameter effects such as user mobility and signal propagation. In summary, the following achievements were achieved using our iterative investigations as shown in Fig. 1.3:

- Generic mathematical models for end-to-end delay and routing overhead for proactive and reactive routing approaches over free-space and obstacle environments.

- The aforementioned models were applied to AODV and OLSR protocols to understand protocol operation, quantify performance and identify a theoretical value for NST in scalable MANETs which was found to be in the range of 10-12 nodes.

- Performance evaluation of AODV and OLSR using ns-2 under the above scenarios using ns-2 with HUMO [64] model extensions for simulating obstacles. The results validated theoretical models and confirmed that a converged hybrid routing approach such as CML would be beneficial for variable size MANETs such as in PPDR communication scenarios.

2. Novel converged hybrid and adaptive routing protocol: We have designed a converged hybrid adaptive routing approach called CML in Chapter 5 which is based on OLSR and AODV. As a consequence of identifying the existing of the NST, we have developed CML and identified as well as proposed solutions to emerging challenges. The main challenges that were solved using the CML design was the oscillation problem, a monitoring system for network size for both proactive and reactive routing approaches as well as an adaptive method for converged hybrid approaches. Further an Energy Efficient (E2) mechanism was designed in order to prevent critical network node battery exhaustion and prolongation of network lifetime by load balancing during routing. We also evaluated the performance of

flat routing protocols, CML and E2CML using ns-2 simulator. Furthermore, the superior performance of CML was compared with other scalable routing protocols using model based simulations. It may be important to note that CML has been presented and discussed at the IETF where we try to influence the acceptance of a hybrid routing track as a result. An overview of the research achievements in this area of investigation is:

- The design, implementation and evaluation of the lightweight CML protocol: the novel converged and hybrid protocol switches from a proactive to reactive routing approach based on the MANET size as compared to a preset value of the NST monitoring the size of MANETs, establishing a threshold for network size with regards to performance of flat routing protocols and converging the routing approach in the MANET if a switch in protocol is required. An O-phase operation is introduced to tackle the oscillation problem identified for such converged approaches.

- We implemented and evaluated the novel E2 mechanism for CML protocol in order to reduce the residual energy variance among nodes in the network as a result of routing. One of the main aim of E2CML as compared to flat routing approaches is to prevent over-use of critical nodes in MANETs so that there probability of network segmentation is reduced.

- We have also simulated and compared the performance of both CML and E2CML against other well-known flat and scalable routing protocols in literature e.g. AODV, OLSR, DYMO and ZRP.

3. Innovative CAM: We have designed, developed and have a patent pending lightweight MANET routing framework that can facilitate the implementation of protocols including advanced cognitive and adaptive approaches. We have used a modular approach to the problem of simplifying the implementation of flexible framework so that a pluggable 3-tier structure could be designed depending on the essence of routing mechanisms. Therefore, all essential mechanisms have been implemented in the CAM Core, the required routing functionalities such as route selection and data storage are defined in CAM Components and the actual system or context specific logics are implemented in CAM Parts. In Chapter 6, we provide an instance of CAM suite for implementing CML and use further simulations to

demonstrate the way CAM suite can be useful for implementing and testing research findings. Briefly, our achievements on this research area can be summarised as:

- We designed and specified a lightweight CAM suite and necessary implementation structures. The CAM suite encompasses a full set of definitions that can be used to implement advanced concepts for adaptive as well as hybrid routing such as traffic QoS requirement based route selection, network context adaptation and portability of logic across platforms.

- We implemented the CAM suite over Android, iOS and Linux mobile platforms and their interoperability.

- We evaluated the performance of flat routing protocols in different topological contexts in order to demonstrate need for adaptation beyond relationship of NST e.g. considering mobility and traffic type.

- We instantiate protocol logic implementation in the CAM suite using the example of CML converged adaptive hybrid approach and logic for adapting routing for mobility and traffic pattern from findings above.

7.2 Future Work

Although the field of routing in MANETs has been heavily investigated in literature, there are interesting areas of research especially in the field of adaptive approaches and frameworks for MANET routing so that realistic solutions can be provide. It has been discussed in [2, 3, 4, 12, 17, 18, 48] that the substantial amount of research so far in MANETs has been much more theoretic than realistic. Therefore, there is much interest in model based frameworks that can be validated and tested in real-life scenarios. This necessitates validation of particular functionalities as being accepted in literature and IETF so that other design issues can be researched and solutions implemented. Thus, the CAM suite is a good candidate for the emerging research interest of using a framework for provisioning of hybrid routing in MANETs. Researchers should use the CAM suite in the future to design their Components and Parts in order to test their models and simulation results in real-life environments. Furthermore, once matured solutions for routing functionalities are standardised or widely accepted e.g.

NHDP for neighbourhood routing and the generalised MANET packet format [28], the CAM suite can be suitably utilised to test competing alternatives in real-life scenarios. The CAM suite allows for flexible plug-and-play approach towards routing functionalities and thus will allow researchers and engineers further down the years to test combinations and permutations of competing components and parts.

Another interesting future work related to our contributions is the extension of cognitive and adaptive concepts of CML protocol. As presented in the discussed sections, although the network size is an important factor in determining the adaptive actions of converged hybrid protocols, there are other triggers for marco-level adaptivity (change in routing approach) as well as micro-level adaptivity (change in routing parameters such as signalling intervals). There are further investigations that need to be carried out for identifying the effect of different levels of mobility on various approaches and protocols and determine the balance between cost of signalling and improvement of QoS. As identified in Chapter 6, another interesting stimulus to be considered towards macro-level adaptation and threshold determinations in converged hybrid approaches should be the traffic profile that circulates in the MANET. Our prior investigations have indicated that a higher number of data connections may lead to an increase in the value of the NST for a given scenario. The cognitive part of adaptive protocols can play a major role towards reduction of routing cost and significant improvement in the QoS of routing protocols in MANETs. One such cognitive evolution should be towards predictive algorithms that can use network statistics to dictate the path selection process. Although work can be found in literature for such approaches, more research work can be carried out in the sphere of validated realistic model based predictive algorithms rather than simplified heuristic approaches.

Other important areas of research that are necessary for the deployment of MANETs in real-life scenarios are overlays for MANETs and secure cross-layer solutions. For instance, the area of cross-layer mechanisms for overlay-network layer routing using Distributed Hash Tables (DHTs) has seen significant research interest in recent past. The authors of [97] specifically examine cross-layer DHT MANET protocols such as Etka [98], MPP [99], a Gnutella optimisation for MANETs [100] and MADPastry [101]. Hence, the CAM suite could be extended to provide the necessary interfaces between the overlay functionalities and the network layer operation in order to test such examinations and provide more realistic evaluations. As mentioned in our work [23, 24], converged hybrid approaches such as CML should have security countermeasures. Although, different secure versions of AODV and OLSR have been proposed in the literature, CML introduces new vulnerabilities e.g. any malicious node can generate a change phase packet so that there is inefficient changes in the routing approach. Also, a set of malicious nodes that coordinate their actions and create oscillations in order to drain the battery levels of devices. Basic security requirements such as confidentiality, authentication, integrity and availability have to be implemented. Here, CAM should be extended to define an essential security component where logics for security measures are defined in the future implementations using concepts from literature such as in [23, 24, 94].

7.3 My List of Publications

7.3.1 Accepted

Journal

1. T. A. Ramrekha, E.A. Panaousis and C. Politis, Standardisation Advancements in the Area of Routing for Mobile Ad-hoc Networks,The Journal of Supercomputing (Special Issue on Advancements in Communication Networks for Pervasive & Ubiquitous Applications), vol. Online, pp. 1-26, 2011.

2. T. A. Ramrekha, V. Talooki, C. Politis and J. Rodriguez, Energy efficient and Scalable Routing Protocol for Extreme Emergency Ad Hoc Communications, ACM/Springer Mobile Networks and Applications (MONET) Journal (Special Issue on Future Internet for Green and Pervasive Media,), pp. 113, 2011.

3. E.A. Panaousis, G Drew, G. P. Millar, T. A. Ramrekha and C. Politis, A Testbed implementation for securing OLSR in mobile ad hoc networks, International Journal of Network Security and its Applications, vol. 2, no. 4, pp. 143-162, Oct 2010.

4. E.A. Panaousis, T. A. Ramrekha, G. P. Millar and C. Politis, Adaptive and secure routing protocol for emergency mobile ad-hoc networks, International Journal of Wireless and Mobile Computing, vol. 2, no. 2, pp. 62-78, May 2010.

Chapter In Book

5. T. A. Ramrekha and C. Politis, An adaptive QoS routing solution for MANET based multimedia communications in emergency cases in Mobile Lightweight Wireless Systems, Granelli, F. et al., Eds., Springer Berlin Heidelberg, pp. 74-84, 2009.

Conference and Workshop

6. T. A. Ramrekha, C. Politis and P. Remagnino, A Novel Ubiquitous Cooperative Communication Platform (NEOCOP) for Future Emergency Management Systems in 27th Wireless World Research Forum (WWRF) meeting, A new convergence framework CLOUD, PIPE and DEVICE over Mobile Broadband, WWRF, Dusseldorf, Germany, pp. 132-138, Oct 18-20 2011.

7. T. A. Ramrekha, G. P. Millar and C. Politis, A Model for designing Scalable and Efficient Adaptive Routing Approaches in Emergency Ad hoc Communications in 16th IEEE Symposium on Computers and Communications (IEEE ISCC 2011), Kerkyra (Corfu), Greece, pp. 916-923, Jun 28 Jul 1 2011.

8. G. P. Millar, T. A. Ramrekha and C. Politis, A cross-layer model to reduce control traffic overhead in peer-to-peer mobile ad-hoc networks in 25th Wireless World Research Forum (WWRF) meeting, London, UK, pp. 221-228, 16 Nov 18 Nov 2010.

9. A Mehdi Toussi, T. A. Ramrekha and C. Politis, Energy efficiency and QoS in wireless sensor networks in 25th Wireless World Research Forum (WWRF) meeting, London, UK, pp. 140-146, 16 Nov 18 Nov 2010.

10. E.A. Panaousis, T. A. Ramrekha and C. Politis, Secure routing for supporting ad-hoc extreme emergency infrastructures in Proceedings of the Future Network and Mobile Summit, IEEE, Florence, Italy, pp. 1-8, Jun 16-18 2010.

11. T. A. Ramrekha, V. Talooki, C. Politis and J. Rodriguez, Energy efficient and scalable routing protocol for extreme emergency ad hoc communications in 6th

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12. T. A. Ramrekha and C. Politis, A Hybrid Adaptive Routing protocol for Extreme Emergency Ad Hoc Communication in In Proceedings of the 19th International Conference on Computer Communications and Networks (ICCCN 2010), IEEE, ETH Zurich, Switzerland, August 25 2010, pp. 1-6.

13. T. A. Ramrekha and C. Politis, Impact of Mobility on QoS Routing for Extreme Emergency Mobile Ad-hoc Networks in In Proceedings of the 24th Wireless World Research Forum (WWRF) meeting , Penang, Malaysia, pp.126-132, Apr 12-14 2010.

14. E.A. Panaousis et al., A Framework Supporting Extreme Emergency Services in Proceedings of the Mobile Summit, IEEE, Sandanter, Spain, pp. 280-286, June 10-12 2009.

15. G. P. Millar, T. A. Ramrekha and C. Politis, A peer-to-peer overlay approach for emergency mobile ad hoc network based multimedia communications in Proceedings of the 5th International Mobile Multimedia Communications Conference, London, U.K., pp. 59-64, 7 Sept 9 Sept 2009.

16. T. A. Ramrekha, E.A. Panaousis and C. Politis, Routing challenges and directions for smart objects in future internet of things inInterconnecting Smart Objects with the Internet Workshop, IETF, Prague, Czech Republic, Mar 25 2011.

White Paper

17. J. Wu et al., Requirements and vision for NG-Wireless White Paper, Work Group 3, OUTLOOK Visions and research directions for the Wireless World, Wireless World Research Forum (WWRF), no. 7, Oct 2011.

18. H Abramowicz et al., Future Networks and Management White Paper, Net!Works European Technology Platform, Expert Working Group, Jun 2011.

Standard

19. T. A. Ramrekha, E.A. Panaousis and C. Politis, ChaMeLeon (CML): A hybrid and adaptive routing protocol for Emergency Situationin IETF Internet Draft, draft-ramrekha-manet-cml-02.txt (Work in Progress), IETF MANET Working Group, February 2011.

20. T. A. Ramrekha, E.A. Panaousis and C. Politis, A generic Cognitive and Adaptive Module (CAM) for MANETs in IETF Internet Draft, draft-ramrekha-manet-cam-01.txt (Work in Progress), IETF MANET Working Group, Dec 2010.

21. T. A. Ramrekha, E.A. Panaousis and C. Politis, A generic Cognitive and Adaptive Module (CAM) for MANETs in Proceedings of the Internet Engineering Task Force (IETF) Meeting 78, Mobile Mobile Ad-hoc Networks (MANET) Working Group, Maastricht, Netherlands, Jul 2010.

22. T. A. Ramrekha, E.A. Panaousis, G. P. Millar and C. Politis, ChaMeLeon (CML): A hybrid and adaptive routing protocol for Emergency Situations in Proceedings of the Internet Engineering Task Force (IETF) Meeting 77, Mobile Ad-hoc Networks (MANET) Working Group, Mar 2010.

7.3.2 Submitted

Journal and Patent

23. T.A. Ramrekha, G. Millar, E. Panaousis, and C. Politis, Method and apparatus for Framework for Ubiquitous Networking, UK Patent 1111955.9 (under review), July 2011.

24. T. A. Ramrekha and C. Politis, A validated model for evaluating scalability of hybrid ad-hoc routing protocols, IEEE/ACM Transactions on Networking (TON) (submitted).

25. E.A. Panaousis, G. P. Millar, T. A. Ramrekha and C. Politis, A Game Theoretic Framework for Security in Mobile Ad-hoc Networks, IEEE Transactions on Parallel and Distributed Systems (TPDS) (submitted).

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Declaration

I herewith declare that I have produced this thesis without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This thesis has not previously been presented in identical or similar form to any other UK or foreign examination board.

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