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Research Article

RCTP: An Enhanced Routing Protocol Based on Collection Tree Protocol

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Due to implementation of routing protocols in limited power supply devices in wireless sensor networks (WSNs), this paper presents and evaluates Rainbow Collection Tree Protocol (RCTP) as an enhanced version of Collection Tree Protocol (CTP). CTP is a lightweight, efficient, robust, and also reliable routing protocol for WSNs. CTP as a cross layer routing protocol is also a platform-independent protocol. It uses Trickle Algorithm to optimize the overhead cost and also makes it quickly adaptable to changes in topology. The basic foundation of CTP is on link quality identification and it uses expected transmission count (ETX). ETX is not stable during the time in real environments and ETX fluctuations cause the routing protocols to not work in optimum level. RCTP uses average expected transmission count (AETX) as link quality metric that has shown it is more stable than ETX. It also uses a new mechanism in parent selection to make it more accurate. Rainbow mechanism is used in RCTP to detect and route around connectivity nodes and avoid route through dead end paths. The Omnet++ has been used as a simulator and the results show RCTP performs more efficiently than CTP in dynamic and crowded environments.

1. Introduction

The main duty of WSNs as a distributed computing network is collecting data from a large amount of nodes that they have capacity of sensing the environment, processing data, and also communicating in short range distance. WSN applications collect data from wireless sensors and a proper routing protocol could help them to achieve scalability and improve performance. Data collection protocols can form planner or tree topology that could be in cluster or mixed data collection form. CTP is one of the many-to-one routing protocols which has been proved to be extremely efficient and is based on spanning tree method. It establishes at least one data collection tree with a sink as the root node in the topology [1]. All data which is produced by sensors is forwarded to root node. Each node not only is responsible for sending its own data but also is responsible for relaying other's data that they have more distance to root node. CTP has shown that it is far better as a data collection protocol than any other existing protocols [2]. CTP uses Trickle algorithm [3] to optimize the overhead cost and make it more flexible. The control protocol packets are sent based on changes on topology and if there is no change in topology, the interval times would be increased each time to decrease the number of network control packets in stable topology. It also makes it react quickly and adaptable to any changes in topology and if any change in topology is sensed then the interval time resets to minimum to update topology very quickly [4]. CTP covers four goals: reliability, robustness, efficiency, and hardware independency. CTP uses the best quality available links in the path and it also avoids them when they fail. CTP considers the link estimation in every 5 packets to keep it accurate with agility.

CTP uses ETX as link quality metric to avoid lossy links [5]. ETX stands for the expected total number of transmissions required to successfully deliver a packet [6]. The greater value in ETX in a link shows that the reliability of that link is lower. The ideal value for ETX for a perfect link is 1. Researchers show that ETX value is fluctuating during the time even by fixing all environment properties in real testbed [7–11]. CTP cannot show a good performance in dynamic environments [8–11]. The work in [4, 12] proposed that typical

ETX or delivery ratio is between 70 and 90%. The work in [13, 14] has shown that the typical delivery ratios could even be worse as 20–40%. The reasons that the successful delivery ratio is significantly fluctuated are the objects entering into the communication area even such as rain or wind that they affect radio frequency propagation. Even other kinds of equipment that are working in the same radio frequency band make interference to data communication [15].

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

In this paper we approach the problem of instability of ETX in real environment and proposed a new method to improve CTP. The proposed method does not increase the overhead in terms of increasing number of packets to maintain the topology. We define a cross-layer protocol, named RCTP based on data collection protocol that is a lightweight routing protocol and it is fit for low power devices. In our proposed routing protocol, we have changed the link quality metric between nodes from ETX to AETX that makes the protocol more stable. RCTP enhances greedy forwarding by considering congestion and packet delivery information when making decision to find the best path to destination. The new relay selection scheme that implements media access control (MAC) and routing protocol functions in a cross-layer combination makes an achievement in performance in routing protocol. RCTP uses a new mechanism to choose a parent that it is based on AETX value of each neighbour plus the AETX value of the link that in total choose the best possible parent between existing qualified neighbours. RCTP avoids causing a loop in topology. RCTP shows a better performance in terms of energy efficiency, packet delivery ratio, and packet end-to-end delivery time. These properties make RCTP able to guarantee packet delivery in realistic deployment. In this paper, some mechanisms employ RCTP that make it capable to avoid loops in the network and a new mechanism choosing parents that is more accurate than CTP.

Omnet++ as a wireless sensor network simulator has been employed to measure the performance of RCTP in comparison with existing CTP protocols. Simulation is able to show how the unique features of RCTP could be determined in overall performance in terms of comparison with previous versions. In different scenarios, we make a few nodes to advertise wrong root cost to their neighbours to make them choose the relay selection and then observe the performance of RCTP. Rainbow mechanism is used in RCTP to avoid using dead ends routes. The principal of rainbow is to avoid forwarding packets away from the sink. It will guarantee that the packets travel toward the sink and it avoids sending the packets toward dead end routes. RCTP uses a detection mechanism during the data packet transmission to validate the routing path and topology. This mechanism makes RCTP avoid loops. It also uses the link-layer distance estimate in each packet to validate the topology.

This paper is organized as follows. Section 2 describes the motivation for this research and Section 3 reviews the state of the art on CTP. Previous works have been described in detail in Section 4. Section 5 shows the design details of RCTP and system model in Section 6. Evaluation and results from simulation come in Section 7. And finally conclusion is provided in Section 8.

2. Motivation

WSN contents comprise small devices in which energy consumption is a vital key (Figure 6). Any protocols that are used should be energy aware. CTP is a lightweight, simple, and efficient routing protocol and also is a best-effort, reliable, and many-to-one routing protocol. This simple and effective routing protocol is the foundation for sensor applications that could work on top of the network layer. It is almost a decade that CTP suffers from poor performance with delivery ration of 2–68% [8–11]. Adding some simple mechanism could improve CTP performance and make it work with more efficiency. Our previous experience in considering different metrics and finding a stable version of ETX was a motivation key to improve CTP. Implementing AETX as a link quality metric in CTP, improving the mechanism of parent selection, and also using rainbow mechanism make RCTP a new version of CTP with better performance.

3. Collection Tree Protocol

CTP is a data collection protocol based on tree topology. It forms the routes to a single or a small number of designated roots (sinks) in a network of wireless sensor devices. The two principals of CTP are data path validation and adaptive beaconing [4]. Based on these two principals, goals of reliability, robustness, efficiency, and hardware independence could be achieved. In terms of reliability, the packet delivery ratio should not be less than 90% in case of end-to-end delivery ratio and 99.9% in case of simple delivery. Robustness guarantees that the network will work without any configuration or tuning regarding working in a wide range of network conditions such as different channel characteristic, number of nodes, and even payload. Efficiency comes up in terms of using the resources that should be as small as possible and energy consumption in total system should be minimum. Hardware independence implies the design that does not need special hardware or specific radio chips and the design should apply to all existing platform of WSNs [4].

A few nodes in the network advertise themselves as tree roots. Other nodes in the network form a tree network topology and send data toward these root nodes. Each node chooses the path to root by selecting the next hop based on a routing gradient [11]. CTP uses ETX as its routing gradient. Each node is labelled as an ETX value. Roots ETX values are 0 and other nodes' value is calculated by

$$\text{Node}\,(\text{ETX}) = \text{Parent}\,(\text{ETX}) + \text{Link}\,(\text{ETX})\,. \quad (1)$$

Each node selects its parent from a group of its qualified neighbours that have already advertised their ETX values. The neighbour that is selected as the node's parent is the neighbour with less ETX value. Routing loop could occur in case of losing connectivity with current parent and selecting a new parent with ETX value higher than ETX of previous parent. If the new route to the sink includes the current node then a loop occurs in the packet transmission. CTP uses data path validation mechanisms to avoid making loops in the topology. If CTP receives a data packet that the ETX value of sender is equal to or less than its own ETX, it shows an inconsistency in the tree topology and it sets the trigger to reconsider the topology. If the tree topology has been set up properly, the packet travels from the source to sink by travelling to the routers and each router should be closer to sink with ETX value or cost of reaching sink lower than previous router. If a data packet arrives at a router and its ETX value is higher than the previous router, it shows that it is not travelling toward the destination and it is going further from the sink [4].

Packet duplication is another challenge in WSNs that affects the total energy consumption in the system. When a packet has arrived at a node successfully and the receiver node sends acknowledgement (ACK) to the sender, but this ACK is not received by sender, the sender considers sending data packet again and it makes packet duplication in the network. This data duplication propaganda through other nodes in the network and it grows exponentially. CTP also uses time has lived (THL) value to suppress the duplicated packets. THL is decremented by network layer on each hop. CTP keeps originating address, sequence number, and THL value of each transmitting packet. When packet arrives, CTP compares these values with their own keeping table and will drop the packet that has been transmitted before [4].

4. Related Works

CTP Neo [4] has been proposed to employ two mechanisms, validating data path and using 4-bit link estimator. CTP Neo has been used in 12 different testbeds and the results show the delivery ratio is improved by more than 90%. They also show that by using CTP Neo it uses on average 73% fewer beacons in comparison with standard beaconing. CTP-TICN [16] is another version of CTP. CTP-TICN has done some changes in link estimation calculation and it also provides load balancing. It uses EETX instead of ETX that is the extra expected transmission and it is calculated based on probability of successfully received packet on both sides of a link. CTP-TICN uses a weighted mechanism that uses the old EETX and current EETX based on a parameter that is set in implementation. POCTP [17] is a Qos routing protocol based on CTP. POCTP is based on the definition of Pareto optimal route that it has been evaluated by using hierarchical Petri Net modelling technology. BCTP [6] is a balanced version of CTP. It enhances CTP by enabling the nodes to balance the traffic to avoid some nodes that drain their energy because all traffic passes through them. It uses a strategy to balance the load through the network to balance energy consumption by nodes. ICTP [18] is a load balanced version of CTP. The concept of ICTP is based on using both long path with good link quality and also short path with weak quality link that on the one hand it decreases reliability and on the other hand it avoids congestion that improves reliability. With the combination of two above factors, the results show ICTP performs better than CTP. O-CTP [15] is based on investigation of WSN routing protocols behaviour in networks that are affected by interference. O-CTP is a hybrid routing protocol that uses the high packet delivery ratio of opportunistic routing in error-prone networks and it also is energy efficiency routing protocol.

ICTP [19] uses both long with good link quality path and also short with bad link quality. It may decrease the reliability but it improves efficiency to avoid congestion. The authors have shown that the energy consumption in ICTP is less than CTP in same scenarios based on reducing possibility of congestion.

BCTP [20] is balanced version of CTP that enables the network to avoid the heavy traffic nodes. It uses average transmission rate as a metric. BCTP has been evaluated by a testbed and the results show that the load in hotspot drops by 61.9%.

5. RCTP: The Improvement of CTP

5.1. Challenges. CTP as a light and efficient routing protocol in WSNs suffers from poor performance for almost a decade. Some deployments report the delivery ratio of 2–68% [4] and it is not clear why CTP performance is poor in practical experience even in low data rates (Table 1). The challenge is to improve performance of CTP and makes it a robust and efficient routing protocol with high reliability in WSNs. CTP uses ETX as link quality metric and the ETX value is fluctuating during the time even by fixing all environment properties. The reasons that the successful delivery ratio is significantly fluctuated are the objects entering into the communication area or interference made by other kinds of equipment that are working in the same radio frequency band. This ETX fluctuation may cause the routing protocols to make a wrong decision regarding finding the best path to the destination. RCTP uses AETX that has been proven more stable than ETX. Some CTP implementation uses a weighted system to use current ETX and old ETX. The challenge is to improve CTP performance in dynamic environments and the goal is to improve packet delivery ratio. Parent selection is one of the main keys in CTP routing protocol. This procedure is repeated periodically or based on some trigger. Parent selection trigger will be set in these scenarios: a parent is unreachable, current parent gets congested, one or some neighbours are no longer congested, and a special beacon is reached or is finding inconsistency during transferring a packet by processing the packet header. The parent selection chooses the parent between qualified neighbours based on ETX value of each neighbour. The ETX value of each neighbour represents the cost of transmission from each neighbour to the root. CTP chooses the neighbour with lower ETX to be its parent and it is the best possible parent between

Table 1: Omnet++ simulation parameters.

Simulation parameters	
Number of nodes	10, 20, . . ., 100
Node deployment	Random
Field area	200 × 200 (m)
Simulation time	18–3000 sec
Wireless Channel Sigma	0, 1, 3, and 5
Radio parameters	CC2420
Routing protocols	CtoNoe, RCTP, and REL
Application	CtpTesting
App packet rate	5
APP payload	Constant 2000 bytes
Max frame size	2500 bytes
Radio Tx power	−5 dBm
Radio Collision Model	1 (more collision)
Mobility Manager	LineMobilityManager

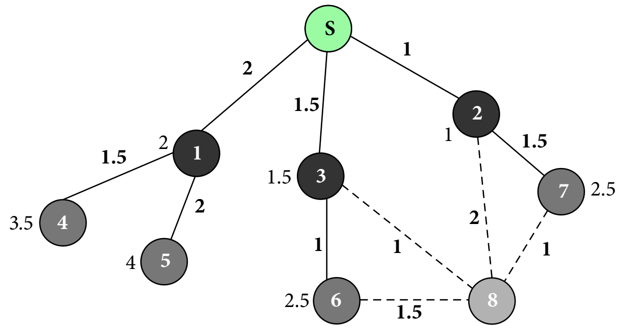

Figure 1: CTP parent selection.

the neighbours. In CTP parent selection, the link cost to each parent candidate is not taken into account and in worst case scenario it is possible to choose a parent with lower ETX value but with high link cost and the total cost may be higher than other available candidates.

Figure 1 shows a topology that node number 8 is going to select its parent. Node number 8 is in communication area with nodes 2, 3, 6, and 7 and these 4 nodes are the neighbours of node 8 and they send their ETX values to this node. CTP parent selection mechanism chooses the parents with lower ETX value. Based on these pieces of information, $ETX_2 = 1$, $ETX_3 = 1.5$, $ETX_6 = 2.5$, and $ETX_7 = 2.5$, CTP chooses node number 2 as the parent of node 8. You can see the link cost between node 8 and node 2 is equal to 2 ($ETX_{82} = 2$) and also the link cost between node 8 and node 3 is equal to 1 ($ETX_{83} = 1$). The actual cost from node 8 to sink through node 2 is equal to 3 and the total cost through node 3 is 2.5 and even its parent ETX value is higher. RCTP uses the whole cost to select the parent. In RCTP protocol, node 8 selects node 3 as its parent because the total cost through node 3 is 2.5 that is lower than the cost through node 2 that is 3.

5.2. Design. AETX is a moving average of the last three ETXs. The work in [7] has simulated several scenarios and based on huge data that has been collected through simulations, they have shown the average of last three ETXs is more stable and also senses the variation on radio frequency (RF) channel [7]. Using the last three ETXs makes AETX more stable than ETX and also makes it flexible enough to follow the changes in the network

$$\text{AETX} = \frac{\left(\sum_{i=n,-1}^{n-3} \text{ETX}(i)\right)}{3}. \tag{2}$$

RCTP uses AETX in all calculation instead of ETX. It also contents a change in parent selection procedure. The parent selection procedure is repeated periodically or it is run when the network feels inconsistency. Inconsistency happens when a node receives a beacon that asks to reconsider the topology, a neighbour comes out from congestion mode, a parent is unreachable, or the node receives a data packet that the AETX value of sender is equal to or smaller than its own AETX. Parent is selected among the neighbours that are not congested and also they are not the child of the current node. All eligible neighbours have already reported their AETX values. The parent cost is selected based on this formula

$$\begin{aligned} \text{AETX}_j &= \text{AETX}_{ji} + \text{AETX}_i, \\ \text{Parent}_j &= \text{Min}_{i \in \text{Neighbours of } j}\left(\text{AETX}_{ji} + \text{AETX}_i\right). \end{aligned} \tag{3}$$

RCTP uses a detection mechanism during the data packet transmission to validate the routing path and topology. This mechanism makes RCTP avoid loops by checking the last 5 nodes that packet comes to this node through them. If the current node is in the list of 5 last nodes, the network loop would occur and reconsidering the topology is needed to be in order. It also uses the link-layer distance estimation in each packet to validate the topology. If the distance estimate of the packet that is received to this node is equal to or less than the distance estimate of its own then the topology needs to be revised and RCTP takes an action to review the topology. This is another RCTP mechanism to avoid loops in the network.

5.3. Rainbow Mechanism in RCTP. In this section the rainbow mechanism has been considered and how it is used in RCTP to avoid dead ends routes has been demonstrated. The principal of rainbow is to avoid forwarding packets away from the sink. In this mechanism every node has a colour code based on how far it is from the sink. The order list of colours shows how by selecting the next relay node could travel toward the sink. Let $C_k(i)$ be the colour code of node i and node i will forward only to next relay nodes with colour code equal to C_{k-1} or C_k. It will guarantee that the packets travel toward the sink and it avoids sending the packets toward dead end routes. Figure 2 shows how the nodes select their parents based on rainbow mechanism. Each node selects its parents with its colour code or with colour code in order to close to sink.

5.4. Loop Avoidance in RCTP. RCTP uses a detection mechanism during the data packet transmission to validate the routing path and topology. This mechanism makes RCTP avoid loops by checking the last 7 nodes that packet comes

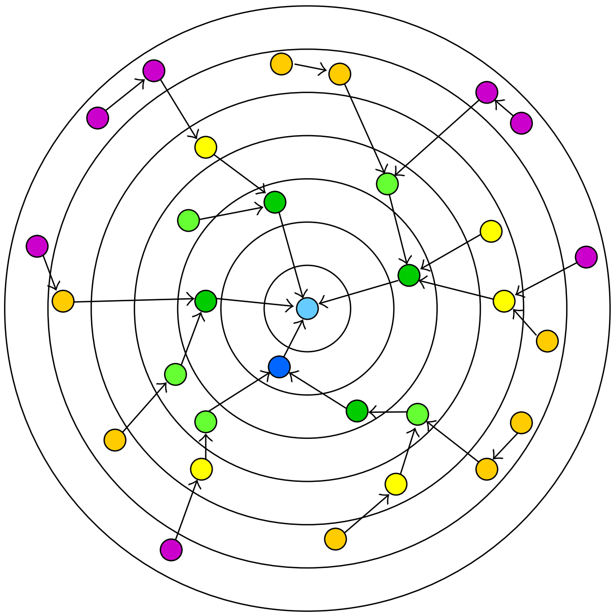

Figure 2: Rainbow colouring technique.

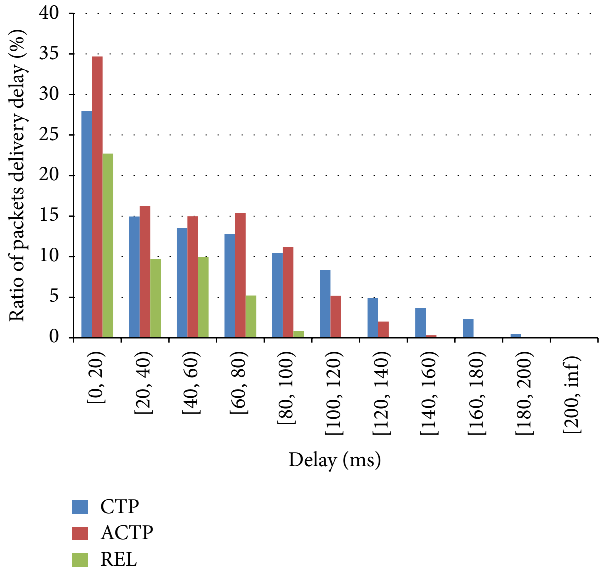

Figure 3: Packet delivery delay time in CTP, RCTP, and REL.

to this node through them. If the current node is in the list of 7 last nodes, the network loop would occur and reconsidering the topology is needed to be in order. It also uses the link-layer distance estimate in each packet to validate the topology. If the distance estimate of the packet that is received to this node is equal to or less than the distance estimate of its own then the topology needs to be revised and RCTP takes an action to review the topology. This is another mechanism of RCTP uses to avoid loops in the network.

6. System Model

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

7. Evaluation

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

The application layer measures the level of packet latency in ms. Figure 3 shows the packet delivery delay level in three routing protocols: CTP, RCTP, and routing by energy and link (REL) quality indicator. The results show that RCTP has better performance than CTP and also REL in terms of packet delivery delay. RCTP has delivered on average about 35% of packets in less than 20 ms instead of CTP that it delivered about 26%. It is obvious that RCTP has better performance than CTP in terms of packet delivery delay time.

Application layer also measures the percentage of packet delivery ratio that it shows the amount of packets that successfully received in their destinations. Figure 4 shows the packet delivery ratio in three routing protocols. The results show CTP and RCTP have the same result in terms of packet delivery ratio in scenarios that wireless nodes are less than 70 nodes. When the nodes in the fields increase to 70 nodes, it is obvious that RCTP could deliver more packets than CTP. In scenario with 100 nodes in the fields, RCTP packet delivery ratio is 55% and CTP could manage to deliver around 47% of the packets.

Figure 5 shows the parameters of Collection Tree Protocol engine. It is obvious that the most parameters do with better performance in RCTP than CTP, for example, Rx-forwarded total that shows the number of packets that are received after forwarding; it is slightly better in RCTP than CTP. Figure 5 shows the energy consumption based on received and transferred packets by Collection Tree Protocol engine. It shows that RCTP performs better than CTP in terms of energy consumption in nodes.

Figure 7 shows the ratio of radio reception with interference based on three routing protocols: CTP, RCTP, and REL

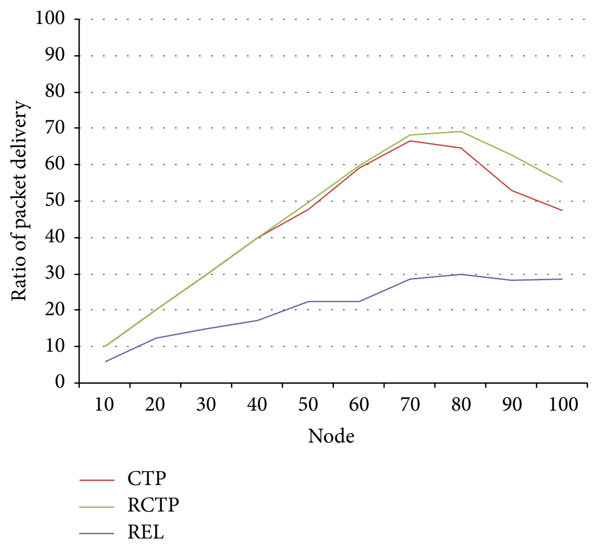

Figure 4: Packet delivery ratio based on CTP, RCTP, and REL.

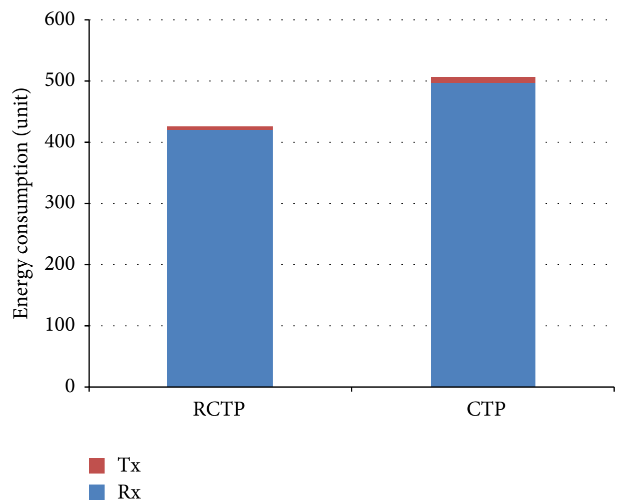

Figure 6: Energy consumption in CTP and RCTP.

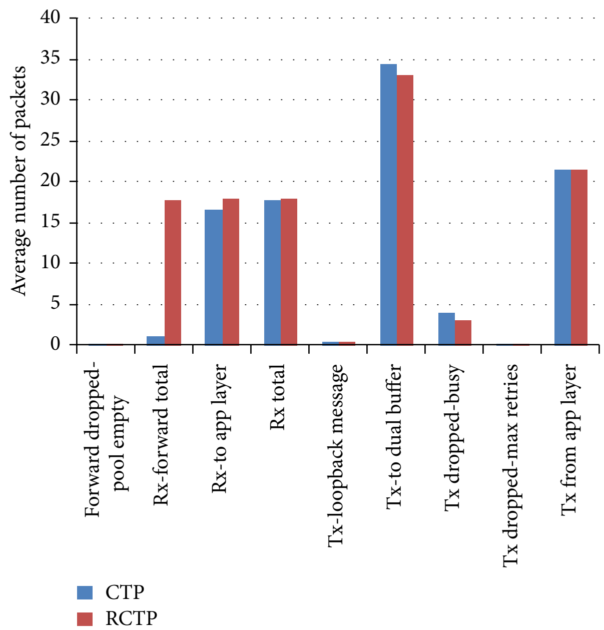

Figure 5: Collection Tree Protocol engine parameters.

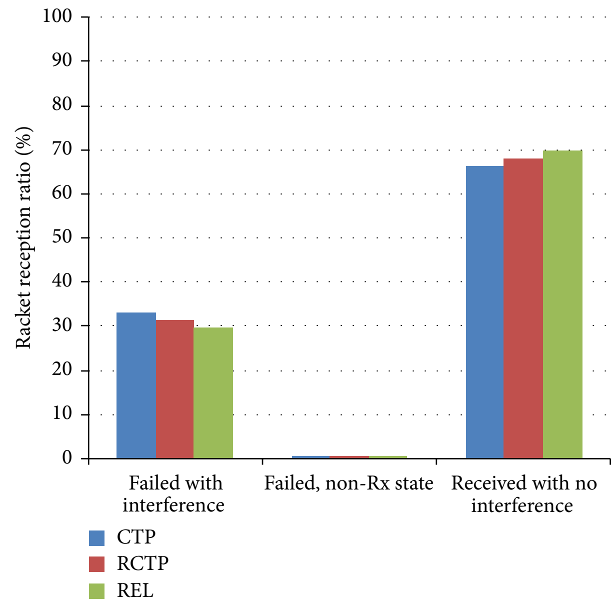

Figure 7: Radio reception and interference.

in different scenarios. RCTP performs slightly better than CTP in packet reception with no interference and also in failed reception in case of existing interference. It could be considered as a result of finding better parents to form a tree topology in different scenarios.

8. Conclusion

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

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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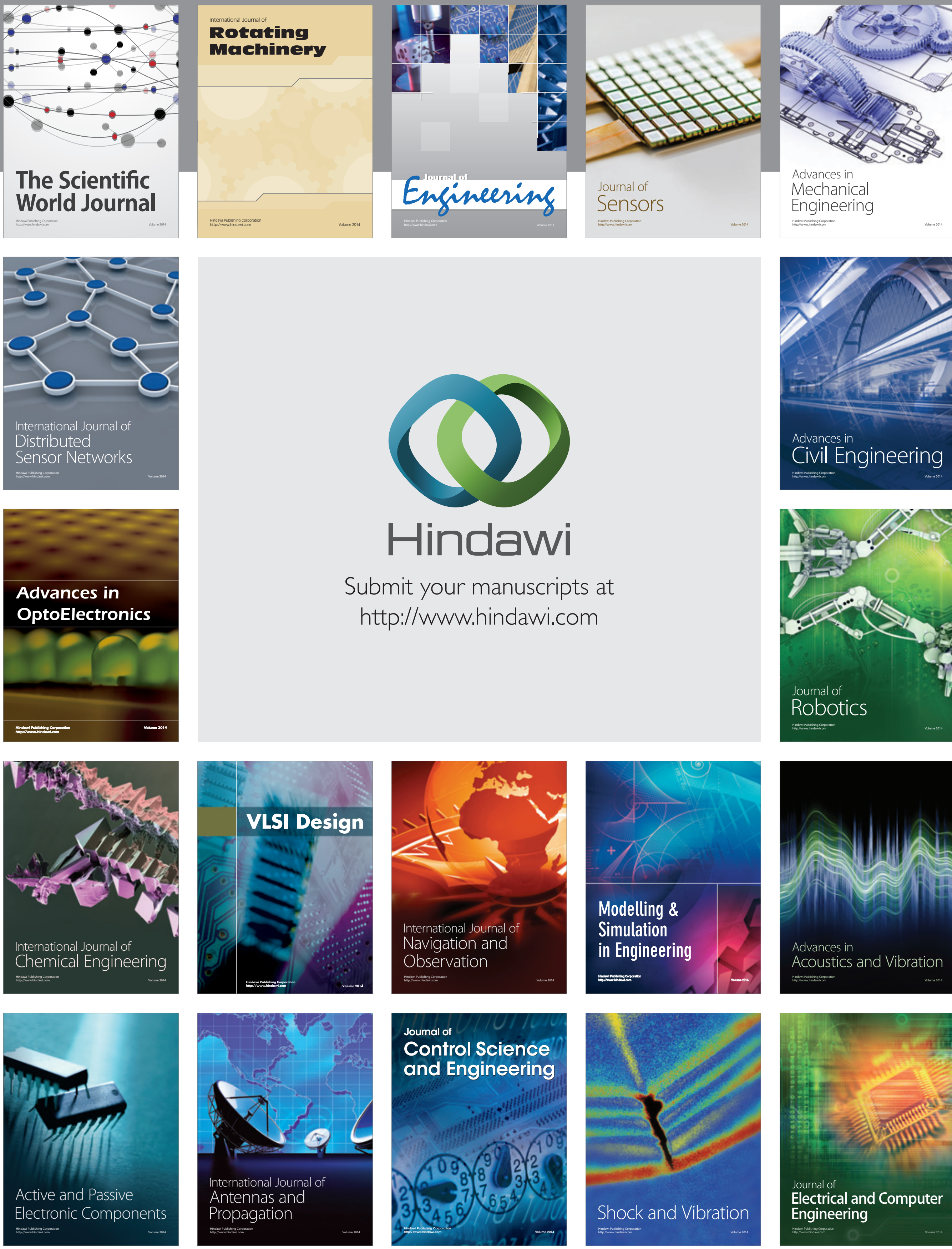

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