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Research Article

The Design and Implementation of the XWCETT Routing Algorithm in Cognitive Radio Based Wireless Mesh Networks

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The Wireless Mesh Networks (WMNs) technology has recently emerged as a promising high-speed wireless technology, which provides the last mile broadband Internet access and delivers integrated wireless communication solutions. Integrating the traditional wireless with new wireless technologies such as cognitive radio (CR) technology creates a platform for high-speed broadband communication. In a multihop ad hoc cognitive radio network (CRN) environment, the performance of the network is degraded by the routing protocols, which are adapted from the traditional wireless networks. In an endeavor to optimize the performance of the CRNs, existing routing protocols can be adapted and optimized. Secondly, new dynamic routing protocols can be designed to meet the requirements of CRNs. This paper investigates the existing routing protocols in WMNs and proposes a new routing protocol called extended Weighted Cumulative Expected Transmission Time (xWCETT). The xWCETT routing protocol was evaluated through network simulations using the NS 2. Its performance was evaluated with respect to the end-to-end average latency, the throughput, jitter, packet delivery ratio, and the normalized routing load. The comparative evaluation results show that the xWCETT achieves superior results in terms of average throughput, latency, and the normalized routing load.

1. Introduction

The realization of ubiquitous computing in recent years has brought greater and promising opportunities for users residing in rural and remote areas as well as the developing countries. In the past decade, greater advances in various technologies such as social networking, the online gaming, mobile voice over Internet protocol (VoIP), mobile cloud storage, and videoconferencing have been experienced. These technologies require high-speed communication infrastructure that serves as an effective transport system. The Wireless Mesh Networks (WMNs) and Cognitive Radio (CR) technologies have emerged as one of the promising high-speed wireless broadband wireless solutions. The WMN [1–4] is defined as a dynamic multihop network that has the capabilities to self-organize and self-configure. Conceptually, the WMNs have evolved from Mobile Ad Hoc Networks (MANETs) and inherited the forwarding and self-configuration capabilities from the MANETs. On the other hand, the CR technology is defined as a fully programmable wireless system that is capable of sensing its operating environment and intelligently adapting its transmission parameters [5, 6]. These two technologies may be integrated to provide the next generation of intelligent, frequency-switching, and autonomous mesh networks.

The WMN architecture consists of two main components, namely, the mesh routers (MRs) and the mesh clients (MCs). The MRs are interconnected to form a multihop mesh backbone. The end-user MCs typically consist of client devices such as laptops and mobile devices that access the Internet through the MC backbone. Depending on the location and functionalities, the MCs are further divided into three categories [2]: the mesh routers which provide connectivity to the end users are called the Mesh Access Points (MAPs) and are usually located at the user premises. The MCs which reside inside the WMNs backbone and are responsible for forwarding the MCs data are called the Mesh Points (MPs). The third category of MCs located at the edge of backbone of WMNs is called the mesh gateways (MGs) and it provides connectivity between WMNs backhaul and the Internet through the wired medium. This type of communication network provides the benefits such as low deployment and maintenance costs, network robustness, and extended coverage [7, 8]. The network also provides the capabilities designed to cope with the ever-increasing demands of end users such as the need for scalability, data rate, and mobility support. However, the scalability and bandwidth are constrained due to the nature of wireless media and the availability of finite spectrum [9]. As a result, for these limitations of WMNs, the CR technology offers supplementary communication solution that can enhance the capabilities of traditional WMNs.

The design and the architecture of CR technology increase the radio frequency (RF) spectrum utilization by allowing unlicensed users to sense and opportunistically access licensed spectrum bands. However, the licensed primary user (PU) should be protected from interference. Hence, adapting WMNs to use the CR technology is likely to improve substantial the performance gain in terms of efficient utilization of the spectrum and network capacity. In a multihop network environment, communication depends on the reliability of the network connectivity. On the other hand, reliable and robust connectivity depends on the efficiency and effectiveness of a routing strategy employed. Hence, both the mesh routers and client nodes play a fundamental role in routing decision-making. As a result, the implementation and optimization of efficient routing protocol remain a significant part in the CR-WMN.

2. Related Work

Researchers in wireless ad hoc networks have proposed a number of routing protocols to improve the performance of multihop cognitive radio networks [10–13]. Recent work focused on routing in the traditional Mobile Ad Hoc Networks as well as the cognitive radio ad hoc networks (CRAHNs). They addressed the unique problems and challenges introduced by the paradigm shift from static spectrum access to dynamic spectrum access. The proposed frameworks and protocols are based on unique or similar design and optimization goals such as the avoidance of PU interference, minimization of end-to-end-delay, maximization of achievable bandwidth, and increasing the throughput rates.

The authors in [11] proposed a reactive Cognitive Ad Hoc On-Demand Distance Vector (CAODV) protocol for CRAHN. Their work optimizes routing protocol based on avoiding the regions of PU activities, joint path, and channel selection at each forwarding node. It also exploits multiple channels to improve the network performance. However, the proposed CAODV protocol is based on a common control channel (CCC) strategy which creates another challenge in dynamic CRN environment. The assumption of having the CCC may not be feasible due to nondeterministic channel availability.

The proposed scheme is based on joint routing and spectrum selection criteria that compute the most likely path that satisfies the requirements stated by the application. However, its concurrent utilization of multiple channels creates an overhead on all available channels and this leads to inefficient utilization of the bandwidth.

The authors in [12] proposed a location-based routing protocol to address a problem of multiple control traffic flows in the network. When the path selection and channel decisions are made sequentially, higher routing overhead occurs. Furthermore, in [14], a spectrum-aware mesh routing (SAMER) protocol as a routing solution for multihop cognitive radio mesh networks was proposed. The protocol opportunistically selects the channels with higher spectrum availability probability and quality while balancing between long-term route stability (i.e., route based on most stable channels) and short-term opportunistic performance.

Authors in [13] proposed a routing scheme that computes source-destination path by considering the activities of the PUs. The proposed algorithm makes use of the possibility of exploiting multiple frequencies at the same time between two SU nodes. The proposed scheme is based on joint routing and spectrum selection criteria that compute the most likely path that satisfies the requirements stated by the application. However, it implements concurrent multiple channel broadcast strategy, which creates an overhead on all available channels, resulting in inefficient utilization of the bandwidth.

In [15], a routing protocol for CRAHNs called the Robustness-Aware Cognitive Ad Hoc Routing Protocol (RACARP) was proposed. The proposed RACARP protocol's goal is primarily to provide the robust transmission path in the presence of PUs while offering the fast route recovery strategy. The proposed protocol uses the Expected Path Delay (EPD) as a routing metric for path decision and fast route recovery. The protocol was implemented using the Network Simulator 2 (NS-2) and its performance was compared with the Dual Diversity Cognitive Ad Hoc Routing Protocol (D2CARP) which was proposed in [16]. The RACARP protocol performed better than the D2CARP protocol in terms of the average throughput, packet loss rate, average end-to-end delay, and average jitter. The RACARP and the D2CARP protocols are able to adapt to dynamic PU activities; however, the D2CARP employs the hop count routing metric which does not take into account the quality of links. As a result, inefficient hop count routing metric may frequently cause the D2CARP to establish nonoptimal transmission paths, thereby significantly degrading the performance of the protocol.

Other notable routing protocols for multihop CRN environments include the schemes proposed in [10, 17–21]. Most routing techniques proposed attempt to address the inefficiencies in route discovery mechanisms, usage of CCC, mechanisms to reduce routing overhead, and different ways to deal with connectivity failure due to intermittent PU activities.

3. System Model

We studied a number of routing protocols and routing metrics proposed for both the traditional WMN and CRN environments. Based on an understanding of these protocols and how they perform, we propose a routing scheme called the extended Weighted Cumulative Expected Transmission Time (xWCETT). The proposed routing scheme considers the merits of the Ad Hoc On-Demand Distance Vector (AODV) routing protocol as well as the merits of the multiradio based the Weighted Cumulative Expected Transmission

Time (WCETT) routing metric. It combines the benefits of the AODV protocol with the WCETT into a new enhanced routing scheme.

The xWCETT routing scheme is based on a distributed local spectrum knowledge whereby each node is responsible for constructing information about its surroundings. The local information is shared amongst the neighbouring nodes through the common control channel (CCC). We assumed that all the nodes are tuned to the CCC to avoid broadcasting the control messages through all the channels, which reduces the amount of routing overheads.

To compute the optimal source-destination path, our proposed xWCETT routing protocol implements the three components, namely, the expected transmission count (ETX), expected transmission time (ETT), and the WCETT routing metrics. The ETX component measures the packet loss rate by estimating the number of MAC layer transmission attempts expected to successfully transmit the packet from source to destination node. The ETT routing metric integrates the link transmission rate and the path cost in order to improve the performance of the ETX metric.

The third component of our routing scheme is the WCETT metric which is formulated by combining the two terms that are considered a trade-off between the end-to-end latency and the throughput. We introduced the probability variable, P_c, which provides the channel availability probabilities of all the channels given each link. P_c computes the estimated probability that a channel is unavailable for the SUs due to the PU activities. The resulting routing metric for our proposed scheme is given by

$$\begin{aligned}\text{xwcett\_metric} = {} & (1-\alpha)\sum_{i=1}^{n}\mathrm{ETT}l_i \\ & + \left[(1-P_c)\,\alpha \max_{1\le c\le C} X_c\right].\end{aligned} \tag{1}$$

P_c represents the estimated probability that channel c in a given C set of channels is unavailable for the SUs because of the PU activities. We made an assumption that each SU node is able to monitor and calculate the probabilistic availability of a channel based on the local knowledge of PU channel usage statistics. In the real scenario, this assumption would mean that each node will share its knowledge about the spectrum environment with its neighbours.

The protocol, however, incurs overhead in sharing the spectrum information. The sharing of the spectrum information enables the SUs to have a global view of the network and to use the spectrum opportunistically without interfering with the PU. This is a necessary cost, which facilitates the functionality of the CR-WMN.

The nodes share their spectrum information: a global knowledge about availability of channels would be known by all the nodes in the network. Given the PU channel usage statistics derived from the channel availability table, this routing metric prioritizes stable source-destination routes by avoiding to select the channels with a higher probability of being occupied by the PUs.

The proposed xWCETT routing protocol implements the xwcett_metric (depicted in equation (1)) to select the best routes from the source to destination nodes. Our system model employs two radios per SU node in CRN where one radio constantly monitors availability of channels and the second radio switches amongst available channels for data transmission. The channel switching was set to between 1 and 10 ms in our simulations to demonstrate the effects of the channel switching delays. A smaller channel switching delay is desirable as it improves the performance of the network.

The SU nodes monitor the PU activities on a set of allocated channels and associated probabilities for each channel based on PU activities. In each case, during the route establishment process, a RREP packet is generated based on the routing metric in (1). The lowest metric value is used to determine the best route and, therefore, data packets are transmitted on the selected path.

The xWCETT routing protocol was implemented based on the design of multiradio multichannel architecture. The TCL script was used to configure the number of radios and channels needed for simulations. In our study, the number of radios was set to two (2) and the number of channels was set to four (4) to closely emulate the functionality of the CRN.

4. Simulation Model

In this study, we adopted a quantitative experimental approach in which the experiments were performed using the Network Simulator. The simulation experiments were conducted using the open source object-oriented discrete-event network simulation software called NS-2 version 2.31 [22].

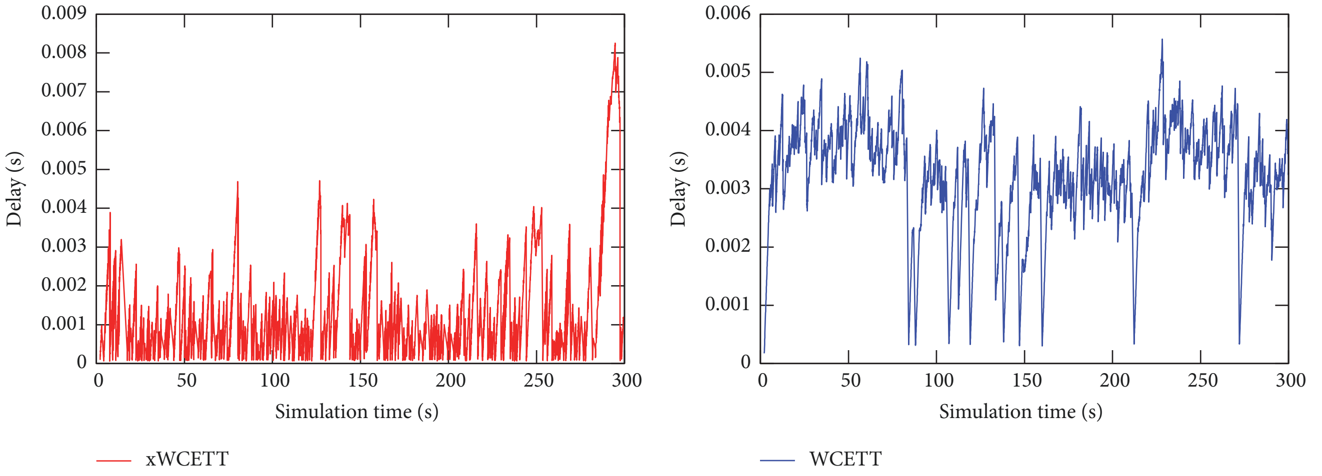
The NS-2 simulator was configured to run on Ubuntu 12.04 distribution of the Linux operating system (OS). Our simulation experiments were performed on NS-2 platform with cognitive radio cognitive network (CRCN) [23] patch which enables the cognitive radio capabilities on NS-2. We used other utilities such as AWK programming language, perl scripting, python scripting, and the Gnuplot plotting utility for data manipulation, analysis, and graphical representation of the results.

We conducted a series of extensive simulation experiments based on a small to medium scale CR-WMNs. We evaluated the performance of the three (3) routing protocols, namely, the AODV routing protocol, the WCETT routing protocol, and our proposed xWCETT. The simulation parameters were configured according to Table 1.

In each of the simulation scenarios, we monitored and recorded the results of each simulation scenario and observed how each routing protocol performed. The performance of the protocols was evaluated with respect to the end-to-end latency, throughput, jitter, packet delivery ratio, and the normalized routing overhead.

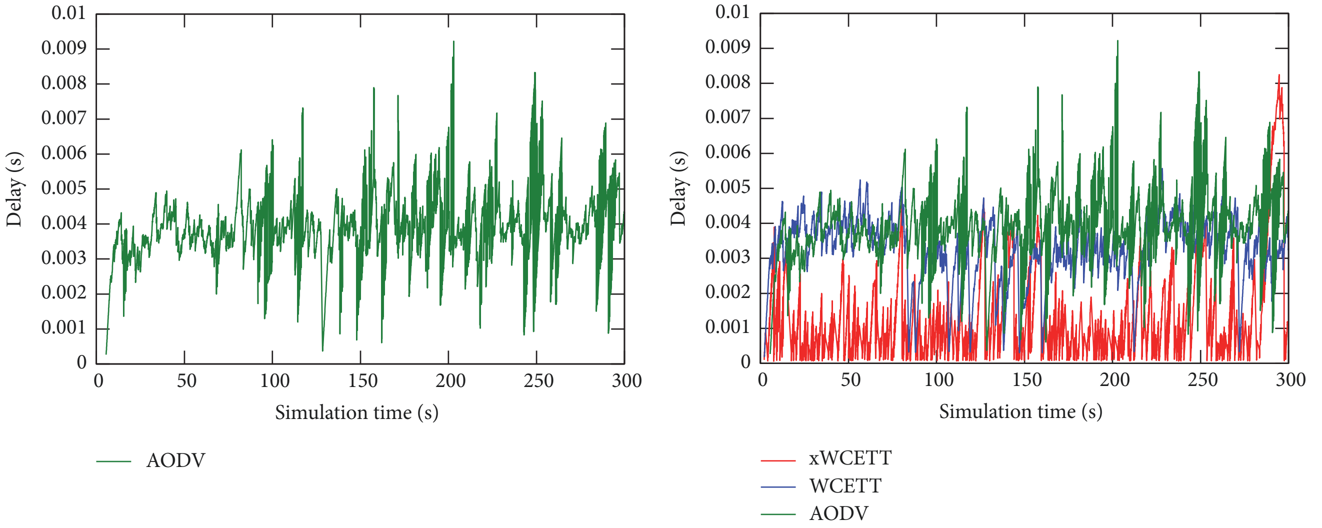
5. Results and Discussion

We performed a series of experiments by varying the number of network nodes for each experiment. In the first simulation scenario, the number of cognitive radio nodes was set to twenty (20) and the number of PUs was set to two (2). The results for the experiment are presented in Figures 1–8.



(a) End-to-end latency, xWCETT

(b) End-to-end latency, WCETT



(c) End-to-end latency, ADDV

(d) End-to-end latency comparison: 20-node configuration

Figure 1: The end-to-end latency performance results.

Figure 1(a) presents the end-to-end latency performance results obtained by the proposed routing protocol the xWCETT. Figures 1(b) and 1(c) present the end-to-end latency performance results obtained by AODV and WCETT, respectively. Figure 1(d) presents the comparative end-to-end latency results obtained by the three (3) routing protocols.

Figure 1 shows that the xWCETT is able to maintain a stable and minimal end-to-end latency in comparison to AODV and WCETT. The low end-to-end latency indicates a stable and robust performance in a multihop CRN environment where the random and intermittent PU activities are likely to result in network partitioning and the degradation of network performance.

Figure 2 presents the end-to-end average latency results obtained by the three (3) routing protocols: the xWCETT, the WCETT, and the AODV.

In Figure 2, we observed that the average latency obtained by the xWCETT is minimal as compared to AODV and the WCETT. The AODV and WCETT routing protocols obtained the higher average latency than xWCETT primarily because the protocols are not designed for the cognitive radio environment.

In Figures 3 and 4, we present the end-to-end jitter performance results obtained by the three (3) routing protocols. Figures 3(a)–3(c) present the end-to-end jitter performance results obtained by xWCETT, WCETT, and AODV, respectively. Figures 3(d) and 4 present the comparative end-to-end jitter and average jitter results of the three protocols.

The end-to-end and average jitter performance results obtained in Figures 3 and 4 indicate that the performance of xWCETT protocol suffers delay variations. The AODV and xWCETT obtained higher average jitter results as compared to the WCETT routing protocol. The xWCETT is optimized for dynamic operational environment of CRN.

In Figures 5, 6, 7, and 8, we present the throughput performance results obtained by the three (3) cognitive radio based routing protocols. In Figures 5(a)–5(c) we present the end-to-end throughput performance results. Figure 5(d)

Table 1: Cognitive radio based wireless mesh network simulation parameters.

Simulation parameter	Assigned value
Number of nodes	20, 40, 60, 80, 100
Topography	1000 m × 1000 m
Primary users	4
Secondary users	20, 40, 60, 80, 100
Cognitive radio mesh interfaces	2
Mobility model	Random Waypoint
Mobile client node speed	1 m/s–10 m/s
Number of primary users	0, 1, 2
Transmission range	200 m
Medium access control	IEEE 802.11b MACCON
RF Propagation Model	Two-ray ground reflection
Antenna type	Omnidirectional
Traffic type	CBR
Packet size	1500 bytes
Packet rate	2, 4, 6, 8, 10 (packet/s)
Data rate	11 Mbps
Routing protocols	AODV, WCETT, xWCETT
Simulation time	300 s

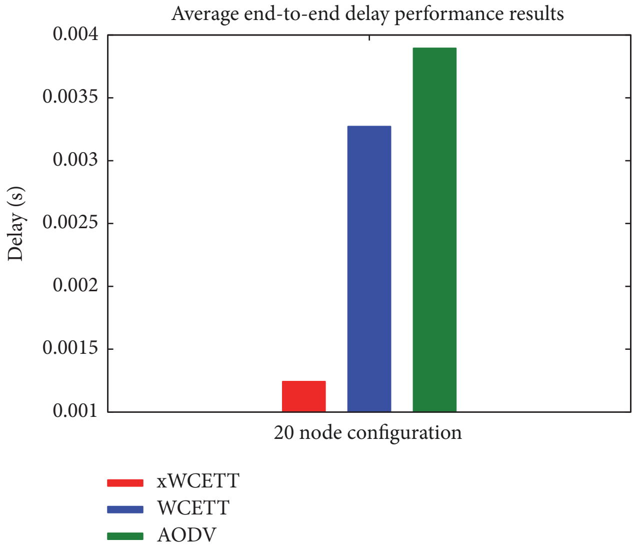


Figure 2: The average latency performance results.

shows the end-to-end comparative throughput results while Figure 6 presents the average throughput results.

The end-to-end throughput results presented in Figure 5 demonstrate unsteady performance in all the three (3) routing protocols. The xWCETT protocol obtained the highest achievable throughput when compared to AODV and WCETT. The AODV protocol obtained the least average throughput as depicted in Figure 6.

Figure 7 presents the end-to-end PDR results. The results show that xWCETT achieved the highest percentage of PDR. This shows that xWCETT protocol loses fewer packets when compared to the WCETT and AODV routing protocols.

Table 2: Total hop count, average hop count, routing load, and normalized routing load (NRL) analysis for the three (3) routing protocols.

Routing protocol	Total hop count	Ave hop count	Routing load	NRL
AODV	134256	20	8068	0.27
WCETT	148192	23	7527	0.25
xWCETT	140512	22	7031	0.21

The final set of simulations evaluated the impact of the number of hops, the routing load, and the normalized routing load (NRL) on the performance of the protocols. The results are presented in Table 2 and Figure 8, respectively.

We observe in Table 2 that AODV used the least number of hops and has a lowest average hop count as compared to xWCETT and WCETT routing protocols.

The higher routing overhead shows that the routing protocol consumes more network resources and this results in inefficient bandwidth utilization. Hence, WCETT and xWCETT provide better and more improved performance as depicted in Figure 8 in terms of NRL because they are optimized to consider the channel diversity. The xWCETT protocol further obtained the lowest routing load because it improves the mechanisms to establish the best path in cognitive radio environment, taking into account the presence of the PUs.

6. Conclusion

This study highlighted a number of routing issues and challenges encountered in the CR-based multihop networks. The common challenge underpinning the ineffective performance of CR-based multihop networks is the need to dynamically share the spectrum and reconfigure the network parameters. To address these challenges, we proposed a spectrum-aware, spectrum-agile, and interference-aware routing scheme called the xWCETT routing protocol.

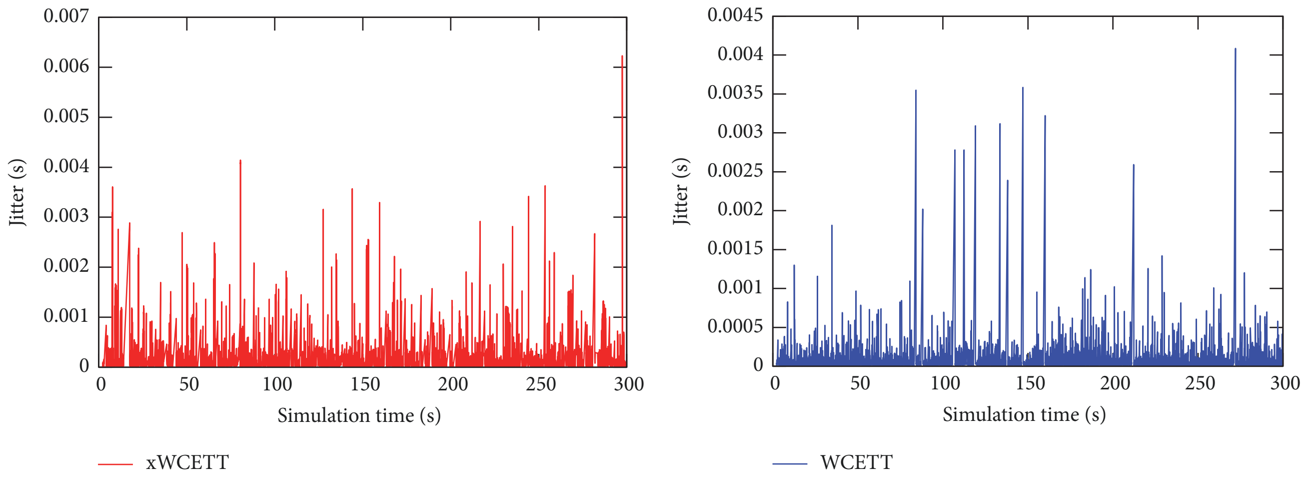
The extensive simulations were conducted to investigate its effectiveness in a dynamic CR-WMN environment. The results depict that the proposed xWCETT protocol is superior to the AODV and the WCETT routing protocols in the cognitive radio environment. The xWCETT enhances the performance of cognitive radio Wireless Mesh Networks and is optimized for spectrum awareness, agility, and interference. The performance of xWCETT shows that the protocol is resilient and stable in the presence of PUs. It reduces end-to-end delay and improves average end-to-end throughput.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

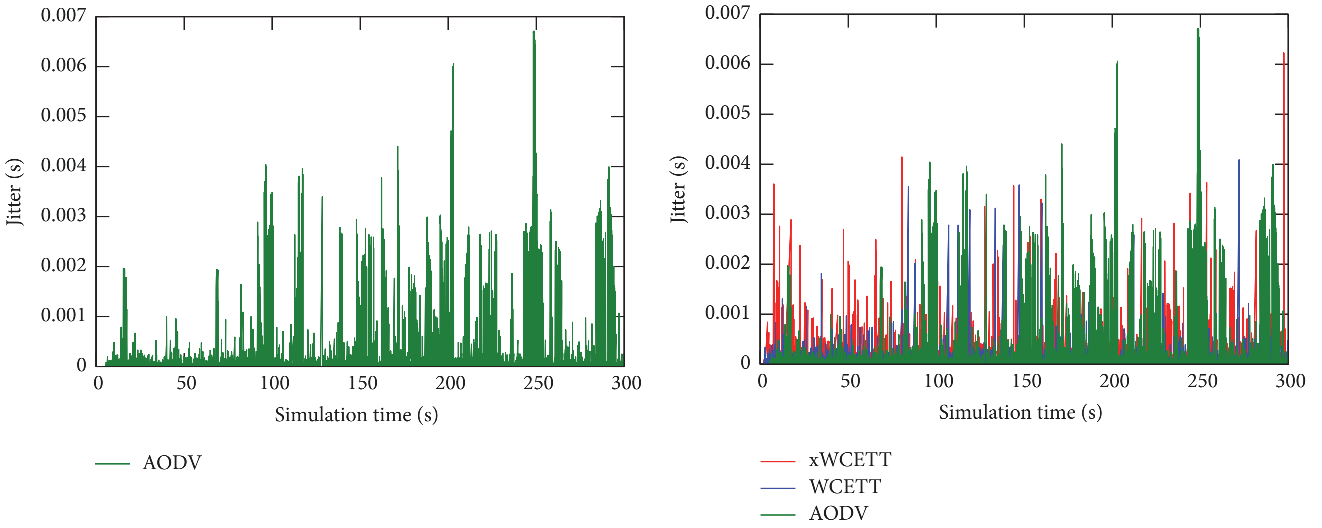
Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.



(a) End-to-end jitter, xWCETT

(b) End-to-end jitter, WCETT



(c) End-to-end jitter, ADDV

(d) End-to-end jitter comparison: 20-node configuration

Figure 3: The end-to-end jitter performance results.

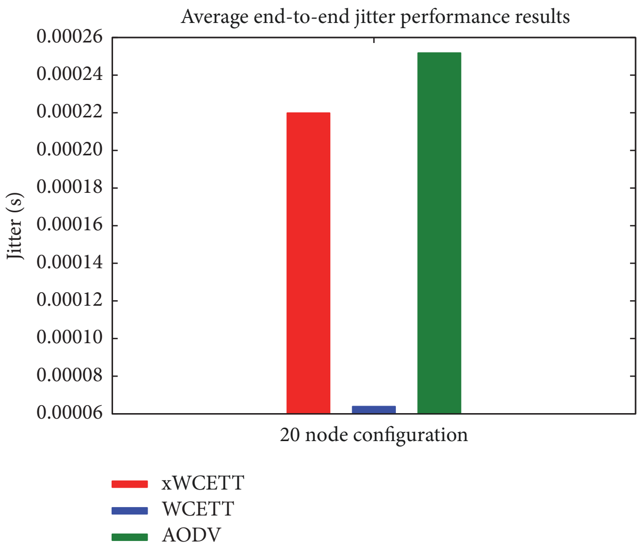
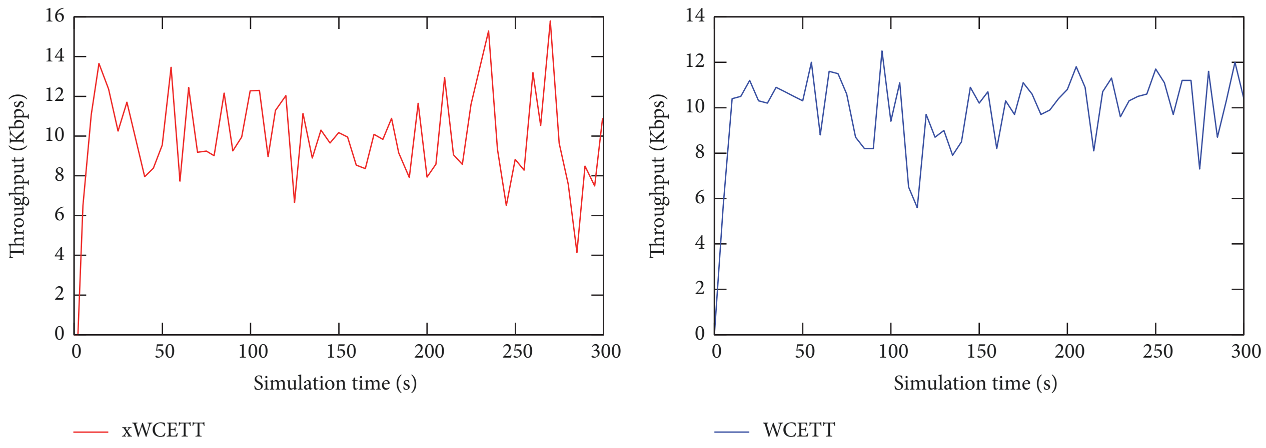
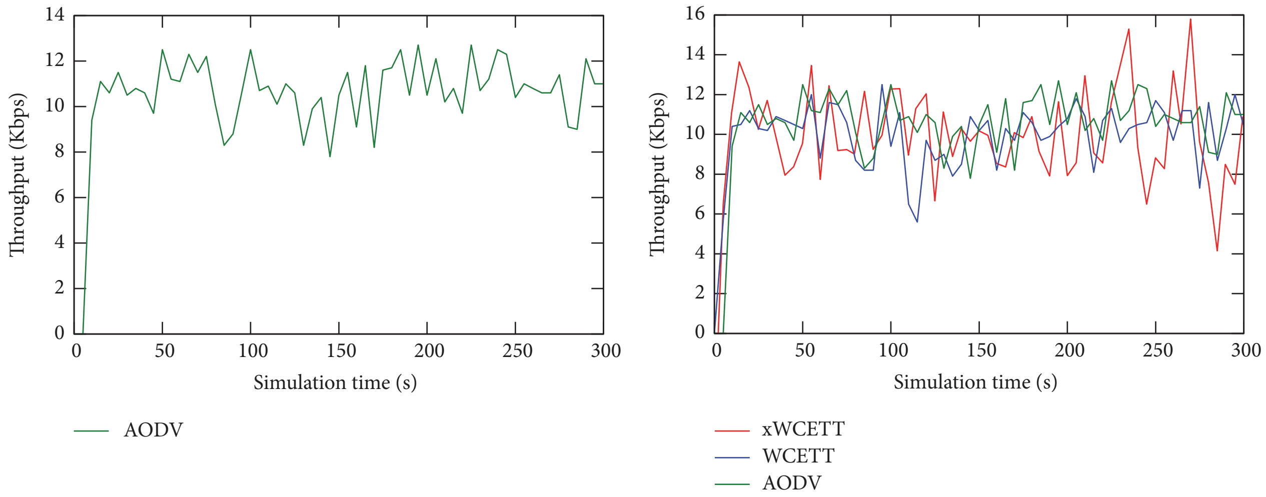


Figure 4: The average jitter performance results.



(a) End-to-end throughput, xWCETT

(b) End-to-end throughput, WCETT



(c) End-to-end throughput, ADDV

(d) End-to-end throughput comparison: 20-node configuration

Figure 5: The end-to-end throughput performance results.

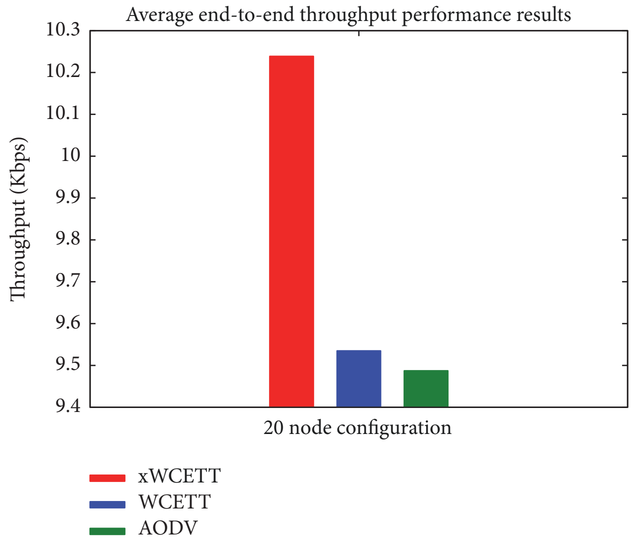


Figure 6: The average throughput performance results.

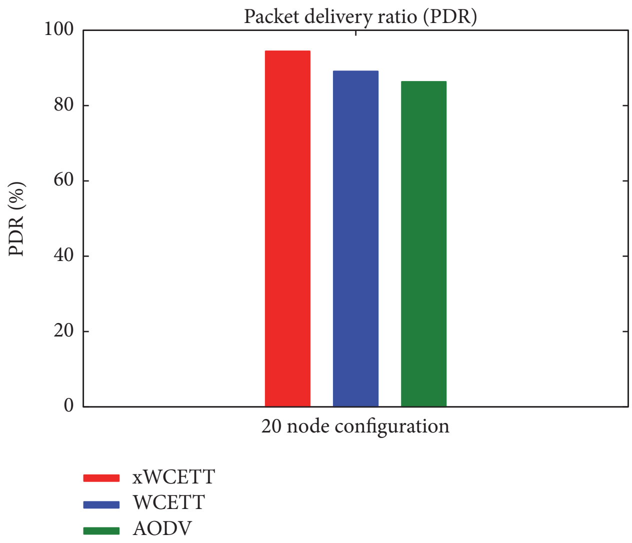


Figure 7: PDR results obtained by three routing protocols.

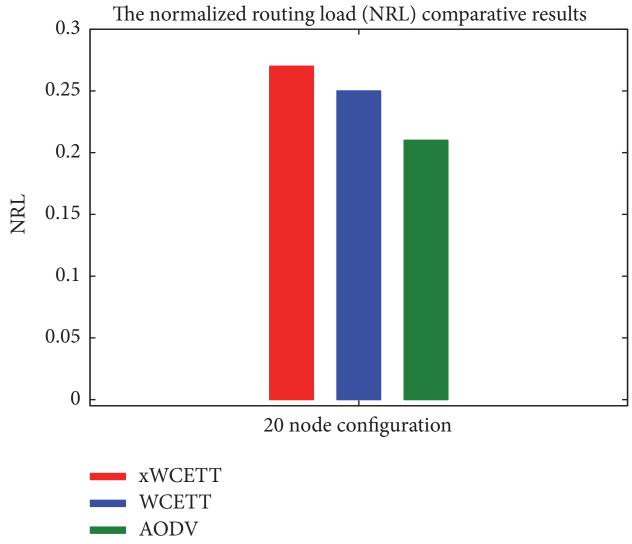


Figure 8: The NRL analysis results of the three routing protocols.

Acknowledgments

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