Load Balancing Routing Under Constraints of Quality of Transmission in Mesh Wireless Network based on Software Defined Networking

Le Huu Binh and Thuy-Van T.Duong

Abstract: Load balancing routing and quality of transmission (QoT) aware routing have been increasingly studied in mesh wireless networks (WMN) to improve their performance. For the load balancing routing, the traffic bottleneck in the network can be resolved. However, it can decrease QoT because the routes may pass through multiple hops. On the other hand, the QoT aware routing often improves the QoT of the routes, but it can increase the traffic bottleneck due to the unbalanced traffic load in the network. Therefore, the investigation of load balancing routing taking into account QoT is very essential, especially in the case of a wide and ultra-high speed WMN. In this paper, we propose a load balancing routing algorithm under the constraints of QoT for WMN. Our method uses the principle of the software defined networking (SDN) to choose the load balancing routes satisfying the constraints of QoT. Our performance evaluations using OMNeT++ have shown the effectiveness of the proposed algorithm in improving QoT of the data transmission routes, increasing the packet delivery ratio and the network throughput, decreasing the end-to-end delay.

Index Terms: Load balancing routing, QoT aware routing, software defined networking, WMN.

Fig. 1. The general architecture of the wireless mesh networks.

I. INTRODUCTION

WIRELESS communication technology is growing and increasingly being used in many fields, especially in the era of the Internet of things (IoT) and the fourth industrial revolution. Currently, there are several wireless network models such as the mobile ad hoc networks (MANET), wireless sensor networks (WSN), wireless mesh networks (WMN), and hybrid wireless networks [1], in which WMN is becoming more and more widely used in many fields, such as broadband home networking, community and neighbourhood networking, enterprise networking, metropolitan area networks, transportation systems, health and medical systems, security surveillance systems [2]. The general architecture of WMN is shown in Fig. 1, where the nodes connect to each other via wireless transmission medium that forms a mesh topology. A node of WMN can be either mesh
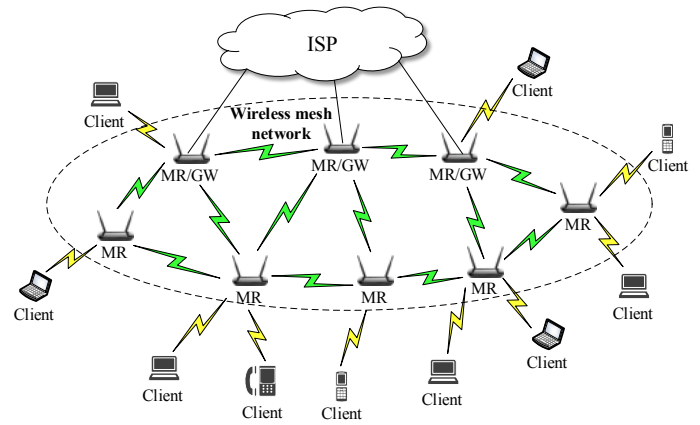
router (MR) or mesh router with the gateway (MR/GW). The clients connect to the MRs or MR/GWs via wireless transmission medium to access the Internet.

To improve the performance of the WMN, it is necessary to research and improve control protocols. This has also been done by many research groups recently, where the routing protocols have become an important topic, and various routing strategies have been investigated [3]–[7]. Two routing strategies that have recently attracted significant researches are the load balancing routing and QoT aware routing.

The load balancing routing is one of the effective methods to reduce the traffic congestion, this has been validated in [8]–[11]. However, considering another aspect, the load balancing routing can be the cause of the QoT impairment due to the existence of some long routes in the network. These routes pass through many hops and intermediate nodes, so the accumulated noise along with the routes increase. As a result, the QoT on the data transmission routes decreases. To clarify this issue, we consider an example as shown in Fig. 2, where the numerical value on each wireless link is the load traffic which offers to itself, expressed in Erlang. Let us assume that there is a request to discover a new route from node 1 to node 9 using load balancing routing technique. For the topology as shown in Fig. 2, there are three possible routes which are $1 \rightarrow 5 \rightarrow 4 \rightarrow 9$ (route 1), $1 \rightarrow 2 \rightarrow 3 \rightarrow 9$ (route 2) and $1 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9$ (route 3) with the signal to noise ratio (SNR) of 27, 25, and 23 dB, respectively. In these routes, the load balancing routing algorithm will choose the route 2 or route 3 to balance the traffic load in the network.

Thuy-Van T.Duong is with the Center for Applied Information Technology, Ton Duc Thang University, Ho Chi Minh City, Vietnam; and Faculty of Information Technology, Ton Duc Thang University, Ho Chi Minh City, Vietnam, email: duongthithuyvan@tdtu.edu.vn.

L. H. Binh is with the Institute of Engineering and Technology, Thu Dau Mot University, Binh Duong Province, Vietnam. email: lehuubinh@tdmu.edu.vn.

Thuy-Van T.Duong is the corresponding author. Corresponding author at: Ton Duc Thang University, Ho Chi Minh City, Vietnam. email: duongthithuyvan@tdtu.edu.vn.
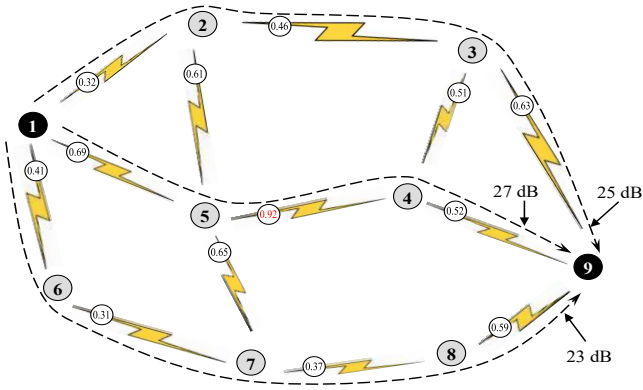
Fig. 2. An example of load balancing routing and QoT aware routing in WMN.

The route 1 is not chosen due to the heavy traffic load of the link $5 \rightarrow 4$ (0.92 Erlang), although the QoT of this route is the best (27 dB).

To ensure the QoT in the network, several published works have proposed routing algorithms that take into account the constraints of the QoT [12]–[15], where the proposed algorithms attempt to find out the best QoT route. As a result, the QoT on the data transmission routes is improved. However, for the mesh topologies such as the WMN, the routing technique with the best QoT can increase the bottlenecks due to unbalanced traffic load. This is more clearly visible from the example in Fig. 2. Consider the case where node 1 wants to discover a new route to node 9 using the best QoT routing algorithm. For the topology as shown in Fig. 2, the route of $1 \rightarrow 5 \rightarrow 4 \rightarrow 9$ is chosen because its QoT is the best. We can observe that, this route passes through the link from node 5 to node 4 with a heavy traffic load (0.92 Erlang). As a result, the bottlenecks may happen at this link.

We have the following comments based on the analyzed results above. It is necessary to investigate the routing algorithms that take into account both QoT and load balancing. This is the research motivation of this paper. In [16], we have also studied this problem for MANET, where we have presented the source-based load balancing and quality of transmission aware DSR (SLBQT-DSR) algorithm that is modified from the route discovery algorithm of the dynamic source routing (DSR) protocol. SLBQT-DSR algorithm operates according to the principle of the distributed routing. The load balancing is based on route information stored in the route cache of the source node. Although the simulation results have shown that SLBQT-DSR is better than DSR in terms of the packet blocking probability and throughput, the load balancing efficiency of SLBQT-DSR may not be the best because the load balancing of SLBQT-DSR is based only on local information from the source node. In this paper, we propose a novel load balancing routing algorithm under the constraints of QoT for WMN. The proposed algorithm is based on the principle of the software defined networking (SDN), called load balancing routing under constraints of quality of transmission (LBRCQT). The LBRCQT algorithm works according to the principle of centralized routing, and the routing function is implemented at the SDN controller.

The next sections of this paper are organized as follows. Sec-

tion II presents the published works related to load balancing routing and QoT aware routing. Section III presents the structure of SDN using open flow protocol for the routing control in WMN. Section IV presents the analytical model of the performance parameters in WMN that is used for our proposed algorithm. Section V is our proposed routing algorithm. Section VI presents the simulation results and discussion. Finally, concluding remarks and promising future work items are given in Section VII.

II. RELATED WORKS

A. Load Balancing Routing

For telecommunications networks in general and WMNs in particular, the load balancing routing are often used to reduce bottlenecks in the network. Based on the number of used routing paths, load balancing routing algorithms are classified into two main types, which are single path routing and multiple path routing [8]. For the single path routing, the route cache of each node stores only one path to the destination node. This path is used for data transmission. Therefore, the load balancing must be done during route discovery. For this method, the authors of [9] have proposed a load balancing routing algorithm for WMN by modifying the discovery principle of the ad hoc on-demand distance vector (AODV) protocol. To discover new route by AODV protocol, the source node broadcasts the route request packet (RREQ) to all its neighbors. At each node receiving RREQ, if this RREQ has already been received, delete the RREQ. Otherwise, return the route reply packet (RREP) if its route cache has a route to the node destination, else, forwards the RREQ packet to its neighbors, except the origin node. This process repeat until a route has been found. To balance the traffic load, the authors of [9] have improved the process of processing RREQ packets. When an intermediate node receives a RREQ packet from another node, it will check its current load based on the status of its buffer. If the current load is greater than the defined maximum, the node discards RREQ. Otherwise, RREQ is forwarded to the next nodes. For this method, the found routes will not go through nodes with heavy traffic. By simulation method, the authors have shown that this load balancing technique will improve the performance of WMN.

Another method that is often used for single-path load balancing routing is to build load aware metrics. For this method, the authors of [17] have proposed a routing metric namely weighted cumulative expected transmission time with load-balancing (WCETT-LB) for WMN. This metric is extended from WCETT [18] by incorporating load-balancing into it. The simulation results have shown that WCETT-LB outperforms the WCETT and Hop count metrics in terms of packet delivery ratio, average end-to-end delay and congestion level for WMN. In [10], the authors have proposed a routing metric namely contention window based (CWB). This metric assigns weights to individual links in the network. The routing algorithm uses this metric in order to choose the load balancing routes.

The multi-path routing method has also been used for the load balancing routing recently. For this method, the routing algorithm selects multiple routes between each source - destination pair. These routes are used for transmitting the data packets ac-

cording to a given rule. The authors of [11] have used the Fibonacci sequence [19] as the rule for distributing data packets over routes. Their proposed algorithm called Fibonacci multipath load balancing (FMLB). The simulation results illustrated that the performance of the network using FMLB protocol is improved in terms of packet delivery ratio and end-to-end delay as compared to other well known protocols.

B. QoT Aware Routing

In order to improve the network performance in terms of QoT, some research groups have been interested in QoT aware routing recently [12]–[15]. The authors of [15] have used the cross-layer model to improve the AODV protocol. Their method modifies the format of the route reply packet (RREP) by adding a field to store the link cost value. This value is a function of the SNR, end-to-end delay and node lifetime. The routing algorithm then chooses the route with the best link cost. In [12], [20], the authors have improved three routing protocols, DSR, optimized link state routing (OLSR), and AODV. These protocols were modified by adding two fields in RREP to store the metrics of SNR and received power (RP). The route with the best value of SNR or RP will be chosen for the data transmission.

Another method that was used for the study of QoT aware routing uses the routing metric. This method often constructs a metric that contains the parameters of the QoT. Then, the best route is chosen based on this metric. For this method, the authors of [13] proposed a routing metric namely weighted signal to noise ratio average (WSA) for dynamic sequence distance vector (DSDV) routing protocol. The WSA metric uses the SNR parameter provided by the physical layer based on the cross-layer model. By simulation method, the authors have shown the network performance is improved in terms of throughput, packet delivery ratio and end-to-end delay. In [3], [21], we have also studied the QoT aware routing technique for AODV and DSR protocols, respectively. Our method uses the layered model in combination with a local agent to determine the constraints of QoT during the route discovery process.

Through the published works that have been surveyed above, we could comment that, the QoT aware routing can improve the network performance in terms of QoT on the data transmission routes. However, it can increase the traffic bottleneck due to the unbalanced traffic load in network. On the other hand, the load balancing routing often reduces the traffic bottleneck, increase the packet delivery ratio and network throughput, but it can decrease the QoT due to existing the long routes. Therefore, it is necessary to integrate QoT aware routing and load balancing routing to ensure network performance on both QoT and traffic bottleneck. This is the research motivation of this paper, our proposed algorithm is presented in detailed in Section V.

III. THE STRUCTURE OF SOFTWARE DEFINED NETWORKING USED FOR ROUTING IN WMN

A subject that has recently attracted significantly many research groups is using SDN to improve the architecture, to model, and to control protocols in wireless networks. For this subject, the authors of [22] have proposed a routing protocol namely SDN-cluster based routing protocol (S-CBRP) which

is improved from the cluster based routing protocol in ad hoc networks. The aim of S-CBRP is to increase the lifetime of the nodes in ad hoc networks by choosing the optimal route to the destination node with minimum energy consumption. S-CBRP also takes into account the remaining energy of the node and delay constraints. The simulation results demonstrated that S-CBRP outperforms FF-AOMDV protocol [23] in terms of energy consumption, network overhead, average source-to-destination delay and packet delivery ratio.

The authors of [24] have also proposed an architecture of SDN for MANET called RDSNET. The aim of this work is to provide a solution to the design and deployment of the controllers for MANET. The authors have built several simulation scenarios using OMNeT++ [25] in order to decide whether the design of a distributed or centralized controller is the most suitable for the implementation of MANET. The results demonstrated that the RDSNET distributed configuration yields better performance. However, the authors have proved that, the latency is the main disadvantage of SDN architecture for MANET.

The study of SDN architecture for the vehicle ad-hoc networks (VANET) has been also deployed by some research groups recently. The authors of [26] have used SDN in order to improve the on-demand routing protocol in VANET, called SDN based vehicle adhoc on-demand routing protocol (SVAO). SVAO protocol uses the separation of the data transfer layer and network control layer of SDN in order to enhance the data transmission efficiency for VANETs. The simulation results demonstrated that SVAO outperforms DSR, DSDV, OLSR and DB protocols.

In most of the proposed SDN architectures for wireless networks as well as other network models, the open-flow protocol is often used for the connection interface between the infrastructure layer and the control layer [22], [24], [26]. In this paper, we use the architecture of SDN using open-flow protocol for the WMN as shown in Fig. 3. The network system is divided into three layers according to the principle of SDN, which are the infrastructure layer, control layer and application layer. Infrastructure layer is the mobile devices of MANET. However, these devices only perform switching packet data based on the flow table that is provided from the control layer. The functions of routing and signaling are separately implemented at the control layer.

In this model, we also used the open-flow protocol for the connection interface between the infrastructure layer and the control layer. When the network topology at the infrastructure layer changes due to the movement of the access nodes or the error links, a control packet (CP) will be sent from the infrastructure layer to the control layer in order to update the network status information, used for implementing the routing algorithm and rebuilding the flow table by SDN controller. In the case that there is a request of the data transmission from the source node to the destination node, the source first checks in its flow-table whether there is a route to the destination node or not. If so, it uses this route to transmit the data packets. Otherwise, it will send a CP to SDN controller to request a new route discovery according to given routing algorithm. If a new route is found, SDN controller sends CP to the source node to provide route information. The source node at the infrastructure layer
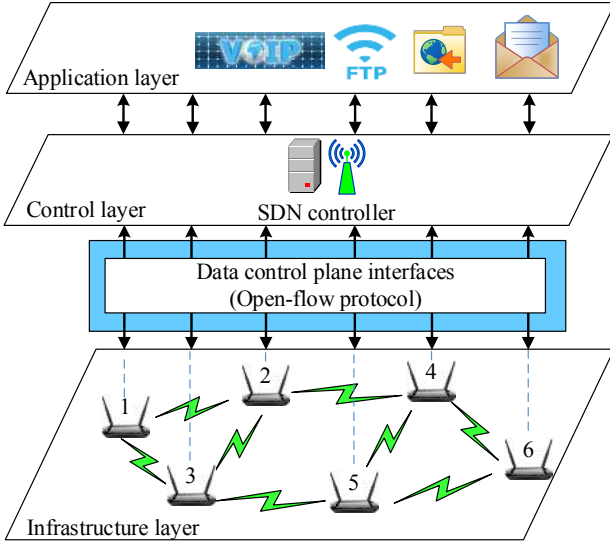
Fig. 3. The architecture of SDN using open-flow protocol for the WMN.

Fig. 4. An example of the traffic load offers to a link in WMN.
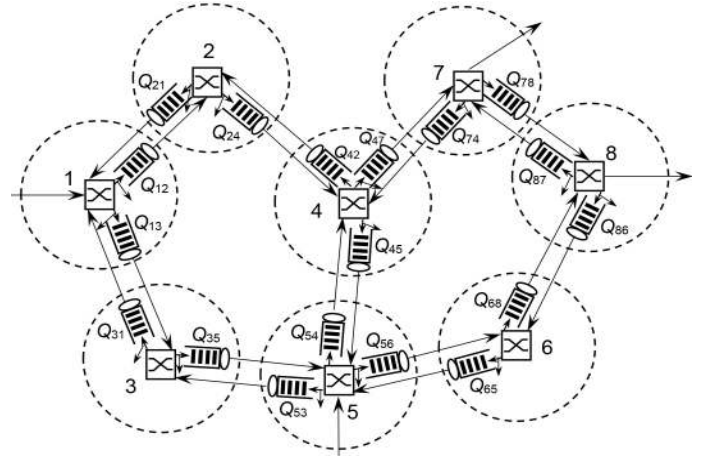
Fig. 5. A queuing network model for the WMN in Fig. 4.

uses this information to transmit the data to destination node. In our model, the routing algorithm that used at SDN is LBRCQT, presented in detail in Section V.

IV. ANALYTICAL MODEL OF THE PERFORMANCE PARAMETERS IN WMN

In this section, we use the analytical model to analyze parameters that have the most influence on the performance of WMN, including the load offers to each link in the network, end-to-end delay (EED), SNR, and BER. These parameters are used for the objective function and constraint conditions of the proposed routing algorithm in the Section V.

A. Load Offers to Each Link (LoL) in the Network

LoL is used for the objective function of the load balancing selection in our proposed algorithm. For each link in the WMN, LoL depends on the number of the data transmission routes passing through that link and the blocking probability of the data packets in the network. Let ρ_{sd} be the load offers to the route r_{sd} and $\rho_{ij}^{(sd)}$ be the load offers to the link l_{ij} by the route r_{ij}, then $\rho_{ij}^{(sd)}$ is determined as follows.

$$\rho_{ij}^{(sd)} = \rho_{sd} \prod_{\forall l_{uv} \in r_{sd}, l_{uv} \dashv_{sd} l_{ij}} (1 - B_{uv}), \qquad (1)$$

where B_{uv} is the blocking probability when the data packet is transmitted over the link l_{uv}. The symbol $\dashv_{sd}$ in (3) denotes that the link l_{uv} strictly precedes the link l_{ij} along the route r_{sd}. From (3) we have the load offers to the link l_{ij} by all routes in the network which is determined by

$$\rho_{ij}^{(l)} = \sum_{\forall r_{sd}} \left(\rho_{sd} \prod_{\forall l_{uv} \in r_{sd}, l_{uv} \dashv_{sd} l_{ij}} (1 - B_{uv}) \right). \qquad (2)$$

To clearly see how to determine the load offering to a link according to (2), we consider an example as shown in Fig. 4.
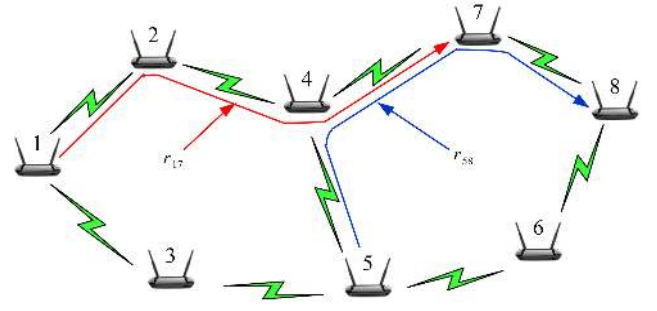
At the present time, there are two data transmission routes, $1 \to 2 \to 4 \to 7$ and $5 \to 4 \to 7 \to 8$. According to (2), we have the traffic load offers to the link l_{47} which is determined as follows.

$$\rho_{47}^{(l)} = \rho_{17} \prod_{\forall l_{uv} \in r_{17}, l_{uv} \dashv_{17} l_{ij}} (1 - B_{uv}) \qquad (3)$$

$$+ \rho_{58} \prod_{\forall l_{uv} \in r_{58}, l_{uv} \dashv_{58} l_{ij}} (1 - B_{uv}) \qquad (4)$$

$$= \rho_{17}(1 - B_{12})(1 - B_{24}) + \rho_{58}(1 - B_{54}). \qquad (5)$$

Equation (2) shows that, to be able to determine $\rho_{ij}^{(i)}$, we need to determine the blocking probability of the data packet over each link (B_{ij}) in the network. In our context, Kleinrock's independence approximation in [27] is used to model the WMN as a queuing network. Assuming data packets offered to MRs arrive according to a Poisson process and all arrival processes are independent. Since the service time of each packet is directly proportional to its length, this time is also exponentially distributed. Data packets go out of the queue at each node according to the Poisson distribution and to the next queue also according to the Poisson distribution. For these assumptions, the WMN network is modelled as an open queue network as shown in Fig. 5, where each link l_{ij} in the network is modelled as an M/M/1/K queuing, where K is the length of the queuing in packets. Thus, B_{ij} is

determined by [28]

$$B_{ij} = \begin{cases} \dfrac{\rho_{ij}^K(1 - \rho_{ij})}{1 - \rho_{ij}^{K+1}} & \text{if } \rho_{ij} \neq 1 \\ \dfrac{1}{K+1} & \text{otherwise,} \end{cases} \quad (6)$$

where $\rho_{ij} = \lambda_{ij}/\mu_{ij}$ is the traffic density which offers to l_{ij}, λ_{ij} and μ_{ij} are the arrival rate and service rate of data packets on the link l_{ij}, respectively.

B. End to End Delay (EED)

EED is used for the constraint condition in our proposed algorithm. This parameter is the summation of the time taken by a data packet to travel from a source node to a destination node. When a data packet is transmitted over the route r_{sd}, its EED is determined by

$$\tau_{sd}^{(r)} = \sum_{\forall l_{ij} \in r_{sd}} \tau_{ij}^{(l)}, \quad (7)$$

where $\tau_{sd}^{(r)}$ and $\tau_{ij}^{(l)}$ are the EED of the route r_{sd} and the link l_{ij}, respectively. $\tau_{ij}^{(l)}$ consists of four components which are the processing delay ($\tau_p^{(i)}$), queuing delay ($\tau_q^{(i)}$), transmission delay ($\tau_t^{(ij)}$) and radio propagation delay ($\tau_r^{(ij)}$) [29]. In the case that the processing delay and radio transmission delay are small enough to be ignored, $\tau_{ij}^{(l)}$ depends on two main components, $\tau_t^{(ij)}$ and $\tau_q^{(i)}$. $\tau_t^{(ij)}$ is determined based on the bit rate of the channel and the data packet size, $\tau_q^{(i)}$ is determined based on the queue mechanism at the nodes [21]. In [30], [31], the authors have assumed that M/M/1/K queuing is used in WMN to determine the service delay at each link. In this work, we also use M/M/1/K queuing, thus $\tau_q^{(i)}$ is determined by [32]

$$\tau_q^{(i)} = \frac{\overline{K}}{\lambda_{ij}(1 - B_{ij})} + \frac{1}{\mu_{ij}}, \quad (8)$$

where B_{ij} is determined according to (6). $\overline{K}$ is the average number of the packets in queuing, determined as follows [32]:

$$\overline{K} = \begin{cases} \dfrac{\rho_{ij}}{1 - \rho_{ij}} - \dfrac{\rho_{ij}(K\rho_{ij}^K + 1)}{1 - \rho_{ij}^{K+1}} & \text{if } \rho_{ij} \neq 1 \\ \dfrac{K(K-1)}{2(K+1)} & \text{otherwise.} \end{cases} \quad (9)$$

C. Signal to Noise Ratio (SNR)

SNR of each data transmission route is determined as the ratio of signal power to the noise power at the receiver of the destination node. When the data is transmitted through the routes in multi-hop, the power of the accumulative noise increases along the route, causing SNR to decrease. The decline of the SNR depends on the relay type of the intermediate nodes. In the multi-hop wireless network, the intermediate nodes can forward data in two ways, either amplify and forward (AF), or decode and forward (DF) [25], [33]. SNR of a route depends on these for-
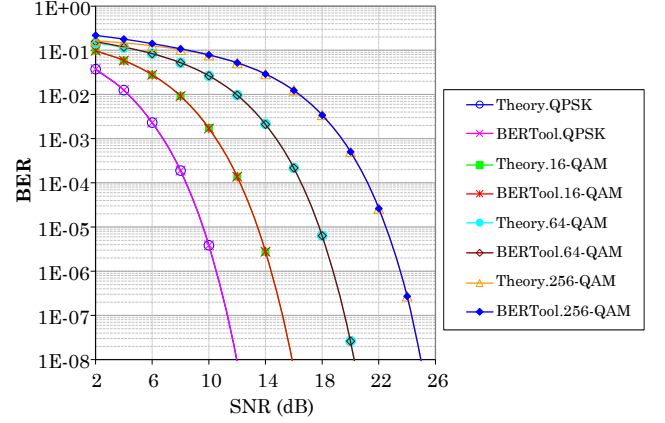

Fig. 6. The characteristics of BER versus SNR.

ward types, which is determined as follows.

$$\beta_{sd}^{(r)} = \begin{cases} \displaystyle\min_{\forall l_{ij} \in r_{sd}} \left(\beta_{ij}^{(l)}\right) & \text{if DF is used} \\ \left(\displaystyle\sum_{\forall l_{ij} \in r_{sd}} \dfrac{1}{\beta_{ij}^{(l)}}\right)^{-1} & \text{otherwise,} \end{cases} \quad (10)$$

where $\beta_{sd}^{(r)}$ and $\beta_{sd}^{(h)}$ are the SNR of the route r_{sd} and the hop h_{ij}, respectively.

For a data transmission route, the higher SNR, the smaller BER and the better QoT. The relationship between SNR and BER can be determined according to the theory of modulation formats [34], or using BERtool in MATLAB software [35]. For these methods, we have determined the theoretical curve of BER versus SNR according to different modulation techniques as shown in Fig. 6. The modulation techniques which are considered are the quadrature amplitude modulation (QAM), including 4-QAM (QPSK), 16-QAM, 64-QAM, and 256-QAM. We can observe that, if the SNR increases, the BER decreases exponentially. For example, in the case of 256-QAM, if SNR is 18 dB, BER is about 3.5×10^{-3}. If SNR increases to 22 and 24 dB, BER decreases to about 2.9×10^{-5} and 3×10^{-7}, respectively.

V. OUR PROPOSED ALGORITHM

In order to improve the performance of WMN in terms of the QoT and congestion probability, we propose a route routing algorithm namely load balancing routing under constraints of quality of transmission (LBRCQT). Our method uses the principle of SDN to collect the information of QoT and traffic load of the links in the network. These information are used for the objective function and the constraints of the proposed routing algorithm.

A. Analytical Model of LBRCQT Algorithm

The objective of LBRCQT algorithm is to choose a load balancing route under the constraints of QoT, where the load balancing is done by selecting a route in which if a data packet is transmitted over that route, the blocking probability is minimal. The constraints of QoT include SNR and EED.

Algorithm 1: LBRCQT algorithm

Input : A WMN topology with current load traffic of all links $\rho = [\rho_{ij}]_{n \times n}$; a request of discovering new route from the source node (s) to the destination node (d).

Output: A load balancing route satisfying the constraints of QoT from s to d or rejection of the request if a new route is not found.

Method:

(1) Determine packet blocking probability of all links (B_{ij}) according to (6);

(2) Determine all possible routes from node s to node d (K routes);

(3) Determine SNR of all possible routes $(\beta_{sd}^{(r_k)}, k = \overline{1..K})$ according to (10);

(4) Determine EED of all possible routes $(\tau_{sd}^{(r_k)}, k = \overline{1..K})$ according to (7);

(5) Formulate ILP problem with the objective function (13) and constraints from (14) to (17) ;

(6) Solve ILP problem at step (5) according to Function 1 ;

(7) **if** *(Find a solution for $\{x_k^{(sd)}\}$)* **then**

(8)   Determine the route from s to d based on $\{x_k^{(sd)}\}$;

(9)   Send the control packets to the nodes to update the new route into flow switch table;

(10) **else**

(11)   Send the control packets to the nodes to reject the request of the data transmission;

(12) **end**

Function 1: Solve ILP problem with the objective function (13) and constraints from (14) to (17)

---

(1) **for** *(i = 1 to K)* **do**

(2) $x_i^{(sd)} \leftarrow 0$;

(3) **end**

(4) $B_{sd} \leftarrow$ 0xFFFF ;   // a big enough value

(5) $k \leftarrow$ -1;

(6) **for** *(i = 1 to K)* **do**

(7) $x_i^{(sd)} \leftarrow 1$;

(8)   Determine the constraint of SNR according to (16);

(9)   Determine the constraint of EED according to (17);

(10)   **if** *(Results of step (7) and (8) are **true**)* **then**

(11)   Determine the value of the objective function (13) $(B_{sd}^{(k)})$;

(12)   **if** $(B_{sd} < B_{sd}^{(k)})$ **then**

(13) $B_{sd} \leftarrow B_{sd}^{(k)}$;

(14) $k \leftarrow i$;

(15)   **end**

(16)   **end**

(17) $x_i^{(sd)} \leftarrow 0$;

(18) **end**

(19) **if** $(k \neq -1)$ **then**

(20) $x_k^{(sd)} \leftarrow 1$;   // route k^{th} is found

(21) **else**

(22)   Solution for $\{x_k^{(sd)}\}$ does not exist;

(23) **end**

Let K be the number of possible routes from the source node (s) to the destination node (d), and $B_{sd}^{(k)}(k = \overline{1..K})$ be the packet blocking probability of the route $r_{sd}^{(k)}$. According to statistical probability theory, $B_{sd}^{(k)}$ is given by

$$B_{sd}^{(r_k)} = 1 - \prod_{\forall l_{ij} \in r_{sd}^{(k)}} (1 - B_{ij}^{(l)}). \qquad (11)$$

Let $x_k^{(sd)}$ be the variable for selecting the route from s to d that is determined by

$$x_k^{(sd)} = \begin{cases} 1 & \text{if route } r_{sd}^{(k)} \text{ is chosen} \\ 0 & \text{otherwise,} \end{cases} \qquad (12)$$

thence LBRCQT algorithm is modeled as an integer linear programming (ILP) as follows.

$$\text{Minimize} \sum_{k=1}^{K} x_{sd}^{(k)} B_{sd}^{(r_k)}, \qquad (13)$$

subject to the following constraints:

$$x_{sd}^{(k)} = 0, 1, \qquad (14)$$

$$\sum_{k=1}^{K} x_{sd}^{(k)} = 1, \qquad (15)$$

$$\sum_{k=1}^{K} x_{sd}^{(k)} \beta_{sd}^{(r_k)} \geq \beta_{req}, \qquad (16)$$

$$\sum_{k=1}^{K} x_{sd}^{(k)} \tau_{sd}^{(r_k)} \leq \tau_{\text{limit}}, \qquad (17)$$

where $\beta_{sd}^{(r_k)}$ is the SNR of the route $r_{sd}^{(k)}$ that is determined according to (10), $\tau_{sd}^{(r_k)}$ is the EED of the route $r_{sd}^{(k)}$ that is determined according to (7). β_{req} and τ_{limit} are the required SNR and limitation of EED to ensure the QoT of the chosen route, respectively. The constraint (14) ensures that $x_{sd}^{(k)} \in \{0, 1\}$. The constraint of (15) is to choose the route, only 1 of K routes. The constraints of (16) and (17) are the SNR and EED of the chosen route to ensure QoT, respectively.

B. Implementing Algorithm based on SDN

When there is a request for transmitting the data from the source node (S) to the destination node (D) in WMN, the source node first checks in its flow switch table whether a route is fresh enough. If so, this route is used for transmitting the data to the destination node. Otherwise, the source node sends a control packet to SDN controller in order to request a new route discovery. At SDN controller, the LBRCQT algorithm (algorithm 1) is implemented to discover a load balancing route under the constraints of QoT. At step (6) of algorithm 1, the ILP problem must be solved to find a route. This problem can be solved by using some optimal tools such as MATLAB, CPLEX,

Table 1. Simulation parameters.

Parameters	Setting
Simulation area	$1000 \times 1000\ m^2$
Number of access point	17 nodes
Number of mobile host	30, 35, 40, 45, 50, 55, 60 nodes
MAC protocol	802.11ac
Modulation technique	256-QAM
Channel bandwidth	20 MHz
Data rate	54 Mbps
Transmit power	12 dBm
Receiver sensitivity	-76 dBm
Transmission range	250 m
BER threshold	10^{-6}
Minimum required SNR	25 dB
Noise model	Thermal noise
Temperature	$300\ {}^{o}K$
Mobility model	Random $-$ Waypoint
Speed of mobile host	$0-20$ m/s
Simulation time	2400 s

Fig. 7. A snapshot of the animation interface during the simulation of WMN.

etc. However, solving the ILP problem directly often has a large computational complexity, leading to an increase in EED in network. In our algorithm, the ILP problem at step (5) is set up similarly to the problem of finding the minimum value that satisfies the given conditions. We have installed this problem on OMNeT ++ [36] according to Function 1. For this method, the computational complexity is only $O(K)$, where K is the number of possible routes from the source node to the destination node.

VI. PERFORMANCE EVALUATION BY SIMULATION

A. Simulation Scenarios

The performance of LBRCQT algorithm is evaluated by simulation method based on OMNeT++ 4.2.2 [36] and the INET framework 2.0. LBRCQT algorithm is compared with the shortest path routing (SPR) algorithm in terms of the SNR, blocking probability of data packet, and network throughput. The simulation assumptions are presented in Table 1. We use a common application scenario of WMN, where the mobile hosts access the Internet via the access points to connect to the gateway. Fig. 7 shows a snapshot of the animation interface during the simulation performance. The network topology consists of 17 access points (AP) that are arranged statistically, the APs connected to each other via a wireless environment. There are three APs that are connected to the gateway via the optical fiber according to the gigabit ethernet standard. In addition, there are from 30 to 60 mobile hosts that connect to APs in order to access Internet. These mobile hosts move randomly according to the Random Waypoint model [37] in the simulation area.

B. Performance Metrics

In our simulation models, the metrics of the SNR of the data transmission channels, packet delivery ratio, end-to-end-delay, and network throughput are used to evaluate and analyze the performance of SPR and LBRCQT algorithms.
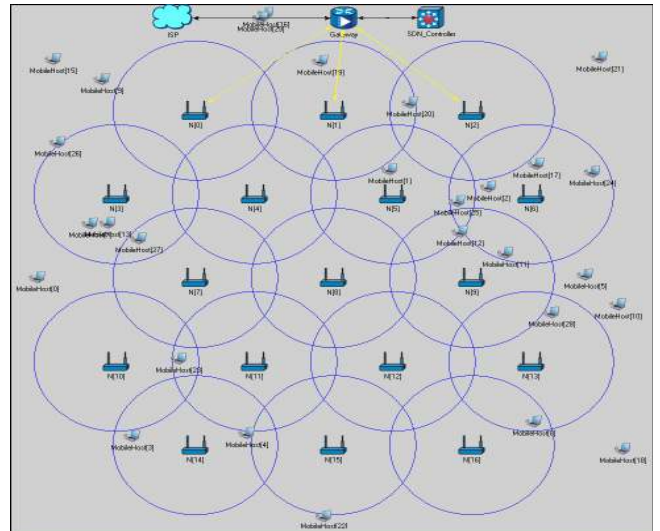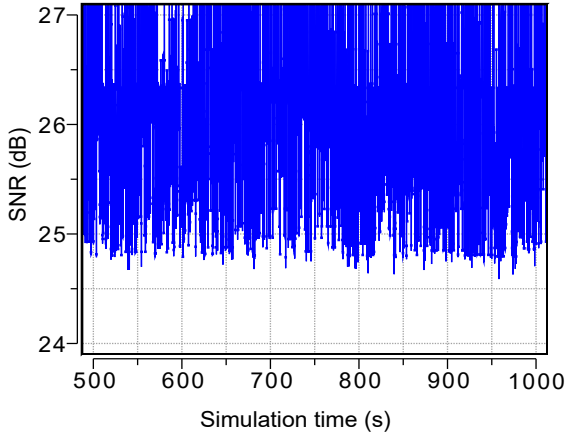
- The SNR of the data transmission channels is the SNR at the receiver of the destination node, measured during simulation.

- Packet delivery ratio (PDR) is determined as the ratio of total of the received packets by the destination nodes to the total of sent packets by the source nodes.

- The throughput is determined as the successfully received data traffic per time unit, expressed in bps or its multiple.

- End-to-end delay (EED) is the summation of time taken by a data packet to travel from the source node to the destination node.

C. Simulation Results

The obtained results in Fig. 8 show the SNR of all data transmission channels for the cases that SPR and LBRCQT algorithms are used. In this case, the number of the mobile hosts and their average mobility speed are 50 and 10 m/s, respectively. According to the simulation scenarios presented in Section VI.A, the minimum required SNR for ensuring QoT is 25 dB. From the charts in Fig. 8 we can observe that, for SPR algorithm (Fig. 8(a)), there are many channels that do not satisfy the constraint conditions of QoT since its SNR is less than minimum required SNR, 25 dB. For LBRCQT algorithm (Fig. 8(b)), SNR values are improved significantly compared with those of SPR algorithm. Most of the channels satisfy the constraint conditions of QoT.

Next, we analyze the packet delivery ratio (PDR). This is an important performance parameter of the network system. The difference in the PDR of SRP and LBRCQT algorithms is shown in Fig. 9, where we plot the PDR as a function of the traffic load of each MH, expressed in Mbps. These results are simulated for the case that the number of the MHs is 40, the average mobility speed of the MHs is 10 m/s. We can observe that, for LBRCQT algorithm, PDR has increased significantly compared with that of SPR algorithm. Considering the case of the traffic load of 5 Mbps, PDR of SPR and LBRCQT algorithms are 92.13 and 98.57%, respectively. Thus PDR of LBRCQT algo-

(a)
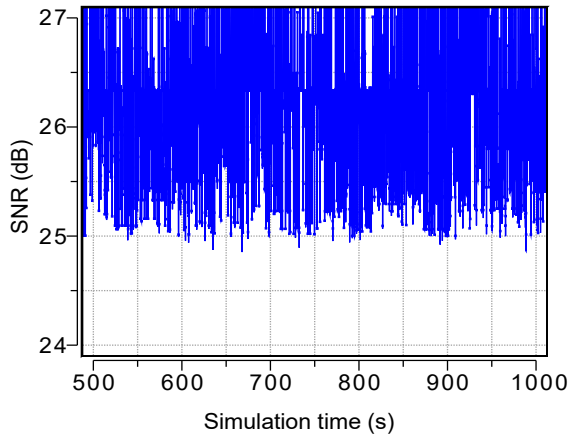
(b)

Fig. 8. The comparison of the SNR of the data transmission channels in cases of (a) SPR and (b) LBRCQT algorithms.
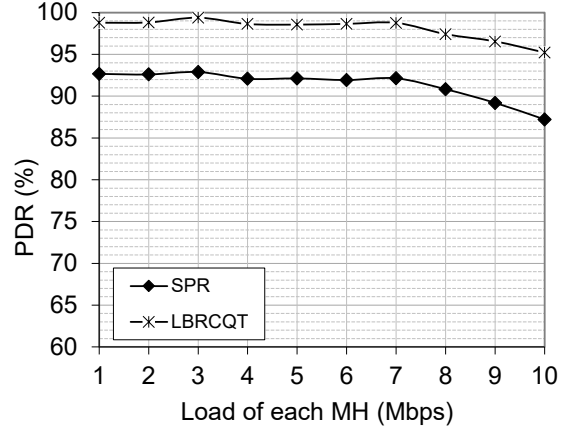

Fig. 9. Packet delivery ratio performances of SPR and LBRCQT in case of the variable traffic load.

Fig. 10. Packet delivery ratio performances of SPR and LBRCQT in case of the variable number of MHs.

rithm increases significantly 6.44% compared with that of SPR algorithm. In case of the heaviest traffic load of each MH, i.e 10 Mbps, PDR increases by 8.01%, from 87.21 to 95.22%. For the remaining cases, PDR increases by an average of 6.71% if LBRCQT algorithm is used.

Fig. 10 shows the difference in PDR of SPR and LBRCQT algorithms in case of the variable number of MHs. Considering the case that the average traffic load of each MH is 5 Mbps, we can observe that, the LBRCQT algorithm always has PDR higher than the SPR algorithm. When the number of MHs is from 30 to 60, PDRs of LBRCQT algorithm ranges from 98.11 to 98.91%. Meanwhile, those of SPR algorithm are only from 90.76 to 92.29%. The result is quite similar in the case of the traffic load of 8 Mbps. Although the PDRs of both algorithms are less than those in the case of 5 Mbps, the LBRCQT algorithm always has PDR higher than the SPR algorithm, the average increase of 7.07%.

Due to the increase in PDR as analyzed in Figs. 9 and 10, the throughput in the case of using LBRCQT algorithm also increases. This is more clearly visible from Fig. 11, where we measure average throughput versus simulation time for the case that the average mobility spend of the MHs is 10 m/s, the number of MHs is 40 MHz, and the traffic load of each MH is 5 Mbps. We can observe that, in the case that the SPR algorithm is used, the average throughput is about 232 Mbps. Meanwhile, this value is about 247 Mbps in case of LBRCQT algorithm. Thence, the throughput increases by 14.7 Mbps if using LBRCQT algorithm. When the number of MHs varies from 40 to 60, the throughput of the LBRCQT algorithm is always greater than that of SPR algorithm as shown in Fig. 12. In cases of the traffic load of the each MH of 5 Mbps and 8 Mbps, the average throughput of the LBRCQT increases by 16.24 and 28.21 Mbps, respectively.

In the next section, we compare the average EED of the SPR and LBRCQT algorithms. The obtained results are shown in Fig. 13, where we denote the average EED as a function of the traffic load of each MH. We can observe that, when the traffic load is low, the EED of LBRCQT algorithm is higher than that of SPR algorithm. Specifically, consider the case of 3 Mbps, the average EED of the SPR and LBRCQT algorithms are about 0.37 and 0.43 ms, respectively. Thus, the average EED of LBR-
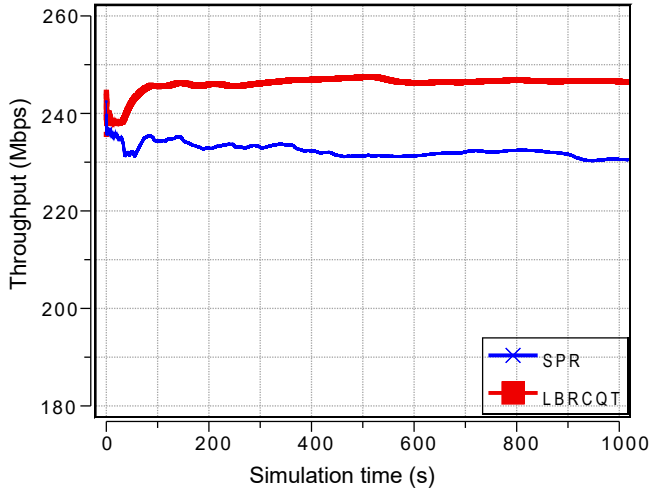
Fig. 11. SPR and LBRCQT throughput performances in case of 50 MHs, load of each MH is 5 Mbps.
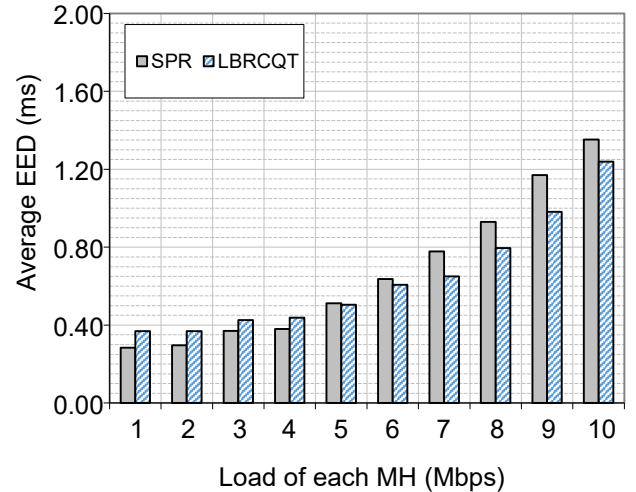

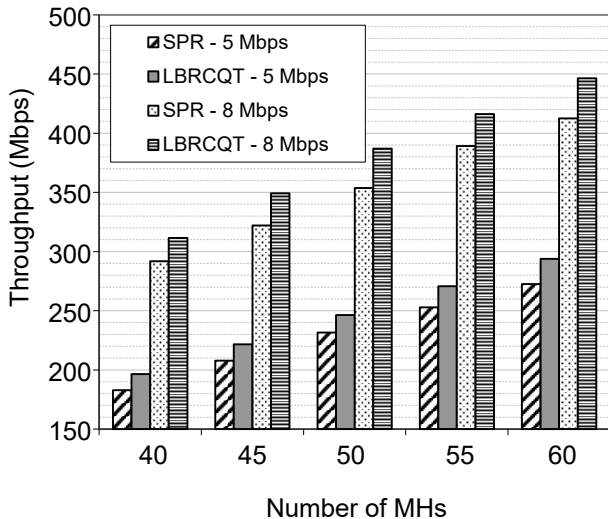Fig. 13. Average end-to-end delay performances of SPR and LBRCQT versus the traffic load of each MH.

Fig. 12. SPR and LBRCQT throughput performances versus the number of MHs.

For the case of the heavy traffic load of each MH (5 Mbps and 8 Mbps), LBRCQT algorithm tends to reduce the average EED. Specifically, the average EED of LBRCQT algorithm reduces by 0.08 ms and 0.11 ms for the cases of the traffic load of 5 Mbps and 8 Mbps.

Thus, the simulation results on average EED have shown that, when the traffic load in the network is heavy, LBRCQT algorithm performs more efficiently than SPR algorithm in terms of the average EED.

Based on the simulation results presented above, we can conclude that LBRCQT algorithm improves significantly the network performance in terms of SNR, PDR and throughput. The cause of the improvement in network performance is due to the fact that the LBRCQT algorithm has chosen load balancing routes, so the bottleneck in the network is reduced. In addition, the constraint conditions of QoT have been also considered, reducing the blocking probability of the data packets due to QoT unguarantees.

VII. CONCLUSIONS

In wireless mesh networks, the load balancing routing is one of the optimal routing technique to improve network performance. With this routing technique, the local congestion at some connections as well as intermediate nodes is minimized because the traffic is distributed evenly for all connections in the network. However, in the case of the WMN with the wide area and high node density, the load balancing routing can reduce the QoT and the end-to-end delay since the data transmission routes can pass through multiple hops. We proposed in this paper a routing algorithm for WMN that takes into account both load balancing and QoT, called LBRCQT. Our proposed algorithm is based on the principle of the software defined networking. The performance of the LBRCQT algorithm is demonstrated by the simulation method using OMNeT++. The simulation results have shown that the proposed algorithm can improve the network performance in terms of SNR, packet delivery ratio (PDR),

CQT algorithm has increased by 0.06 ms. This is caused by the data transmission routes of LBRCQT algorithm passing through to balance the load. In this case, the EED depends mainly on the transmission delay because the queue delay is very small. In case of the heavy traffic load, the average EED of LBRCQT reduces significantly compared with that of SPR. For example, the average EED reduces from 1.17 ms downto 0.98 ms for the case of the traffic load of 9 Mbps. This is caused by the LBRCQT algorithm has reduced the queue delay at each node due to the load balancing.

In case of the variable number of MHs, the difference in the average EED of SPR and LBRCQT is shown in Fig. 14. In the case that the traffic load of each MH is low (2 Mbps), the average EED of SPR and LBRCQT algorithms are about 0.31 and 0.39 ms, respectively. Thus the EED of LBRCQT algorithm is higher than that of SPR algorithm with the value of 0.08 ms.
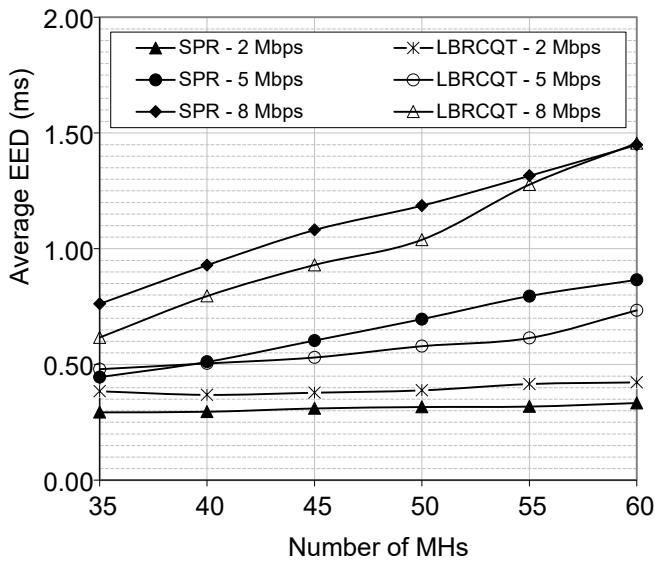
Fig. 14.   Average end-to-end delay performances of SPR and LBRCQT versus the number of MHs.

and throughput compared with SPR algorithm.

In the near future, we continue to develop this subject with respect to the multi-channels, multi-carriers WMN, and some other wireless network models.

REFERENCES

[1] Y. Zhang, J. Luo, and H. Hu, *Wireless Mesh Networking - Architectures, Protocols and Standards*. Taylor & Francis Group, LLC, 2007.

[2] I. F. Akyildiz and X. Wang, *Wireless Mesh Networks*. John Wiley & Sons Ltd, 2009.

[3] L. H. Binh and V. T. Tu, "QTA-AODV: An improved routing algorithm to guarantee quality of transmission for mobile ad Hoc networks using cross-layer model," *J. Commun.*, vol. 13, no. 7, pp. 338–349, 2018.

[4] Istikmal, A. Kurniawan, and Hendrawan, "Selective route based on SNR with cross-layer scheme in wireless ad hoc network," *J. Comput. Networks Commun.*, vol. 2017, pp. 1–13, May 2017.

[5] H. Bakhsh and M. Abdullah, "ARPM: Agent-based routing protocol for MANET," *Int. J. Internet Protocol Tech.*, vol. 3, no. 2, pp. 136–146, 2008.

[6] E. Kulla *et al.*, "Investigation of AODV throughput considering RREQ, RREP and RERR packets," in *Proc. IEEE AINA*, 2013.

[7] H. Li, C. Dan, W. Min, and L. Shurong, "Mobile agent based congestion control AODV routing protocol," in *Proc. IEEE WiCOM*, 2008.

[8] S. Kaur and M. Kumar, "Review on load balancing in mobile ad-hoc networks," *Int. J. Advanced Research Comput. Sci. Software Eng.*, vol. 5, no. 4, p. 5, 2015.

[9] M. I. Gumel, N. Faruk, and A. A. Ayeni, "Routing with load balancing in wireless mesh networks," *Int. J. Current Research*, vol. 3, no. 7, pp. 87–92, 2011.

[10] L. T. Nguyen, R. Beuran, and Y. Shinoda, "A Load-aware routing metric for wireless mesh networks," in *Proc. IEEE ISCC*, 2008.

[11] Y. Tashtoush, O. Darwish, and M. Hayajneh, "Fibonacci sequence based multipath load balancing approach for mobile ad hoc networks," *Ad Hoc Networks*, vol. 16, pp. 237–246, May 2014.

[12] F. Alnajjar, "SNR/RP aware routing model for MANETs," *J. Select. Areas Telecommun.*, pp. 40–48, Mar. 2011.

[13] M. Elshaikh, M. F. M. Fadzil, N. Kamel, and C. M. N. C. Isa, "Weighted signal-to-noise ratio average routing metric for dynamic sequence distance vector routing protocol in mobile ad-hoc networks," in *Proc. IEEE CSPA*, 2012.

[14] S. Srivastava and A. K. Daniel, "An efficient routing protocol under noisy environment for mobile ad hoc networks using fuzzy logic," *Int. J. Advanced Research Artificial Intell.*, vol. 2, no. 9, pp. 34–39, Sept. 2013.

[15] A. Yadav and T. Sharma, "Cross-layer approach for communication in MANET," *Int. J. Comput. Sci. Mobile Computing*, vol. 4, no. 3, pp. 285–292, Mar. 2015.

[16] L. H. Binh, V. T. Tu, and N. V. Tam, "SLBQT-DSR: Source-based load balancing routing algorithm under constraints of quality of transmission for MANET," *J. Comput. Sci. Cybern.*, vol. 34, no. 3, pp. 265–282, Nov. 2018.

[17] L. Ho and H. Gacanin, "Design principles for ultra-dense Wi-Fi deployments," in *Proc. IEEE WCNC*, 2018.

[18] D. A. Dugaev, I. G. Matveev, E. Siemens, and V. P. Shuvalov, "Adaptive reinforcement learning-based routing protocol for wireless multihop networks," in *Proc. IEEE APEIE*, 2018.

[19] Y. M. Tashtoush and O. A. Darwish, "A novel multipath load balancing approach using Fibonacci series for mobile ad hoc networks," *Int. J. Comput. Theory Eng.*, vol. 4, no. 2, pp. 220–225, 2012.

[20] F. Alnajjar and Y. Chen, "SNR/RP aware routing algorithm: Cross-layer design for MANETs," *Int. J. Wireless Mobile Networks*, vol. 1, no. 2, pp. 127–136, Nov. 2009.

[21] L. H. Binh, V. T. Tu, and N. V. Tam, "Quality of transmission aware routing in adhoc networks based on cross-layer model combined with the static agent," *J. Comput. Sci. Cybern.*, vol. 32, no. 4, pp. 351–366, 2016.

[22] A. J. Kadhim, S. A. H. Seno, and R. A. Shihab, "Routing protocol for SDN-cluster based MANET," *J. Theoretical Applied Inform. Tech.*, vol. 96, no. 16, p. 5, Aug. 2018.

[23] A. Taha, R. Alsaqour, M. Uddin, M. Abdelhaq, and T. Saba, "Energy efficient multipath routing protocol for mobile ad-hoc network using the fitness function," *IEEE Access*, vol. 5, pp. 10369–10381, May 2017.

[24] S. Mora and J. Vera, "RDSNET: A proposal for control architecture for software defined MANETs," *Int. J. Eng. Tech.*, vol. 10, no. 3, pp. 816–827, June 2018.

[25] A.-S. K. Pathan, M. M. Monowar, and S. Khan, *Simulation technologies in networking and communications - selecting the best tool for the test*. CRC Press, Taylor & Francis Group, LLC, 2015.

[26] D. Baihong, W. Weigang, Y. Zhiwei, and L. Junjie, "Software defined networking based on-demand routing protocol in vehicle ad-hoc networks," in *Proc. IEEE MSN.*, 2017.

[27] L. Kleinrock, *Queueing systems, Volume II: Computer Applications*. John Wiley & Sons, New York, 1976.

[28] N. T. Thomopoulos, *Fundamentals of queuing systems statistical methods for analyzing queuing models*. Science+Business Media, New York, 2012.

[29] D. Bertsekas and R. Gallager, *Data Networks, Second Edition*. Prentice-Hall, 1992.

[30] T. Liu and W. Liao, "Location-dependent throughput and delay in wireless mesh networks," *IEEE Trans. Veh. Tech.*, vol. 57, no. 2, pp. 1188–1198, Mar. 2008.

[31] V. Ramamurthi, A. S. Reaz, D. G. S. Dixit, and B. Mukherjee, "Channel, capacity, and flow assignment in wireless mesh networks," *Computer Networks*, vol. 55, pp. 2241–2258, 2011.

[32] D. Gross, J. F. Shortie, J. M. Thompson, and C. M. Harris, *Fundamentals of Queueing Theory, Fourth Edition*. John Wiley & Sons, Inc., Hoboken, New Jersey, 2008.

[33] S. Khan, A.-S. K. Pathan, and N. A. Alrajeh, *Wireless Sensor Networks - Current Status and Future Trends*. CRC Press, 2012.

[34] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[35] A. H. M. Mohamed and A. K. M. Ahmidat, "End to end testing of digital transmission systems using Matlab," *American J. Engineering Research*, vol. 6, no. 4, pp. 52–59, Apr. 2017.

[36] A. Varga, *OMNeT++ discrete event simulation system, Release 4.6*, 2015, [Online]. Available: http://www.omnetpp.org.

[37] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful," in *Proc. IEEE INFOCOM*, 2003.

Le Huu Binh received the B.E. degree in Telcommunications and Electronics from Da Nang University of Technology, Vietnam, the M.Sc degree in Computer Sciences from Hue University of Sciences, Vietnam, and the Ph.D degrees in Informatics from Vietnam Academy of Science and Technology (GUST) in 2001, 2007, and 2020, respectively. He worked as a senior engineer with Transmission and Switching Exchange of the Hue Telecommunications Centre, Thua Thien Hue of the Vietnam Posts and Telecommunications Group (VNPT) from 2001 to 2009. Currently, he is working at the Faculty of Information Technology and Telecommunications,

of Hue Industrial College, Vietnam. He is also with the Faculty of Engineering and Technology, Thu Dau Mot University, Binh Duong, Vietnam as a visiting lecturer and Research Associate. His current research interests are the next generation wireless network technologies, software defined networking, the routing protocols in wireless mesh and ad hoc networks, analysis and evaluation of network performance.

Thuy-Van T.Duong received the B.E. degree in Information Technology from Post Telecommunication Institute of Technology (PTIT), Viet Nam, in 2004, the M.Sc. degree in Computer Science from the HOCHIMINH University of Technology, VietNam, in 2008, and Ph.D. degrees from PTIT, Viet Nam in 2015. She has been a lecturer of the Faculty of Information Technology, Ton Duc Thang University, Vietnam since 2005. She is currently the Director of the Center for Applied Information Technology, Ton Duc Thang University, Vietnam. Her research interests include artificial intelligence, data mining, mobile data management and communication technology. She received a USPTO patent in 2017.