A Load-aware Routing Metric for Wireless Mesh Networks

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Abstract

Routing metrics play a critical role in wireless mesh networks (WMNs). Several metrics have already been proposed but none of them can effectively capture both local traffic load and hidden node issues. This paper proposes a load and interference-aware routing metric for wireless mesh networks, named Contention Window Based (CWB) metric. Our metric assigns weights to individual links based on both channel utilization and the average Contention Window used on these links. The individual link weights are combined into path metric that accounts for load balancing and interference between links that use the same channel. Thus the CWB metric helps the routing protocol to balance traffic and improve network capacity by avoiding routing traffic through congested areas. The preliminary quantitative experiments show significant improvement over hop-count based method when using the proposed metric.

1. Introduction

Wireless networks are traditionally designed to be used as access networks to a wired network such as PSTN or the Internet. Such networks usually use one-hop wireless links to connect mobile clients to Access Points (APs) that are directly attached to wired network. The advantage of these networks is their simpleness; however they fail to provide sufficient connectivity and coverage and require an important budget for the wired infrastructure if we want to cover large areas such as cities, metro stations and so on. Recently, there has been a growing interest in extending the coverage of the wireless access networks. Wireless Mesh Networks (WMNs) is an emerging network technology that offers wireless broadband connectivity. WMNs have been attracting a lot of research [1], [2], commercial [3], [4], and standardization [5] interests in recent years. They can provide a cost-effective and flexible solution for extending broadband services to areas where cabling is difficult.

In WMNs most of the nodes are either static or minimally mobile and do not rely on batteries. The goal of routing algorithms is hence to improve network capacity [6] or the performance of individual communications instead of dealing with mobility or minimizing power consumption. The technical challenges in WMNs include load balancing, optimal routing, network auto-configuration, fairness and mobility management. The current routing solutions for general ad hoc networks can not be directly applied to WMNs because of the differences in not only their node characteristics but also in the traffic patterns between them. Since most users of WMNs are interested in accessing the Internet or using services provided by some servers, the traffic is mainly towards the Gateways (GWs) or from the GWs to clients. With that traffic pattern, if multiple wireless mesh routers choose the best throughput path to route their traffic to the GWs, the load of this path will increase significantly and lead to the tremendously decrease of the overall network performance. A good routing algorithm needs to balance the load not only between GWs but also on the entire mesh network as well. Efficient load balancing can help to improve network capacity by avoiding routing traffic through congested areas.

In order to achieve load balancing, we need appropriate routing protocols for WMNs. They should be designed carefully to adapt to the above characteristics of WMNs. This can be done through gateway-based load balancing, path-based load

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balancing or router-based load balancing. In gateway-based load balancing the traffic is distributed among a set of gateways by decisions carried out at gateways. Some schemes for load balancing in WMNs in which the load balancing decisions are considered at the gateway side are proposed in [7-10]. In path-based load balancing, the traffic is distributed across multiple paths to the gateways [11], [12]. Router-based load balancing can improve the network performance and reliability by distributing the traffic over the entire network to avoid creating bottleneck links. Those routing protocols have to introduce good link metrics that can reflect the amount of existing traffic on the links and also quality of the links. Router-based load balancing protocols designed for other networks, such as ad hoc network, are not suitable for WMNs because of the differences between them. Recently, protocols that are dedicated to WMNs are considered (e.g. ETX [13], ETT [14], WCETT [14], and MIC [15]); however, none of these routing metrics capture both aspects of interference and load balancing among nodes.

This paper proposes a routing metric that accounts for load-balancing among nodes in WMNs while considering interference. Our metric assigns weights to individual links based on both channel utilization and the average Contention Window used on these links. The individual link weights are combined into a path metric that accounts for load balancing and interference between links using the same channel. Thus the CWB metric helps the routing protocol to balance traffic and improve network capacity by avoiding routing traffic through congested areas.

The rest of this paper is organized as follows: Section 2 discusses existing related work. Section 3 presents the proposed routing metric and the routing protocol into which the routing metric is integrated. The simulation results and discussion are presented in Section 4. Finally, the conclusion is drawn in Section 5 with the indication of future research.

2. Related work

Due to the existence of many parameters that affect on wireless link quality such as channel load, inter-flow/intra-flow interferences, link stability, a load-aware routing protocol plays an important role in WMNs. As mentioned above, load balancing could be achieved through gateway-based load balancing, path-based load balancing or router-based load balancing.

Routing metrics are very critical to network performance. Good routing metric should carry enough information about the link quality so that a node can determine the best path to reach to a gateway. The recently proposed routing metrics for WMNs include hop-count, Expected Transmission Count (ETX) [13], Expected Transmission Time (ETT) [14], Weighted Cumulative ETT (WCETT) [14] and Metric of Interference and Channel-switching (MIC) [16].

Hop-count is the most commonly used routing metric in many routing protocol for multi-hop ad hoc networks such as AODV [17], DSR [18], DSDV [19]. It reflects the path length in hop and thus in the most cases the shortest path is used. However, from the hop-count metric we can not determine the qualities of the wireless links in the path such as link load, transmission rate, packet loss ratio, interferences thus using hop-count metric may not lead to a good network performance.

The ETX routing metric, proposed by De Couto *et al.* [13], is defined as the expected number of MAC layer transmissions for successfully delivering a packet through a wireless link. ETX reflects the difficulty of MAC layer to send a packet to its destination. The weight of path is defined as a summation of the ETX of all links along the path. In this way, ETX considers both path length and packet loss ratio. However, ETX fails to capture the link transmission rate and also the interference from other links because of the nature of CSMA/CA mechanism used in MAC layer.

The ETT routing metric, put forward by Draves *et al.* [14], is improved from ETX by considering the differences in link transmission rates. ETT is defined as the amount of time that is needed to transmit a packet through the link. The weight of path is a summation of the ETT of all links on this path. Despite the improvement from ETX, ETT still fails to capture the interferences among different links.

The WCETT routing metric, proposed by Draves *et al.* [14], introduces enhancement over ETT by taking into account the intra-flow interference. WCETT try to reduce the number of nodes along a path of a flow that transmit on the same channel. It captures the intra-flow interference of a path since it give low weights to the paths that have more diversified channel assignments on their links or in other words, that paths have lower intra-flow interference. Although WCETT can capture the intra-flow interference, it fails to consider explicitly the effects of inter-flow interference. Hence, WCETT can route traffic to congested areas.

The MIC routing metric improves the WCETT by capturing both intra-flow and inter-flow interference. It introduces IRU (Interference-aware Resource Usage) for inter-flow interference and CSC (Channel Switching Cost) for intra-flow interference. The ETT and number of neighbor nodes are used to compute the IRU. CSC takes into account the intra-flow interference by comparing the current link and the previous link. If the current link uses the same channel as the previous link then the CSC of the current link will be assigned a higher value.

The above routing metrics do not consider load-balancing. Load-balancing can be achieved by using multi-path routing protocol. In multi-path routing protocol, each node maintains multiple paths from itself to a set of GWs. Based on the routing metric used, the node chooses one path called best path to route its traffic. If the current best path is congested the node can switch to one of the remaining paths. There are some multi-path routing protocols applied for ad-hoc network such as those in [11], [12]. In such protocols, the paths are established by selecting maximal disjoint paths.

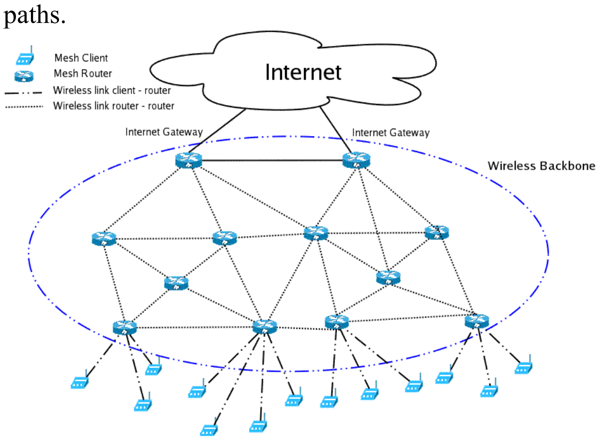

Figure 1. Wireless mesh network architecture

3. Proposed load balancing scheme

In this paper, we introduce a routing metric that takes into account both local traffic load and interference to provide load balancing in WMNs. The proposed scheme introduces load balancing features at the mesh routers and support global load-aware routing. The metric introduced here will consider traffic load into two parts. The first part which is the traffic load of the current node represents how busies the channel at the current node. The second part being traffic load of the peer node, that represents how busy the channel at the peer node or receiving node. Our proposed load-balancing scheme assumes an architecture as that shown in Figure 1. The upper part is the wired Internet with Internet gateways. These gateways connect wireless mesh routers to the Internet. The middle layer consists of wireless mesh routers that connect to both Internet gateways and mesh clients through wireless links. The wireless mesh routers form a wireless backbone network to provide Internet connectivity to mesh client. Mesh clients can access the Internet by relaying their packets through the wireless backbone. Mesh clients can be connected to wireless backbone in either single-hop mode or multi-hop mode.

3.1. Proposed routing metric

The proposed routing metric consists of two parts: the congestion level and the channel utilization on a given node.

The congestion level on each link of the node represents how hard to transmit successfully a frame on that link. We measure the congestion level by using average value of Contention Window ($\overline{CW}$) on the wireless link. Because of the Binary Exponential Back-off mechanism (BEB) used in IEEE 802.11, the value of $\overline{CW}$ increases when the probability that a frame being collided when transmitting increases. Let *FER* be Frame Error Rate, CW_0 minimum Contention Window and r maximum back-off stage. The relation between $\overline{CW}$ and *FER* is made by computing $\overline{CW}$ as the weighted average of the Contention Windows that a frame has to undergo before being received successfully [20]:

$$\overline{CW} = \frac{1-FER}{1-FER^{r+1}} \frac{1-(2\cdot FER)^{r+1}}{1-2\cdot FER} CW_0 \qquad (1)$$

The channel utilization represents the fraction of channel time in which the channel is sensed busy. Clearly, the channel utilization is proportional to the traffic is sent through the channel. The higher the value of channel utilization, the less the traffic can be added to send over the channel and the longer the node has to defer before it can send its own frame. In order to figure out the relation between channel utilization and input data load we did simple simulation. In this simulation, with a given number of transmitters we tried to vary the aggregate input data traffic and measured the channel utilization. All the nodes were in the same collision domain and packet size was set to 1000 bytes, channel data rate was set to 1 Mbps. Figure 2 shows the relation between input data traffic and channel utilization. It is observed that channel utilization increases linearly with input traffic and then it gets saturated as the input traffic reaches 800 Kbps. When channel is saturated, although input traffic increases, channel utilization still is constant because all time slots are utilized.

In order to determine the capability of channel for accepting more traffic at different channel utilizations we carried out a simple simulation. In that simulation, there are 5 pairs of nodes sending data from one to the other. All the nodes are in the same collision domain. From the result of this simulation, we can derive the relation between channel utilization and packet delay. Figure 3 shows packet delay time as a function of channel utilization. When channel utilization is not so high the cost (packet delay time) for putting more traffic on the channel is not too much. Packet delay time changes slightly in this period but when channel utilization is rather high the packet delay time changes considerably due to packet time-out. This result indicates that the role of channel utilization is vitally important at high channel utilization but its effect may be ignored in the case of low channel utilization.

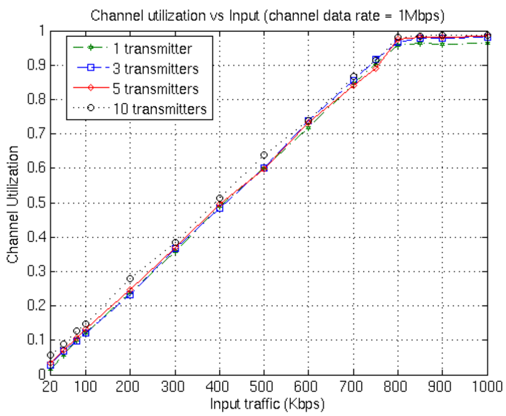

Figure 2. Channel utilization as a function of input traffic

Considering the preliminary remarks, we proposed the new routing metric called Contention Window Based (CWB) routing metric. The routing metric consists of two parts, one part β is based on the channel utilization and the other part is based on the average Contention Window ($\overline{CW}$) of links. The first part is designed so that value of β is one when channel utilization is smaller than a threshold and β will increase dramatically when channel utilization is over the threshold.

$$\beta = \begin{cases} 1 & if\ u \le T_1 \\ \min\left(\alpha(u - T_1) + \exp(\frac{u - T_1}{T_2 - u}), \beta_{\max} \right) & if\ T_1 < u < T_2 \\ \beta_{\max} & if\ u \ge T_2 \end{cases} \quad (2)$$

where T_1 and T_2 are respectively min and max threshold, value of α will decide how fast β will increase with the increase of channel utilization u after u gets over value of threshold T_1. By setting T_1 = 30%, T_2=90%, α = 25, β_{max} = 100, we get the β - u curve shown in Figure 4.

The second part is the average value of Contention Window of successfully transmitted frames. This value is calculated at MAC layer and then sent up to routing layer in a cross-layer scheme. The average $\overline{CW}$ depends on Frame Error Rate ratio following the Equation 1. Figure 5 shows this dependence. Value of the average Contention Window reflects the quality of the link.

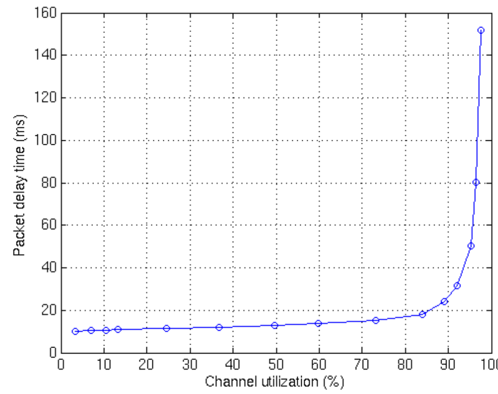

Figure 3. Packet delay time as a function of channel utilization

To capture the affects of both channel utilization level and congestion level, we define a new wireless routing metric called CWB based on β given by equation (2) and $\overline{CW}$ given by equation (1).

$$CWB = \beta \cdot \overline{CW} \quad (3)$$

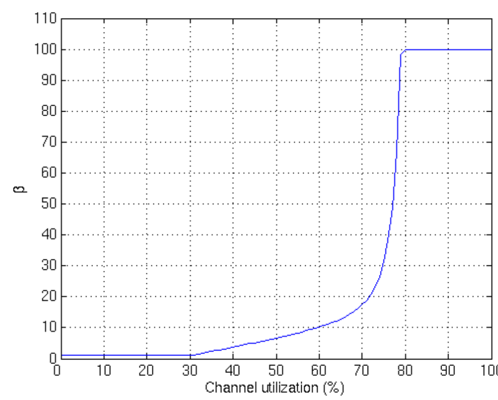

Figure 4. β as a function of channel utilization

From equations (1), (2), (3) we can derive CWB routing metric as a function of Frame Error Rate and channel utilization. As we can see in Figure 6, the value of CWB routing metric is small when both values of *FER* and Channel utilization are small. *CWB* increases when either FER increases or channel utilization increases. When channel utilization is smaller than the min threshold, the value of CWB depends only on value of *FER* but it increases rapidly when channel utilization gets over the min threshold. The dependence of CWB on *FER* is also revealed in Figure 8 with a similar shape with one in Figure 5.

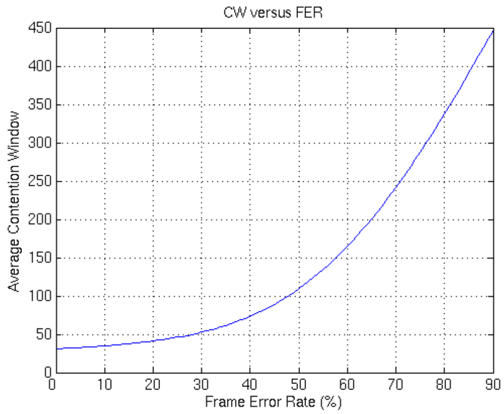

Figure 5. Average Contention Window as a function of *FER*

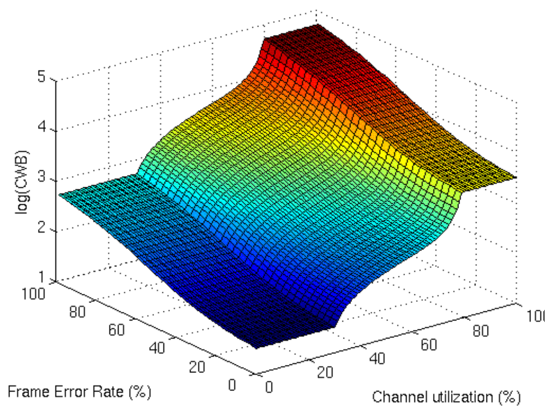

Figure 6. CWB routing metric as a function of channel utilization and *FER*

3.2. Contention Window based routing protocol

The Contention Window Based routing protocol uses the well-known Optimized Link State Routing protocol (OLSR) [21].

The OLSR protocol is a proactive ad hoc routing protocol. Its operation is similar to classic link state routing protocol. However to avoid the overhead related to the advertising of the link state information, a clever flooding optimization is used. The OLSR consists of four major elements:

- *Neighbour Sensing*: Each OLSR node collects the information about its local neighbourhood by processing the received *HELLO* messages. Every node has to send *HELLO* messages periodically.
- *MPR Selection*: From its neighbour set OLSR choose several nodes to be *Multi Point Relays* (MPRs) that will be used to optimize flooding of routing signalling packets. *MPR* selecting is taken carefully to make sure that all 2-hop nodes have direct link with one of *MPR* node.
- *Optimized Flooding*: To decrease the overhead of advertising link state information only *MPR* nodes send out the *Topology Control (TC)* messages. The *TC* messages that *MPR* send only contain the links to their *MPR* selectors to decrease the packet size. This scheme reduces signalling overhead while still guaranteeing that there exists at least one route between each pair of nodes that are connected in topology graph.
- *Route Selection*: Routes are computed using link state information to find the shortest path in number of hops between nodes. The algorithm used is similar to Dijktra algorithm.

The value of both Contention Window and Channel Utilization is computed at the MAC layer and send up to Network layer. The interval for statistics is 2 seconds. Two main changes have been made to the routing protocol to integrate the *CWB* routing metric. Firstly, in the new protocol, we modified the source code so that TC message will include the links to neighbors instead of links to MPR node as the original version. Secondly, TC messages are sent by all the nodes instead of only MPR nodes. Those changes make additional overhead as signaling packets and they should be optimized to get a good network performance.

4. Simulation and discussion

We have performed several preliminary quantitative experiments. To this end, the performance of our proposed routing metric was evaluated using NS2 [22] with the OLSR extension provided by MAXIMUM project [23]. The two performance metrics, total network throughput and average end-to-end delay, were used to compared CWB metric with hop count based one. Each data point in the graphical results is computed as the average of 10 different simulations.

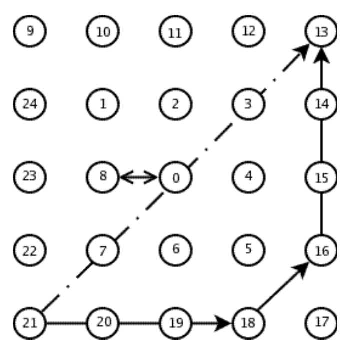

Figure 7. Predefined topology

The first simulation we have performed is intended to show that the CWB metric can recognize network traffic load and effectively route new traffic flow around congested area. The simulation was conducted in the area of 800 x 800 square unit, included 15 nodes that are uniformly distributed in that area as shown in Figure 7. The Constant Bit Rate (CBR) traffic source were used with packet sized set to 1000 bytes. To simplify the simulation we set both transmission range and interference range equal to 250m, the distance between nodes is set to 176 m. At the beginning of the simulation, there is a flow (flow 0) from node 0 to node 8 called Interference traffic. This traffic creates an area where traffic load is higher than in normal area. What will happen if node 21 wants to send data to node 13 (flow 1)?. To show the effectiveness of proposed routing metric, we keep data rate of the flow 1 at 100 Kbps while varying data rate of flow 0 (Interference flow). With hop count based metric, the data will be sent through nodes 21-7-0-3-13, while with the *CWB* metric data will be sent through nodes 21-20-19-18-16-15-14-13. It is clear that CWB metric based routing protocol can route data around the congested area.

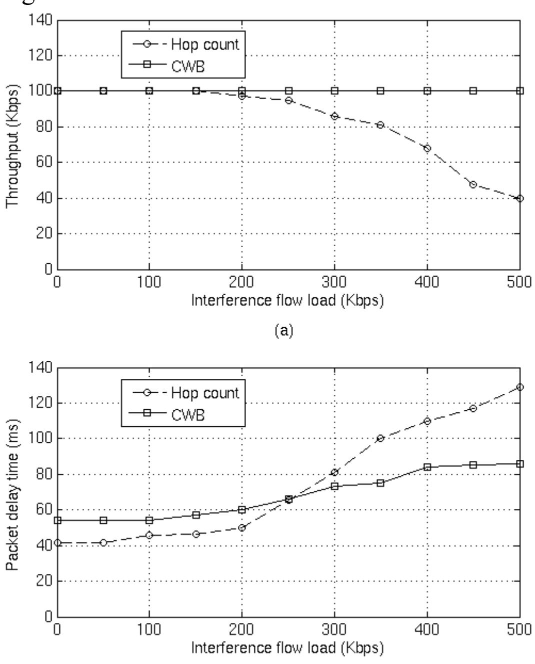

Figure 8. Network performance with determined topology

The performance of hop count based metric and CWB metric is shown in the Figure 8. Each data point in the graphic results was the average value of 10 different simulations. Hop count metric has dramatic drop of packet and increase of end-to-end packet delay when there is a hot spot in the path. CWB has ability to detect hot spot in the network so routing protocol can route data avoiding this area. Thus the flow throughput in Figure 8(a) is not affected by interference flow. However, end-to-end packet delay in Figure 8(b) when using CWB metric is a little higher than one of hop count based metric at the light load of Interference flow. The reason for this discrepancy is the longer path in number of hops is selected. But end-to-end packet delay of CWB metric quickly gets lower than that of hop count based metric when interference traffic is remarkable.

In the second simulation, the simulation environment consists of 1 GW and 80 nodes with 10 traffic flow sources. The nodes are uniformly distributed and the traffic source nodes are randomly chosen in these nodes. All the other simulation parameters are set similar to the first simulation.

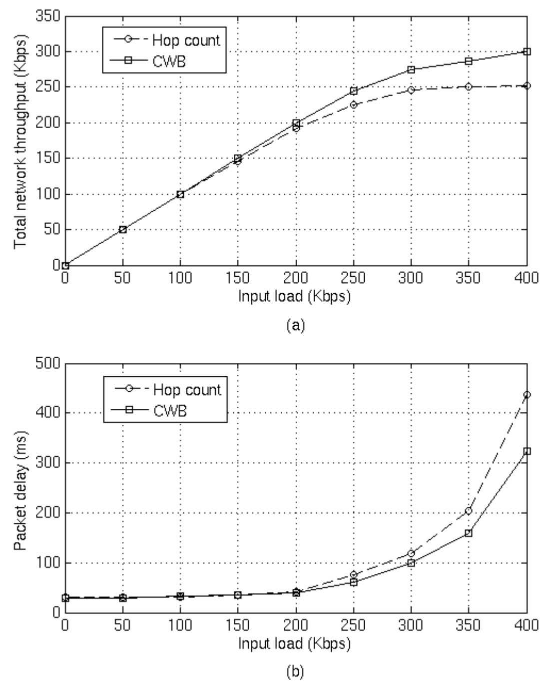

Figure 9. Network performance with random topology

Figure 9 shows the network performance with random topology as a function of input load. With hop count metric, packets are dropped when there are hotspots on the path while CWB shows a steady increasing in total network throughput as in Figure 9(a). The throughput gain is better at higher input load. Simulation results also confirm that CWB metric can guarantee end-to-end packet delay lower than hop count metric as Figure 9(b). The increase of network performance gain with input load indicates that CWB is suitable for providing a scalable network solution.

5. Conclusions and future work

In this paper, we proposed a routing metric for load balancing in wireless mesh networks. The basic features of the proposed scheme were described and compared with a well-known existing similar scheme. The quantitative evaluation has been carried out using NS2 simulation tool. Based on those results, we unambiguously demonstrated that this proposed routing metric is quite promising although further work needs to be done. In this sense the present work opens up a lot of future investigation directions. For example, more experimental evaluations have being carried out to compare CWB metric with other similar metrics. We are also investigating the affect of values of *max/min threshold* and *α* on the overall network performance. Another investigation has being carried out to decrease the overhead by introducing *Multi Point Relay* features but still guarantee the optimization of the proposed scheme. Future work includes the extensions of the proposed scheme for load balancing in multi-gateway, multi-radio and multi-channel networks. How to integrate the proposed scheme with the 802.11e standard is also interesting part of future work.

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