This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the ICC 2008 workshop proceedings.

Delay and Throughput Analysis of IEEE 802.11s Networks

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***Abstact*—The emerging IEEE 802.11s standard draft is a key technology of next-generation wireless networks. It can provide end users with broadband access of fast deployment, low cost, large coverage, and robust architecture. Recently, IEEE 802.11s draft has defined hybrid routing as default routing protocol. When tree-based topology is enabled, different mesh points (MPs) and mesh access points (MAPs) will achieve different loads according to their hops to the root, while previous discussions assumed that all the stations in the network have the same load. In this paper, we proposed an analytical model for IEEE 802.11 networks which considers different loads in hybrid routing. In the model, MPs/MAPs are classified into different groups according to their hops from the root and those closer to the root have a heavier load. We calculate their packet arrival rates in reasonable assumptions and derive the throughput and end-to-end delay. At last, numerical results show the factors, such as hops, affect network performance.**

Keywords—IEEE 802.11s, Hybrid routing, Tree-based topology.

I. Introduction

The increasing demand for wireless broadband access is boosting several technologies such as IEEE 802.16d/e standards and emerging IEEE 802.11s standard draft. They provide end users with last-mile access in different manners. IEEE 802.16d/e standards are based on centralized control while the IEEE 802.11s standard provides the distributed access [1], [2], [3]. IEEE 802.11s draft adds the peer-to-peer connections between APs in WLAN. So, it is not necessary to connect every AP to wired network in establishing a mesh backhaul infrastructure. Recently, the draft has taken the advantages of both WLAN and ad hoc network and tries to achieve better performance than any one of the two [3]. Compared with IEEE 802.16d/e, IEEE 802.11s networks provide end users with faster deployment, lower cost, larger coverage, and more robust architecture. It is a key part of the next-generation wireless networks and has been developed quickly in recent years. There have been many applications on IEEE 802.11 mesh networks in the world [4], [5], [6]. More attentions are kept on IEEE 802.11s networks since more applications are run on them.

The 802.11s network consists of MPs, MAPs, and simple 802.11 stations (STAs). Both MP and MAP can provide mesh services such as forwarding while STA does not support those services. MAP is a special type of MP, which provides access to its STAs. In real situations, MAPs usually have little mobility. They may be mounted on roofs, telegraph poles, or other high places, and often have unlimited power and function as backbone networks. According to [7], we assume all the STAs communicate with their MAPs using IEEE 802.11b standard while MPs/MAPs communicate with each other using IEEE 802.11a standard. So, the communications between MAPs and STAs do not interfere with forwarding actions between MPs/MAPs. Because of its architecture, IEEE 802.11s standard draft can provide end users with better experiences of more achievable bandwidth, fewer cost, and more fairness than IEEE 802.11 standards do. Many services are expected to be applied to IEEE 802.11s networks as described in Fig. 1.

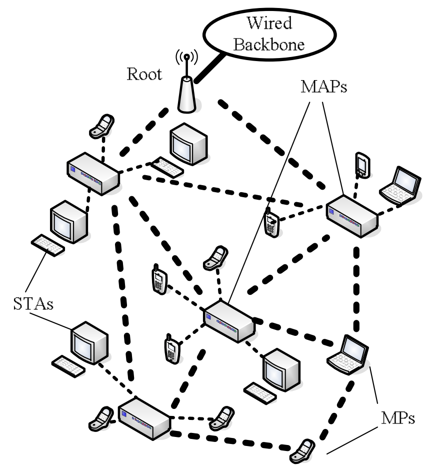

Fig. 1. The IEEE 802.11 mesh.

IEEE 802.11s is based on previous IEEE 802.11 standards and both MAC layers are similar except adding some amendments about multi-hop contents. Many efforts have been allocated on performance analysis of IEEE 802.11 networks. [8] provided an accurate model to evaluate the performance of IEEE 802.11 DCF MAC layer. Foh and Tantra added the discussions on freezing time in the backoff procedure [9]. However, all the analyses of [8] and [9] were built on the saturation condition, which is not the usual condition. We should consider the idle state that is important in mesh networks. [10] provided the analysis of idle state for IEEE 802.11 networks. But, all discussions mentioned above did not adapt well to wireless mesh networks (WMNs). There were also efforts on performance analysis of whole WMN. Delay and maximum achievable throughput for a WMN were discussed in [7]. It assumed a packet at a mesh router will be

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delivered to other mesh routers with equal probability if it is not absorbed. But, it is not true in the tree-based topology, which is a part of hybrid wireless mesh protocol (HWMP). In the tree-based topology, packets in inter-mesh delivery are forwarded to parent mesh router. The process continues until the packet reaches the root. Therefore, we propose a new model for IEEE 802.11s networks with different packet arrival rates of MPs/MAPs and derive average throughput and average end-to-end delay. We classify the MPs/MAPs according to the distance to the root. The MP/MAP obtains a heavier forwarding load if it is closer to the root. Therefore, it adapts to the actual conditions better.

The rest of this paper is organized as follows. The related IEEE 802.11s standard draft is overviewed in Section II. Section III proposes our analytical model for IEEE 802.11s networks. In Section IV, performance analyses are conducted. And, simulation results are given in Section V. Finally, conclusions are made.

II. Related Work

The IEEE 802.11 MAC layer uses CSMA/CA mechanism with exponential backoff algorithm to access channels in DCF [11], [12]. It has been popularly used in wireless LANs because it is simple and effective. The IEEE 802.11e standard provides QoS support by using enhanced DCF (EDCF) mechanism [12]. The IEEE 802.11s [3] provides multi-hop enhancement to the former IEEE 802.11 standards. So, it can achieve large coverage with low cost. It also permits multi-channel operations to increase network capacity [13]. However, multi-hop enhancement brings additional costs on routing. To maintain good performance, HWMP is selected as the default path selection protocol for interoperability which combines the flexibility of on-demand routing and effectiveness of tree-based routing. If the tree-based routing is not enabled, the on-demand routing will be used for all routing in WMNs. Otherwise, the tree-based routing will be configured as default routing mechanism while on-demand routing still works together. There will be a tree-topology formation process. The first step is to configure the root from MPs. After the configuration, every MP selects its parent MP according to the metrics in root announcements as shown in Fig. 2. All the MAPs, MPs and STAs register to the root providing the tree-topology information. When a packet is delivered to outside mesh, the MP first checks its forwarding table. If there is no entry for the delivery, it will forward the packet to its parent MP, which checks its own forwarding table. If there is an entry about the destination, the delivery will be done. Otherwise, it will encapsulate the packet to its parent MP. The process continues until the packet reaches the root if there is no entry in the middle MP. It can provide an effective method to deliver a packet to the outside of WMN. However, the tree-based routing protocol does not work well if the delivery is inside the WMN. In intra-mesh routing, the tree-based routing is used at the first delivery if no effective on-demand route exists. The destination node can build on-demand route for the following delivery if it is possible. It can optimize route cost while the tree-based routing does not work well when the delivery is inside WMNs. Since WMNs in 802.11s standard draft may function as the last-mile access, the majority of data flows are inter-network. The root may form a bottleneck to the flows due to many inter-mesh services. And, the MP closer to the root has heavier forwarding load.

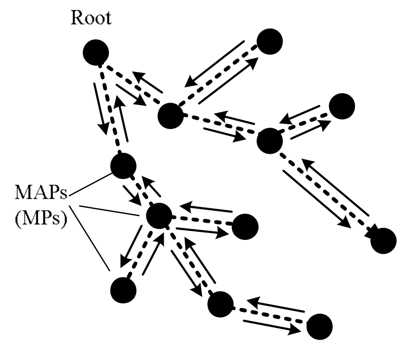

Fig. 2. Tree-based mesh topology.

III. Model of Mesh Stations

Based on the models mentioned above, we propose a model in which MPs may have different loads according to their distance away from the root.

To simplify the discussion, we assume that all the MPs are MAPs in the WMP. Here, we also neglect collisions. Therefore, it is not necessary to consider the cost of retransmission and backoff time for deeper stages due to transmission collisions. That may fit for the WMN with light load. In such networks, collisions seldom happen, and we hardly need retransmission. [8] and [10] provide detailed discussions about accurate calculation of backoff time and collision cost.

The backoff time is denoted as $T_{backoff}$ when MAP is trying to transmit a packet. Since the backoff window is a random value, it is uniformly selected from [0, $W_{backoff}$). So, we have

$$E(T_{backoff}) = \frac{W_{backoff}}{2} \quad . \tag{1}$$

Let H denote the hop number in tree-based topology, and ρ_h denote the utilization factor of MAP with h hops away from the root in the tree-based topology.

$$\rho_h = \frac{\lambda_h}{\mu_h} \tag{2}$$

where λ_h and μ_h are packet arrival rate and service rate of the MAP, which is h hops away from the root.

Let I_h denote the number of interfering neighbors of a h-hop MAP, and M_h denote the number of freezing times in the process that a MAP is in h-hop class transmitting a packet. Once the tree-based topology is established in the given network, I_h (h is from 0 to H-1) is a certain number. So, the number of active neighbors of a MAP can be expressed as $\sum_{h=0}^{H-1} I_h \rho_h$.

Because backoff time conforms to exponential distribution and the expirations of timer happen as Poisson distribution, the mean of M_h can be derived as [7]

$$E(M_h) = \sum_{h=0}^{H-1} I_h \rho_h \tag{3}$$

Let X_h denote the service time of a MAP of h-hop for services. According to [7], we have

$$X_h = T_{backoff} + M_h \frac{L}{W} + \frac{L}{W} \tag{4}$$

$$\begin{aligned} E(X_h) &= E(T_{backoff}) + E(M_h)\frac{L}{W} + \frac{L}{W} \\ &= \frac{W_{backoff}}{2}\delta + \sum_{l=0}^{H-1} I_l \rho_l \bullet \frac{L}{W} + \frac{L}{W} \\ &= \frac{W_{backoff}}{2}\delta + \sum_{l=0}^{H-1} I_l \lambda_l E(X_l) \bullet \frac{L}{W} + \frac{L}{W} = \frac{1}{\mu_h} \end{aligned} \tag{5}$$

where L is the average length of a packet, W is the average available channel bandwidth, $W_{backoff}$ is the maximum contention window, and δ is the time of a backoff slot. Here, we assume a station has infinite processing ability, so the processing time at a MAP is independent of packet arrival rate and can be neglected.

Let D_h denote the average delay at a MAP of h-hop. According to Little's law, $k=\lambda\tau$, where k is the average queue length (i.e., all the customs in the system) and τ is the average waiting time including service time (i.e., D in the model). So, we can derive the formula.

$$E(D_h) = \frac{\rho_h}{\lambda_h(1-\rho_h)} = \frac{1}{\mu_h - \lambda_h} \tag{6}$$

Let S_h denote the normalized throughput of a h-hop MAP.

$$S_h = \frac{(\frac{L}{W})_{effective}\lambda_h}{E(D_h)\sum_{h=0}^{H-1} N_h \lambda_h} \tag{7}$$

where $(L/W)_{effective}$ is payload transmission time. And, N_h is the number of h-hop MAP from the root.

IV. PERFORMANCE ANALYSIS

Before the analysis, we make the following assumptions:

The root is the only entrance to outside networks and there is only one tree in a WMN. Every MAP generates packets with rate λ_G. The packets, whose destinations are inside WMN, are absorbed by MAPs uniformly.

There are two kinds of flow in WMN, intra-mesh flow and inter-mesh flow. The intra-mesh flow is responsible for packet delivery from a MAP to another. The whole delivery is inside mesh. Here, we assume the packets in intra-mesh flow will be absorbed uniformly. The inter-mesh flow is responsible for packet delivery from a MAP to outside or inverse delivery. It gives heavier pressure on the root and MAPs close to the root.

Now, we calculate the average forwarding rate. The average inter-mesh packet forwarding rate of a MAP of h-hop can be denoted as: (here we do not consider the packets that are delivered inside mesh and assume that a MAP forwards packets which are received from outside mesh to its child MAPs evenly.)

$$\lambda'_0 = \lambda'_{0\_down} = \lambda_{outside}(1-p) \tag{8}$$

$$\begin{aligned} \lambda'_h &= \lambda'_{h\_down} + \lambda'_{h\_up} \\ &= \frac{N_{h-1}}{N_h}\lambda'_{h-1\_down}(1-p) + \frac{N_{h+1}}{N_h}\lambda'_{h+1\_up} + \lambda_G p_{G\_inter} \\ & \qquad 1 \le h \le H-2 \end{aligned} \tag{9}$$

$$\lambda'_{H-1} = \lambda'_{H-1\_up} = \lambda_G p_{G\_inter} \tag{10}$$

$\lambda_{outside}$: the packet arrival rate of the root from outside networks.

p: absorption probability of a MAP.

p_{G_inter}: the probability of a packet delivered to the outside of WMN after generation.

λ_G: the packet arrival rate generated by MAP (and its associated STAs if it has any).

If we want accurate inter-mesh rate of a MAP, we just need to know those of its neighbors.

The arrival rate of packets whose delivery is inside mesh of a MAP can be derived [7].

$$\lambda_{intra} = \frac{\lambda_G(1-p_{G\_inter})}{p} \tag{11}$$

The average packet forwarding rate for MAP of h-hop (for all packets) can be denoted as:

$$\lambda_h = \lambda'_h + \lambda_{intra}(1-p) \tag{12}$$

where h is from 0 to H-1.

Substituting (6) and (13) into (5), we can solve $E(X_h)$ and $E(X_h)$. Then, $E(D_h)$ and S_h can be calculated from (7) and (8).

The average delay for a MAP due to intra-mesh packets can be denoted as:

$$\bar{D}' = \frac{\sum_{h=1}^{H} N_h D_h}{N} \tag{13}$$

where N is the total number of MAPs in the network.

We assume a packet whose delivery is inside WMN traverses every MAP with equal probability and gets average delivery distance [7] shown as:

$$\bar{k} = \frac{1}{p} \tag{14}$$

So, the average delay of packets for inside delivery is

$$\bar{D}_{on\_demand} = \bar{k} \bullet \bar{D}' \tag{15}$$

The average delay of a packet delivered from inside mesh to outside one is the same as that from outside mesh to inside one. It can be derived as:

$$\bar{D}_{tree} = \frac{\sum_{h=1}^{H-1} (N_h \bullet \sum_{i=1}^{h} D_i)}{N} \tag{16}$$

We classify packets into three types based on the tree-based routing:

- Packets generated by a MAP or its associated STAs and delivered to the outside network.
- Packets entering the mesh from outside network.
- Packets generated by a MAP or its associated STAs and delivered to other MAPs or their associated STAs inside the network.

We assume the packet arrival probability of each type is known.

Let p_{tree} denote the probability that a packet is delivered from or to outside networks. It is shown as:

$$p_{tree} = 1 - \frac{N \bullet \lambda_G \bullet p_{G\_intra}}{N \bullet \lambda_G + \lambda_{outside}} \tag{17}$$

The average end-to-end delay of a packet is

$$D(n) = p_{tree} D_{tree} + (1 - p_{tree}) D_{on\_demand} \tag{18}$$

Let S_{total} be the total average throughput. A MAP contributes its proportion according to its forwarding rate. Hence, we have

$$S_{total} = \sum_{h=0}^{H-1} \frac{N_h \lambda_h}{\sum_{h=0}^{H-1} N_h \lambda_h} S_h \tag{19}$$

V. Numerical Results

We consider a WMN where stations are uniformly distributed. The network is configured as IEEE 802.11s draft and the hybrid routing is enabled. We group stations according to their distance from the root. Stations in the same group have the same parameters, such as packet generation rate, packet arrival rate, absorbing probability, and so on. MAC layer is based on IEEE 802.11e standard. The default parameters are set as follows:

$W_{backoff}$=32,
$\lambda_{outside}$=3, λ_G=0.3,
p_{G_intra}=0.8, p=0.2,
L/W=0.00137s, $(L/W)_{effective}$=0.001s.

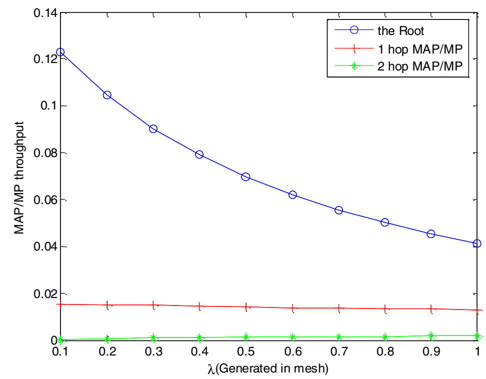

Fig. 3. Average throughput (differentiating λ_G) vs. number of stations.

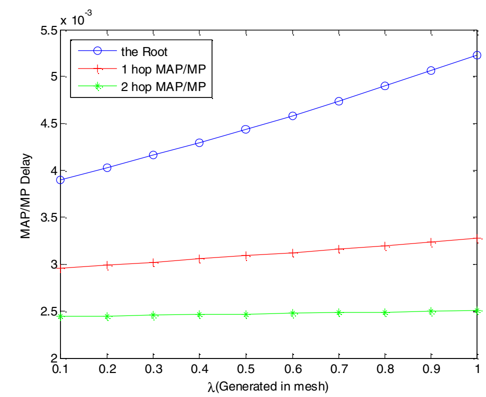

Fig. 4. Average delay (differentiating λ_G) vs. number of stations.

In order to evaluate the distance effect on MAPs, we simulate the throughput and end-to-end delay of MAPs which have different hops to the root. There are 100 MAPs and 3-hop topology in the network. From Figs. 3 and 4, the performances of MAPs closer to the root degrade as λ_G increases. And, the root suffers the worst degradation because of the centralized loads from its child MAPs.

We also simulate the average throughput for the whole network. In our simulation, we add the hops to accommodate more MAPs in WMNs. As shown in Fig. 5, the average throughput decreases as the number of MAPs or λ_G increases, which causes heavier load. And, we show the average end-to-end delay in Fig. 6.

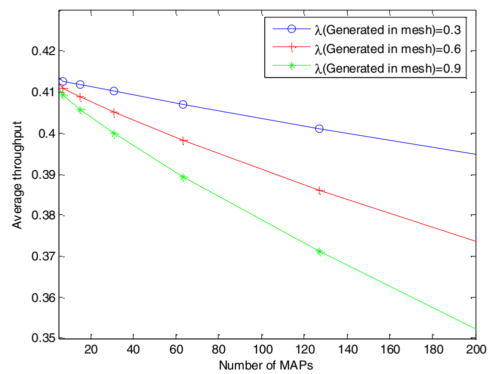

Fig. 5. Average throughput (differentiating λ_G) vs. number of MAPs.

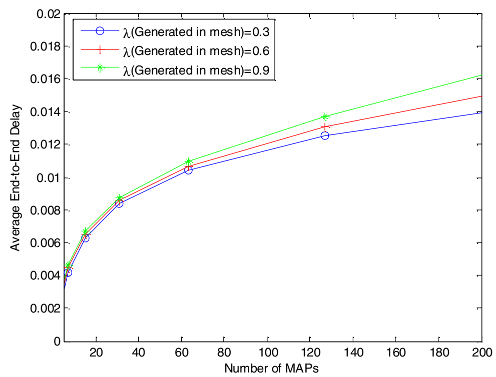

Fig. 6. Average end-to-end delay (differentiating λ_G, second) vs. number of MAPs.

The network performance can be improved by reducing the hops in the scenarios. Fewer hops reduce the path length of delivery and may obtain shorter end–to-end delay and better throughput in light-loaded network. We can validate the theory from the results in Figs. 7 and 8. However, middle MAPs forward more packets in the condition and that with insufficient bandwidth or processing ability will form the bottleneck.

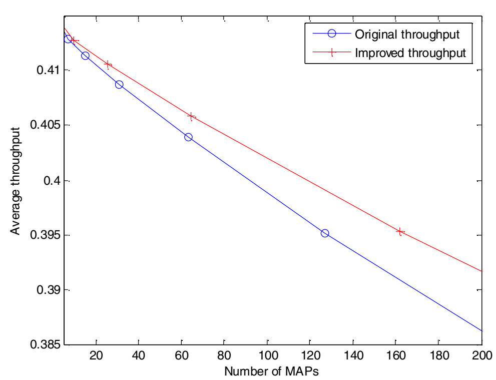

Fig. 7. Average throughput (original vs. improved).

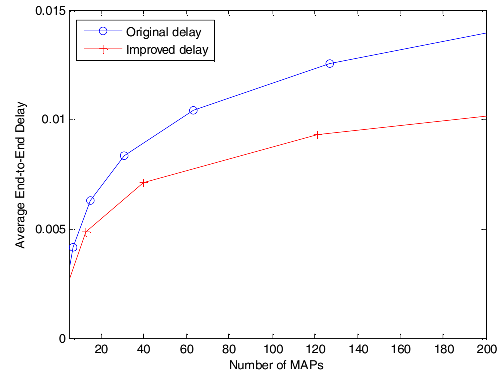

Fig. 8. Average end-to-end delay (original vs. improved).

VI. Conclusion

The purpose of this paper is to propose a model of IEEE 802.11s network according to the standard draft. In the model, we consider different arrival rates for MAPs which have different hops to the root. The related throughput and end-to-end delay have been derived. The simulation results of the model correspond with the IEEE 802.11s draft. When the number of stations increases, the throughput and end-to-end delay vary accordingly. We optimize network performance by adjusting maximum hops in some scenarios. Our further work is to verify the model using OPNET-based IEEE 802.11s simulation platform developed by us. And, the main effort will be allocated on providing a more accurate model considering collision and providing the real-time applications on IEEE 802.11 WMNs.

Acknowledgment

The work of the second author was supported by the National Science Council of Taiwan under Grant NSC 96-2416-H-004-019.

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