Performance Analysis of MAC Protocols for Location-Independent End-to-end Delay in Multi-hop Wireless Mesh Networks

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1. Introduction

Backbone wireless mesh networks (WMNs) are emerging alternatives to conventional wired backbones for metropolitan and have attracted much attention from both academic and industrial world as an infrastructure network for realizing the ubiquitous computing environment. WMN is a generalization of Wireless Ad-Hoc Networks that considers the use of heterogeneous nodes (e.g., clients and routers) and both wired and wireless connections to exchange data between these devices. The basic architecture of a WMN consists of a backbone of mesh routers (MR) and the clients that access communication services through the use of this backbone. Therefore, this backbone serves as a last mile solution that is interconnected to provide direct communication between clients (i.e., without routing the interclient traffic through any other intermediate network). This characteristic of a WMN enables it to function as an isolated autonomous network or as a last mile solution depending on the telecommunication facilities available at the place where the WMN is deployed.

In a multi-hop WMN, communication between two nodes is basically carried out by forwarding packets through a number of intermediate nodes. In WMNs, nodes are comprised of mesh routers in fixed sites and mobile clients as shown in Fig.1. We call a mesh router (also called mesh node) with gateway functions a gateway node, which is equipped with wireline network interfaces to connect the internet backbone. In this chapter each mesh node operates not only as an access point (AP) for mobile clients in its own basic service set (BSS) but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations (see Fig. 1). Mobile clients are attached to a node in their BSS. Data originating from mobile clients are relayed by intermediate relay nodes hop by hop and delivered to the gateway.

One of the important problems to be solved in WMNs is the unfair bandwidth sharing problem depending on the nodes' location. More specifically, the per node throughput may decrease and the end-to-end delay may dramatically increase with an increasing hop-count distance from the gateway. In particular, WMNs based on single radio, irrespective of its simplicity and high fault tolerance, face a significant limitation of limited network capacity. It has been shown (2) that the theoretical upper limit of the per node throughput is asymptotically limited by $O(1/\sqrt{n})$ where n is the number of nodes in the networks. Therefore, with increasing number of nodes in a WMN, the per node throughput becomes unacceptably low. It has also been found (3) through experiments using carrier sense multiple access with collision avoidance (CSMA/CA)-based MAC protocol such as IEEE 802.11 that on a string topology, the throughput degrades approximately to $1/n$ of the raw channel bandwidth.

To resolve the above problem in single radio WMNs, multi-radio WMNs are under intense research. Therefore, recent advances in WMNs are mainly based on a multi-radio approach. While multi-radio WMNs promise higher capacity compared with single radio WMNs, they also face several challenges. One of them is location-dependent problem (10; 11) as in single radio WMNs in the sense that the per-node throughput decreases and the end-to-end delay increases dramatically with an increasing hop count to the gateway node. In particular, delay-sensitive application such as VoIP is expected to be serviced in WMNs in the near future. Such a service requires to be delivered to the destination within a given delay requirement regardless of its generated location. Thus, to support delay-sensitive traffic in WMNs, we need a proper method to guarantee the location-independent end-to-end delay in WMNs. This chapter focuses in detail on these issues. As a preliminary, we survey recent studies which deal with location-dependent problem in WMNs or investigate the performance of WMNs in terms of throughput and end-to-end delay mostly based on the analytical modeling method.

1.0.1 Single radio WMNs

In recent years, there have been several studies focused on the unfairness problem of multi-hop wireless networks under single radio scenario. In (12; 32), queue management schemes for restoring the fairness in a WMN has been proposed, which in part share a common emphasis with this chapter which intends to devise packet management scheme in relay node for location-independent end-to-end delay in WMNs. Nandiraju et al.(32) showed that Queue management, at intermediate relay mesh nodes, plays an important role in limiting the performance of longer hop length flows. They (32) proposed a queue management algorithm for IEEE 802.11s based mesh networks that improves the performance of multihop flows by fairly sharing the available buffer at each mesh point among all the active source nodes whose flows are being forwarded. Gambiroza et al. (10) proposed a centralized scheme to solve the unfairness problem of IEEE 802.11 based multi-hop wireless networks. In this scheme, each mesh router collects information on the global topology including link capacities and offered traffic, and then calculates the optimal sending rate based on the information. Then, each node in the network limits its ingress rate according to the given optimal rate. They studied the critical relationship between fairness and aggregate throughput based on simulation. Above mentioned researches (10; 12; 32) were interested in throughput and were only based on the simulation method. Liu et al. (29) developed an analytic model to model throughput and end-to-end delay in wireless mesh networks with single radio and single channel. Based on their analytical model, they (29) proposed two network design strategies to provide fair resource sharing and minimize the end-to-end delay in wireless mesh networks. But, the study was carried out based on the simplified MAC protocol, not CSMA/CA protocol such as IEEE 802.11 DCF, which is characterized by only the parameter of successful transmission probability. Bisnik et al. (28) characterized the average end-to-end delay and capacity in random access MAC based WMNs with single radio. They (28) modeled residential area WMNs as open G/G/1 queuing networks. The analytical model takes into account the mesh client and router density, the random packet arrival process, the degree of locality of traffic and the collision avoidance mechanism of random access MAC. Even though the above mentioned studies (28; 29) developed analytical models for obtaining performance measures in WMNs such as end-to-end delay and throughput, the derivation are mainly based on the simplified MAC scheme apart from CSMA/CA protocol in IEEE 802.11. Without devising any queue management mechanism to give higher priority for the channel access to flows experiencing longer hops, they (28; 29) were interested in finding the achievable maximum throughput in WMNs while the end-to-end delay is guaranteed for a given value. Sarr et al.(30) developed an analytic model for evaluating average end-to-end delay in IEEE 802.11 multi-hop wireless networks with single radio.

1.0.2 Multi-radio WMNs

With a multi-radio functionality, the performance of WMN can be enhanced if relay nodes can transmit and receive simultaneously (6), (7) and nodes in different contention zones can transmit concurrently without any interference. For recent works on the performance of WMNs under multi-radio scenario, see (15; 19; 20). Raniwala et al. (15) aimed to expand WLAN into an enterprise scale backbone network technology by developing a multi-radio wireless mesh network architecture where each node equips with multiple transceivers and supports distributed channel assignment to increase the overall network throughput. The central design issues of multi-radio WMN architecture in (15) are channel assignment and routing. They (15) showed that even with just 2 radios on each relay node, it is possible to improve the network throughput by a factor of 6 to 7 when compared with the conventional single-channel ad hoc network architecture. Regarding the channel assignment issue in backbone WMNs as shown in Fig.1, we rely on the method in (15). Aoun et al. (33) showed the capacity of a WMN is constrained by the bottleneck collision domain; hence, placing an equal number of radios at all nodes is not necessary. They proposed that additional radios should be placed according to the distribution of traffic load in WMN. By giving the collision domains that need to support higher traffic load to more bandwidth by setting up additional radios, interfering wireless links would operate on different channels, avoiding interference and enabling multiple parallel transmissions. Duffy et al. (34) developed a tractable analytic model of throughput performance for 802.11 multi-hop networks where the relay node is equipped with multi-radio and each of them operates on different channel. They (34) tried to solve upstream/downstream unfairness problem induced by the 802.11 MAC at aggregation points in a relay node. With the use of the flexibility provided by the 802.11e standard (specifically, TXOP and CWmin adjustment), they proposed a scheme to restore fairness at relay aggregation points. But, their focus was not the unfairness problem depending on nodes' location in WMNs, but the well-known unfairness problem between access point (AP) and station in IEEE 802.11 one-hop network in the sense that AP and each station share the channel equally so that AP may be a bottleneck for the downstream. In (35), the authors mathematically modeled the channel and interface assignment problems by introducing link and node channel assignment binary vectors. They developed a formulation for cross-layer fair bandwidth sharing problem as a non-linear mixed-integer network utility maximization which takes into account the number of radios at each relay node, the number of channels, and the interference constraints. Lee et al.(20) proposed a fair throughput allocation scheme for nodes in 802.11-based WMN regardless of their hop distances to the gateway. To achieve the fair throughput, they differentiated the contention window size of 802.11 mesh routers according to their weights based on the number of active nodes attached to each router. This work (20) shares a common interest with this chapter from the view point of network topology, i.e., WMN with tree structure. But, the works (20; 35) did not deal with the end-to-end delay in WMNs. (19) proposed a multi-channel ring-based wireless mesh network. In (19), the WMNs are divided into several rings, which are allocated with different channels. In the proposed WMN, a simple ring-based frequency planning is used to effectively utilize the available multiple channels. They developed a cross-layer analytical framework to evaluate the end-to-end delay and throughput in the proposed WMN. Based on their analytical model, they provided a method to determine the optimal number of rings in a WMN and the associated ring widths to maximize the coverage for a WMN.

1.0.3 Location-independent end-to-end delay in WMNs

This chapter focuses on discussing the schemes for location-independent end-to-end delay in WMNs. More specifically, this chapter extends the result of most recent work (23) which has tried to guarantee location-independent end-to-end delay in WMNs where each relay node is equipped with the functionality of multi-channel and multi-radio. Furthermore, this chapter provides more details than the work by Bae et al. (23) by adding new results. They (23) proposed two packet management schemes, called the *differentiated CW policy* and the *strict priority policy*, which are employed by relay nodes to obtain almost equal end-to-end delay, independent of source nodes' locations. In (23), it is assumed that each node is equipped with multiple transceivers, each of which is tuned on a particular channel. With these employments, the WMN can be decomposed into disjoint zones such a way that each zone uses its own channel different from channels used in neighbor zones. At a relay node in each zone, relay packets are buffered in different queues according to their experienced hop count, we call the queue storing the packets passing by k hops as *priority queue of class k*. A queue in which packets passing by more hops are stored has a higher priority in the sense that it has a shorter CW_{min} at the *differentiated CW policy* and a higher priority for the service at the *strict priority policy*. For the differentiated CW policy, a relay node adopts IEEE 802.11e EDCA protocol where a higher priority queue has a shorter minimum contention window. For the strict priority policy, a relay node is regarded as a single queueing system where the service discipline among priority queues at the relay node follows strict priority. The relay node has shorter minimum contention window than that of end node.

In summary, $i)$ a typical zone is modeled as a one-hop IEEE 802.11e EDCA network under non-saturation condition where nodes have different packet arrival rates and different minimum contention window sizes. The probability generating function (PGF) of the HoL-delay of packets priority queue of class-k at a relay node in a zone is derived. Eventually, the packet delay (the sum of the queueing delay and the HoL delay) in a zone is obtained, by modeling each queue as $M/G/1$ queue with the HoL-delay as a service time. $ii)$ A method to determine the minimum contention window sizes of each priority queues satisfying almost same end-to-end delays of packets regardless of their source's location is presented.

The rest of this chapter is organized as follows. The network model is presented in Section 2. Section 3 describes the differentiated CW policy and presents its analytic model. The probability generating function (PGF) of the HoL-delay is derived and then the average end-to-end delay of packets is obtained. Section 4 deals with the strict priority policy.

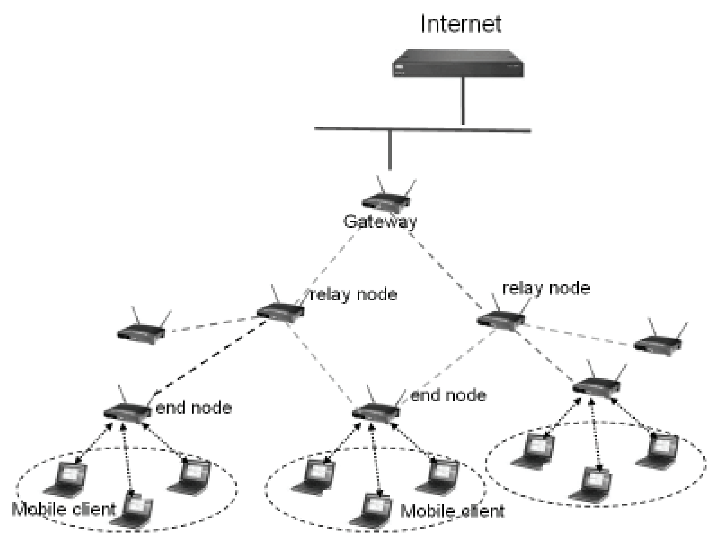

Fig. 1. Backbone Wireless Mesh Network

2. System model

2.1 Network model

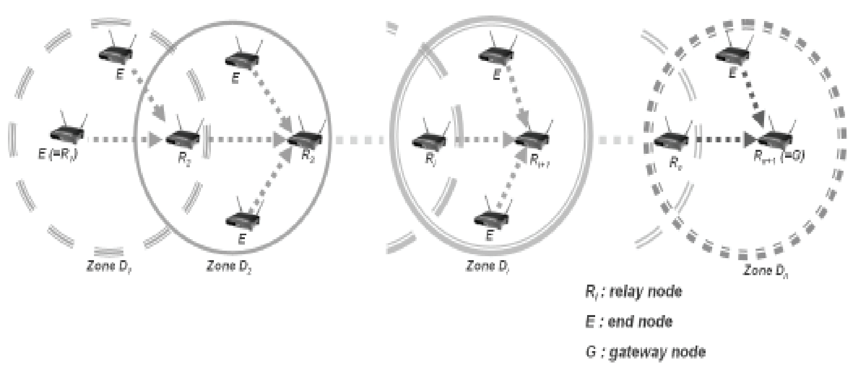

Fig. 2. A variant of n-hop linear network

In general, a backbone WMN can be viewed as a network with tree structure as shown in Fig.1, where the root node corresponds to the gateway. Backbone WMN consists of a gateway connected to the wired networks and multiple mesh nodes connected to the gateway through the multi-hop communications. In such a tree network, the traffic is skewed such that most packets flow toward or from the gateway node (33). Therefore, the nearer to the gateway a mesh node is, the more traffic the mesh node should have the capability to process. Thus it is required that an appropriate packet management scheme is employed in the mesh node to avoid the congestion and to deliver the traffic in time.

Since nowadays a gateway connected to wired networks are available in most of places, practically the coverage of WMN is not too wide. Due to this and also for the simplicity of analysis, we consider a variant of linear wireless mesh network as shown in Fig.2. This kind of topology is useful and quite general in the following aspects: Applying the static channel and interface assignment scheme (36; 37) to WMNs with tree structure, each channel and interface is permanently assigned to each relay node and the set of mesh nodes interfering with the

relay node forms a collision domain (20), which is not changed for a long period as long as a new mesh node is not deployed in the network or a node failure does not occur. In addition, if a static routing algorithm in which a routing path of a flow is not changed for a relatively long period (e.g, several minutes), is employed in WMNs, the set of relay nodes through which the flow passes from its source to the destination (gateway), and end nodes interfering with them, can be viewed as a variant of linear network as in Fig.2. Therefore, with the setting of multi-channel and multi-radio, and a static routing, WMNs with a tree structure can be decomposed into several linear networks, each of which forms a independent and separate sub-network without imposing any interference to each other. If there are enough channels available in the WMN, performance analysis of WMN with a tree structure can be obtained by the following similar method developed in Section 3 with complexity of expressions.
Uplink communication from nodes to the gateway is considered. In Fig.2, WMN consists of a gateway, n relay nodes and multiple end nodes where each end node is attached to a relay node. Mobile clients are attached to relay nodes and end nodes. Every *end node E* receives its local traffic from mobile clients in its BSS and sends the local traffic to an upstream node. Every *relay node* R_i forwards not only its local traffic from mobile clients in its BSS but also relay traffic from relay node R_{i-1} to relay node R_{i+1}. The n-hop linear network with $n-1$ relay nodes $R_2, \cdots, R_n$ is decomposed into n disjoint zones $D_1, D_2, \cdots, D_n$. It is assumed that there are enough channels available in WMN. A different channel is assigned to each zone: one for the transmission of relay traffic from R_i to R_{i+1} in zone D_i and the other for transmission of relay traffic from R_{i-1} to R_i in zone D_{i-1}, respectively. In other words, the WMN can be decomposed into disjoint zones as shown in Fig.2 so that nodes in a zone use one channel and those in neighbor zones use different channels in order to avoid the hidden node problem and the exposed node problem. As illustrated on Fig.2, zone D_i has a parent node R_{i+1} and child nodes consisting of one relay node R_i and several end nodes E. The parent node R_{i+1} plays a role as an AP in zone D_i, and child nodes consist of several end nodes E and a relay node R_i, (which plays a role as parent node in zone D_{i-1}). Relay node R_i has 3 transceivers operating on different channels: one for the uplink transmission with relay node R_{i+1} in zone D_i, another for communications with its child nodes in zone D_{i-1} and the other for communication with mobile clients in its BSS. By using multiple transceivers, the relay node can transmit and receive simultaneously. Each end node is equipped with 2 transceivers to communicate with its parent node and mobile clients. Assuming that every node in each zone is within the one-hop distance, collisions may occur only when two or more nodes within a zone transmit simultaneously. Since neighbor zones use different channels, there are no interferences between neighbor zones. Thus we may focus on the analysis of one zone D_i, and then the analytic results on one zone will be used in multi-hop WMN.

2.2 Modeling of a zone

As illustrated in dotted circle region in Fig. 4, we assume that the parent node R_{i+1} in zone D_i has total N_i child nodes: one relay node R_i and $N_i - 1$ end nodes E. (Note that in the case of a tree topology, the parent node may have multiple relay nodes as child nodes, the mathematical analysis in Section 3.2 can be extended to the tree topology with some tedious calculation.)
It is assumed that each end node E has one local uplink buffer where local packets transmitted from mobile clients in its BSS to the end node are stored before transmitting to relay node R_{i+1}. Packets' arrival at the local uplink buffer is assumed to follow a Poisson process with arrival rate λ(/sec).

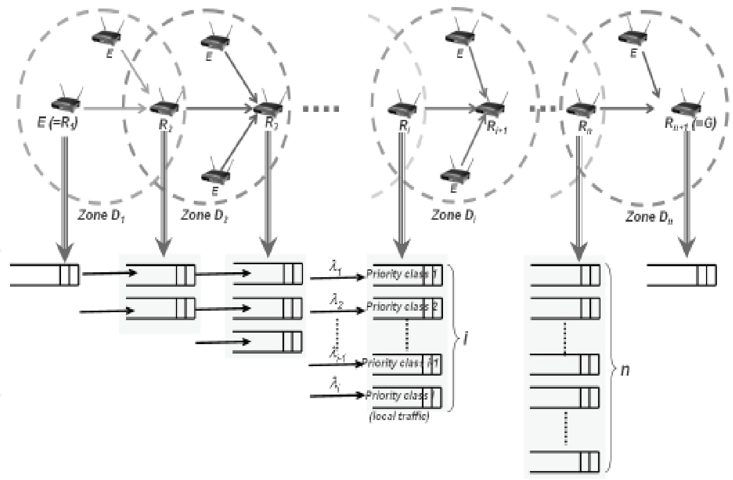

Fig. 3. Packet management scheme

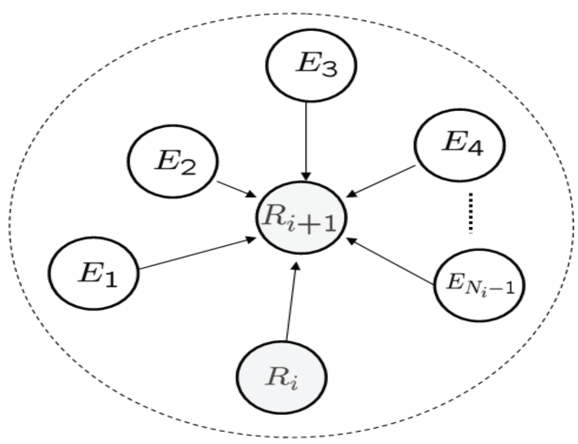

Fig. 4. Zone D_i

The relay node R_i has i uplink buffers, as shown in Fig.3: one is a local uplink buffer where local packets generated in its BSS are stored, and others are relay uplink buffers where relay packets forwarded from relay node R_{i-1} are stored before transmitting to relay node R_{i+1}. Relay packets in node R_i are stored in different uplink buffers according to their hop count passing by. To be precise, the kth uplink buffer ($k = 1, 2, \cdots, i$) in relay node R_i stores packets originated from all end nodes in the zone D_k and we call it *priority queue of class-k*, i.e., priority queue of class-1 is the highest priority class, which is for the relay packets originated from zone D_1 with the longest hop count to the relay node R_i. Priority queue of class-i is the lowest priority class for the local packets generated from the BSS of relay node R_i. Local packets' arrival at the local uplink buffer of each relay node R_i is assumed to follow a Poisson process with arrival rate λ just as the arrival at an end node.
In general, relay node R_i is heavily loaded compared to end nodes, and it relays both local traffic and relay traffic forwarded from zone D_{i-1}. Thus it is necessary to give more opportunities for transmission to the relay node R_i than end nodes E in order to shorten the end-to-end delay. Also, among all relay packets at the relay node, it is necessary to give a higher priority to relay packets experiencing more hops to reduce the end-to-end delay. The

differentiated CW policy and the *strict priority policy* for relay packets in relay node R_i in zone D_i are described in the next two sections.

3. Differentiated CW policy

3.1 Description of differentiated CW policy

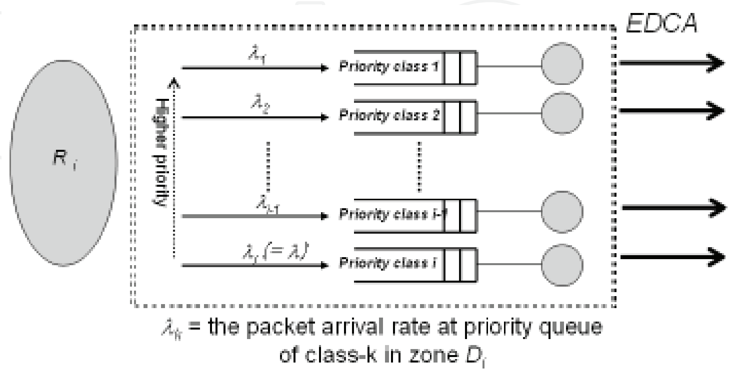

Fig. 5. Priority Queues at Relay Node R_i in zone D_i

First, *differentiated CW policy* (23) which adopts the functionality of IEEE 802.11e EDCA, is described. Fig.5 describes priority queues of class-k, ($k = 1, 2, \cdots, i$), at relay node R_i in zone D_i. Each priority queue of class-k is regarded as a separate entity with EDCA. Here each priority queue of class-k uses different CW_{min}, more specifically, a priority queue of higher class has a shorter CW_{min} value than priority queues of lower class. Each priority queue of class-k competes with each other and also end nodes to transmit a packet to the next relay node R_{i+1}. By assigning the shorter CW_{min} value to the priority queue of higher class, it has more opportunities to access channel than priority queues of lower class and other end nodes, and thus the delay of the packet passing by more hops can be shortened.

3.2 HoL-delay of packet at priority queue in zone D_i

In order to obtain the end-to-end delay of packets in WMN under the differentiated CW policy, first of all, we focus on zone D_i and find the probability generating function (PGF) of the HoL-delay of packets at each priority queue in zone D_i, where the HoL-delay is defined as the duration from the instant when a packet arrives at the head of the queue to the instant when its successful transmission is completed.

For the differentiated CW policy, priority queue of class-k have different traffic arrival rates and different contention window sizes, $k = 1, 2, \cdots, i$. An end node is regarded as priority queue of class-i in zone D_i because the end node and priority queue of class-i have the same type of local packets. Thus there are one priority queue of class-k for each $k = 1, 2, \cdots, i-1$, and N_i priority queues of class-i in zone D_i. Thus there are $N_i + i - 1$ contending entities in zone D_i. The packet arrival process to priority queue of class-k is assumed to follow a Poisson process with rate λ_k(/sec), where λ_k is the total arrival rate of packets generated at end nodes in zone D_k, $k = 1, 2, \cdots, i$, (note that the arrival rate λ_i(/sec) of packets generated in D_i is λ(/sec) in Subsection 2.2). Thus zone D_i can be modeled as non-saturated IEEE 802.11e EDCA model where there are $N_i + i - 1$ stations and i different queues have different arrival rates and different CW_{min}s, respectively.

For mathematical simplicity, assume $i = 4$, that is, there are 4 priority queues in zone D_i, and so there are N_i priority queues of class-4 and one priority queue of class-k, $k = 1, 2, 3$.
The payload sizes of all packets are equal, and let T_p be the duration for one packet to transmit. Slots are distinguished by following types:

- idle slot with length σ when no nodes transmit.
- successful slot when only one node transmits; the slot duration is $T_s = T_p + SIFS + t_{ACK} + DIFS$. Let us denote $T_s^* = T_s/\sigma$
- collision slot when two or more nodes transmit simultaneously; the slot duration is $T_c = T_p + DIFS$. Let us denote $T_c^* = T_c/\sigma$

Let τ_k be the transmission probability of the priority queue of class-k in a generic slot, $k = 1, 2, 3, 4$, which will be given by Eq.(3). With each transmission attempt and regardless of the number of retransmissions, each packet of priority queue of class-k is assumed to collide with the constant probability p_k as in (31). p_k is a conditional collision probability, meaning that this is the probability of a collision seen by a packet at the time of its being transmitted on the channel. Then the probability p_k is given by

$$p_k = 1 - \prod_{1 \le j \le 3, j \ne k} (1 - \tau_j)(1 - \tau_4)^{N_i}, 1 \le k \le 3 \tag{1}$$

$$p_4 = 1 - \prod_{1 \le j \le 3} (1 - \tau_j)(1 - \tau_4)^{N_i - 1} \tag{2}$$

For the analysis, the following parameters and probabilities are defined:

- Let $W_0^{[k]}$ be the minimum contention window size CW_{min} of priority queue of class-k and $W_i^{[k]} = 2^i W_0^{[k]}$, $k = 1, 2, 3, 4$.
- The maximum backoff stage is set to m and the retry limit is infinite, i.e, no packet is discarded.
- Let S_k be the HoL-delay (measured in idle slot length σ) of priority queue of class-k.

In order to obtain packet delay of IEEE 802.11 DCF under non-saturation condition, first it is essential to find the transmission probability τ_k. Once τ_k is obtained, performance measures such as delay and throughput can be expressed in terms of τ_k. For calculating transmission probability τ_k, there have been two different approaches in the literatures: i) Markov chain-based approach initiated by Bianchi (31) and ii) a method developed by (24). In the former approach, transmission probability τ is determined by the steady state probability of Markov chain. In this chapter, the second approach is adopted to obtain the transmission probability τ_k. The paper (24) developed an analytic model for IEEE 802.11 DCF in the non-saturated and homogeneous condition in the sense that all stations use the same contention parameter and packet arrival process to each station is identical. The analytical model (24) is extended to modeling of IEEE 802.11 DCF in the non-saturated heterogeneous condition in the sense that the packet arrival rate of per-node is different and also the minimum contention window of per-node is different.
The transmission probability is calculated as follows: In the saturated condition, the average backoff window $\overline{W}^{[k]}$ of priority queue of class-k is given (31) by

$$\overline{W}^{[k]} = \left(\frac{1 - p_k - p_k(2p_k)^m}{1 - 2p_k} \right) \frac{W_0^{[k]}}{2}.$$

In the saturated case, the probability that priority queue of class-k transmits a packet in a randomly chosen time slot is equal to $\frac{1}{\overline{W}^{[k]}}$ (31). For the non-saturated case, the conditional probability P[priority queue of class-k transmits|the queue is not empty] will be approximated by $\frac{1}{\overline{W}^{[k]}}$ (24). Now let the traffic intensity of the priority queue of class-k be ρ_k, which is defined by $\rho_k = \lambda_k E[S_k]\sigma$ and we assume that $\rho_k < 1$, where HoL-delay S_k of the priority queue of class-k regarded as service time will be given by (7) below. Then the transmission probability τ_k of priority queue of class-k is given by

$$\tau_k = 0 \cdot (1-\rho_k) + \frac{1}{\overline{W}^{[k]}}\rho_k. \tag{3}$$

We define the probabilities representing the channel state during the backoff procedure of the priority queue of class-k. During the backoff procedure of the priority queue of class-k, the channel is in one of the following states; idle, collision transmission and successful transmission.

The probability P^k_{idle} of the channel being sensed idle during the backoff procedure of the priority queue of class-k, $(k = 1, 2, 3, 4)$, is given by

$$P^k_{idle} = \prod_{1 \le j \le 3, j \ne k} (1-\tau_j)(1-\tau_4)^{N_i} \text{ for } k = 1, 2, 3, \tag{4}$$

$$P^4_{idle} = \prod_{1 \le j \le 3} (1-\tau_j)(1-\tau_4)^{N_i - 1}. \tag{5}$$

The probability P^k_s of the channel being sensed busy due to successful transmission of other priority queues during the backoff procedure of the priority queue of class-k is given by

$$\begin{aligned}
P^1_s &= \tau_2(1-\tau_3)(1-\tau_4)^{N_i} + (1-\tau_2)\tau_3(1-\tau_4)^{N_i} \\
&\quad + N_i(1-\tau_2)(1-\tau_3)\tau_4(1-\tau_4)^{N_i-1} \\
P^2_s &= \tau_1(1-\tau_3)(1-\tau_4)^{N_i} + (1-\tau_1)\tau_3(1-\tau_4)^{N_i} \\
&\quad + N_i(1-\tau_1)(1-\tau_3)\tau_4(1-\tau_4)^{N_i-1} \\
P^3_s &= \tau_1(1-\tau_2)(1-\tau_4)^{N_i} + (1-\tau_1)\tau_2(1-\tau_4)^{N_i} \\
&\quad + N_i(1-\tau_1)(1-\tau_2)\tau_4(1-\tau_4)^{N_i-1} \\
P^4_s &= \tau_1(1-\tau_2)(1-\tau_3)(1-\tau_4)^{N_i-1} \\
&\quad + (1-\tau_1)\tau_2(1-\tau_3)(1-\tau_4)^{N_i-1} \\
&\quad + (1-\tau_1)(1-\tau_2)\tau_3(1-\tau_4)^{N_i-1} \\
&\quad + (N_i-1)(1-\tau_1)(1-\tau_2)(1-\tau_3)\tau_4(1-\tau_4)^{N_i-2}
\end{aligned}$$

The probability P^k_c of the channel being sensed busy due to collision transmission of other priority queues during the backoff procedure of the priority queue of class-k is given by

$$P^k_c = 1 - P^k_{idle} - P^k_s.$$

As for deriving the PGF of HoL-delay in the non-saturated and homogeneous conditions, refer to (22). To derive the distribution of HoL-delay S_k, the method (22) can be extended to the heterogeneous condition (23).

Let us consider a priority queue of class-k as the tagged station. Let X, Y and Z be the number of collision slots of other stations, successful transmission slots of the other stations and empty slots experienced until the backoff counter of tagged station becomes zero during a backoff stage, respectively. As a remainder, during the backoff process of the tagged station the length of the slot is empty slot time σ with probability P^k_{idle} or collision time T^*_c with probability P^k_c, or successful transmission time T^*_s with probability P^k_s. If the value of the backoff counter of the tagged station is chosen by a at a given backoff stage, then (X, Y, Z) has a trinomial distribution whose probability mass function is given by

$$P\{X = j, Y = h, Z = l\} = \frac{a!}{j!h!l!}(P^k_c)^j (P^k_s)^h (P^k_{idle})^l, \;\; j + h + l = a. \tag{6}$$

Denoting $T^k_i(z)$ by the PGF of the time duration that the tagged priority queue of class-k stays at the i-th backoff stage, $T^k_i(z)$ is obtained as follows:

$$\begin{aligned}
T^k_i(z) &= \sum_{a=0}^{W_i^{[k]}-1} \frac{1}{W_i}\left(\sum_{j=0}^{a}\sum_{h=0}^{a-j} P\{X = j, Y = h, Z = a-j-h\} z^{jT^*_c + hT^*_s + (a-j-h)}\right)\\
&= \sum_{a=0}^{W_i^{[k]}-1} \frac{1}{W_i^{[k]}}\left(\sum_{j=0}^{a}\sum_{h=0}^{a-j} \frac{a!}{j!h!(n-j-h)!} P^j_c P^h_s P_i^{a-j-h} z^{jT^*_c + hT^*_s + (a-j-h)}\right)\\
&= \sum_{a=0}^{W_i-1} \frac{1}{W_i}(P^k_c z^{T^*_c} + P^k_s z^{T^*_s} + P^k_{idle} z)^a = \sum_{a=0}^{W_i^{[k]}-1} \frac{1}{W_i^{[k]}} B^k(z)^a\\
&= \frac{B(z)^{W_i^{[k]}} - 1}{W_i^{[k]}(B^k(z) - 1)},
\end{aligned}$$

where $B^k(z) = P^k_c z^{T^*_c} + P^k_s z^{T^*_s} + P^k_i z$ and $B^k(z)$ is the PGF of the length of one slot.

By conditioning on the number of collisions experienced until the packet transmitted successfully, we obtain the PGF of S_k as follows:

$$\begin{aligned}
E[z^{S_k}] &= \sum_{n=0}^{\infty} E[z^{S_k} | N = n] P\{N = n\}\\
&= \sum_{n=0}^{\infty}\prod_{i=0}^{n} T^k_i(z)(z^{T^*_c})^n z^{T^*_s}(p_k)^n(1 - p_k)\\
&= \sum_{n=0}^{m}\prod_{i=0}^{n} T^k_i(z)(z^{T^*_c})^n z^{T^*_s}(p_k)^n(1 - p_k)\\
&+ \prod_{i=0}^{n} T^k_i(z) T^k_m(z) \frac{(p_k z^{T^*_c})^{m+1}(1 - p_k)}{1 - T^k_m(z) z^{T^*_c} p_k}
\end{aligned} \tag{7}$$

3.3 Extension to the tree structure

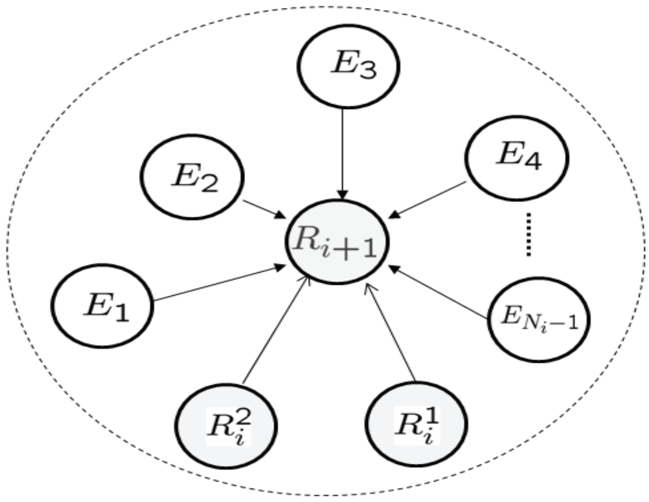

Fig. 6. Zone D_i in the case of tree structure

In the case of tree structure, if we decompose the WMN into disjoint zones, each zone D_i can contain relay nodes more than one as shown in Fig.6. In Fig..6, zone D_i contains two relay nodes R_i^1 and R_i^2 which compete each other and other end nodes to transmit their packets to the relay node R_{i+1}. Assuming that relay node R_i^1 should deliver packets generated at $x-1$ zones, R_i^1 has x uplink buffers for relay traffic. On the other hand, assuming that relay node R_i^2 should forward packets generated at $y-1$ zones, R_i^2 has y uplink buffers for relay traffic. Assume that $x \geq y$. Since the priority queue with packets experiencing the same hop-count uses the same CW_{min}, we note that there are x priority queues in zone D_i where each of them uses a different CW_{min} and has a different arrival rate. The number of contending entities is equal to $(N_i - 1) + x + y$. Thus, with the complexity of expression, it is straightforward to extend the analytical method presented in Section 3.2 to the case of tree structure.

3.4 Average end-to-end delay

The packet delay in a zone is obtained from $M/G/1$ queueing theory. The packet delay $A_{i,k}$ at priority queue of class-k in zone D_i is defined by the sum of queueing delay and service time (HoL-delay), and is given by

$$E[A_{i,k}] = \frac{\lambda_k E[S_k^2]}{2(1-\rho_k)} + E[S_k],\ k = 1, 2, 3, 4 \tag{8}$$

where the first and second moments of S_k are obtained from (7).
Then, the end-to-end delay of a packet generated at an end-node until reaching the gateway node, is obtained. Thus the end-to-end delay $W_{end}^{(i)}$ of the local packet generated at the priority queue of class-i (i.e., end node) in zone D_i is given by

$$W_{end}^{(i)} = E[A_{i,i}] + E[A_{i+1,i}] + \cdots + E[A_{n,i}].$$

3.5 A method to determine CW_{min}s for location-independent end-to-end delay and numerical results

3.5.1 Analytic method to determine CW_{min}

channel bit rate	11Mbps
DIFS	50 μsec
slot size(σ)	20 μsec
SIFS	10 μsec
transmission time of PHY header	192 μsec
MAC header	34 byte
Payload length	1500 byte
ACK	14 byte + PHY header

Table 1. System parameters

The goal in (23) is to guarantee that the end-to-end delays of local packets generated at each end node are almost same by choosing the appropriate minimum contention window size of each priority queue of class-k at zone D_i. More specifically, it is a goal to find a natural number CW_{min} of each priority queue of class-k at zone D_i so that the end-to-end delays $W_{end}^{(i)}$ of the local packets generated at each zone $D_i, (i = 1, 2, \cdots, n)$ should satisfy the following equalities approximately:

$$W_{end}^{(1)} \approx W_{end}^{(2)} \approx \cdots \approx W_{end}^{(n)}. \tag{9}$$

Note that zone D_i has priority queue of class-k $(k = 1, 2, \cdots, i)$. Since each priority class uses different value of CW_{min}, there are i CW_{min}s to be determined in zone D_i. Thus the total number of CW_{min}s to be determined is $1 + 2 + \cdots + n = \frac{(n+1)n}{2}$. On the other hand, (9) provides ${}_nC_2 = \frac{(n-1)n}{2}$ equations. Thus we have $\frac{n(n+1)}{2}$ equations with $\frac{n(n+1)}{2}$ unknown variables. Therefore, if n CW_{min}s of highest priority queue in each zone are given initially, we have $\frac{n(n-1)}{2}$ non-linear equations with $\frac{n(n-1)}{2}$ unknown variables of CW_{min}. Thus we find one of the solutions CW_{min}s to satisfy Eq.(9) approximately. Thus we obtain one of solutions CW_{min}s satisfying (9) numerically by *trial and error* method.

For numerical example, system parameters for the numerical example are given by table 1 and the number of hops is set to $n = 3$. We display the end-to-end delays of packets as the arrival rate λ(/sec) of each end node increases, for the case that the number N_i of end nodes in zone D_i is set to 5 and 7 for all zones, respectively. We set CW_{min} of the highest priority queue in each zone as 32. One of solutions CW_{min}s satisfying criterion (9) approximately can be obtained in table 2 and 3 for $N_i = 5$ and $N_i = 7$. The simulation is performed using Matlab software under same environment as assumptions in our analytic models. Table 2 and 3 show that as arrival rate λ increases, the end-to-end delay increases. For a given packet arrival rate λ, we see that end-to-end delays of packets are almost equal regardless of source nodes' locations and the number of end nodes in each zone. Also, table 2 and 3 shows that analytical results match well with the simulation results.

3.5.2 Heuristic method to determine CW_{min}

Above mentioned method to determine CW_{min} is a centralized one which requires a coordinator to control overall WMNs. The central coordinator should know the network information such as the network size (maximum hop count), the number of mesh nodes and the packet generation rate of each zone. Based on those information, the controller

	$\lambda = 10/\text{sec}$			$\lambda = 11/\text{sec}$			$\lambda = 12/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		69	76		66	73		64	71
CW_3			192			180			171
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	7	7	7	7.5	7.2	7.2	7.6	7.5	7.5
simulation	7.1	6.2	6.2	7.1	6.3	6.4	7.4	6.6	6.5

	$\lambda = 13/\text{sec}$			$\lambda = 14/\text{sec}$			$\lambda = 15/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		61	67		59	65		57	63
CW_3			159			151			143
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	7.8	7.6	7.6	7.9	7.6	7.6	8	7.8	7.8
simulation	7.2	6.7	6.8	7.4	6.7	6.8	7.5	6.8	6.9

Table 2. $CW_k (= CW_{min})$ of the priority queue of class-k and end-to-end (ete) delay vs. arrival rate for $N_i = 5$

	$\lambda = 10/\text{sec}$			$\lambda = 11/\text{sec}$			$\lambda = 12/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		58	65		55	62		43	60
CW_3			149			138			131
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	7.9	7.5	7.5	8.1	7.8	7.8	8.4	8.1	8.3
simulation	7.5	6.5	6.2	7.4	6.6	6.4	7.7	6.8	6.9

	$\lambda = 13/\text{sec}$			$\lambda = 14/\text{sec}$			$\lambda = 15/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		51	58		49	55		48	56
CW_3			124			116			119
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	8.7	8.5	8.9	9.1	9.0	9.6	9.4	9.8	10.9
simulation	8.0	7.0	7.2	8.3	7.3	7.4	8.5	7.6	8.0

Table 3. $CW_k (= CW_{min})$ of the priority queue of class-k and end-to-end (ete) delay vs. arrival rate for $N_i = 7$

periodically (or if necessary) calculates the CW_{min} of each node according to the rule presented above and informs each node to use newly calculated contention window. As an alternative to centralized method, a method to distributively determine CW_{min} in each zone is considered. The principle of our proposed packet management scheme is that relay packets experiencing longer hops are buffered into the higher priority queue. By assigning a smaller value of CW_{min} to a higher priority queue of class, we intend that the packet in the higher priority queue with passing by longer hops is served faster than the packet in a lower priority queue. The question is how smaller value of CW_{min} is assigned to the higher priority queue of class.

Let $f(x)$ be a nondecreasing nonnegative function of x, where x denotes a hop count as a positive integer. Let μ_k denote the service rate of packets in priority queue of class-k, $(k = 1, 2, \cdots, i)$, in zone D_i, i.e, μ_k is the reciprocal of the mean HoL-delay derived in Subsection 3.2, which is given by $\mu_k = 1/E[S_k]\sigma$, and is a function of CW_{min}'s of priority queue of class-k. We introduce the following criterion to differentiate CW_{min}s betweens priority queues of classes:

$$\frac{\mu_j}{f(i-j)} = \frac{\mu_k}{f(i-k)}, \quad j \neq k. \tag{10}$$

In zone D_i, relay packets passing by $i-k$ hops are stored in priority queue of class-k. Since $f(x)$ is a nondecreasing function, according to the criterion (10), a higher priority queue of class occupies a larger portion of the serving capacity by having smaller value of CW_{min}. In each zone D_i, Eqs. (2), (3) and (10) can be solved using numerical technique to obtain the minimum contention window size for each priority queue of class. It is worth noting that, in the heuristic method, CW_{min} of nodes in each zone is independently determined without considering other zones.

For the numerical example, the considered topology is 4-hop linear WMN as shown in fig.2. We assume that there are five end nodes and one relay node in zone $D_i, i = 1, 2, 3, 4$. We set CW_{min} of the highest priority queue in each zone as 31. Lower priority classes including end nodes use the CW_{min} determined by the constraint (10), which is larger than 31. As a weight function for our proposed scheme, we set $f(k) = k$ for numerical examples, that is, $\mu_1 : \mu_2 : \mu_3 : \mu_4 = 4 : 3 : 2 : 1$. Table 4 depicts the CW_{min} of each priority queue in each zone determined by criterion (10) and the end-to-end delays of local packets generated at each zone versus the arrival rate λ. From table 4, we see that our heuristic method achieves almost equal end-to-end delays of packets regardless of their generated zones under moderate packet arrival rate. But as the packet arrival rate λ is high, there is a little, but not great, difference of end-to-end delays depending on the generated zone. This result is expected due to the weight function which we heuristically choose.

λ	15				16				17				18			
zone	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4
CW_1	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
CW_2		41	50	49		39	50	49		38	49	48		38	48	47
CW_3			73	82			71	80			68	78			66	75
CW_4				159				152				144				135
ete-delay(ms)	11.9	11.9	12.3	12.6	12.5	12.6	13.4	13.9	13.2	13.6	15.3	15.6	14.2	15.1	19.6	18.2

Table 4. $CW_i(= CW_{min})$ of the priority class of i and end-to-end (ete) delay vs. arrival rate

4. Strict priority policy

4.1 Description of the strict priority policy

Next another packet management scheme at the relay node called the *strict priority policy* (23) is presented. As similar to the differentiated CW policy, in the strict priority policy, relay node R_i in zone D_i has i uplink buffers for relay packets as depicted in Fig.7, and the priority queue of class-k stores relay packets originated from zone D_k, which pass by $i-k$ hops,

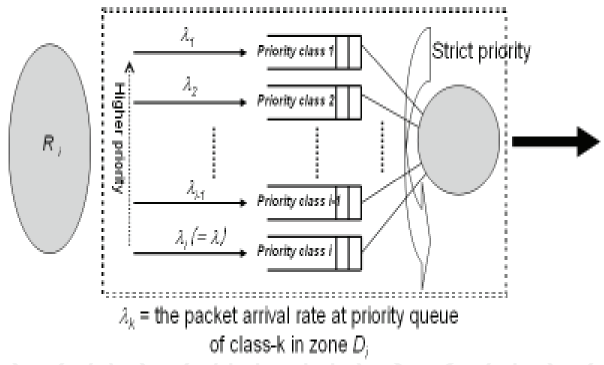

Fig. 7. Strict priority policy

$(k = 1, 2, \cdots, i)$. However, in the strict priority policy, there is only one contending entity of CSMA/CA protocol in relay node R_i. The relay node and end node use different CW_{min}s, respectively. Thus relay node R_i competes with end nodes in a zone D_i to access the channel. If relay node R_i has an opportunity to transmit a packet, the transmission occurs in the order of high priority classes among i uplink buffers. The service discipline among priority classes follows the order of strict priority

4.2 HoL-Delay of packet at priority queue in zone D_i

Under the strict priority policy, zone D_i can be modeled as a non-saturated IEEE 802.11e EDCA model with two different kinds of nodes, where CW_{min} values are differentiated between relay node and end node and also packet arrival rates are different from each other. We assume that the packet arrival processes to relay node R_i and an end node follow Poisson processs with rate Λ_i and λ, respectively, where Λ_i is given by $\Lambda_i = \sum_{k=1}^{i} \lambda_k$ and λ_k is the packet arrival rate to priority queue of class-k, which is the total arrival rate of local packets generated in zone D_k far away $i - k$ hops from relay node R_i as illustrated in Fig.3. Recall that there are N_i contending nodes in zone D_i; $N_i - 1$ end nodes and one relay node R_i. Thus we model zone D_i under the strict priority policy as the non-saturated IEEE 802.11e EDCA network and this model can be regarded as that with two classes under the differentiated CW policy. Therefore the PGF of the HoL-delay can be obtained directly from (7) by simply changing the parameters such as the arrival rate and the number of contending nodes in a zone D_i.

Similar to the argument in Section 3.3, even for the strict priority policy, the analytical method to derive the PGF of HoL-Delay can be extended to the case of tree structure with the complexity of expression.

4.3 Average end-to-end delay

As illustrated in Fig.7, relay node R_i in zone D_i has priority queue of class-k, $(k = 1, 2, \cdots, i)$. The priority queue of class-k stores the packets passing by $i - k$ hops and originated from zone D_k, as shown in Fig. 3. Then, relay node R_i can be modeled as $M/G/1$ queueing system with strict priority as shown in Fig.7.

Let $W_{i,k}, (k = 1, 2, \cdots, i)$, denote packet delay of priority queue of class-k at relay node R_i, where packet delay is defined as the sum of the queueing delay and the service time

	$\lambda = 10/\text{sec}$			$\lambda = 11/\text{sec}$			$\lambda = 12/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		144	195		137	182		130	170
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	7.2	7.4	7.8	7.2	7.6	8	7.4	7.5	8
simulation	6.9	7.2	7.4	7.1	7.2	7.5	7.3	7.4	7.6
	$\lambda = 13/\text{sec}$			$\lambda = 14/\text{sec}$			$\lambda = 15/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		124	160		118	151		113	142
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	7.6	7.8	8.1	7.6	7.8	8.2	7.8	8	8.2
simulation	7.3	7.5	7.6	7.4	7.5	7.6	7.6	7.6	7.7

Table 5. $CW_i (= CW_{min})$ of relay node and end node, respectively, and end-to-end (ete) delay vs. arrival rate for $N_i = 5$

	$\lambda = 10/\text{sec}$			$\lambda = 11/\text{sec}$			$\lambda = 12/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		148	147		139	136		131	126
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	7.5	8.5	8.0	7.6	8.7	8.2	7.8	8.9	8.5
simulation	7.2	7.3	7.0	7.4	7.6	7.5	7.5	7.8	7.6
	$\lambda = 13/\text{sec}$			$\lambda = 14/\text{sec}$			$\lambda = 15/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		123	117		116	109		110	101
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
analysis	8.0	9.2	8.7	8.2	9.5	9.1	8.5	10.0	9.5
simulation	7.6	8.0	7.8	7.8	8.5	7.7	8.1	8.9	8.1

Table 6. $CW_i (= CW_{min})$ of relay node and end node, respectively, and end-to-end (ete) delay vs. arrival rate for $N_i = 7$

(HoL-delay). The average of packet delay for priority class-k is given (25) by

$$E[W_{i,k}] = \frac{\sum_{j=1}^{i} \lambda_j E[S^2]}{2(1-\rho_{k-1}^{+})(1-\rho_k^{+})} + E[S] \tag{11}$$

where

$$\lambda_k^{+} \triangleq \sum_{j=1}^{k} \lambda_j, \;\; \rho_k^{+} \triangleq \sum_{j=1}^{k} \rho_j. \tag{12}$$

and, $E[S]$ and $E[S^2]$ are obtained from Eq.(7).
In zone D_i, the local packet generated at the end node should traverse $n - i + 1$ hops to reach the gateway node. Thus, the end-to-end delay $W_{end}^{(i)}$ of the local packet generated at the priority queue of class-i (i.e., end node) in zone D_i is given by

$$W_{end}^{(i)} = E[A_i] + E[W_{i,i}] + E[W_{i+1,i}] + \cdots + E[W_{n,i}],$$

where $E[A_i]$ is the average of packet delay of generated at an end node in zone D_i and is given by Eq.(8).

4.4 A method to determine CW_{min} for location-independent end-to-end delay and numerical Results

4.4.1 Analytic method to determine CW_{min}

The goal is to guarantee that the end-to-end delays of packets generated at each zone are almost same. We want to find natural number CW_{min}s of relay node and end node so that the end-to-end delay of the local packet generated in each zone should satisfy the following equalities approximately:

$$W_{end}^{(1)} \approx W_{end}^{(2)} \approx \cdots \approx W_{end}^{(n)}. \tag{13}$$

We should determine the minimum contention window sizes of relay node and end node in each zone, which satisfy (13) approximately. Each end-to-end delay in (13) is a function of CW_{min}s of relay node and end node. Under the strict priority policy, relay node and end nodes in each zone compete with each other via different values of CW_{min}s. Note that under the strict policy $E[A_{i,k}]$ involves 2 unknown CW_{min}s and therefore Eq.(13) have $2n$ unknown CW_{min}s. On the other hand, Eq.(13) provides $\frac{n(n+1)}{2}$ equations. Initially setting CW_{min}s of relay node in each zone as 32, respectively, then we can find one of the solutions CW_{min}s to satisfy Eq.(9) numerically by *trial and error* method.
For numerical example, system parameters for the numerical example are given by table 1 and the number of hops is set to $n = 3$. Table 5 and 6 display the end-to-end delays of packets as the arrival rate $\lambda(/\text{sec})$ of each end node increases, for the case that the number N_i of end nodes in zone D_i is set to 5 and 7 for all zones, respectively. CW_{min} of the relay node in each zone is set to 32. One of solutions CW_{min}s satisfying criterion (13) approximately can be obtained in Table 5 and 6 for $N_i = 5$ and $N_i = 7$.
Table 5 and 6 show that as the arrival rate λ increases, the end-to-end delay of packet increases. As depicted in Table 5 and 6, we see that each end-to-end delays of packets are almost same regardless of source node's location and the number of end nodes in each zone.
In Table 2, 3, 5 and 6, we see that two packet management schemes achieve almost equal end-to-end delay of packets regardless of their generated location, respectively. Comparing end-to-end delays between two schemes, we see that there is almost no difference. Since (9) of differentiated CW policy involves more unknown CW_{min}s than (13) of strict priority policy, only computational complexity of differentiated CW policy is higher than that of strict priority policy.

4.4.2 A heuristic method to determine CW_{min}

Unlike the differentiated CW policy, in the *strict priority policy*, relay node R_i unifying all priority queues of classes contends with other end nodes and has a different contention window size from that of an end node. Thus we cannot adopt the weight function depending on hop count as in Eq.(10) of the differentiated CW policy.

In general, relay node R_i is heavily loaded compared to end nodes since relay node R_i forwards its local traffic and relay traffics from zone D_{i-1}. Thus it is necessary to give more chances to access the channel to relay node R_i than end nodes E to avoid congestion. To assign the more chance to relay node R_i, we differentiate the CW_{min}s between relay node R_i and end nodes in zone D_i. The question is how smaller contention window size is assigned to the relay node compared to an end node. We define $g(\lambda)$ as the weight function of the arrival rate λ, which is a nonnegative nondecreasing function of arrival rate λ. Thus we introduce the following constraint to differentiate nodes:

$$\frac{\mu}{g(\lambda)} = \frac{\mu_i}{g(\Lambda_i)} \tag{14}$$

where Λ_i and λ are the arrival rates to relay node R_i and an end node E in zone D_i, respectively, and μ_i and μ are the service rates (reciprocal of the mean HoL-delay) of the relay node and the end node in zone D_i, respectively, which are functions of CW_{min}s. Eq.(14) says that the CW_{min} of the relay node and the end node are determined in such a way that their service rates are proportional to their arrival rates, respectively. By doing so, the highly loaded relay node may have more chances to access the channel, and so the relay node can avoid the congestion.

For the numerical example, the considered topology is 4-hop linear WMN as shown in fig.2. It is assumed that there are five end nodes and one relay node in zone $D_i, i = 1, 2, 3, 4$. CW_{min} of the relay node in each zone is set as 31. An end node use the CW_{min} determined by the constraint (14). As a weight function, $g(x) = \sqrt{x}$, that is, $\mu : \mu_i = \sqrt{\lambda} : \sqrt{\Lambda_i}$. Table 7 illustrates the CW_{min} of relay node and end node in each zone determined by criterion (10) and the end-to-end delays of local packets generated at each zone versus the arrival rate λ. From table 4, we see that the heuristic method to determine CW_{min} achieves the almost equal end-to-end delay of packets regardless of their generated zones. Compared with table 4, we see that strict priority policy with constraint (14) achieves less end-to-end delay than the differentiated CW policy with constraint (10) and moreover end-to-end delays of packets are almost equal regardless of source nodes' locations.

λ	15				16				17				18			
zone	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4
CW_1	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
CW_2		131	140	134		125	132	126		120	125	118		115	119	111
ete-delay(ms)	10.3	11.1	11.1	10.5	10.5	11.4	11.6	10.8	10.7	11.7	12.2	11.1	10.9	12.2	13.5	11.6

Table 7. $CW_i(= CW_{min})$ of the priority class of i and end-to-end (ete) delay vs. arrival rate

4.5 Extension to the case of coexisting of uplink and downlink streams

Next, we discuss whether two packet management schemes achieve location-independent delay of packets regardless of sources' locations in the case that both uplink and downlink streams coexist. First, let us consider the same linear WMN with downlink stream only. Let us consider zone D_i. Keep in mind that relay node R_i has i uplink buffers for uplink streams where the $k-$th uplink buffer in the relay node R_i stores packets originated from all end nodes in zone D_k. As shown in Fig.8, for downlink streams, the relay node R_{i+1} needs

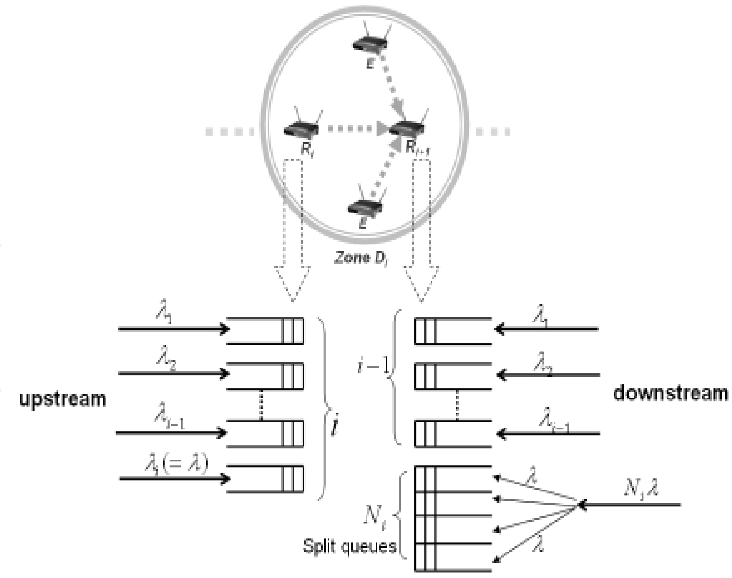

Fig. 8. Application of our proposed scheme to the case of coexisting up/ down streams

	$\lambda = 10/\text{sec}$			$\lambda = 11/\text{sec}$			$\lambda = 12/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		69	76		66	73		64	71
CW_3			192			180			171
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
simulation	8.3	7.9	7.4	8.8	8.7	8.7	9.3	9.6	9.3
	$\lambda = 13/\text{sec}$			$\lambda = 14/\text{sec}$			$\lambda = 15/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		61	67		59	65		57	63
CW_3			159			151			143
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
simulation	10.0	11.0	11.0	11.5	12.0	12.3	15.0	16.5	17.2

Table 8. $CW_k(= CW_{min})$ of the priority queue of class-k and end-to-end (ete) delay vs. arrival rate for differentiated CW policy

i downlink buffers where the $k-$th downlink buffer in the relay node R_{i+1} stores packets destined for the end nodes in zone D_k from gateway, $1 \leq k \leq i-1$, and the $i-$th downlink buffer stores packets destined for all the end nodes in zone D_i. Again, as depicted in Fig.8, we split packets in the $i-$th downlink buffer in relay node R_{i+1} into N_i queues as many as the number of end nodes in zone D_i equally. With these packet management for downlink stream, we have exactly symmetric structure between uplink and downlink schemes. We assume that the arrival rate of upstream packets originated from all the end node in a zone D_i is equal to that of downstream packets destined for end nodes in zone D_i. We assume that the priority queue of class$-k$ in relay node R_{i+1} uses the same CW_{min} as the priority queue of class-k in relay node R_i and also each split queue uses the same CW_{min} as an end node. With

	$\lambda = 10/\text{sec}$			$\lambda = 11/\text{sec}$			$\lambda = 12/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		144	195		137	182		130	170
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
simulation	8.3	7.8	7.8	8.8	8.6	9.0	9.0	9.1	9.7
	$\lambda = 13/\text{sec}$			$\lambda = 14/\text{sec}$			$\lambda = 15/\text{sec}$		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
CW_1	32	32	32	32	32	32	32	32	32
CW_2		124	160		118	151		113	142
ete-delay(ms)	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$	$W_{end}^{(1)}$	$W_{end}^{(2)}$	$W_{end}^{(3)}$
simulation	9.8	10.1	10.8	9.8	11.0	10.5	14.8	15.4	16.6

Table 9. $CW_i (= CW_{min})$ of relay node and end node, respectively, and end-to-end (ete) delay vs. arrival rate for strict priority policy

these assumptions, in each zone, packet delay of priority queue of class-k for uplink stream is exactly same as that of the corresponding priority queue of class-k for downlink stream. Thus, in the case that only downlink stream exists, our proposed schemes can achieve the location-independent end-to-end delay of packets regardless of destination's location just as the case that only uplink stream exists.

In the case that uplink and downlink streams coexist, there are $N_i + i - 1$ contending entities for uplink transmission in zone D_i. Also, for downlink, there are $N_i + i - 1$ contending entities for downlink transmission in zone D_i. Thus, there are $2 \cdot (N_i + i - 1)$ contending entities in zone D_i for the case of differentiated CW policy. (For the case of strict priority policy, note that there are $2 \cdot (N_i + 1)$ contending entities.) In the case that uplink and downlink streams coexist, by symmetric structure between uplink and downlink schemes, we see that the end-to-end delay of upstream packet originated from an end node in each zone is exactly same as that of downstream packet destined for the corresponding end node in each zone.

In order to examine whether our proposed schemes provide location-independent end-to-end delay even in the case that both uplink and downlink streams coexist, we perform simulations using Matlab software. The parameters for simulations are set to the same as the case of uplink only: The number of hops is set to 3. The number of end nodes in each zone is set to 5. The downstream packet arrival process destined for each end node follows Poisson process with rate λ(/sec), which is the same as uplink packet arrival process of each end node. The priority queue of class-k for downlink at the relay node R_{i+1} uses the same CW_{min} of the corresponding priority queue of class-k for uplink, which are given by Table 2. As we see in Table 8 and 9, for a given packet arrival rate λ, our two proposed schemes ensure end-to-end delays of packets to be almost equal in the case that uplink and downlink streams coexist.

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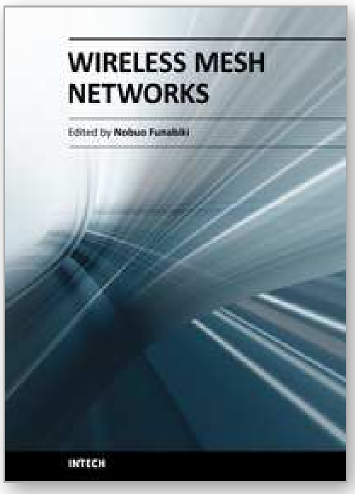

Wireless Mesh Networks

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The rapid advancements of low-cost small-size devices for wireless communications with their international standards and broadband backbone networks using optical fibers accelerate the deployment of wireless networks around the world.â€¨The wireless mesh network has emerged as the generalization of the conventional wireless network. However, wireless mesh network has several problems to be solved before being deployed as the fundamental network infrastructure for daily use. The book is edited to specify some problems that come from the disadvantages in wireless mesh network and give their solutions with challenges. The contents of this book consist of two parts: Part I covers the fundamental technical issues in wireless mesh network, and Part II the administrative technical issues in wireless mesh network,. This book can be useful as a reference for researchers, engineers, students and educators who have some backgrounds in computer networks, and who have interest in wireless mesh network. It is a collective work of excellent contributions by experts in wireless mesh network.

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