An Effective QoS Differentiation Scheme for Wireless Mesh Networks

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Abstract

Wireless mesh networking is emerging as an important architecture for future-generation wireless communications systems. Quality of service provisioning is a challenging issue in WMNs. In this article we study an effective QoS differentiation scheme for IEEE 802.16 WiMAX mesh networks. Both collocated and general topologies are exploited. Illustrative numerical examples are presented to demonstrate the effectiveness of the proposed strategy. The impact of key parameters on performance is discussed for differentiating various services. Moreover, with the proposed scheme, WMN scalability can be greatly improved. The challenges with respect to the integration of WMN and cooperative transmission are discussed, and the fairness problem is addressed with potential solutions.

Wireless mesh networks (WMNs) will play an increasingly important role in future-generation wireless mobile networks. A WMN normally consists of mesh routers and clients, and can be independently implemented or integrated with other communications systems such as conventional cellular networks [1]. WMNs are characterized by dynamic self-organization, self-configuration, and self-healing to enable quick deployment, easy maintenance, low cost, great scalability, and reliable services, as well as enhance network capacity, connectivity, and resilience [1, 2]. Due to these promising features, the international standardization organizations are working actively on the specifications of mesh networking modes (e.g., IEEE 802.11, IEEE 802.15, IEEE 802.16, and IEEE 802.20).

Due to the attractive features of WMNs, IEEE 802.16d/e for wireless metropolitan area networks (wireless MANs) offers standardizations for both point-to-multipoint (PMP) and mesh mode operations [3, 4]. Figure 1 shows the difference between PMP and mesh modes. In PMP mode a base station (BS) performs a central role to coordinate and relay all communications. A subscriber station (SS) under the management of the BS has to communicate with the BS before transmitting data to other SSs. This architecture is similar to a cellular network. Unlike PMP mode, mesh mode has no clearly separated downlink and uplink, and every SS can directly communicate with its neighbors without the help of the BS (here, a neighbor node is defined as a node that is exactly one hop away from a particular node). The set of all neighbor nodes is called a *neighborhood*. In addition, the set of all neighbors of a neighborhood is called the *two-hop extended neighborhood*. In a typical installation one or several nodes play the role of BS to connect the mesh network to the external backhaul link (e.g., Internet or telecommunication networks). Such nodes are called mesh BSs (MBSs), while the other nodes are accordingly called mesh SSs (MSSs).

Future wireless networks promise to support a variety of traffic types. They should satisfy the requirements of both high-data-rate delay-sensitive applications such as video streaming and low-data-rate applications such as Web surfing, and smoothly handle bursty traffic over the Internet. In addition, they may need to deal with all different types of traffic simultaneously. As a consequence, various quality of service (QoS) classes shall be defined according to different traffic types. In IEEE 802.16 PMP mode, four connection-based QoS classes have been specified: unsolicited grant service (UGS), real-time polling service (rtPS), non-real-time polling service (nrtPS), and best effort (BE). Furthermore, in several recent studies various QoS differentiation schemes have been proposed for PMP mode [5, 6]. Comparatively, for mesh mode, no similar studies have been done on QoS priority differentiation schemes, although some work has beeen reported concerning QoS provisioning [7, 8]. In addition, the IEEE 802.16 standard defines a centralized scheduling scheme and a distributed scheduling scheme for mesh mode, but does not specify an algorithm for time slot scheduling to differentiate MSSs. The authors in [9] proposed some QoS provisioning algorithms for centralized scheduling for real-time and non-real-time traffic for IEEE 802.16 mesh networks. The study reported in [10] presented another scheduling algorithm for centralized scheduling. However, the QoS issue for the distributed scheduling mechanism has not been fully addressed.

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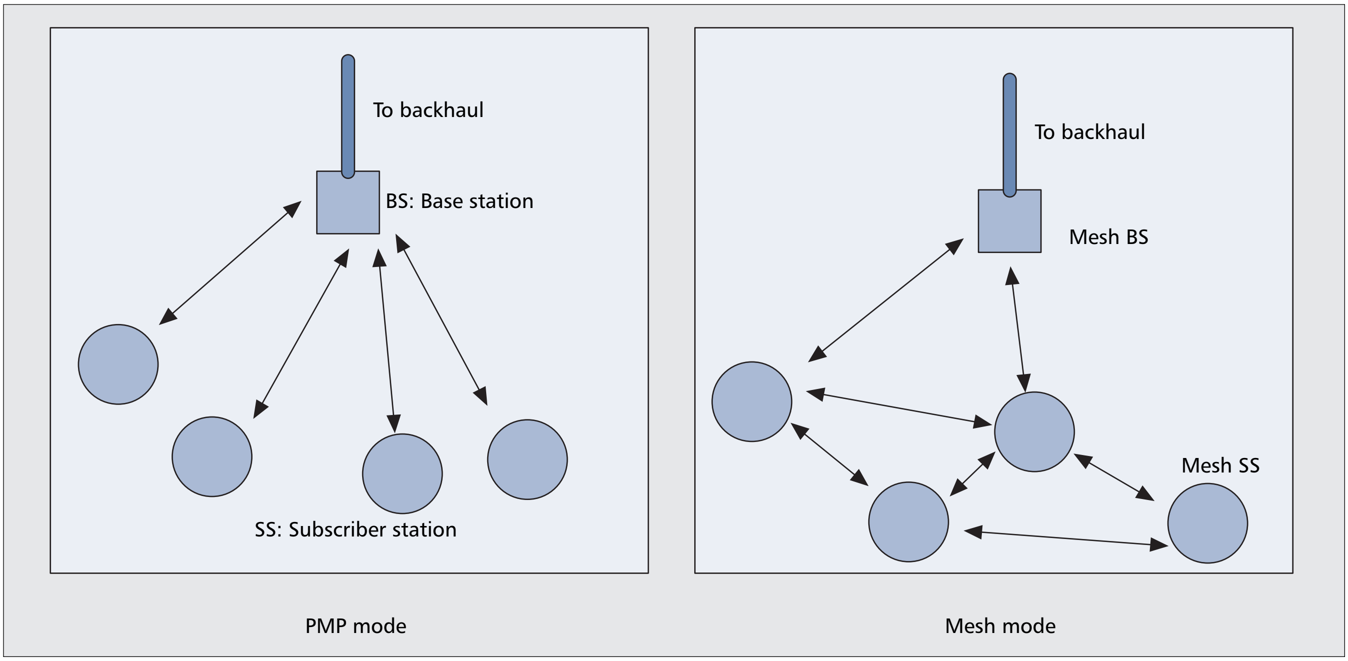


■ Figure 1. *PMP mode and mesh mode.*

In this article we propose an effective strategy to achieve QoS differentiation for different services in the framework of distributed scheduling for IEEE 802.16 WiMAX mesh networks. Both collocated and general topologies are included in our study. In addition, the interaction of cooperative transmission, the scalability problem, and the fairness issue in our proposed strategy are discussed in detail.

The rest of the article is outlined as follows. We present the mesh frame structure and the functionalities in each subframe. The centralized and distributed scheduling algorithms for determining transmission opportunities of control messages and data subframe are introduced. A new priority scheme is proposed to differentiate diverse QoS services in collocated and general topologies. Illustrative numerical examples are given to show the effectiveness of the proposed scheme. We identify the potentials for further performance enhancement with cooperative transmission and other future research topics. Finally, the article is concluded.

System Model for Mesh Networks

In this section we introduce the system model for IEEE 802.16 mesh networks, such as the frame structure, and the centralized and distributed scheduling schemes.

Frame Structure in Mesh Mode

Unlike PMP mode, which supports both frequency-division duplex (FDD) and time-division duplex (TDD), IEEE 802.16 mesh mode only supports TDD operation for transmission. As a result, several MSSs have to share and compete in the common radio channel in a time-division multiple access (TDMA) fashion.

Figure 2 shows the frame structure in mesh mode. A mesh frame consists of a control subframe and a data subframe. The control subframe has two primary functionalities. One is creation and maintenance of cohesion between different MSSs. The other is coordinated scheduling of data transfers among MSSs. The data subframe consists of medium access control (MAC) protocol data units (PDUs) transmitted from different users. A MAC PDU consists of a generic MAC header, a mesh subheader, and optional data.

In a frame the length of the control subframe is fixed as MSH-CTRL-LEN × 7 orthogonal frequency-division multiplexing (OFDM) symbols, where the parameter MSH-CTRL-LEN has four bits (whose value ranges from 0 to 15), and its value is advertised in the structure *Network Descriptor*. The data subframe is divided into a number of minislots. There are two different typies of control subframes: *network control* and *schedule control*. They occur in a frame exclusively. Figure 2 illustrates the definition of these two control subframes, where the network control subframe is shown in Fig. 2a, and the schedule control subframe is shown in Fig. 2b. The network control subframe occurs periodically with the period indicated in the structure Network Descriptor. The schedule control subframe occurs in all frames without the network control subframe. In particular, the *Scheduling Frame* field in the Network Descriptor defines the number of frames having a schedule control subframe between two frames with network control subframes in multiples of four frames. For instance, if the value of the scheduling frame is three, after a certain frame that has the network control subframe, the following 3 × 4 frames have the schedule control subframe, which is again followed by a frame with a network control subframe.

The network control subframe is defined primarily for new nodes to achieve synchronization and join a mesh network. The first transmission opportunity is the network entry component carrying the information of a mesh network entry (MSH-NENT) message. The remaining (MSH-CTRL-LEN-1) transmission opportunities are the network configuration components carrying the information of a mesh network configuration (MSH-NCFG) message. The length of each transmission opportunity accounts for seven OFDM symbols; hence, the length of the transmission opportunities carrying MSH-NCFG is equal to (MSH-CTRL-LEN-1) × 7 OFDM symbols. The schedule control subframe is defined for centralized or distributed scheduling for sharing MSSs in a common radio resource. As indicated in the Network Descriptor, there are MSH-DSCH-NUM mesh distributed scheduling (MSH-DSCH) messages. This implies that the first [(MSH-CTRL-LEN) – (MSH-DSCH-NUM)] × 7 OFDM symbols are allocated for transmitting mesh centralized scheduling (MSH-CSCH) and mesh centralized configuration (MSH-CSCF) messages. The data subframe serves the physical layer (PHY) transmission bursts. The PHY bursts start with a long pream-

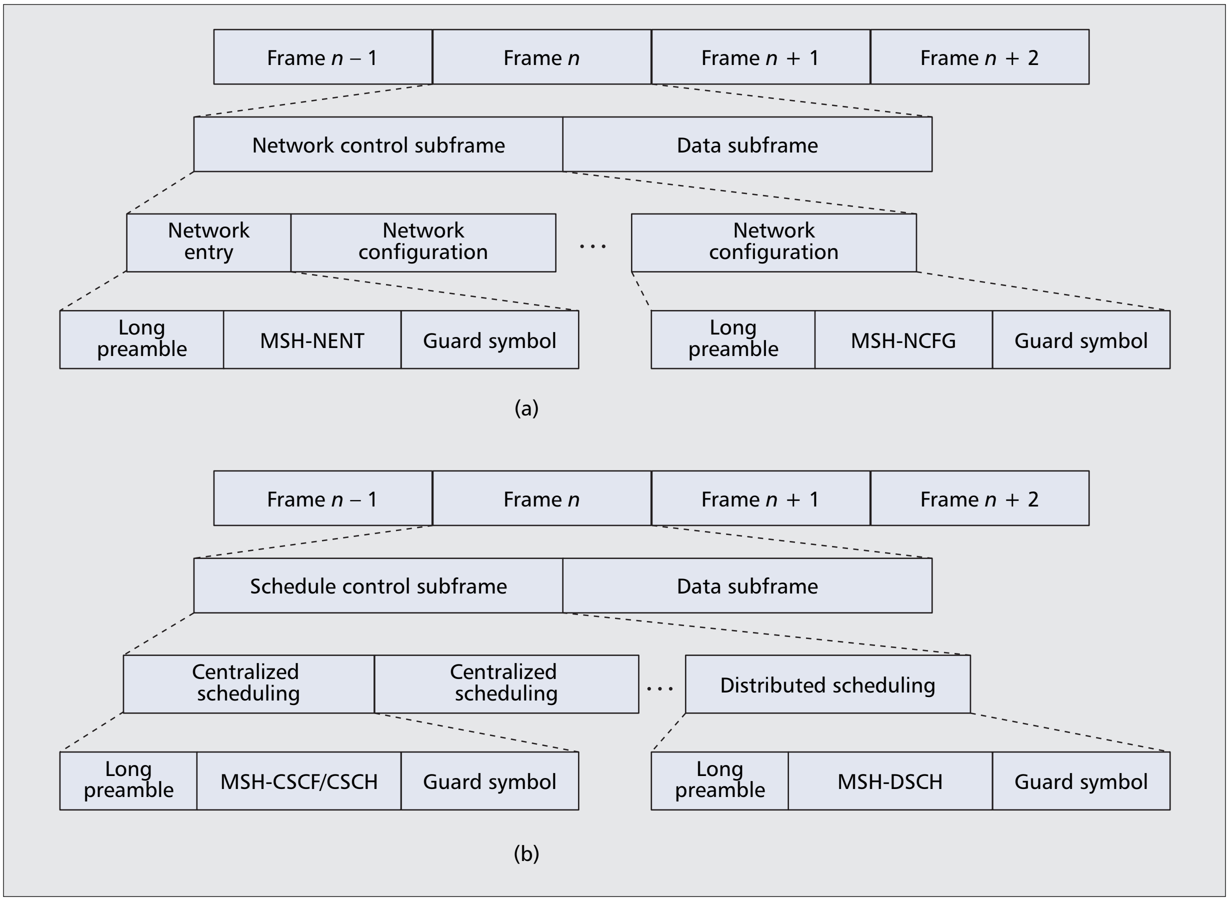


Figure 2. *Frame structure in IEEE 802.16 mesh mode: a) frame* n *has a network control subframe; b) frame* n *has a schedule control subframe.*

ble (two OFDM symbols) serving for synchronization, immediately followed by several MAC PDUs.

Centralized Scheduling Scheme

In mesh mode the transmission opportunities in the control subframe and the minislots in the data subframe are separated. Each MSS competes for control channel access. The contention consequence in the control subframe has no effect on the data transmission that occurs during the data subframe of the same frame. Hence, the contention process in the control subframe shall be elaborated to derive some performance metrics.

A scheduling algorithm is essential to control all the communication links for a wireless network. IEEE 802.16 mesh mode supports both centralized and distributed scheduling of time slots. Centralized scheduling is mainly used to transfer data between the MBS and MSSs. In centralized scheduling the MBS gathers resource requests through MSH-CSCH messages from all MSSs within a certain hop range. The MBS determines the flow assignments from these resource requests and sends these assignments to all the MSSs. Subsequently, the MSSs determine their own transmission opportunities in a distributed fashion using a common predetermined algorithm with the same input information. The MSSs let the MBS know changes in their resource requests through MSH-CSCH messages. Then the MBS rebroadcasts adjusted flow assignment, and the MSSs are able to recalculate their transmission opportunities. Currently, the IEEE 802.16 mesh network supports no spectral reuse with centralized scheduling. Since the QoS issues for centralized scheduling have been extensively studied in the literature [9, 10], we concentrate mainly on distributed scheduling in this article.

Distributed Scheduling Scheme

Distributed scheduling can be divided into coordinated and uncoordinated. The difference lies in whether scheduling messages are coordinated or uncoordinated in competing for the shared radio channel. In the following, we mainly study coordinated distributed scheduling due to its tunable and predictive performance unless otherwise stated. In distributed scheduling the MSH-DSCH message plays a significant role throughout the scheduling process. An MSH-DSCH message carries the following fields:

- *Availabilities IE* indicates the starting frame number, the starting minislot within the frame, and the number of available minislots for the granter to assign.
- *Scheduling IE* shows the next MSH-DSCH transmission time *NextXmtTime* and *XmtHoldoffExponent* of the node and also its neighbor nodes.
- *Request IE* indicates the resource demand of the node.
- *Grants IE* conveys the granted starting frame number, the granted starting minislot within the frame, and the granted minislots range.

The MSH-DSCH message in coordinated distributed scheduling occurs in a control subframe. Distributed election scheduling is defined to determine the *NextXmtTime* of a node's MSH-DSCH during its current transmission time, *XmtTime*.

There are two fields (parameters), *NextXmtMx* and *XmtHoldoffExponent*, in MSH-NCFG to determine the next eligibility interval, $2^{XmtHoldoffExponent} \times NextXmtMx < NextXmtTime \times 2^{XmtHoldoffExponent} \times (NextXmtMx + 1)$. Clearly, the length of the eligibility interval is equal to $2^{XmtHoldoffExponent}$. The node can transmit in any slot during this interval. After the eligibility interval and right before a new transmission, the

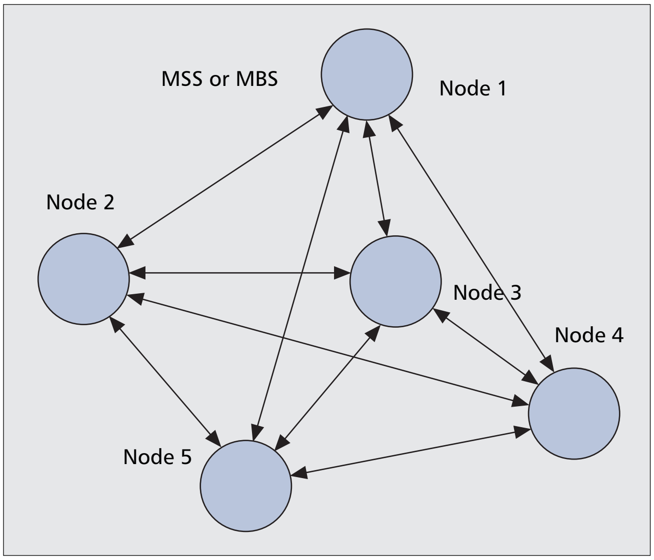


Figure 3. *An example of a collocated topology scenario where all nodes are one-hop neighbors of each other.*

node has to wait a holdoff time $\mathit{XmtHoldoffTime} = 2^{\mathit{XmtHoldoffExponent}+4}$. The node chooses the temporary transmission opportunity *TempXmtTime* equal to the first transmission slot after the holdoff time *XmtHoldoffTime*. Then the node determines the set of all eligible nodes $S_{eligible}$ competing for this slot, *TempXmtTime*. The set of eligible competing nodes $S_{eligible}$ includes all nodes in the extended neighborhood satisfying either of the following properties:

- *NextXmtTime* includes *TempXmtTime*.
- *EarliestSubsequentXmtTime*, which is equal to the summation of *NextXmtTime* and *XmtHoldoffTime*, occurs no later than *TempXmtTime*.
- *NextXmtTime* is unknown.

After set $S_{eligible}$ is built for a specific node, a pseudo-random mixing function will calculate a pseudo-random *MIX* value for each node. If the specific node generates the biggest *MIX* value, it wins the competition, and the next transmission time *NextXmtTime* is set as *TempXmtTime*. Then the node broadcasts to its neighbors in the MSH-NCFG message. Otherwise, the specific node fails in competing for this slot. The node will set *TempXmtTime* as the next transmission slot and repeat similar competing procedures until it wins.

QoS Differentiation Scheme

Due to its promising multimedia service capability, an IEEE 802.16 mesh network is able to support both real-time and non-real-time applications. Real-time applications, such as voice over IP (VoIP) and videoconferencing, have strict QoS requirements with respect to delay and delay jitter. Non-real-time applications, such as FTP file transfer and Web browsing, have much fewer requirements in terms of packet delay. To provide different QoS services to various applications, an efficient scheduling scheme shall be employed. Specifically, in the distributed scheduling mechanism, the MSH-DSCH transmission interval should be different for different classes of services. Real-time VoIP should experience a short transmission interval, while non-real-time email service can tolerate a relatively long transmission interval. In this section we propose a simple but effective scheme to prioritize various traffic types, consequently enabling QoS differentiation.

First, the eligibility interval and its length are generalized. For presentation simplicity, we introduce a transmission holdoff exponent α to denote *XmtHoldoffExponent*. The original base value two is generalized into a real number β in determining the eligibility interval and the length of this interval. It is noteworthy that the parameter generalization of the base value is carried out from the fixed integer two to a real number, instead of a general integer number. This clearly introduces more flexibility. Consequently, the eligible next transmission time *NextXmtTime* becomes $\beta^{\alpha} \times \mathit{NextXmtMx} < \mathit{NextXmtTime} \leq \beta^{\alpha} \times (\mathit{NextXmtMx} + 1)$, where the upper and lower bounds should be rounded to the nearest integer. The node can transmit in any slot during the eligibility interval. As a consequence, the length of the eligibility interval is given by the difference between the lower bound and upper bound as β^{α}. Second, we introduce another real-time base value γ and holdoff exponent λ to denote the transmission holdoff time *XmtHoldoffTime*, which is given as $\gamma^{\lambda+4}$.

We denote the set of QoS differentiated parameters for a node as $P = (\alpha; \beta; \gamma; \lambda)$. For different nodes in a mesh network, P shall be different. Suppose that there are N nodes in the mesh network. Let Φ represent the set of all nodes. For a particular node k ($k \in \Phi$), the set of parameters is accordingly denoted $P_k = (\alpha_k; \beta_k; \gamma_k; \lambda_k)$. Let S_k denote the number of slots in which node k fails during distributed election scheduling before it wins. The variable S_k is not easy to derive since it depends on a variety of other parameters, such as the number of competing nodes and their own *XmtHoldoffTime* values. However, we can develop the expected value of S_k, $E(S_k)$, by using statistical approaches. Since each $E(S_k)$ is related to other $S_k(S_j)$ ($j \in \Phi$), a fixed point algorithm should be employed [11].

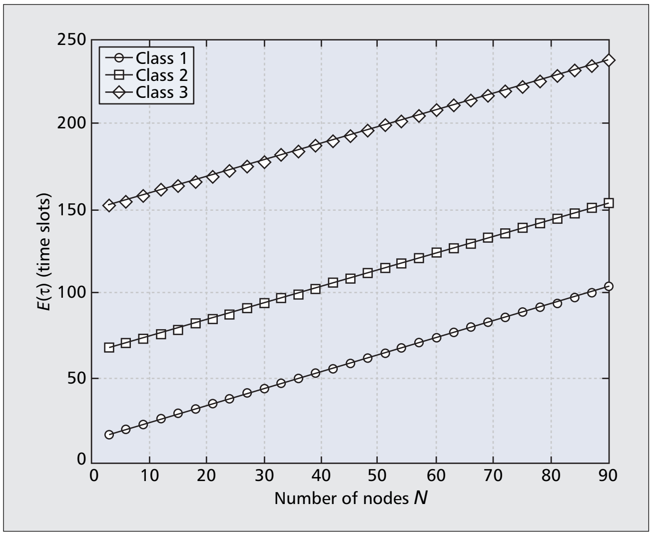
Let τ_k denote the interval between two consecutive MSH-DSCH transmission opportunities for the node k ($k \in \Phi$). In terms of time slots, τ_k is the summation of the holdoff transmission time and S_k. Thus, the expected value of τ_k is given by $(\gamma_k)\lambda + 4 + E(S_k)$. It is clear that S_k will increase with the number of competing nodes. Hence, a WMN with denser nodes has a larger delay τ_k since a denser WMN normally means more competing nodes. It is also noteworthy that more neighboring nodes may induce path diversity and hence less delay if they are not the competing nodes. Two scenarios, collocated topology and general topology, are discussed and analyzed below.

Collocated Topology

In the collocated topology all nodes are one-hop neighbors of each other, as illustrated in Fig. 3. Moreover, the holdoff parameter *XmtHoldoffExponent* can be either identical or nonidentical. Reference [12] has given a comprehensive analysis of these two situations, but without considering QoS differentiation.

When the nodes are collocated, the expected number of nodes competing with the specific node k during slot s, denoted $M_k(s)$, is the summation of the probability that other nodes compete with node k in the same slot. Hence, the probability that node k wins slot s in the pseudo-random election algorithm is $1/M_k(s)$ due to the randomness property of the election algorithm. Note that in the pseudo-random election algorithm, each node has an equal chance or the same probability to win a slot.

With a similar technique used in [12] by counting the nodes competing with node k for a specific slot, the expected value of probability $M_k(s)$ and consequently $E(S_k)$ can be calculated. Finally, the expected transmission interval of MSH-DSCH messages for any $k \in \Phi$ can be derived. Since the QoS differentiation scheme varying four parameters is introduced in this article, the results given in our work are different from those obtained in [12], where only different *XmtHoldoffExponent* was considered. In particular, even if the holdoff exponent,



■ Figure 4. E(τ) *in terms of the number of nodes* N *in a collocated topology.*

XmtHoldoffExponent, is kept the same for all mesh nodes, the expected transmission intervals are different for different nodes in our work, rather than the same as assumed in [12].

We would like to show the effectiveness of achieving QoS in a collocated scenario. For demonstration simplicity, all N nodes are equally partitioned into three priority classes, class i ($i = 1, 2, 3$). It is noted that the proposed model is very flexible for designing various priorities. Accordingly, we denote $[\alpha(i); \beta(i); \gamma(i); \lambda(i)]$ ($i = 1, 2, 3$) as the set of parameters for class i service. Each node belongs to a particular priority class exclusively. The following parameters are used for the three priority classes: $[\alpha(1); \alpha(2); \alpha(3)] = [2; 2; 2]$, $[\beta(1); \beta(2); \beta(3)] = [1.7; 2; 2.3]$, $[g(1); \gamma(2); \gamma(3)] = [1.7; 2; 2.3]$, and $[\lambda(1); \lambda(2); \lambda(3)] = [1; 2; 2]$. Figure 4 shows that class 1 has the shortest delay and class 3 the longest delay, implying the effectiveness of QoS differentiation and prioritization. We can assign class 1 for real-time applications with strict delay constraint (e.g., VoIP), class 2 for applications with flexible delay (e.g., HTTP), and class 3 for best effort applications (e.g., email). The comparison indicates that the proposed scheme is very effective for whatever number of nodes.

Next, let us evaluate the efficiency of parameters α, β, λ, and γ to differentiate QoS services. To examine the effect of α, we choose the following set of parameters for all three classes $\lambda = 2$, $\beta = 2$, and $\gamma = 2$. Figure 5a shows the insignificant contribution of α to QoS assurance. To study the effect of β, we choose $\alpha = 2$, $\beta = 2$, and $\gamma = 2$. Figure 5b demonstrates that β is also inefficient in achieving service differentiation for either small or large N. To see the effect of holdoff exponent λ, we choose $\alpha = 2$, $\beta = 2$ and $\gamma = 2$. Figure 5c indicates that the expected transmission interval $E(\tau)$ increases with λ. To examine the effect of holdoff base-value g, we choose $\alpha = 2$, $\lambda = 2$ and $\beta = 2$. Figure 5d shows that $E(\tau)$ also increases with γ. This is because, with a greater λ or γ, the holdoff transmission time *XmtHoldoffTime* becomes longer and consequently the transmission interval becomes larger. The comparison further indicates that the variations in holdoff exponent λ and holdoff base value γ can achieve service differentiation effectively for both small and large numbers of nodes N. The contribution of β or α is not as obvious as γ or λ to prioritize services.

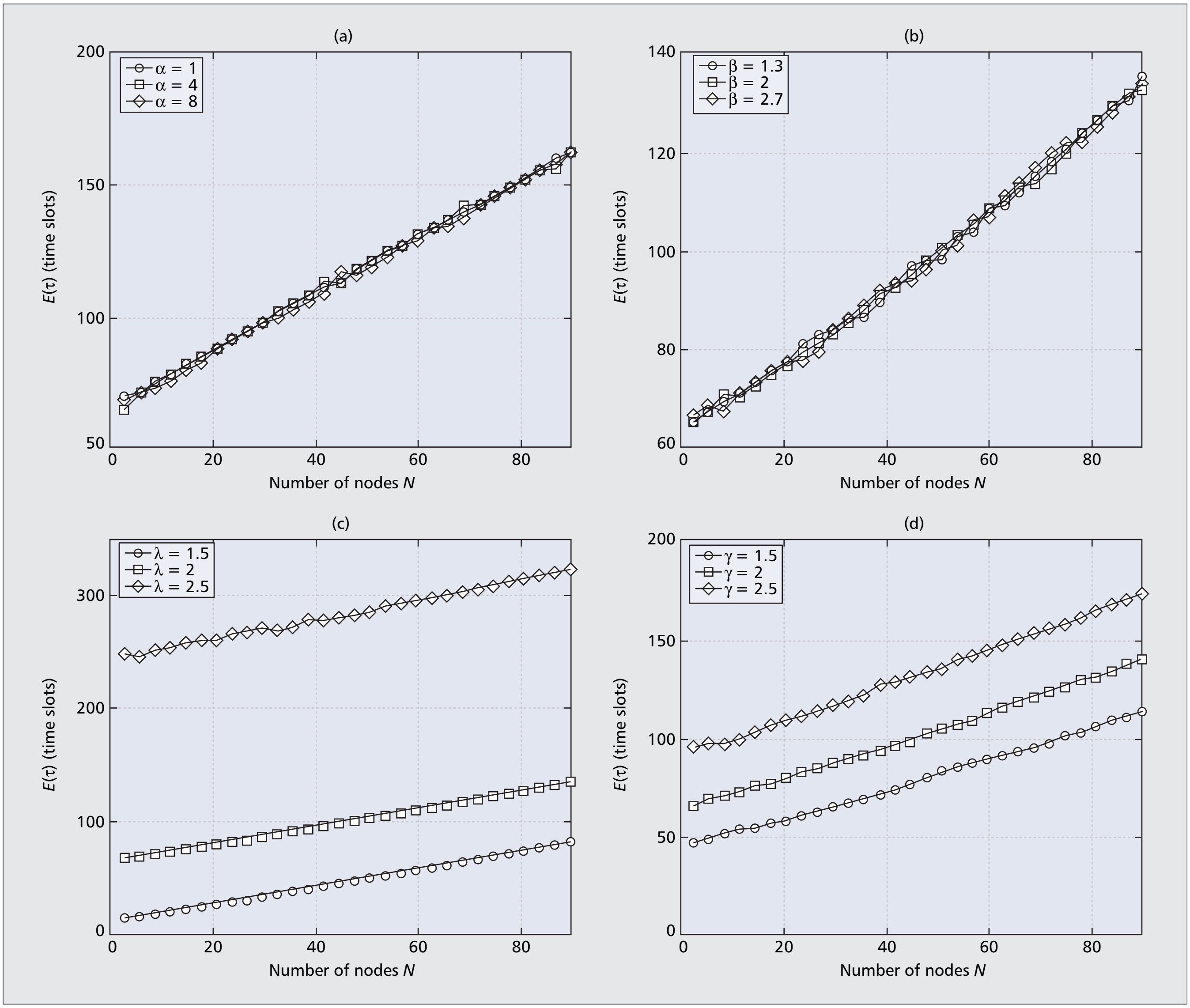
General Topology

In a general topology in a two-hop neighborhood, Φ_k of node k, we denote Φ_k^{known} and $\Phi_k^{unknown}$ as the sets of known nodes and unknown nodes, respectively. Then we have $\Phi_k = \Phi_k^{known} + \Phi_k^{unknown}$. Figure 6 shows an example of a general topology. In this example nodes 2, 3, 4, and 5 are the known nodes, whereas node 6 is unknown to node 1. By following a similar procedure as that used in the collocated scenario, the expected τ_k can be expressed as $(\beta_k)^{\lambda+4} + E(S_k)$. We can also develop the expression of $E(S_k)$, which takes into account the effects of both known and unknown nodes. In a general topology we need to obtain the set of unknown nodes for each node in the mesh network (i.e., the set $\Phi_k^{unknown}$ or, equivalently, Φ_k^{known}) for each node. However, the challenge is that this variable is dependent largely on the mesh network topology and specific protocols used in the network, such as routing algorithms. Different topologies or protocols may result in a significantly different set of unknown nodes for a particular node. Even if all nodes in the mesh network are fixed, the set $\Phi_k^{unknown}$ cannot be predefined as a constant. We take the node of interest k as an example to explain it in more detail. Normally, in a routing protocol the packets should not be broadcast too frequently to request for routing table updates in order not to generate too much network overhead. The broadcast is also employed in transmitting the MSH-DSCH scheduling message in a IEEE 802.16 mesh node to notify its neighborhood. This may lead to untimely delivery of the latest scheduling information to the two-hop neighborhood. In the MAC layer some nodes may experience unexpected collisions and have to delay their scheduling information transmissions. In such a case nodes with out-of-date scheduling information become unknown nodes of node k, while the underlying factors for the unknown nodes are actually not available. Hence, the set of unknown nodes $\Phi_k^{unknown}$ is varying. Furthermore, in a mesh network with mobility, the scenario becomes much more complicated due to the node's movement and frequent topology changes. This motivates us to analyze the issue from a probabilistic point of view to evaluate the scheduling performance in a general topology. In the following we study the characteristics of the set Φ_k unknown or equivalently Φ_k^{known}. The analytical framework is also applicable to a general topology.

Let $q_{k,j}^t$ be the probability that node j ($j \in \Phi$ and $j \neq k$) is an unknown node of node k ($k \in \Phi$) at instant t. If node j is either known or unknown to node k at instant t, node k is also the corresponding known or unknown node of node j. Hence, $q_{k,j}^t = q_{j,k}^t$. At instant t, $q_{k,j}^t$ and $q_{j,k}^t$ equal 1 if nodes k and j do not know each other; otherwise, they equal zero. A sufficiently long duration can be divided into very short time slots, the length of which is associated with the state of a node. The node state is unchanged during a time slot. Stochastically, we have $q_{k,j}^t = q_{j,k}^t$ after a network becomes stablized.

Based on the above discussion, we introduce a characteristics matrix, **Q**, to indicate the known or unknown states for each node in the mesh network. The kth row of matrix **Q** is given by $(q_{k,1}, q_{k,2}, \ldots, q_{k,k-1}, 0, q_{k,k+1}, \ldots, q_k, N)$, and the matrix **Q** is symmetric. Based on matrix **Q** in a general topology, the expected value of S_k and expected transmission interval of an MSH-DSCH message τ_k can be calculated. With the help of the introduced probabilistic model, which is general enough to be applied to other network topologies, we are able to theoretically investigate the scheduling performance in a random topology. For instance, in a collocated scenario the elements in matrix **Q** are given by $q_{k,j} = 1$ ($k \in \Phi$ and $j \neq k$).

Now, we investigate the effectiveness of the QoS differentiation scheme in general topologies. Again, all N nodes are assumed to be equally partitioned into three priority classes, class i ($i = 1, 2, 3$). Each node belongs to only one priority class exclusively. For easy comparison, the parameters are chosen as the same used in Fig. 4. The elements $q_{k,j}$ ($k = 1, 2, \ldots, N - 1$; $j = k + 1, \ldots, N$) in symmetric matrix **Q** are gener-



■ Figure 5. E(τ) *in terms of the number of nodes* N *with different parameters.*

ated from a uniformly distributed random process defined in {0, 1}. Figure 7 shows the results in the general topology, where each point in the curves is the result from an average value of 10,000 topologies.

Similar to the collocated scenario, the three service classes are well differentiated for networks of any size, or different N. Comparing the corresponding lines in the collocated topology and general topology, we can observe that $E(\tau)$ is smaller in the general topology than in the collocated topology. The results can be explained as follows. In the collocated topology, all nodes are competing with each other. On the other hand, in a general topology, some nodes are located far away from the range of the two-hop neighborhood and thus will not compete in the same time slot.

Discussion and Future Work

As illustrated in the previous section, the proposed QoS differentiation scheme is able to enhance the delay performance of an IEEE 802.16 mesh network. It is also noted that recently many new techniques developed for the physical layer network layers are being proposed for WMNs. For instance, cooperative transmission can be an effective way to improve the overall performance of a WMN in terms of its capacity, connectivity, and throughput [13]. Therefore, we would like to also discuss the possible integration of the proposed QoS differentiation scheme with cooperative transmission methods. Furthermore, to support a large number of nodes in a mesh network, scalability and fairness become two important issues. In this sense discussion of the scalability and fairness issues is significant and relevant to the framework of our proposed QoS differentiation scheme.

Cooperative Transmission

The inherent flexibility of WMNs and significant performance enhancement of cooperative transmission techniques motivate us to use them jointly to improve WMN performance. When cooperative strategies are applied to a WMN, each node shall consider not only itself but possible cooperation with other nodes during data transmission. There are several cooperative strategies that have been extensively studied. They include cooperative multiple-input multiple-output (MIMO) and cooperative coding/decoding, in which two or more nodes form a pair to transmit jointly. The selection of the node pair can be based on a variety of criteria, such as optimal orthogonal pairing channels, maximized achievable cooperative data rate, and location-based convenience. If cooperative transmission techniques are taken into account, the issues for the QoS

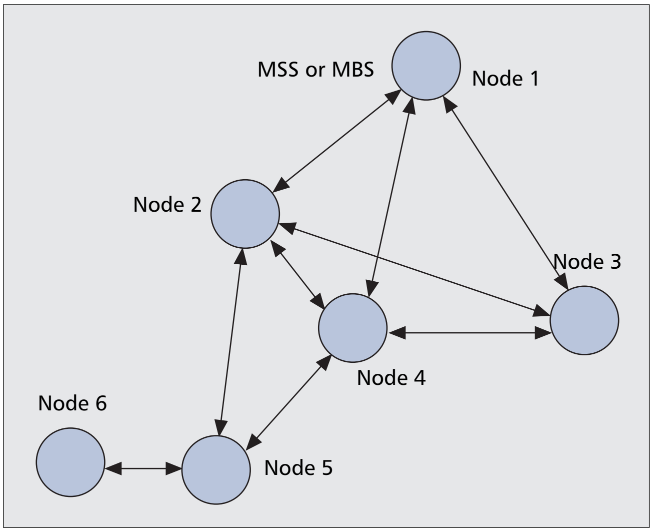


Figure 6. *An example of a general topology, where node 6 is an unknown node to nodes 1 and 3.*

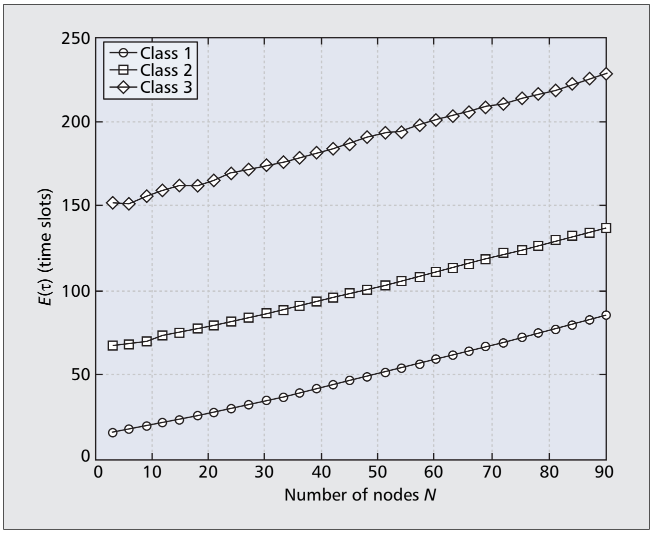


Figure 7. $E(\tau)$ *in terms of the number of nodes* N *in general topology.*

differentiation scheme becomes much more complicated. For instance, if a low-priority node is allowed to pair with another high-priority node, will it still have a chance to obtain high-priority service due to its higher-priority partner? Therefore, in WMNs with cooperative transmission, the priority assignment rule for distributed scheduling needs to take into account the properties of the node pair rather than those of a single node.

Similarly, the proposed QoS differentiation scheme should consider the node pair in cooperative transmission implementation. The expression of the expected τ_k, $E(\tau_k)$, needs to be modified since the number of competing nodes will change. One option is that QoS differentiation based on node pairs should be defined according to the weighted priority of node pairs or simply the higher-priority node in the pair. Alternatively, cooperative transmission may only take place among nodes within the same QoS class.

Scalability Problem

Implementing scalability becomes another important challenge in a WMN, since the network should be able to operate compatibly with both dense and sparse distributions of nodes. As indicated earlier, the presence of more nodes will result in a longer delay. In [14] the authors proposed a dynamic adaptation algorithm to reduce contention among nodes. The nodes are divided into MBSs, active nodes (ACTs), sponsoring nodes (SNs), and inactive nodes (IN-ACTs). Depending on the different node types and a contention indicator of the network, different *XmtHoldoffTime* values as well as their maximal values are specified. Based on this algorithm, contention is reduced, and the scalability problem for a dense WMN is alleviated.

The proposed QoS differentiation scheme in this article can be thought as a general extension to the work done in [14] since we consider three additional parameters to optimize QoS provisioning. Consequently, by introducing a contention indicator for QoS differentiation, we are able to effectively improve the scalability performance of a dense WMN. Furthermore, following the work carried out in [14], we can define different ranges, such as the maximum and minimum values, for the four parameters in the proposed QoS differentiation scheme. The ranges should be practical based on different QoS requirements for different types of nodes. However, how much gain we can obtain and how to optimize the performance in terms of the four parameters needs further investigation.

Fairness Issue

The scheduler used in WMNs should also consider fairness between nodes. The fairness criteria can be mainly categorized into allocation and data rate fairness over a predefined period of time [15]. The allocation fairness for a node concerns the total transmission chances, and the data rate fairness is relevant to accumulated throughput. When QoS differentiation is applied, both allocation fairness and data rate fairness between nodes of different QoS classes will be affected. For example, those nodes previously with the same QoS class will have different priorities after the QoS differentiation process. However, fairness between nodes of the same QoS class could be realized by using some proper scheduling algorithms, such as the proportional fair algorithm [16]. The PF algorithm could achieve a good trade-off between the fairness among nodes and total throughput of the network.

In this article we only analyze average delay performance without considering fairness among nodes in the proposed scheme. However, a pseudo-random election mechanism was employed during the distributed scheduling for the winning node when calculating the expected delay $E(\tau_k)$. Therefore, $E(\tau_k)$ is computed based on a round-robin scheduling algorithm, and the best allocation fairness is kept among nodes within the same QoS class. However, the data rate fairness issue has not been extensively discussed in this article and is left for our future work.

Conclusion

In this article we have proposed an effective QoS differentiation scheme for emerging IEEE 802.16 wireless MAN mesh networks. The illustrative results in this article have validated the effectiveness of the proposed strategy, indicating the interaction between the key parameters and performance metrics. Furthermore, it is shown that the proposed scheme can improve the scalability performance of WMNs. In this article several other relevant issues and potential performance-enhancing approaches are also discussed.

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