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A Simple and Effective QoS Differentiation Scheme in IEEE 802.16 WiMAX Mesh Networking

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Abstract— **Due to the inherent flexibility, scalability and reliability advantages of mesh networking architecture, the IEEE 802.16 working group is actively standardizing the mesh mode. Compared with the Point-to-MultiPoint (PMP) mode, the newly introduced mesh mode has not specified any solution for providing Quality-of-service (QoS) mechanisms in the literature. In this paper, we propose and analyze a simple and effective scheme achieving QoS differentiation in the WiMAX mesh networking mode. In addition, by taking account into the dynamics of networks topologies and also the variations of different protocols, we introduce a characteristics matrix for a mesh network from stochastic point of view. Based on the matrix, we develop a new formula for the performance metrics which enables the theoretical evaluation of a random topology. Illustrative numerical examples are presented to demonstrate the effectiveness of the proposed strategy, and also the impacts of the key parameters in differentiating the various services.**

Index Terms— **Wireless Mesh Networking, WiMAX, IEEE 802.16, QoS, Medium Access Control**

I. Introduction

Wireless Mesh Networking (WMN) is characterized by dynamic self-organization, self-configuration and self-correction to enable flexible integration, quick deployment, easy maintenance, low cost, high scalability and reliable services. Due to these advantages, WMN is believed to be a promising technology converging the future generation wireless mobile networks. Presently, the IEEE 802.16 working group targets designing a high-speed standard for fixed and mobile broadband wireless access. Owing to the attracting benefits of WMN, the version IEEE 802.16a introduced and defined the key operation procedures for the mesh networking mode [1] [2]. Recently, mobility is supported in the new version IEEE 802.16e, including the components supporting point-to-multipoint (PMP) and mesh modes, and seamless handover operation.

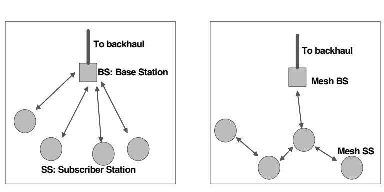

Fig. 1. PMP mode and mesh mode

Fig. 1 compares the PMP and mesh topologies. In PMP mode, a Base Station (BS) performs the centric role to coordinate and relay all communications. The Subscriber Station (SS) under the management of the BS has to communicate with BS first before transmitting data with other SSs. This architecture is similar to the cellular networks. Unlike the PMP mode, there are no clearly separate downlink and uplink in the mesh mode. Every SS can directly communicate with its neighbors without the help of BS. In typical installation, one or several nodes play the role as BS to connect the mesh network to the external backhaul link, e.g. Internet or telecommunication networks. Such nodes are called as Mesh BS while the other nodes are accordingly called as Mesh SS. In IEEE 802.16 PMP mode, the standard defines connection-based four QoS classes [1] [2]: Unsolicited Grant Service (UGS), Real-time Polling Service (rtPS), Non-real-time Polling Service (nrtPS) and Best Effort (BE). Recently, several studies have proposed various QoS differentiation schemes in the PMP mode [3] [4].

Comparatively, for mesh mode, no similar terms or schemes for QoS have been defined. In this paper, we will fill this void by proposing a new scheme achieving QoS differentiation for different services. Another contribution is the proposed analytical framework from the stochastic and probabilistic perspective, which enables the theoretical investigation for a random topology.

II. IEEE 802.16 Mesh Mode

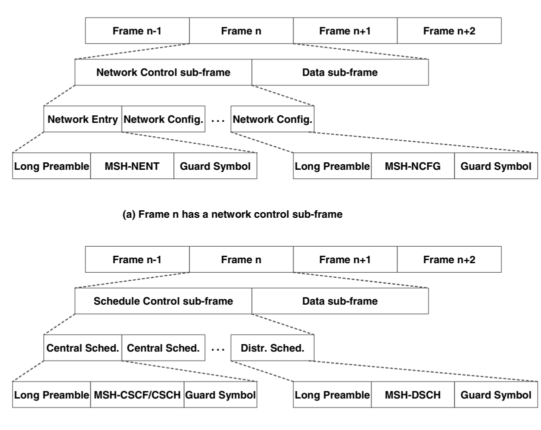

Fig. 2. Frame structure in mesh mode in IEEE 802.16.

Fig.2 shows the frame structure in mesh mode. A frame consists of control sub-frame and data sub-frame. The length of the control sub-frame is fixed as MSH-CTRL-LEN $\times$ 7 OFDM symbols, where the parameter MSH-CTRL-LEN has 4 bits (i.e. value ranges between 0 to 15) and is advertised in the structure `Network Descriptor`. The data sub-frame is divided into minislots. Fig.2 illustrates two control sub-frames, the Network Control sub-frame in case (a) and Schedule Control sub-frame in case (b). The occurrence of Network Control sub-frame is periodically with the period indicated in the `Network Descriptor`. The Schedule Control sub-frame occurs in all other frames without Network Control sub-frame. In particular, the field `Scheduling Frame` in the `Network Descriptor` defines the number of frames having a Schedule Control sub-frame between two frames with Network Control sub-frame in multiples of 4 frames.

The Network Control sub-frame is defined primarily for new nodes gaining synchronization and joining a mesh network. The first transmission opportunity is the network entry component carrying the information of Mesh Network Entry message MSH-NENT. The remaining (MSH-CTRL-LEN - 1) transmission opportunities are the network configuration components carrying the information of Mesh Network Configuration message MSH-NCFG. The length of each transmission opportunity accounts for 7 OFDM symbols; and hence the length of the transmission opportunities carrying MSH-NCFG is equal to (MSH-CTRL-LEN - 1) $\times$ 7 OFDM symbols. The Schedule Control sub-frame is defined for centralized or distributed scheduling the sharing nodes in a common medium. Indicating in `Network Descriptor`, there are MSH-DSCH-NUM number of Mesh Distributed Scheduling messages MSH-DSCH. This implies that the first (MSH-CTRL-LEN - MSH-DSCH-NUM) $\times$ 7 OFDM symbols are allocated for transmitting the Mesh Centralized Scheduling message MSH-CSCH and Mesh Centralized Configuration message MSH-CSCF. The data sub-frame serves the PHY transmission bursts. The PHY bursts starts with a long preamble (2 OFDM symbols) serving for synchronization, immediately following by several MAC PDUs.

III. Distributed Scheduling

In mesh mode, the transmission opportunities in the control sub-frame and the minislots in the data sub-frame are separated. Each node competes the control channel access. The contention consequence in the control sub-frame does not have effect on the data transmission during the data sub-frame of the same frame. Hence, the contention process in the control sub-frame shall be elaborated for deriving the interested performance metrics.

In the distributed scheduling, Mesh Distributed Scheduling MSH-DSCH message plays a significant role in the whole scheduling process. A MSH-DSCH message carries the following fields: 1) the `Availabilities IE` indicating the starting frame number, the starting minislot within the frame and the number of available minislots for the granter to assign; 2) `Scheduling IE` showing the next MSH-DSCH transmission time `NextXmtTime` and `XmtHoldoffExponent` of the node and also its neighbor nodes; 3) `Request IE` having the resource demand of the node; 4) `Grants IE` conveying the granted starting frame number, the granted starting minislot within the frame and the granted minislots range. The message MSH-DSCH in coordinated distributed scheduling occurs in control sub-frame. Distributed election scheduling is defined to determine the next transmission time `NextXmtTime` of a node's MSH-DSCH during its current transmission time `XmtTime`.

There are two fields `NextXmtMx` and `XmtHoldoffExponent` in MSH-NCFG to determine the next eligibility interval $2^{\texttt{XmtHoldoffExponent}} \cdot \texttt{NextXmtMx} < \texttt{NextXmtTime} \leq 2^{\texttt{XmtHoldoffExponent}} \cdot (\texttt{NextXmtMx} + 1)$. Clearly, the length of the eligibility interval is equal to $2^{\texttt{XmtHoldoffExponent}}$. The node can transmit in any slot during this interval. After the eligibility interval and right before a new transmission, the node has to wait a holdoff time $\texttt{XmtHoldoffTime} = 2^{\texttt{XmtHoldoffExponent}+4}$. 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 $\mathcal{S}_{cmpt}$ competing this slot `TempXmtTime`. The set of eligible competing nodes $\mathcal{S}_{cmpt}$ includes all nodes in the extended neighborhood satisfying either of the following property: 1) the `NextXmtTime` includes `TempXmtTime`; 2) the `EarliestSubsequentXmtTime`, which is equal to the summation of `NextXmtTime` and `XmtHoldoffTime`, occurs no later than the `TempXmtTime`; 3) the `NextXmtTime` is unknown. After the building of set $\mathcal{S}_{cmpt}$ for the 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 the neighbors in the MSH-NCFG message. Otherwise, the specific node is failed in competing this slot. The node will set the `TempXmtTime` as the next transmission slot and repeats the similar competing procedures until it wins.

IV. Proposed QoS Scheme

For different services, the MSH-DSCH transmission interval should be different. For instance, real-time Voice-over-IP should experience short transmission interval while non-real-time email service could tolerate long transmission interval. In this section, we propose a scheme to prioritize various traffics and enable the QoS differentiation.

Firstly, the eligibility interval and its length are generalized. For the sake of presentation, we denote $x = \texttt{XmtHoldoffExponent}$ as the transmission holdoff exponent. The original base-value 2 is generalized into a real number α in determining the eligibility interval and the length of this interval. It is noteworthy that the parameter generalization of the base-value is from the fixed integer number 2 to a real number, instead of a general integer number. This shall clearly introduce more flexibility. Consequently, the eligible next transmission time NextXmtTime becomes

$$\alpha^x \cdot \texttt{NextXmtMx} < \texttt{NextXmtTime} \leq \alpha^x \cdot (\texttt{NextXmtMx} + 1) \quad (1)$$

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 V is given by the difference between the lower bound and the upper bound as

$$V = \alpha^x \quad (2)$$

Secondly, we introduce another real-time base-value β and holdoff exponent y to determine transmission holdoff time XmtHoldoffTime H. Then, H is given as

$$H = \beta^{y+4} \quad (3)$$

We denote the set of QoS differentiated parameters for a node as $\mathcal{P} = (\alpha, x, \beta, y)$. For different node in a mesh network, $\mathcal{P}$ shall be different.

Suppose there are N nodes in the mesh network. Let $\mathcal{N}$ represent the set of all nodes. For a particular node k ($k \in \mathcal{N}$), the set of parameters is according denoted as $\mathcal{P}_k = (\alpha_k, x_k, \beta_k, y_k)$. Let S_k denote the number of slots in which the node k fails during the distributed election scheduling before it wins. Denote τ_k as the interval between two consecutive MSH-DSCH transmission opportunities. Then, in terms of time slot, τ_k is the summation of the holdoff transmission time H_k and S_k.

$$E(\tau_k) = H_k + E(S_k) = (\beta_k)^{y_k+4} + E(S_k); \quad k \in \mathcal{N} \quad (4)$$

where $E(X)$ represents the expected value of a non-negative random variable X. We consider two scenarios: collocated scenario and general topology.

A. Collocated Scenario

The collocated scenario, i.e. all nodes are one-hop neighbors of each other, is considered to indicate the effectiveness of the proposed QoS scheme. Denote $M_k(s)$ as the expected number of nodes competing with the specific node k during the slot s. Denote $P_k(j; s)$ as the probability that the node j competes with the node k in the slot s. Then,

$$M_k(s) = \sum_{j=1, j\neq k}^{N} P_k(j; s) + 1. \quad (5)$$

Denote $p_k(s)$ as the probability the node k wins the slot s in the pseudo-random election algorithm. Due to the randomness property of the election algorithm, this probability is given by

$$p_k(s) = \frac{1}{M_k(s)} = \frac{1}{\sum_{j=1, j\neq k}^{N} P_k(j; s) + 1}. \quad (6)$$

After considering the conditional probability above on $S_k = s$, we are able to express p_k as

$$\frac{1}{p_k} = E_{S_k}[M_k(s)] = \sum_{j=1, j\neq k}^{N} E_{S_k}[P_k(j; s)] + 1. \quad (7)$$

Following the similar technique in [5] by accounting the nodes competing the node k in a specific slot, the item $E_{S_k}[P_k(j; s)]$ in the above equation is expressed as

$$E_{S_k}[P_k(j; s)] = \begin{cases} \frac{V_j + E(S_k)}{H_j + E(S_j)}, & H_j \geq H_k; \\ 1, & H_j < H_k. \end{cases} = \begin{cases} \frac{(\alpha_j)^{x_j} + E(S_k)}{(\beta_j)^{y_j+4} + E(S_j)}, & H_j \geq H_k; \\ 1, & H_j < H_k. \end{cases} \quad (8)$$

Combining (7) and (8), we obtain the expected value of S_k as

$$E(S_k) = \sum_{j \in \mathcal{N} - \{k\}} \left[\frac{(\alpha_j)^{x_j} + E(S_k)}{(\beta_j)^{y_j+4} + E(S_j)} \cdot \mathbf{1}_{H_j \geq H_k} + \mathbf{1}_{H_j < H_k} \right] + 1; \quad k \in \mathcal{N} \quad (9)$$

where the indicator function $\mathbf{1}_X$ equals to 1 in case the event X is true, zero otherwise. Since each $E(S_k)$ is related to the other $E(S_j); (j \in \mathcal{N})$, a fixed point algorithm should be employed [6]. Substituting (9) into (4), we are able to compute the expected transmission interval of MSH-DSCH messages for any $k \in \mathcal{N}$,

$$E(\tau_k) = (\beta_k)^{y_k+4} + \sum_{j \in \mathcal{N} - \{k\}} \left[\frac{(\alpha_j)^{x_j} + E(S_k)}{(\beta_j)^{y_j+4} + E(S_j)} \cdot \mathbf{1}_{H_j \geq H_k} + \mathbf{1}_{H_j < H_k} \right] + 1. \quad (10)$$

B. General Topology

In a general topology, among the two-hop neighborhood $\mathcal{N}_k$ of the node k, we denote $\mathcal{N}_k^{known}$ and $\mathcal{N}_k^{unknown}$ as set of known nodes and unknown nodes. Then, $\mathcal{N}_k = \mathcal{N}_k^{known} + \mathcal{N}_k^{unknown}$. Following the similar reasoning leading to (9) in a general topology, the expected value of S_k is given by

$$E(S_k) = \sum_{j \in \mathcal{N}_k^{known} - \{k\}} \left[\frac{(\alpha_j)^{x_j} + E(S_k)}{(\beta_j)^{y_j+4} + E(S_j)} \cdot \mathbf{1}_{H_j \geq H_k} + \mathbf{1}_{H_j < H_k} \right] + |\mathcal{N}_k^{unknown}| + 1; \quad k \in \mathcal{N} \quad (11)$$

where $|\cdot|$ denotes the number of elements in a set. Similarly, a fixed point algorithm shall be employed since each $E(S_k)$ is related to the other $E(S_j); (j \in \mathcal{N} - \{k\})$. The expected transmission interval of MSH-DSCH message τ_k is given by

$$E(\tau_k) = (\beta_k)^{y_k+4} + E(S_k); \quad k \in \mathcal{N} \quad (12)$$

where $E(S_k)$ is given in (11). It is observed that, to apply the formulae (11) (12) for a general topology, we need to obtain the set of unknown nodes for each node in the mesh network, i.e. the set $N_k^{unknown}$ (or equivalently N_k^{known} ($k \in \mathcal{N}$)) for each node. However, the challenge is that this variable is highly dependent on the mesh network topology and additionally the specific protocols in the network such as routing algorithms. Different topologies or protocols may result in significantly different set for a particular node. Even if all nodes in the mesh network are fixed, the set $\mathcal{N}_k^{unknown}$ can not be pre-defined as a constant. We take the node of interest k as an example to explain the reasons. Normally, in routing protocol, the packets requesting the routing table update employ broadcast technique and shall not be sent out too frequently in order to decrease network overhead. The broadcast method is also employed in transmitting the MSH-DSCH scheduling message in the WiMAX mesh node to notify its neighborhood. This may lead to the latest scheduling information untimely delivering to the two-hop neighborhood. In MAC layer, some nodes may experience unexpected collisions and have to delay their scheduling information transmission. In such case, the nodes with out-of-date scheduling information becomes the unknown nodes of the node k while the underlying factors for the unknown nodes are actually not available. Hence, the set of the unknown nodes $N_k^{unknown}$ is varying. Furthermore, in case of mesh networks with mobility, the scenario becomes much more complicated due to the node's free movement and frequent topology changes. This motivates our analysis from the stochastic and probabilistic point of view to evaluate the scheduling performance in a general topology. In the following, we will study the underlying characteristics related to the set $N_k^{unknown}$ or equivalently N_k^{known}. The analytical framework is applicable in a general topology.

Let $q_{k,j}^t$ denote as the probability that the node j ($j \in \mathcal{N} - \{k\}$) is an unknown node of the node k ($k \in \mathcal{N}$) at the instant t. Moreover, at the instant t, if the node j is either known or unknown node of the node k, the node k is also the corresponding known or unknown node of the node j. Hence, $q_{k,j}^t = q_{j,k}^t$. At the instant t,

$$q_{k,j}^t = q_{j,k}^t = \begin{cases} 1, & \text{nodes } k \text{ and } j \\ & \quad \text{don't know each other at time t} \\ 0, & \text{otherwise.} \end{cases}$$

For a sufficiently long duration T, it is divided into very short time slots, the length of which is subject to the unchanged unknown or known state of a node. That is, during a time slot, the node state is regarded as unchanged. Let Δ denote the length of a time slot. We define $q_{k,j}^i$ as the probability that the node k does not know the node j during the slot i, i.e. in the duration $((i-1)\Delta, i\Delta)$.

$$q_{k,j}^i = q_{j,k}^i = \begin{cases} 1, & \text{nodes } k \text{ and } j \\ & \quad \text{don't know each other in slot i} \\ 0, & \text{otherwise.} \end{cases}$$

Stochastically, the node j ($j \in \mathcal{N} - \{k\}$) has the probability $q_{k,j}$ as an unknown node of the node k ($k \in \mathcal{N}$) in a long run. Then,

$$q_{k,j} = \lim_{T \to \infty} \frac{\sum_{i=1}^{\infty} q_{k,j}^i}{T} \tag{13}$$

Based on the reasoning above, we have $q_{k,j} = q_{j,k}$. Define the column vector $\mathbf{q}_k$ as

$$\mathbf{q}_k = (q_{k,1}, q_{k,2} \cdots, q_{k,k-1}, 0, q_{k,k+1} \cdots, q_{k,N}) \tag{14}$$

We introduce the characteristics matrix, $\mathbf{Q}$, to indicate the known or unknown situations for each node in the mesh network.

$$\mathbf{Q} = (\mathbf{q}_1, \mathbf{q}_2, \cdots, \mathbf{q}_N)^T = \begin{pmatrix} 0 & q_{1,2} & q_{1,3} & \cdots & q_{1,N} \\ q_{2,1} & 0 & q_{2,3} & \cdots & q_{2,N} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ q_{N,1} & q_{N,2} & q_{N,3} & \cdots & 0 \end{pmatrix} \tag{15}$$

where $q_{i,j} = q_{j,i}$ and hence the matrix $\mathbf{Q}$ is a symmetric matrix. Based on the matrix $\mathbf{Q}$ in a general topology, the expected value of S_k and the expected transmission interval of MSH-DSCH message τ_k are given by

$$E(S_k) = \sum_{j \in \mathcal{N}_k - \{k\}} (1 - q_{k,j}) \left[\frac{(\alpha_j)^{x_j} + E(S_k)}{(\beta_j)^{y_j+4} + E(S_j)} \cdot \mathbf{1}_{H_j \geq H_k} + \mathbf{1}_{H_j < H_k} \right] + \sum_{j \in \mathcal{N}_k - \{k\}} q_{k,j} + 1; \quad k \in \mathcal{N} \tag{16}$$

$$E(\tau_k) = (\beta_k)^{y_k+4} + E(S_k); \quad k \in \mathcal{N} \tag{17}$$

Due to the introduced probabilistic significance, the developed result has the advantage of general applicability. In addition, by supposing the elements in the matrix, we are able to theoretically investigate the scheduling performance in random topologies. In collocated scenario, the elements in the matrix $\mathbf{Q}$ is given by

$$q_{k,j} = 1; k \in \mathcal{N} \text{ and } j \neq k \tag{18}$$

Substituting the above result (18) into (16), we obtain the same expression as (10). This is able to indicate the general applicability and flexibility of the developed analytical framework.

V. Numerical Results

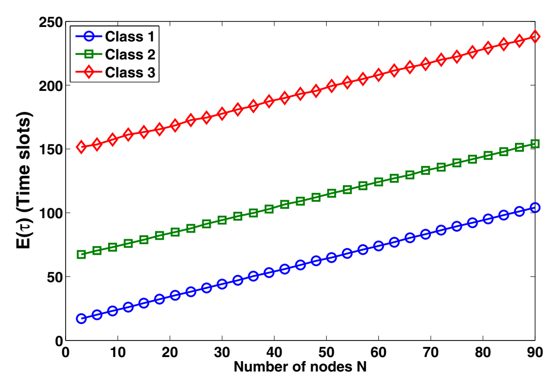

Fig. 3. $E(\tau)$ in terms of the number of nodes N in collocated topology

We first show the effectiveness of achieving QoS in collocated topology. For demonstration, all N nodes are equally partitioned into three priority classes, i.e. class-i ($i = 1, 2, 3$). It is noteworthy that the proposed model is very flexible for designing various priorities. Accordingly, we denote $(\alpha^{(i)}, x^{(i)}, \beta^{(i)}, y^{(i)}); (i = 1, 2, 3)$ as the set of parameters

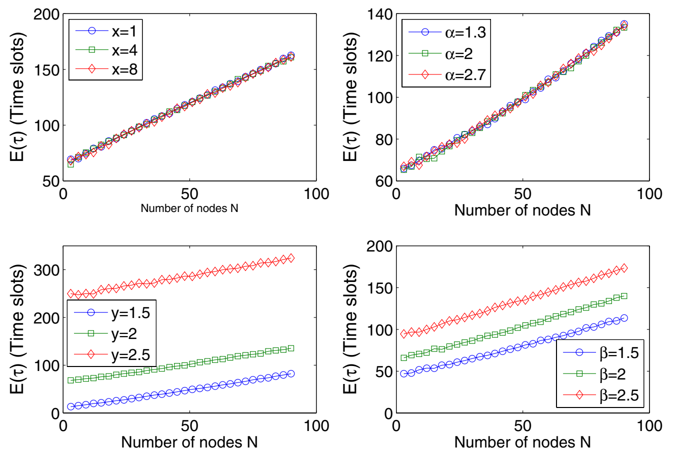

Fig. 4. $E(\tau)$ in terms of the number of nodes N with different parameters

for class-i priority. Each node belongs to one or the other priority class exclusively. The following parameters are used for the three priority classes: $[\alpha^{(1)}, \alpha^{(2)}, \alpha^{(3)}] = [1.7, 2, 2.3]$, $[\beta^{(1)}, \beta^{(2)}, \beta^{(3)}] = [1.7, 2, 2.3]$, $[x^{(1)}, x^{(2)}, x^{(3)}] = [2, 2, 2]$, $[y^{(1)}, y^{(2)}, y^{(3)}] = [1, 2, 2]$. Fig. 3 shows that the class 1 has the smallest delay and the class 3 has the largest delay, which implies the effectiveness of the QoS differentiation and prioritization. One application is to use the class 1 for real-time applications with strict delay constraint (e.g. Voice over IP), class 2 for applications with flexible delay (e.g. HTTP) and the class 3 for best-effort applications (e.g. email). The comparison indicates that the proposed scheme is very effective in the scenarios when the number of nodes is either small or large.

It is helpful to evaluate the efficiency of x, α, y and β to differentiate services. To exam the effect of x, we choose the following set of parameters for all three classes: $y = 2$, $\alpha = 2$ and $\beta = 2$. Fig. 4 (top-left subfigure) shows the insignificant contribution of x on the QoS achievement. To exam the effect of α, we choose: $x = 2$, $\beta = 2$ and $y = 2$. Fig. 4 (top-right subfigure) demonstrates that α is also inefficient achieving service differentiation for either small or large N. To exam the effect of holdoff exponent y, we choose: $x = 2$, $\alpha = 2$ and $\beta = 2$. Fig. 4 (bottom-left subfigure) indicates that the expected transmission interval $E(\tau)$ increases with larger y. To exam the effect of holdoff base-value β, we choose: $x = 2$, $y = 2$ and $\alpha = 2$. Fig. 4 (bottom-right subfigure) shows that $E(\tau)$ increases with larger β. This is because, with greater y or β, the holdoff transmission time `XmtHoldoffTime` becomes longer and consequently the larger transmission interval. The comparison further indicates that the variations of holdoff exponent y and holdoff base-value β can achieve service differentiation effectively for both small and large number of nodes N. The contribution of α or x is not as efficient as β or y to prioritize services.

Now, we investigate the effectiveness of the QoS differentiation scheme in general topologies. Similarly, all N nodes

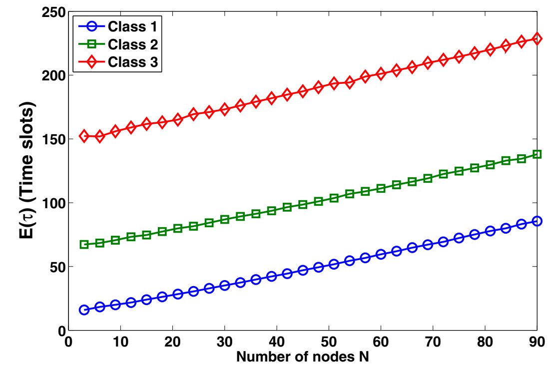

Fig. 5. $E(\tau)$ in terms of the number of nodes N in general topology

are equally partitioned into three priority classes, i.e. class-i ($i = 1, 2, 3$). Each node belongs to one or the other priority class exclusively. For the sake of comparison, the parameters are same as the Fig. 3. The elements $q_{k,j}$ ($k = 1, 2, \cdots, N-1; j = k+1, \cdots, N$) in the symmetric matrix $\mathbf{Q}$ are generated as uniform distributed in (0,1). This shall be regarded as a general scenario and could provide a illustrative result. Fig. 5 shows the results in the general topology. Each point in the curves is the average value of 10000 topologies. Similar as the collocated scenario, the three service classes are well differentiated with either small or large N. Furthermore, comparing the corresponding lines in the collocated topology and the general topology, we can observe that $E(\tau)$ is smaller in the general topology. The reason is as follows. In collocated situation, all nodes are competing with each other. In a general situation, some nodes locates away from the range of two-hop neighborhood and will not compete.

VI. Conclusion

In this paper, we proposed a simple and effective QoS differentiation scheme for the emerging Wireless MAN standard IEEE 802.16 mesh networking. The results have validated the effectiveness of the proposed strategy and illustrated the interaction between the primary parameters and the performance metrics.

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