A Distributed Scheduling Algorithm with QoS Provisions in Multi-Hop Wireless Mesh Networks

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***Abstract*—Multi-hop wireless mesh networks (WMNs) are considered a promising technology to backhaul heterogeneous data traffic from wireless access networks to the wired Internet. WMNs are expected to support various types of applications with diverse quality of service (QoS) requirements, such as end-to-end packet delay, throughput, and packet-error-rate (PER). Recent works in this area are mainly concentrated on network layer routing algorithms with QoS provisioning that unfortunately cannot cooperate efficiently with existing medium access control (MAC) solutions to strictly guarantee multiple QoS constraints. This drawback may significantly deteriorate the end-to-end network performance and end-user experience especially for delay/throughput-sensitive applications such as voice-over IP (voIP) and interactive video. In this paper, we propose a fully distributed multi-constrained QoS scheduling algorithm to overcome this disadvantage. We show by simulation that the proposed scheduling scheme can efficiently organize the resources in physical (PHY) and MAC layers to successfully increase the network goodput, decrease the end-to-end (ETE) packet delay, and achieve less QoS outage probability if compared with other protocols.**

I. INTRODUCTION

Multi-hop wireless mesh networks (WMNs) can be used as a way to provide users with backhaul access to the wired Internet [1]. They are expected to gradually substitute parts of the wired network infrastructures by being able to provide quick and efficient solution for wireless data networking in urban, suburban, and rural environments. A WMN is usually composed of static wireless nodes/mesh routers (WMR) with ample energy supply. Each node operates not only as a conventional access point/Internet gateway to the internet but also as a wireless router able to relay packets from other nodes without direct access to their destinations. WMNs have many features that attracted both the academic and industrial interest. Such features include strict packet delay constraints and various throughput and packet-error-rate (PER) requirements that have to be guaranteed for applications such as voice-over IP (voIP), interactive video, and neighborhood gaming etc.

Recently, several network layer solutions have been proposed that mainly focus on multi-constrained QoS routing algorithms [2], [3]. However, no matter how the routing protocol is individually optimized the lack of cooperation with lower layers can highly degrade the overall performance. Scheduling for wireless mesh networks has been well studied, especially within the area of centralized scheduling algorithms [4], [5], [6]. However, the fact that the optimum decision of such centralized algorithms is an NP-complete problem, makes their applicability inappropriate for large scale networks. On the other hand, opportunistic scheduling has been proven a promising technology enabler to increase network throughput since it can take advantage of the multi-user diversity and the dynamic nature of the wireless channel. For instance, the distributed, proportional-fair scheduler proposed in [7], [8] can achieve network throughput improvement close to optimum. However, such proportional fair schemes come with a certain drawback, i.e., while they maximize the overall network throughput they cannot perform the hard resource reservations required to provide strict QoS. This has as a result an increased outage probability of the ongoing QoS flows. Therefore, it is of paramount importance the design of MAC protocols that can cooperate efficiently and effectively with higher layers to guarantee QoS while at the same time they exploit the PHY channel characteristics to enhance the network throughput.

These are primarily why in this paper we are aiming to devise a fully distributed multi-constrained QoS scheduling algorithm in WMNs that tries to exploit multi-user diversity gain in wireless environments with multiple strict QoS provisions. We propose a novel concept of link QoS utility in terms of both channel quality and network congestion to overcome the potential performance degradation. This utility captures the effects of all three QoS constraints, real-time PHY channel quality, and MAC queue status, to achieve a near-optimal scheduling decision. Moreover, we propose a distributed framework for such scheduling algorithm.

II. RELATED WORK

Scheduling for wireless mesh networks has drawn a lot of research attention recently. However, existing scheduling algorithms do not fit the backhaul features very well for either centralized or distributed algorithms.

Centralized scheduling algorithms [4], [5], [6] are based on graph theory. These methods assume that there is a central controller having full knowledge about all links in the network. They find the optimal set of non-overlapping links, i.e., a perfect matching with the highest total throughput of the graph. However, it has been proved [9], [10] that to find such an optimal link set in the graph is NP-complete, thus not feasible in large-scale backhaul networks. On the other hand, several distributed scheduling works have been done.

The distributed coordination function (DCF) with the request-to-send (RTS) and clear-to-send (CTS) mechanism proposed in IEEE 802.11 ad hoc mode [11] is commonly used as the MAC protocol in wireless ad-hoc networks. Since the protocol is to select the active transmission, it has been used as a candidate scheduling algorithm for backhaul applications. The election-based scheduling algorithm that specified in the IEEE 802.16 standard [12] is another scheduling scheme. Both 802.11 and 802.16 scheduling algorithms are distributed and collision free. However, due to the completely random link selection, neither of the algorithms takes advantage of multi-user diversity in wireless environments, nor multi-QoS provisions are provided. Another scheduling technique for multi-hop mesh networks has been proposed in [13], referred to as the tree structure that maps the backhaul network into a tree. The main shortcoming of the this method is that the tree mapping only considers part of the network links as scheduling candidates, and misses some "horizontal links" between nodes closely located but mapped into different branches. Furthermore, proportional fair scheduling (PFS, [14], [15], [16]) algorithms have been widely conceived as an attractive solution since it provides a good compromise between the maximum throughput and user fairness by exploiting multi-user diversity and game-theoretic equilibrium in fading wireless environment. Work in [7], [8] is a most recent extension of PFS to provide throughput-allocation with proportional fairness among neighboring links.

To overcome the difficulties of providing strict multi-constrained QoS provisions in WMNs, we propose a distributed scheduling algorithm with multi-QoS constraints for delay and throughput sensitive applications. Our major contribution is threefold,

- We provide a new link QoS utility taking into account multiple QoS constraints in a unified approach, trying not to violate any delay constraints while exploiting opportunistic nature of wireless channel for good throughput link with less packet loss.
- We propose a distributed framework of performing scheduling decisions by using defined link QoS utility, to secure ETE QoS requirements will not be violated.
- We successfully achieve best overall performances in terms of higher network goodput, less average packet delay and QoS outage probabilities, compared with benchmark protocol like round robin and recent proposed scheduling algorithms.

The rest of the paper is organized as follows. PHY and link layer model is introduced in Section III. Section IV describes the multi-constrained QoS scheduling utility for each link. Section V provides a thorough description of the proposed distributed QoS scheduling framework. Extensive simulation results are given in Section VI. Finally, we make conclusions in Section VII.

III. PHY AND LINK LAYER MODEL

Consider a wireless mesh network which comprises a set of n_r number of wireless mesh routers, denoted as $V_R = \{v_r | r = 1, 2, \ldots, n_r\}$ and a set of n_g number of gateways denoted as $V_G = \{v_g | g = 1, 2, \ldots, n_g\}$. QoS flow with index q is generated with a set of constraints, ETE packet delay D_q^r, throughput T_q^r and PER E_q^r. If further consider an arbitrary node i, it has K_i number of one-hop neighbors within fixed transmission range, where these neighbors are $k = 1, 2, ..., K_i$. Meanwhile, a separate queue is attached to each mesh router for each direction of transmission, and multi-hop packets are queued into a specific queue according to pre-found routing sequence.

The network runs under a time-division multiple access (TDMA) slotted framework, and we assume all nodes are perfectly synchronized. The time frame consists of f_d fixed-size time slots for data, and f_c fixed-size time slots for control messages. During the period of one time frame, we assume block fading channel that remains relatively constant. Scheduling decisions are taken by all nodes in the network simultaneously at the beginning of each time frame at the control phase, and stay unchanged until the next frame. The PHY layer employs the adaptive modulation and coding techniques (AMC), where there are a finite number V of transmission modes, each of which corresponds to a unique modulation and coding scheme and one particular interval of the received signal to interference plus noise ratio (SINR). The transmission rate at each mode is proportional to its spectral efficiency, i.e., transmission mode v can transmit maximum c_v packets in one time slot, where $v = 1, 2, ..., V$, or $H = f_d c_v$ packets in a time frame. Furthermore, in order to reduce the interference to adjacent concurrent transmissions, increase the frequency reuse and channel capacity, the nodes are equipped with directional antennas.

IV. QOS SCHEDULING UTILITY

The aim of our distributed QoS scheduling algorithm is to provide strict multi-QoS constraints at link level by each node i, $\forall i \in V_R$. In order to facilitate the integration of three constraints, we define a set of link-level metrics, namely, (1) link delay outage $\mathbf{R}_{ik}^D$, (2) link throughput outage $\mathbf{R}_{ik}^T$, and (3) link PER outage $\mathbf{R}_{ik}^E$, as follows.

A. Link delay outage

$\mathbf{R}_{ik}^D$ is defined for the ratio between average monitored queuing and transmission delays, D_{ik}^a, during the past frame for link (i, k), and the maximum *residual* delay requirements of all packets queued. This is because in the multi-hop wireless network, any queued packet j has already suffered some queuing and transmission delays in previous hops, and an efficient scheduler would count in this delay before making scheduling decision. We denote this as D_j^p. Suppose the packet has h_j^s hops to go towards the gateway, and due to the distributed nature of such scheduler, node i is not aware of delay statistics in the following hops, we use the average "residual delay requirement" per hop, D_j^s, to characterize this more strict packet delay requirement, which must not be violated in the following hops, as,

$$D_j^s = \frac{D_j^r - D_j^p}{h_j^s} \tag{1}$$

Remind that the f_d is the scheduling period, during which the scheduling decision remains the same, and thus all packets queued in buffer (i,k) could potentially be scheduled, and should be taken into account to further secure QoS. Let Q denotes this packet transmission set whose length $|Q|$ is calculated as the minimum of transmission capacity H_k on link (i,k), and current queue length q_k, as $|Q| = \min(H_k, q_k)$. This means that maximum $|Q|$ packets could be transmitted in direction (i,k) during the time frame.

Hence, taking into consideration of the definition of link delay outage introduced, "residual delay requirement", and most strict requirements of all queued packets, we could express $\mathbf{R}^D_{ik}$ as,

$$\mathbf{R}^D_{ik} = \frac{D^a_{ik}}{\min_{\forall j \in Q} D^s_j} \leq 1 \tag{2}$$

where the denominator is the minimum average "residual delay requirements" per hop value among all queued packets. For any successful scheduler should this outage be less or equal than one.

B. Link throughput outage

$\mathbf{R}^T_{ik}$ is introduced for link throughput outage, as the maximum throughput requirement among all queued packets in set Q, over the estimated instantaneous data rate T^a_{ik}. At time frame t, the link instantaneous data rate is predicted by using Shannon capacity through sending out pilot symbols in the control channel and measuring receiving signal to noise ratio (SNR) γ_t, i.e.,

$$T^a_{ik} = W \log(1 + \beta_t \gamma_t) \tag{3}$$

where W is the system bandwidth, and β_t captures the unpredicted interference effects. Since throughput is a concave constraint for any session, the bottleneck throughput along the entire of route of communication should be bigger or equal than the session requirement. Therefore, we choose to use the maximum throughput requirement among all sessions in the transmission set as the constraint for the outgoing link as,

$$\mathbf{R}^T_{ik} = \frac{\max_{\forall j \in Q} T^r_j}{T^a_{ik}} \leq 1 \tag{4}$$

Again, for any successful scheduler should this outage be less or equal than one. It is interesting to see that if we minimize this outage among neighbors, implicitly we exploit the multi-user diversity gain of the wireless channel to maximize the instantaneous data rate among neighboring links. This becomes another important feature for the proposed scheduling metric.

C. Link PER outage

$\mathbf{R}^E_{ik}$ is defined as the ratio between average measured PER value, E^a_{ik}, and the most severe "residual PER requirement" per hop. The concept of "residual PER requirement" E^s_j is similar to (1), but due to the multiplicative nature of end-to-end error, we also derive E^s_j accordingly. Similarly, we suppose any of the queued packet j has suffered some PER E^p_j up to node i, and node i is not aware of PER statistics in the following h^s_j hops so that we treat them equally. Thus, the ETE route PER constraint could be formulated by,

$$\begin{aligned} 1 - (1 - E^p_j)(1 - E^s_j)^{h^s_j} &\leq E^r_q \\ \text{or, } E^s_j &\leq 1 - \sqrt[h^s_j]{\frac{1 - E^r_j}{1 - E^p_j}} \end{aligned} \tag{5}$$

to make sure the QoS will not be violated. Because the scheduling decision remain the same for the whole time frame, and any packet in transmission set Q should be taken into consideration not to violate QoS, we thus should select the most severe "residual PER requirement" as the link PER constraint, and finally we have,

$$\mathbf{R}^E_{ik} = \frac{E^a_{ik}}{\min_{\forall j \in Q} E^s_j} \leq 1 \tag{6}$$

for any successful scheduler should this outage be less or equal than one.

D. Link QoS Utility

So far we have introduced three separate link constraints for delay, throughput and PER, however, trying not to violate none of the three simultaneously is not easy. This is because these three constraints represent different aspects of link/network in terms of network congestion level and wireless channel quality. It is known that traditional opportunistic scheduler always selects the "best" outgoing link in terms of link capacity, provided by the multi-user diversity gain of multiple neighboring wireless fading channels. However, as a result, this method will cause unexpected congestions/unfaireness for other transmission directions, thus delay constraints are easily violated. On the other hand, if the scheduler treats delay constraints prior to instantaneous link capacity, the multi-user diversity gain may not be fully exploited, thus throughput and PER constraints are not guaranteed. We see these two, i.e., to alleviate network congestion and exploit wireless channel quality, as the fundamental trade-offs for scheduling decision. Hence, our main goal is to satisfy all three QoS requirements simultaneously, but may not need to take full advantage of the multi-user diversity gain offered by wireless channel as long as the session operates above the QoS bottom line. Therefore, we devise a heuristic method to optimize three constraints in a unified manner in order to reach the sub-optimal performance of these trade-offs.

We define a "channel quality indicator", $\mathbf{I}^C_{ik}$, considering throughput and PER as,

$$\mathbf{I}^C_{ik} = \max\left(\mathbf{R}^T_{ik}, \mathbf{R}^E_{ik}\right) \leq 1 \tag{7}$$

where the "max" operator takes the bigger outage probability value between throughput and PER as the "link quality outage". This indicator shows the quality of current wireless channel to guarantee required throughput and error performance. Hence, it can be seen that in order to select the "best" outgoing channel, or, take advantage of multi-user diversity gain, the minimum outage $\mathbf{I}^C_{ik}, \forall k$ among all outgoing links of node i should be chosen. Meanwhile, however, we want to provide some degree of fairness in terms of ETE packet delay QoS, by potentially selecting the link with higher link delay outage, which is most likely to be violated if not scheduled soon.

To be more clear, we define a "network congestion indicator", $\mathbf{I}_{ik}^{D}$, as,

$$\mathbf{I}_{ik}^{D} = \mathbf{R}_{ik}^{D} \leq 1. \tag{8}$$

Finally we define the outgoing and incoming "link QoS utility", $\mathbf{U}_{ik}^{\text{out}}$ and $\mathbf{U}_{ik}^{\text{in}}$, to integrate both channel quality and network congestion indicators. One heuristic way is to use the division of the two:

$$\mathbf{U}_{ik}^{\text{out}} = \frac{\mathbf{I}_{ik}^{D}}{\mathbf{I}_{ik}^{C}} = \frac{\mathbf{R}_{ik}^{D}}{\max\left(\mathbf{R}_{ik}^{T}, \mathbf{R}_{ik}^{E}\right)} \tag{9}$$

$$\mathbf{U}_{ki}^{\text{in}} = \frac{\mathbf{I}_{ki}^{D}}{\mathbf{I}_{ki}^{C}} = \frac{\mathbf{R}_{ki}^{D}}{\max\left(\mathbf{R}_{ki}^{T}, \mathbf{R}_{ki}^{E}\right)} \tag{10}$$

where any of the outages should be less or equal than one, i.e., $\mathbf{R}_{ik}^{D}, \mathbf{R}_{ik}^{T}, \mathbf{R}_{ik}^{E} \leq 1$, and $\mathbf{R}_{ki}^{D}, \mathbf{R}_{ki}^{T}, \mathbf{R}_{ki}^{E} \leq 1$.

E. Selection Criterion

Given the incoming and outgoing link QoS utilities defined, the final selection criterion for any node in the network is to select one of neighboring links that has the maximum link QoS utility, so that the "best" link k^* considering both channel quality in terms of throughput and PER, and network congestion level in terms of delay outage is chosen. We have,

$$\begin{aligned} \mathbf{S}_{k^*} &= \max_{\forall k} \left(\mathbf{U}_{ki}^{\text{in}}, \mathbf{U}_{ik}^{\text{out}} \right) \\ &= \max_{\forall k} \left(\frac{\mathbf{R}_{ik}^{D}}{\max\left(\mathbf{R}_{ik}^{T}, \mathbf{R}_{ik}^{E}\right)}, \frac{\mathbf{R}_{ki}^{D}}{\max\left(\mathbf{R}_{ki}^{T}, \mathbf{R}_{ki}^{E}\right)} \right) \end{aligned} \tag{11}$$

where any of the outage should be less or equal than 1, i.e., $\mathbf{R}_{ik}^{D}, \mathbf{R}_{ik}^{T}, \mathbf{R}_{ik}^{E} \leq 1$, and $\mathbf{R}_{ki}^{D}, \mathbf{R}_{ki}^{T}, \mathbf{R}_{ki}^{E} \leq 1$.

V. DISTRIBUTED QOS SCHEDULING FRAMEWORK

A formal description of proposed distributed QoS scheduling framework is introduced in this section, which is composed of six control phases. These procedures are done in f_c control time slots simultaneously provided by synchronized TDMA scheme. Specifically, the pseudo code of the proposed algorithm is given by Algorithm 1.

Step 1: QoS requirements exchange:

The algorithm starts with QoS requirements exchange phase. For every outgoing transmission direction k, for every packet queued in the attached queue, node i firstly does the computation of residual delay requirement D_j^s in (1), bottleneck throughput requirement T_j^r, and residual PER requirement E_j^r in (5). These information will be passed to its neighbor k to assist for incoming link QoS utility computations and initial decision-making. Then, pilot symbols are sent out to estimate the SNR and therefore instantaneous data rate of each neighboring link.

Step 2: Link QoS utilities computation:

Each node i measures real-time statistics of delay, throughput and PER $(D_{ki}^{a}, T_{ki}^{a}, E_{ki}^{a})$ for any incoming direction (k, i). Then it does the computation of link delay, throughput, and PER outages: $\mathbf{R}_{ik}^{D}, \mathbf{R}_{ik}^{T}, \mathbf{R}_{ik}^{E}$ given the QoS requirements in Step 1. The computations of incoming channel quality indicator $\mathbf{I}_{ki}^{C}$ and network congestion indicator $\mathbf{I}_{ki}^{D}$ follow next. Finally, it integrates the above two utilities into link QoS utility $\mathbf{U}_{ki}^{\text{in}}$ as in (9) for each incoming direction (k, i).

Step 3 and 4: Utility exchange and initial decision-making:

So far, each WMR has information on incoming link QoS utilities. Step 3 allows all nodes in the network exchange their incoming utilities with nearby neighbors to obtain the outgoing utilities, i.e., $\mathbf{U}_{ik}^{\text{out}} = \mathbf{U}_{ki}^{\text{in}}$. After this exchange, under the full traffic condition (where traffics exist for all incoming and outgoing directions), each node i is aware of maximum $2 \times K_i$ number of utilities.

Step 4 is initial decision-making phase, where all nodes compare these utilities as (11) , node i chooses the link with the maximum utility to be the initial scheduling decision. This initial decision-making informs each node to be either in "transmit" or "receive" status.

Step 5 and 6: Initial decision, collision avoidance, and final decision-making:

After the initial-decision making, it is likely that the collision will happen for adjacent nodes (a node may be in "transmit" stage while being selected as a "receive" object by its neighbor). This is because neighboring nodes are not aware of their mutual decisions, and they only try to select the "best" link in Step 4. In order to avoid this and obtain the mutual decision, Step 5 allows each node to exchange initial decisions to all its neighbors again. Based on the initial decision exchanges, each node i with an initial decision status "transmit" checks if the desired receiving node is in status "receive" and the transmission side is node i. If not, the node gives up the intended transmission. Otherwise, the initial decision becomes the final decision and the status is fixed for both sides. Meanwhile, each node with an initial decision of "receive" also find outs the best transmitter based on the initial decision exchanges, and configures its PHY layer (adaptive modulation and coding schemes, directional antenna pattern, etc.) to prepare for data reception. These are Step 6: collision avoidance and final decision-making.

Taking into account the definition of multi-constrained link QoS utility, this framework has demonstrated following merits:

- It is fully distributed without deadlock. Nodes make scheduling decisions simultaneously (if perfect time synchronization is assumed), and do not need to wait for other nodes' decisions to make its own decision.
- It exploits multi-user diversity. Due to the nature of fast-fading wireless environments, unstable network conditions and fluctuated input traffic loads, the multi-user diversity of each WMR can be realized by exploiting the incoming and outgoing channel conditions as well as dynamic cross-link interferences.
- It provides some degree of fairness in terms of ETE packet delay by giving more priority to higher delay outage links.

Algorithm 1 : Scheduling algorithm description

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Step 1: QoS requirements exchange
for all node $i$, $\forall i \in V_R$ do
    for all outgoing transmission direction $(i,k)$ do
        for all queued packet $j \in Q$ do
            computations of:
            1. average residual delay requirement $D_j^s$ per hop
            2. bottleneck throughput requirement $T_j^r$
            3. average residual PER requirement $E_j^r$ per hop
        end for
    end for
    node $i$ broadcasts $\{D_j^s\}, \{T_j^r\}, \{E_j^r\}$ sets to every outgoing direction
end for

Step 2: Link QoS utilities computation
for all node $i$, $\forall i \in V_R$ do
    for all incoming reception direction $(k,i)$, $\forall k \in N(i)$ do
        1. measurements of delay, throughput, and PER statistics $(D^a, T^a, E^a)$
        2. computation of $\mathbf{R}_{ki}^D, \mathbf{R}_{ki}^T, \mathbf{R}_{ki}^E$
        3. computation of channel quality indicator $\mathbf{I}_{ki}^C$ and network congestion indicator $\mathbf{I}_{ki}^D$
        4. computation of link QoS utility $\mathbf{U}_{ki}^{\text{in}}$
    end for
end for

Step 3 and 4: Utility exchange and initial decision-making
for all node $i$, $\forall i \in V_R$ do
    incoming link QoS utility exchanges among neighbors to get outgoing utilities $\mathbf{U}_{ik}^{\text{out}} = \mathbf{U}_{ki}^{\text{in}}$
end for
for all node $i$, $\forall i \in V_R$ do
    $\max_{\forall k} \left(\mathbf{U}_{ki}^{\text{in}}, \mathbf{U}_{ik}^{\text{out}}\right)$
    to set initial status of either "transmit" or "receive"
end for

Step 5 and 6: Initial decision, collision avoidance, and final decision-making
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- It guarantees multi-constrained QoS in a unified manner, i.e., not only do we take the advantage of opportunistic nature of wireless channel and multi-user diversity gain by real-time measured statistics, but also delay will not be violated.

VI. SIMULATION RESULTS

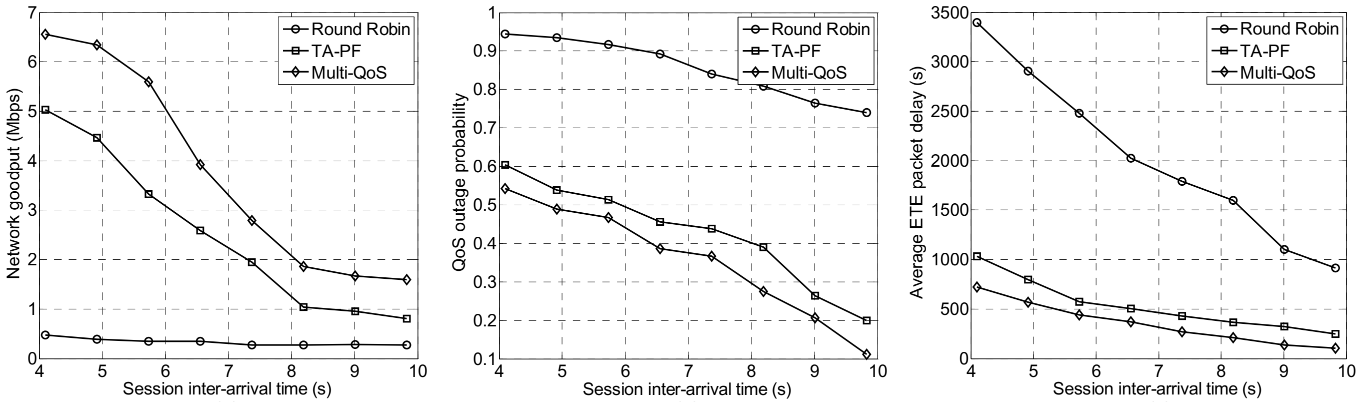
We develop a slotted, time-driven cross-layer simulation platform to assess the proposed distributed multi-constrained QoS scheduling algorithm. A number of WMRs are randomly and independently deployed, some of which have gateway functionality. Sessions are uniformly generally out of three types of applications, namely, voice-over IP, interactive video, and broadband data services, with three QoS constraints (ETE packet delay, throughput and PER). In PHY Layer, the Rayleigh fading channel model [17] is used for the wireless channel representation while the required PER is derived based on SINR curves for the used modulation and coding scheme. In order to reduce the interference to adjacent concurrent transmissions, increase the frequency reuse, and channel capacity, the WMRs are equipped with directional antennas. In network layer, the integrated QoS routing protocol [2], [3] is used to provide sub-optimal candidate routes with multiple QoS constraints.

Moreover, as introduced in Section IV and V, performances of the proposed scheduling algorithm highly depends on the accurate estimations of multiple system parameters required for scheduling decisions. They include real-time monitored/measured link statistics: T_{ik}^a, D_{ik}^a, and E_{ik}^a for throughput, delay and PER respectively, for any link (i,k). These statistics are updated periodically to represent the most recent channel qualities and queue status.

We access our scheme, as multi-constrained QoS scheduling algorithm (Multi-QoS), to compare with the exiting throughput-allocation proportional fair scheduling algorithm (TA-PF, [7], [8]), and another well-know benchmark protocol, Round Robin scheduler [18]. The performances are investigated in terms of network goodput (received throughput satisfying QoS constraints) in Fig. 1a, average QoS outage probability (Fig. 1b), and average ETE packet delay (Fig. 1c), all with respect to (w.r.t) different traffic load.

Fig. 1a shows the overall network goodput performance. Compared with standard scheme round robin and TA-PF, the proposed algorithm can successfully achieve high overall network goodput 1.8Mbps even for small number of offered network traffic. This is primarily because by considering delay requirement into the scheduling utility, the trade-off between channel quality (throughput and PER) and network congestion (delay violence) is fully exploited. As a result, the "best" link in terms of satisfying all three QoS requirements is chosen. Therefore, it is expected that more QoS successful sessions will be delivered to the gateway, which turns into network goodput volume. Furthermore, because in the link QoS utility, real-time statistics representing instantaneous channel quality is inherently included, the multi-user diversity is fully exploited. Combing with proper adaptive modulation and coding scheme in PHY layer, higher goodput is expected. However, as for fixed transmission schedule, round robin scheduler knows no information about channel quality, network congestion status and application requirements. It can only provide relatively constant throughput.

Fig. 1b depicts the QoS outage probability among all sessions also as a function of the traffic load. This is defined as the probability of any one of the QoS requirements to fail during the lifetime of the given session. It is interesting to observe that our algorithm (Multi-QoS) can even guarantee all QoS requirements of the underlying applications for 6%higher than TA-PF scheme and 40% than round robin. This is because the impact of delays has been accurately characterized in the



(a) (b) (c)

Fig. 1. Simulation results on (a) Network goodput, (b) Average QoS outage probability among all sessions, and (c) Average ETE packet delay, all w.r.t. the new session inter-arrival time.

new utility definition, unlike in TA-PF scheme, only long-term throughput is achieved proportionally.

The effect of proposed new link QoS utility in scheduling decisions becomes more clearer in Fig. 1c where the average ETE packet delay is demonstrated. The packet delay is composed of queuing delays of each hop and transmissions delays in the air. Sever queuing delays can even deteriorate the whole system performance and yield no goodput. It could be seen that proposed scheme can still achieve 6 times less delay than round robin and 30% less than TA-PF scheme even for the high traffic load offered. This is because although TA-PF scheme can somehow alleviate certain direction of queuing delays by exploiting the instantaneous channel quality, some links may be less likely to be arranged for transmission because of fading wireless environment.

VII. CONCLUSIONS

In this paper, a fully distributed scheduling algorithm with multi-constrained QoS provisions for wireless mesh networks has been proposed. By defining a link QoS utility, we successfully integrate multiple QoS requirements (delay, throughput, and PER) into a unified utility function. This utility captures not only these requirements, but also channel qualities and network congestion status through real-time link quality statistics in PHY and MAC layer. Moreover, the proposed utility exploits the multi-user diversity gain in wireless channel, but still strictly secure delay constraints, which is especially expected for delay-sensitive applications like voIP and interactive video. Extensive simulation results show that proposed scheduling scheme could successfully increase the network goodput, decrease the ETE packet delay, and achieve significant QoS outage probability gain compared with benchmark protocol round robin scheduler and TA-PF scheme.

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