Pareto Optimal Resource Management for Wireless Mesh Networks with QoS Assurance: Joint Node Clustering and Subcarrier Allocation

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***Abstract*— Node clustering and subcarrier allocation are imperative to ameliorate system throughput and facilitate quality-of-service (QoS) provisioning by means of effective interference control and maximum frequency reuse. In this paper, we propose a novel node clustering algorithm with effective tax-based subcarrier allocation tailored for wireless mesh networks with QoS support. With increased frequency reuse, our proposed approach is shown to achieve a higher system throughput than a conflict-graph approach and a baseline approach. Also, our approach is demonstrated promising in balancing packet delay and end-to-end transmission rate. By carefully adjusting an upper bound of subcarriers allocated to each cluster, we can achieve improved system performance. The proposed resource allocation achieves the Pareto optimality, demonstrating efficient use of network resources. Further, our analysis reveals that how to allocate resources in a wireless network in a decentralized manner can affect the solution space of a performance tradeoff between QoS provisioning and throughput maximization.**

***Index Terms*—Frequency reuse, game theory, node clustering, quality-of-service (QoS) provisioning, subcarrier allocation, wireless mesh network (WMN).**

I. INTRODUCTION

WIRELESS mesh networking has emerged as a promising technology for future broadband wireless access [1], [2]. Wireless mesh networking is expected to provide a viable and economical solution for both peer-to-peer applications and last-mile Internet access. Wireless mesh networks (WMNs) generally comprise gateways, mesh routers, and mesh clients, organized in a three-tier hierarchical architecture [2]. Recently, wireless mesh networking for suburban and rural residential areas has been attracting a plethora of attentions. To provide an *all-wireless* ambience to the suburban or rural area of interest, mesh routers can be set up at premises in the neighborhood, forming a resilient mesh backbone.

Concerning the capacity of a wireless network, the throughput of a wireless node decreases with the number of nodes. The implication is that a node should only communicate with nearby nodes, thereby favoring *clustering* [3]. In the literature, clustering is an effective way to manage a large wireless network [4]. Multi-level hierarchical clustering schemes are shown to achieve better system performance [5]. In fact, the notion of clustered WMNs has recently received an increasing attention from industry such as MeshAP-Pro and MeshBroschure. Although clustering has been researched in the context of sensor networks and mobile ad hoc networks (MANETs) for years, applying the existing clustering schemes to WMNs may not be efficient or effective due to different networking characteristics and design objectives. The goal for establishing WMNs is to provide ubiquitous communications to users and render an efficient mesh backbone with quality-of-service (QoS) support [2], while the primary purpose for deploying sensor networks is to offer environmental monitoring (e.g., temperature, pressure, etc) and/or surveillance (e.g., military field surveillance) [6]. Mobility and energy efficiency are the major concerns in MANETs [4], where the nodes are mobile and have power constraints, but there are no such limitations in WMNs. Further, the deployment of WMNs is relatively permanent, giving rise to the need of high efficiency of WMNs with QoS support. Thus, a new node clustering approach specifically tailored for QoS-sensitive WMNs is indispensable.

In order to efficiently support multimedia services and ameliorate system capacity, effective channel assignment and hence interference control are imperative to facilitate QoS provisioning and *frequency reuse* [7]. However, austere suburban and rural environments discourage the notion of centralized control. With the help of node clustering, interference control and hence frequency reuse can be facilitated by channel allocation via clusterheads in a decentralized manner. In a cluster, collision-free scheduling is feasible, to satisfy various QoS demands. Resource allocation can be carried out in a hybrid centralized-distributed fashion (i.e., centralized intra-cluster and distributed inter-cluster resource allocation).

The contribution of this work is three-fold.

- First, we study the problem of node clustering and subcarrier allocation. By introducing an upper bound on the number of subcarriers allocated to a cluster, we propose a node clustering algorithm with effective subcarrier allocation. The proposed node clustering algorithm is QoS-aware, and the subcarrier allocation is optimality-driven and can be performed in a decentralized manner.
- Second, our proposed resource allocation achieves high

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system throughput, and provides a good performance compromise between packet delay and end-to-end transmission rate for real-time traffic. Simulation results show that, by adjusting the value of the upper bound of subcarriers allocated to clusters carefully, we can achieve better system performance. The proposed scheme is also shown to be Pareto optimal, making efficient use of scarce radio resources.

- Third, our results not only confirm the fact that QoS provisioning and throughput maximization are two conflicting performance metrics [8], but also reveal that how to allocate resources in a decentralized wireless network can affect the solution space of a performance tradeoff between QoS provisioning and throughput maximization.

The remainder of this paper is organized as follows. Related work is given in Section II. The system model is described in Section III. The proposed joint QoS-aware node clustering and tax-based subcarrier allocation is presented in Section IV. Efficiency of the proposed resource allocation approach from the perspective of game theory is addressed in Section V. Performance evaluation is given in Section VI. Finally, conclusions and further work are presented in Section VII.

II. RELATED WORK

Node clustering is an effective way to maintain network stability and scalability, where changes in cluster membership only introduce the information update locally (i.e., in the corresponding clusters) rather than globally (i.e., the entire network), thereby lessening the overhead of message exchanges [4]. In [9], an adaptive clustering algorithm is proposed to provide guaranteed QoS to real-time multimedia traffic in a decentralized manner. Similar work with power control is also presented in the recent literature (e.g., [10], [11]). In the aforementioned work, inter-cluster communications are facilitated by means of code division multiple access (CDMA). However, channel allocation and interference control are not taken into consideration, thereby hindering system throughput improvement. Besides, the work focuses on small-scale ad hoc networks, where the issue of frequency reuse is not addressed properly. Other node clustering schemes based on different system metrics (i.e., node degree and cluster size) are proposed for MANETs [4]. Most of the existing schemes aim at maximizing network connectivity and minimizing energy consumption; however, packet-level QoS provisioning is often neglected. Thus, applying those node clustering algorithms directly to WMNs can be ineffective or inefficient to support different multimedia applications (e.g., voice, video, and data) with diverse QoS requirements. In addition, ameliorating throughput is the key to the success of providing a robust wireless mesh backbone in large-scale WMNs. Therefore, the notion of frequency reuse and QoS provisioning should be taken into account in designing a node clustering algorithm.

In the literature, there exists a wide range of channel assignment schemes for wireless networks [12]–[18]. The objective of most existing techniques is to achieve optimal channel allocation [12]–[14], [18]. In the context of cellular systems, channel allocation is relatively straightforward, thanks to the robust hexagonal cellular structure [18]. For fixed channel allocation, a nominal channel set is assigned to every cell. In order to deal with the traffic load variations, channel reassignment and negotiation (e.g., channel borrowing [19]) can be effectively done with the help of mobile switching centers. To further attain high channel efficiency, dynamic channel allocation schemes are proposed (e.g., dynamic channel selection [20]), where centralized control is usually needed to ensure the effectiveness of frequency reuse at the cost of computational complexity. Since the mesh routers of a large WMN are likely scattered around, the clustered WMN is not expected to be as structured as its counterpart. In addition, mobile switching centers are not always available in WMNs, especially in suburban and rural areas. Therefore, simply applying existing channel allocation schemes designed for the cellular systems to large-scale WMNs can plausibly degrade the system performance. On the other hand, centralized algorithms are devised to maximize the number of transmission links in the network and balance the traffic load among different channels in [12] and [13], respectively. For practical implementation, distributed schemes based on an interference conflict graph are proposed [15]–[18]. With the set of vertices representing the transmission links in the network and the set of edges representing the transmission conflicts, channel allocation is performed in such a way that the adjacent links (or vertices) in the interference conflict graph cannot use the same channel(s) for packet transmissions. However, most of the existing approaches are not QoS-aware. In addition, packet scheduling deduced by the interference conflict graph may not guarantee collision-free transmissions in a large-scale WMN, for the aggregate interference coming from the transmissions outside the neighborhood can be very large. The schedule deduced by an interference conflict graph can discourage feasible concurrent transmissions and/or reduce the transmission rates of adjacent nodes. *TiMesh* is proposed to avoid a *ripple effect* [14], but hampers the notion of frequency reuse, underutilizing the scarce radio resources. Thus, combining topology control with channel assignment and distributed channel allocation tailored for a clustered mesh backbone are necessary.

In this paper, we propose a QoS-aware node clustering algorithm with effective tax-based subcarrier allocation tailored for WMNs. Our novel resource allocation approach achieves the Pareto optimality and outperforms the approach using an interference conflict graph.

III. SYSTEM MODEL

Consider a WMN for suburban or rural residential areas, consisting of one wireline gateway attached to the Internet backbone and a number of mesh routers scattered around, rendering a multi-hop network (see Fig. 1). The system model takes account that suburban and rural environments are usually austere, which thwarts one-hop direct communications as opposed to multi-hop transmissions, providing ease of deployment and offering greater coverage of wireless access [2]. A gateway can be set up anywhere in the suburban or rural residential area of interest. In this work, the gateway is chosen to be located at (or close to) the center of the network. Notice that how to place multiple gateways effectively in a mesh network is beyond the scope of this paper. We assume that mesh routers are non-mobile and the channel gains can be estimated

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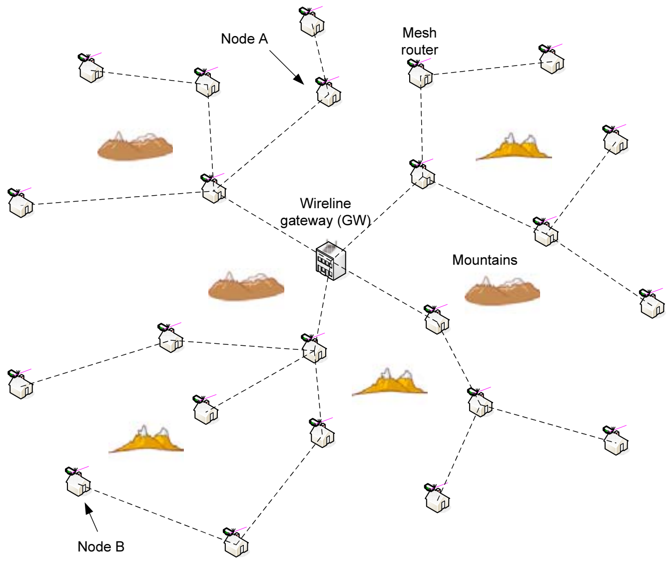

Fig. 1. An illustration of network topology.

accurately. Traffic is assumed to be *vertical*, traversing from mesh routers to the gateway, and vice versa. In this work, we consider the upstream traffic from the mesh routers to the gateway. Three types of traffic are considered, namely voice, video, and data. Voice traffic and video traffic are considered as real-time traffic, while data traffic is considered as non-real-time traffic. Time is partitioned into frames, each of which is further divided into a beacon slot, a control slot, and L DATA slots. Call admission control (CAC) is assumed in place such that the QoS requirements of an admitted call (flow) can be satisfied. With a physical layer based on orthogonal frequency division multiplexing (OFDM) technology, each router can choose a set of subcarriers for DATA transmissions and/or receptions, allowing simultaneous transmissions over different subcarriers in the mesh backbone.

IV. JOINT QOS-AWARE NODE CLUSTERING AND TAX-BASED SUBCARRIER ALLOCATION

We propose a QoS-aware node clustering algorithm with tax-based subcarrier allocation tailored for WMNs. As ameliorating throughput in a mesh backbone is the key to the success of providing an all-wireless ambience, the objective of the joint node clustering and subcarrier allocation is chosen to maximize the system throughput. Notice that the objective function can be modified to optimize other system performance measures (e.g., a tradeoff between throughput and fairness with QoS support [8]). Nonetheless, the node clustering problem and the subcarrier allocation problem are coupled. To reduce the computational complexity, our approach is to solve the node clustering problem and to allocate subcarriers in succession alternatively (as discussed in Section IV-D).

Considering various aspects such as system capacity, QoS provisioning, the burden on clusterheads, packet delivery delay, and the austere suburban (and rural) environment, we formulate the node clustering problem by setting an upper bound on the number of subcarriers allocated to a cluster. Denote $B^{\max}$ as the upper bound of the number of allocated subcarriers in a cluster. The bound caps the maximum traffic load in a cluster and hence the burden on a clusterhead, controls a cluster size to a certain extent, and facilitates packet scheduling assisted by clusterheads. In fact, choosing the value of this upper bound carefully can further improve system performance (discussed in Section VI).

A clusterhead essentially collects the transmission requests (along with the traffic load demands) from its clustermembers in the control slot of a frame. The resource allocation decision based on the algorithm employed in [7] is announced in the subsequent beacon slot, and the clustermembers will then transmit their packets in their allocated DATA slots. Notice that intra-cluster resource allocation (e.g., packet scheduling), however, is not the main focus of this paper. The proposed approach for the joint node clustering and subcarrier allocation problem includes: 1) neighbor discovering, 2) initial path establishment, 3) traffic load estimation, 4) node clustering algorithm, and 5) subcarrier allocation.

A. Neighbor Discovering

A mesh router can discover its neighbor(s) via any routing protocol. In this work, a neighbor is identified if the channel gain between the node of interest and the neighboring node is above a certain threshold. As mesh routers are assumed to be stationary, all the possible paths of a mesh router to the gateway can be pre-determined.

B. Initial Path Establishment

Establishing an initial path is imperative to facilitate traffic load estimation and hence QoS-aware node clustering. Denote p_m^e as the e^{th} link along the p^{th} shortest path of the m^{th} node to the gateway. The initial path of a mesh router to the gateway is determined by the following condition:

$$p^* = \arg\max_{p}\{\min_{\forall e \in p}\{\widetilde{R}_m(p_m^e)\}\}, \forall m \qquad (1)$$

where $\widetilde{R}_m(y) = \ln\left(1 + \widetilde{G}_m(y)P_m^{\max}/\eta\right)$ can be viewed as a data rate obtained at the m^{th} node on the y^{th} link with $\widetilde{G}_m(y)$ being the (constant) channel gain over the available radio spectrum on the y^{th} link, $P_m^{\max}$ the maximum power constraint of the m^{th} node, and η the noise power. The effect of co-channel interference is discussed in Section IV-E. The objective given in (1) is to find the shortest path of a node to the gateway which maximizes the minimum of all link rates (i.e., maximize the end-to-end rate). This initial path establishment criterion ends in a tree architecture for a WMN (see Fig. 1). For simplicity, the shortest paths are used as an example to demonstrate node clustering and subcarrier allocation. Notice that one pitfall of the suggested initial path establishment is that some nodes may be overloaded. A feasible solution is to cap the maximum traffic load supported by a node. Another solution is to employ multi-stream routing methodology. The issue of routing (and traffic load balancing), however, is beyond the scope of this work.

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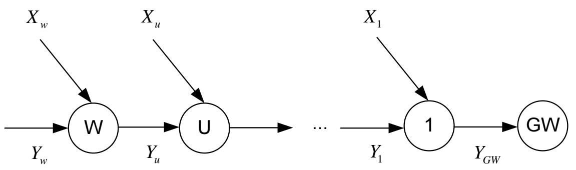

Fig. 2. Traffic load estimation.

C. Traffic Load Estimation

To facilitate resource allocation at the medium access control (MAC) layer, traffic load estimation is necessary [2]. Each node estimates the traffic load of real-time traffic by averaging the rate requirement over a fixed observation window (e.g., 100ms). The sum of the local traffic load estimate of a node and the relay load received is forwarded to its next-hop neighbor (toward the gateway) determined by its initial established path. Let X_m be the local traffic load estimate at the m^{th} node, and Y_m be the relay load received by the m^{th} node. Fig. 2 illustrates how the traffic load estimation works. Then, $Y_u = X_w + Y_w$, where the u^{th} node is the next-hop neighbor (toward the gateway) of the w^{th} node. We assume that there is no local traffic generation at the gateway. Such traffic load estimation is also shown to be crucial for supporting QoS in intra-cluster resource allocation [7].

D. Node Clustering Algorithm

We assume that clusterheads can operate in a dual-power mode [6], where higher power levels are reserved for inter-cluster signaling[1] and lower power levels are for intra-cluster communications. Define an I-tier cluster as a cluster formed at the I^{th} clustering level from the gateway. The proposed node clustering algorithm is described as follows:

Step 1: All nodes are set to be unassigned (i.e., neither clusterheads nor clustermembers). The gateway is set to be the default clusterhead. Set I=1.

Step 2: The clusterhead of interest selects one of its 1-hop unassigned nodes[2] and collects its QoS requirement (i.e., traffic load demand). If no neighbors can be selected, go to Step 5.

Step 3: The clusterhead of interest chooses the best available subcarrier(s) for the selected node based on the subcarrier allocation criterion given in (5), to be discussed in Section IV-E. If the QoS requirement of the selected node cannot be satisfied, go to Step 5.

Step 4: If the total number of subcarriers acquired is less than or equal to $B^{\max}$ in the cluster of interest, the selected node becomes a clustermember of that cluster, the chosen subcarriers are recorded in a table stored at the clusterhead of interest, and go back Step 2.

Step 5: An I-tier cluster is created. The clusterhead of interest keeps selecting the best available subcarrier(s), if feasible, until the total number of chosen subcarriers is $B^{\max}$ so as to further improve both the total throughput and interference tolerance of that cluster. Repeat Steps 2-4 with another I-tier clusterhead, if any, until no more clusters can be formed at the I-tier.

Step 6: The set of (I+1)-tier clusterhead(s) is chosen by the J-tier clusterhead(s) by means of Black-Burst jamming [2][3], where $J = 1, 2, \ldots, I$: The J-tier clusterhead(s) is(are) to signal its(their) unassigned neighbors, and the closest unassigned neighbor(s) then transmit its(their) Black-Burst jamming signal. Note that the length of a Black-Burst jamming signal is a decreasing function of the smallest number of hops from a node to the gateway. Therefore, with the gateway as a coordinator, the unassigned node(s) with the longest Black-Burst jamming signal (i.e., the smallest number hops to the gateway) *win(s)* the contention and is(are) chosen to be the (I+1)-tier clusterhead(s), and the order of their cluster formation is randomly assigned. If a clusterhead can be elected, set I=I+1 and go back to Step 2.

Step 7: Any unassigned node joins its closest clusterhead(s). Any node that is a 1-hop neighbor of a clusterhead automatically becomes a clustermember of that cluster. Any clustermember that is a 1-hop neighbor of more than one clusterhead and any clusterhead that is a clustermember of another clusterhead can be viewed as a clustergateway. Notice that a node can have multiple roles in the network.

Step 8: If there are any subcarriers unallocated, the remaining subcarriers are allocated according to the subcarrier allocation criterion given in (5) in sequence, starting from the first formed clusterhead (i.e., the gateway) to the last formed clusterhead, until all subcarriers are employed. The value of $B^{\max}$ is adjusted accordingly.

Clusters closer to the gateway have higher priority, whereas the ones farther away from the gateway have lower priority. The rationale is that traffic bottlenecks are usually found at (and near) the gateway and hence those clusters close to the gateway are assigned higher priority in the proposed resource allocation approach. Besides, a clustered WMN will consist of 1- and/or 2-clusters[4], and different clusters may have different sizes. Clusterheads are usually located in the middle of their cluster. Further, clusterheads form a connected graph.

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[1] In case direct inter-cluster transmissions fail (e.g., due to path loss), we assume that cooperative communications [21] are in place such that the inter-cluster signaling is always feasible.

[2] For simplicity, we only consider the case where a clusterhead selects its 1-hop neighbors as its clustermembers in this work.

[3] The notion of Black-Burst jamming was originally proposed for channel contention and service differentiation in the MAC layer [2]. In our work, we use the approach to select a set of clusterheads.

[4] A j-cluster is defined as a subset of nodes which are mutually reachable by a path of length at most j-hops for a positive integer j.

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E. Subcarrier Allocation

Without any effective subcarrier allocation, it is plausible that large co-channel interference is introduced by unfavorable simultaneous transmissions. Consider the case where clusterheads do not exchange any information and myopically maximize the aggregate throughput in their clusters. Since there is no penalty for a cluster to use all the (chosen) subcarriers for its intra-cluster communications, the resultant co-channel interference generated to other clusters can be very large, decreasing overall system throughput. The above solution can be far from optimal, and hence an effective resource allocation tailored for large WMNs is vital. In the following, we view a clusterhead as the representative of its cluster.

We propose a novel QoS-aware subcarrier allocation scheme motivated by Karush-Kuhn-Tucker (KKT) optimality conditions [22] (see Appendix). Let M denote the number of clusterheads, N the number of available subcarriers, and L the number of timeslots (i.e., DATA slots) in a frame. Consider the following payoff function of the m^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot

$$S^l_{m,n}\left(a^l_{m,n}, p^l_{m,n}\right) = a^l_{m,n} r^l_{m,n} - p^l_{m,n} \sum_{k \neq m}^{M} T^l_{km,n} \tag{2}$$

where $r^l_{m,n} = \ln(1+\gamma^l_{m,n})$ represents the achievable data rate of the m^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot with the received signal-to-interference-and-noise-ratio (SINR) $\gamma^l_{m,n}$, $a^l_{m,n}$ is the indicator of allocating the n^{th} subcarrier to the m^{th} clusterhead on the l^{th} timeslot, i.e., $a^l_{m,n} \in \{0,1\}$, $p^l_{m,n}$ is the transmit power, and $T^l_{km,n}$ is *tax* paid by the m^{th} clusterhead for generating interference to the k^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot, defined as

$$\begin{aligned} T^l_{km,n} &= -\frac{\partial U_k(\mathbf{a},\mathbf{p},R^d_k)}{\partial p^l_{m,n}} \\ &= \left(\frac{\partial U_k(\mathbf{a},\mathbf{p},R^d_k)}{\partial \gamma^l_{k,n}}\right) \cdot \left(-\frac{\partial \gamma^l_{k,n}}{\partial P^l_{I,k,n}}\right) \cdot \left(\frac{\partial P^l_{I,k,n}}{\partial p^l_{m,n}}\right) \\ &= \varepsilon^l_{k,n} \cdot I^l_{k,n} \cdot a^l_{m,n} G_{km,n} \end{aligned} \tag{3}$$

where $U_k(\mathbf{a},\mathbf{p},R^d_k)$ is the utility function of the k^{th} clusterhead with R^d_k being the QoS demand of the k^{th} clusterhead, $P^l_{I,k,n} = \sum_{i \neq k} a^l_{i,n} G_{ki,n} p^l_{i,n}$ being the received interference power level of the k^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot, $\mathbf{a} = [a^l_{k,n}]_{M \times N \times L}$, and $\mathbf{p} = [p^l_{k,n}]_{M \times N \times L}$. The SINR of the m^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot is given by $\gamma^l_{m,n} = \frac{\varphi G_{mm,n} p^l_{m,n}}{\sigma \sum_{k \neq m} a^l_{k,n} G_{mk,n} p^l_{k,n} + \eta}$, where $G_{mk,n}$ is the channel gain from the k^{th} clusterhead to the m^{th} clusterhead over the n^{th} subcarrier, φ is a bit-error-rate measure, and σ is the cross-correlation factor between any two signals, i.e., $\sigma \in [0,1]$. The utility function of the k^{th} clusterhead is defined as

$$\begin{aligned} &U_k(\mathbf{a},\mathbf{p},R^d_k) \\ &= \begin{cases} \sum_l^L \sum_n^N a^l_{k,n} r^l_{k,n} - R^d_k, & \sum_l^L \sum_n^N a^l_{k,n} r^l_{k,n} - R^d_k \geq \epsilon \\ 0, & \sum_l^L \sum_n^N a^l_{k,n} r^l_{k,n} - R^d_k < \epsilon \end{cases} \end{aligned} \tag{4}$$

where $0 < \epsilon \ll 1$. We assume that for $0 < \sum_l^L \sum_n^N a^l_{k,n} r^l_{k,n} - R^d_k < \epsilon$, $\frac{\partial U_k(\mathbf{a},\mathbf{p},R^d_k)}{\partial \gamma^l_{k,n}} \rightarrow \infty, \forall k$. Notice that $T^l_{km,n}$ can be interpreted as the marginal decrease in the utility obtained by the k^{th} clusterhead per unit increase in the transmit power of the m^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot. Thus, $T^l_{km,n}$ is always non-negative. Similarly, $\varepsilon^l_{k,n}$ represents the sensitivity of utility obtained by the k^{th} clusterhead per unit change in the received SINR of the k^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot, and $I^l_{k,n}$ represents the marginal decrease in the received SINR of the k^{th} clusterhead per unit increase in the received interference power level over the n^{th} subcarrier on the l^{th} timeslot. Notice that $\varepsilon^l_{k,n}$ is an indispensable measure to strive for the balance between effective QoS provision and efficient frequency reuse (to be discussed). With the tax interpretation of the KKT conditions, each clusterhead, therefore, essentially maximizes the difference between its throughput obtained minus its *lump-sum* tax paid to the other clusterheads in the mesh backbone due to the induced interference. Each clusterhead is to optimize $a^l_{m,n}$ and $p^l_{m,n}$ such that its own payoff function is maximized. Overall, $\mathbf{a}$ and $\mathbf{p}$ are the *optimization variables*. The proposed subcarrier allocation strategy is more suitable and applicable than a traditional coloring approach to WMNs, mesh routers of which are not evenly distributed. More importantly, with the tax information, subcarrier allocation and hence frequency reuse can be carried out in a sequential manner.

In this work, we only focus on the subcarrier allocation by fixing power allocation (i.e., uniform power distribution), though subcarrier allocation and power allocation should be jointly considered for the sake of optimality. Thus, the criterion of subcarrier allocation can be deduced as follows: For the m^{th} clusterhead on the l^{th} timeslot, choose n^* such that

$$n^* = \arg\max_n \left\{ S^l_{m,n}\left(a^l_{m,n}\right) \right\} \tag{5}$$

and set $a^l_{m,n^*} = 1$. Note that an information exchange among clusterheads is triggered whenever there is any change in subcarrier allocation.

F. Complexity

Consider that, with message signaling among clusterheads, the clusterheads have complete knowledge of their lump-sum tax. Since each clusterhead behaves individually in sequence, the time complexity of the proposed subcarrier allocation is on the order of $O(NL)$. Thus, the time complexity of the proposed node clustering algorithm given in Section IV-D is on the order of $O(MNLB^{\max})$. With the help of effective *data structure* (e.g., binary tree implementation [23]), the complexity can be further reduced to the order of $O(MLB^{\max} \log_2 N)$.

V. EVALUATION BY GAME THEORY

Here, we show that the subcarrier allocation solution obtained from our proposed approach achieves efficient use of network resources. In game theory, efficient resource uti-

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lization is determined by the concept of *Pareto optimality*[5] [24]. Modeled by a round-robin game, our proposed QoS-aware subcarrier allocation approach (or game) also attains a *Nash equilibrium*[6] (NE) [24] in the case where all available subcarriers are active and all the clusters are heavily loaded.

Proposition 1: Suppose all available subcarriers are chosen by the clusterheads at least once on every timeslot (i.e., $\sum_m a^l_{m,n} \geq 1, \forall n, l$). The subcarrier allocation solution obtained from our proposed approach is Pareto optimal.

Proof: Given the action profile or solution $\mathbf{a}^*$ (i.e., subcarrier allocation) obtained from (5), $U_m(\mathbf{a}^*, R^d_m)$ is the utility acquired by the m^{th} clusterhead. Consider another action profile $\tilde{\mathbf{a}}$. For some m, if $U_m(\tilde{\mathbf{a}}, R^d_m) > U_m(\mathbf{a}^*, R^d_m)$, then $U_n(\tilde{\mathbf{a}}, R^d_n) < U_n(\mathbf{a}^*, R^d_n)$ for some n, as either $\tilde{\mathbf{a_m}} \succeq \mathbf{a_m}^*$ or $\tilde{\mathbf{a_n}} \preceq \mathbf{a_n}^*$ or both. According to the definition of Pareto optimality, the subcarrier allocation solution $\mathbf{a}^*$ obtained from our proposed approach achieves the Pareto optimality. ■

The proposed node clustering algorithm ensures that all the available subcarriers are to be selected at least once. Thus, from the perspective of game theory, the proposed QoS-aware subcarrier allocation approach attains Pareto optimality, and hence the resources are efficiently utilized.

Proposition 2: Suppose all available subcarriers are active. If all the clusters are heavily loaded (i.e., $0 < \sum_l^L \sum_n^N a^l_{m,n} r^l_{m,n} - R^d_m < \epsilon, \forall m$), frequency reuse is prohibited.

Proof: If $0 < \sum_l^L \sum_n^N a^l_{m,n} r^l_{m,n} - R^d_m < \epsilon, \forall m, \varepsilon^l_{m,n} \rightarrow \infty, \forall m, n, l$, and hence $T^l_{mj,n} \rightarrow \infty, \forall j, m, n, l$. According to the subcarrier allocation criterion given in (5), a subcarrier can be selected only once (i.e., $\sum_m a^l_{m,n} = 1, \forall n, l$). Therefore, frequency reuse is prohibited. ■

Proposition 3: Suppose all available subcarriers are active and all the clusters are heavily loaded. Modeled by a round-robin game played by the clusterheads, the proposed subcarrier allocation solution attains an NE.

Proof: Rewrite the payoff function of the m^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot as $S^l_{m,n}(a^l_{m,n}, a^l_{-m,n})$, where $a^l_{-m,n} = (a^l_{1,n}, ..., a^l_{m-1,n}, a^l_{m+1,n}, ...a^l_{M,n})$. The proposed subcarrier allocation approach can be modeled by a round-robin game, where clusterheads (players) take turn to maximize their payoffs based on the subcarrier allocation criterion given in (5). Under the conditions that all available subcarriers are active and all the clusters are heavily loaded, all the clusterheads would have no intention to re-allocate the subcarriers, for $S^l_{m,n}(a^{*,l}_{m,n}, a^{*,l}_{-m,n}) \geq S^l_{m,n}(a^l_{m,n}, a^{*,l}_{-m,n}), \forall m, n, l,$ where $\mathbf{a}^*$ is the currently obtained subcarrier allocation solution and $\mathbf{a}$ is another solution. According to the definition of an NE, the subcarrier allocation solution $\mathbf{a}^*$ obtained from our proposed approach attains an NE. ■

Corollary 1: If an NE is attained, all available subcarriers are in use.

Proof: Suppose that there exists a subcarrier allocation solution $\tilde{\mathbf{a}}$ at an NE, where not all the subcarriers are in use, i.e., $\sum_m \tilde{a}^l_{m,n} = 0, \exists n, l$. However, we can always find another solution $\mathbf{a}^*$ where $\mathbf{a}^* \geq \tilde{\mathbf{a}}$ such that $S^l_{m,n}(a^{*,l}_{m,n}, \tilde{a}^l_{-m,n}) > S^l_{m,n}(\tilde{a}^l_{m,n}, \tilde{a}^l_{-m,n}), \exists m, n, l,$ which contradicts to the definition of an NE. Thus, no such solution $\tilde{\mathbf{a}}$ exists at an NE, and all available subcarriers are in use at an NE. ■

When all the subcarriers are in use and all the clusters are fully loaded, an NE is attained (i.e., Proposition 2), leading to a stable clustered networking structure. However, under the same aforesaid conditions, the notion of frequency reuse is discouraged due to zero tolerance to any additional co-channel interference (i.e., Proposition 3), thereby reducing system throughput. The implication is that, to foster frequency reuse and hence increase system throughput, clusters should not be heavily loaded so as to allow certain interference margin. Since throughput improvement is indispensable in a mesh backbone, frequency reuse should be the first issue to be addressed in developing a resource allocation algorithm. On the other hand, in order to procure a desired balance between QoS provisioning and system throughput maximization, CAC should be in place, which limits the number of calls admitted into the system and the number of clustermembers affiliated to a cluster. Our evaluation reinforces the fact that QoS provisioning and throughput melioration are conflicting with each other [8]. More importantly, our study also reveals a crucial principle that how to allocate resources to the wireless nodes in a decentralized fashion is critical in determining the solution space of a performance tradeoff between QoS provisioning and throughput maximization. For instance, a clusterhead should not select too many nodes as its clustermembers; otherwise, the effectiveness of frequency reuse and hence the system throughput would be reduced. How to acquire a desired tradeoff between QoS provisioning and throughput improvement is, however, left for further research. Nonetheless, as long as all the subcarriers are active, our proposed subcarrier allocation approach achieves Pareto optimality, making efficient use of network resources.

VI. PERFORMANCE EVALUATION

We consider a WMN with nodes randomly distributed over the network coverage area, with a node density of 1 node per 1000m^2. Parameters for performance evaluation are chosen as follows: $\varphi = 1$, $\sigma = 1$, $\eta \sim N(0, 10^{-12}\text{W})$, $P^{\max}_m = 1\text{W}, \forall_m$, and $L = 4$. The maximum transmission rate of each subcarrier is 100Kbps. We adopt the channel model suggested in [25]. We employ the traffic models for voice, video, and data, the MAC protocol, and CAC as described in [7]. Voice traffic is generated according to a two-state ON-OFF model. In the ON state, a fixed-size packet arrives at a constant rate, whereas in the OFF state, no packet is generated. The duration of an ON

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[5] An action profile $\mathbf{b}^* = (b^*_1, b^*_2, ..., b^*_M)$ is said to be Pareto optimal if and only if there exists no other action profile $\tilde{\mathbf{b}}$ such that for some m, $Y_m(\tilde{\mathbf{b}}) > Y_m(\mathbf{b}^*)$ and $Y_n(\tilde{\mathbf{b}}) \geq Y_n(\mathbf{b}^*)$, for $n \neq m$, where $Y_m(\cdot)$ is a utility function of user m in the context of game theory. In words, an action profile (or resource allocation) is Pareto optimal if there exists no other action profile that makes some user(s) better off without making the other user(s) worse off.

[6] An action profile $\mathbf{b}^* = (b^*_1, b^*_2, ..., b^*_M)$ attains an NE if no unilateral deviation in strategy by any single user is profitable, i.e., $Z_m(b^*_m, b^*_{-m}) \geq Z_m(\tilde{b}_m, b^*_{-m}), \forall m$, where $\tilde{b}_m$ is another strategy other than b^*_m of user m, b_{-m} is an action profile of all users except for user m, and $Z_m(\cdot)$ is a payoff function of user m in the context of game theory. In words, an action profile (or resource allocation) attains an NE if no player can do better by unilaterally changing its strategy.

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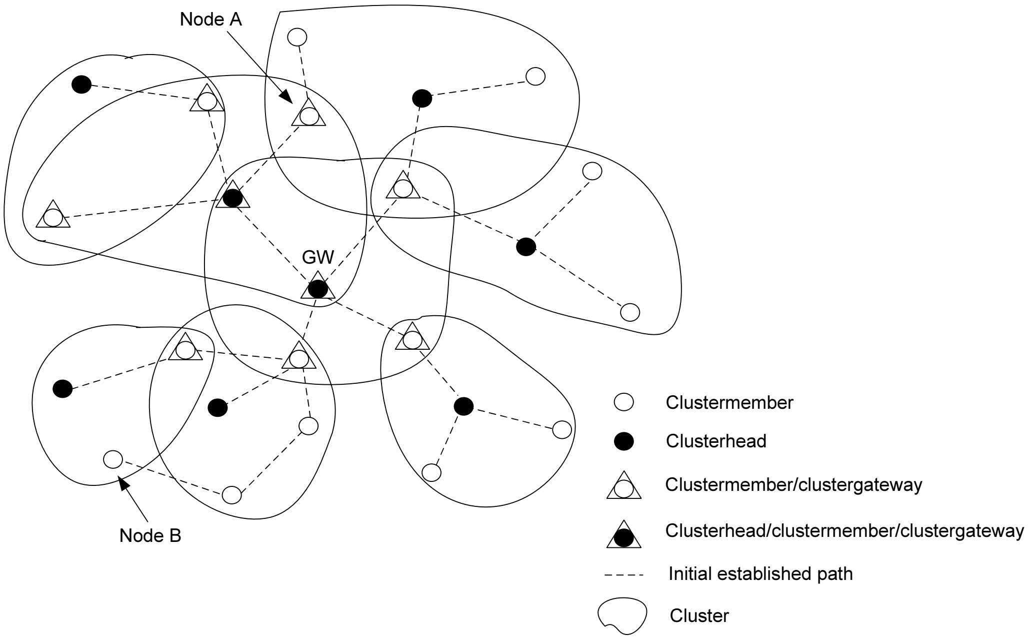

Fig. 3. An illustration of a clustered WMN with 25 nodes.

period and that of an OFF period both follow an exponential distribution. For simplicity, video traffic is characterized by a two-state ON-OFF model, where different incoming packets have different packet sizes, generating a variable-rate traffic in the ON state [26]. Data traffic is the background best-effort traffic and available anytime, which is assigned the lowest priority and does not have any rate requirements. Data packets can be transmitted whenever there are available resources. We consider that there are a voice source, a video source, and a data source residing at every node. Here, we employ the same MAC protocol for both intra-cluster and inter-cluster communications. The duration of a timeslot is 5ms, and hence the duration of a frame is $5(2+L)$ms. For intra-cluster MAC, each clusterhead collects the transmission requests and traffic demands from its clustermembers by polling them periodically in the control slot, and announces the resource allocation in the subsequent beacon. The polling is done in every 100ms. Similarly, for inter-cluster MAC, a clusterhead collects the transmission requests from its neighboring clusterhead(s) in the control slot, and announces the transmission schedule in the subsequent beacon. The timeslots and subcarriers allocated to a particular node are reserved for packet transmissions of real-time traffic in the DATA slots until the next polling. Moreover, for real-time traffic (i.e., voice and video), the higher the packet dropping rate that a traffic flow experiences, the higher the priority of the packets associated with that flow. A clusterhead grants the requests of those higher-priority packets first, facilitating QoS provisioning. Both the polling and the beacon packet transmissions are assumed error-free. We perform the simulations for 1,000 runs and average the results, where each simulation run sustains 5,000 frames.

The performance measurements are defined as follows:

TABLE I
RELATIONSHIP OF THE NUMBER OF WIRELESS NODES AND THE AVERAGE NUMBER OF CLUSTERHEADS

Number of wireless nodes	25	50	100	200	400
Average number of clusterheads	8.1	17.2	33.7	67.1	98.3

- System throughput – the sum of the throughputs obtained over all the links in the WMN.
- Frequency reuse ratio – the average number of times that a subcarrier is used simultaneously per DATA slot.
- Packet delay – the interval between the instant that a packet is generated at a source node and the instant that packet is successfully received by the gateway.

A. *QoS-aware Node Clustering*

We first study the performance of our proposed QoS-aware node clustering algorithm with $N = 1024$ and $B^{\max} = N/4$. After discovering the neighbors, every node establishes an initial shortest path to the gateway according to the condition given in (1). With CAC in place, each node can estimate the traffic load. The proposed node clustering algorithm is then carried out. Fig. 3 illustrates a simulation result for the cluster structure of a WMN with 25 nodes. Since a clusterhead selects some of its 1-hop neighbors as its clustermembers in this work, the WMN only consists of 1- and 2-clusters. The relationship of the number of nodes and that of clusterheads is given in Table I.

We then compare the system performance in terms of packet delay and throughput of the proposed scheme for the initial path establishment (named *proposed*) with the scheme for random shortest path establishment (named *random*) and

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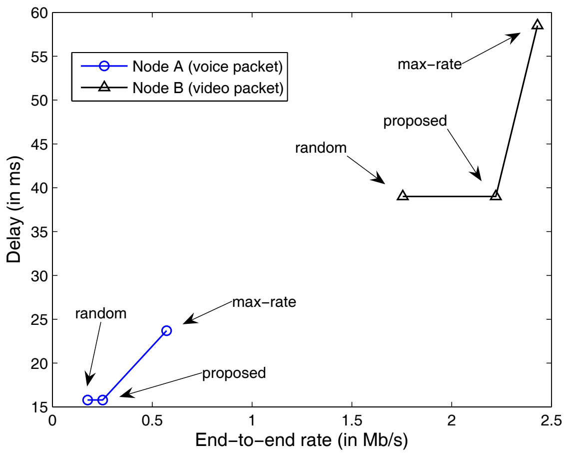

Fig. 4. Packet delays of the real-time traffic using the proposed scheme, the random scheme, and the max-rate scheme vs. the end-to-end rate for Node A and Node B shown in Fig. 3.

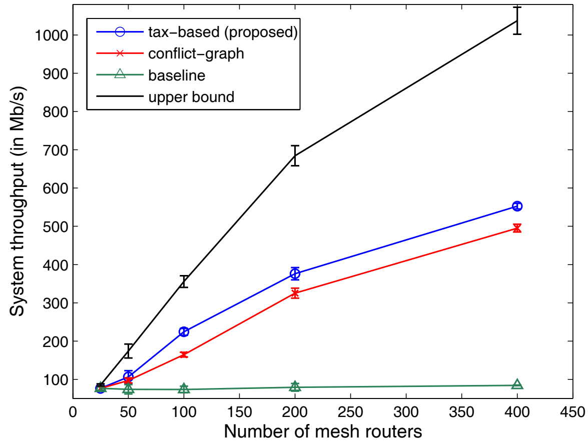

Fig. 5. System throughputs of the proposed approach, the conflict-graph approach, the baseline approach, and the upper bound vs. the number of mesh routers (where $N = 1024$ and $B^{max} = N/4$).

the scheme for path establishment that gives the maximum end-to-end rate among all possible paths (named *max-rate*). The delay-throughput performance comparison of the three schemes for Node A and Node B (in Fig. 3) is depicted in Fig. 4. Notice that the same node clustering algorithm with subcarrier allocation is employed for the three schemes. As seen, using the max-rate scheme for path establishment, both voice packets at Node A and video packets at Node B attain the largest end-to-end data rate (or throughput) at the cost of packet delay. Although both the proposed and random schemes result in the smallest packet delays, the proposed approach achieves higher end-to-end rates. The improvement of the proposed approach over the random approach, however, is not substantial because routing is not taken into consideration. The amelioration is expected to be larger if node clustering, subcarrier allocation, and routing are jointly considered. Nonetheless, the proposed condition for initial path establishment results in a good tradeoff between the packet delay and the end-to-end rate. Other system performance (e.g., packet dropping rates) in regards to intra-cluster resource allocation are reported in [27].

B. Tax-based Subcarrier Allocation

Here, we evaluate the performance of the proposed tax-based subcarrier allocation in terms of system throughput and frequency reuse ratio in a clustered WMN with $N = 1024$ and $B^{\max} = N/4$. For comparison, we consider a baseline approach where there is no frequency reuse and an approach using an interference conflict graph [15]. Notice that, for the approach using an interference conflict graph, the adjacent links (or vertices) in an interference conflict graph cannot use the same subcarrier(s). In the simulations, the same node clustering algorithm and the same value of $B^{\max}$ are applied to all these approaches. To further validate our simulation results, an upper bound of throughput performance is also plotted for reference, which is obtained by an exhaustive search. Notice that this upper bound is the maximum achievable system throughput achieved by the clusters without considering QoS constraints (i.e., best-effort traffic only).

1) Effect of M: Fig. 5 shows the system throughput versus the number of mesh routers. The standard deviations of the results are also plotted for reference. The system throughput curves for all three approaches are very close when the number of mesh routers is small, which is due to the fact that the network size is small and very few subcarriers can be reused in a small WMN. As the number of mesh routers increases (i.e., a larger WMN), our proposed approach clearly achieves a higher system throughput than the other two approaches, thanks to increased frequency reuse. The rationale of our proposed approach being superior to the conflict-graph approach stems from the fact that the interference conflict graph merely yields a condition that adjacent vertices cannot use the same subcarrier(s), thereby suppressing the potential and favorable concurrent transmissions. In contrast, the tax-based subcarrier allocation fosters frequency reuse to a greater extent. We also observe that, on average, our proposed approach conduces to a higher frequency reuse ratio than the conflict-graph approach (see Fig. 6). Notice that the difference between the throughput obtained by the tax-based approach and that by the conflict-graph approach becomes more substantial when the number of subcarriers increases (discussed in Section VI-B2). Without frequency reuse, the system throughput of the baseline approach is almost the same against the number of mesh routers, for each subcarrier can only be allocated once, leading to the worst throughout performance. The upper bounds for the system throughput obtained and frequency reuse ratio are plotted for reference in Fig. 5 and Fig. 6, respectively. As observed, there is an obvious performance gap between the system throughput obtained from the proposed approach and the upper bound, which is due to the fact that QoS provisioning and throughput improvement are conflicting with each other [8]. By taking QoS provisioning into account, some of the resources are reserved for the real-time traffic in the proposed approach, resulting in lower system throughput. On the other hand, our results show that frequency reuse is crucial for

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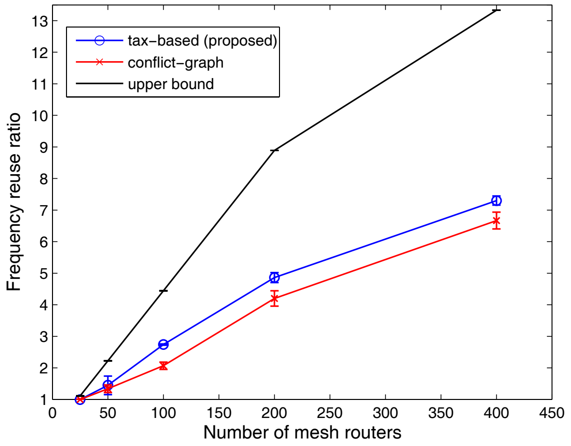

Fig. 6. Frequency reuse ratios of the proposed approach, the conflict-graph approach, and the upper bound vs. the number of mesh routers (where $N = 1024$ and $B^{max} = N/4$).

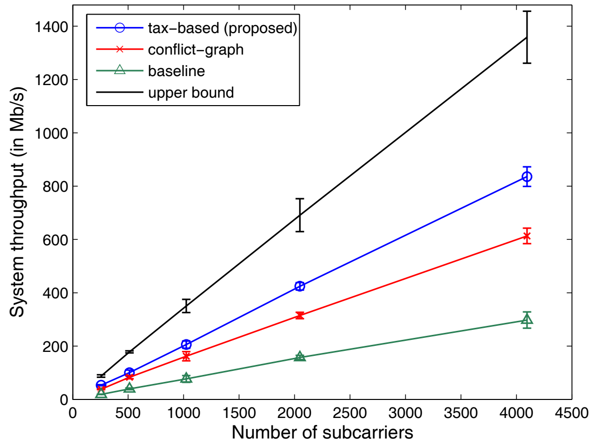

Fig. 7. System throughputs of the proposed approach, the conflict-graph approach, the baseline approach, and the upper bound vs. the number of subcarriers (where the number of mesh routers is 100 and $B^{max} = N/4$).

increasing the system throughput. Our proposed tax-based subcarrier allocation, therefore, can better utilize the network resources, thereby giving rise to a radio spectrum efficient WMN.

2) Effect of N: We consider the effect of the number of available subcarriers on the system performance by fixing the number of mesh routers to be 100 and $B^{\max} = N/4$. Fig. 7 shows the system throughput of all approaches versus the number of subcarriers. Since the number of subcarriers increases, the system throughput of all the approaches increases. As mentioned previously, the tax-based approach performs the best due to the increased frequency reuse. The upper bound of the system throughput is also plotted for reference. We also observe that the frequency reuse ratio achieved by the proposed algorithm is more or less the same with the number of subcarriers (i.e., at the level of 2.8). It shows that the frequency reuse ratio of the proposed approach is almost independent of the number of subcarriers available in the system.

3) Effect of $B^{\max}$: We investigate the system performance with different values of $B^{\max}$ by setting $N = 1024$ and the number of mesh routers to be 100. Figs. 8 and 9 depict the frequency reuse ratio and the system throughput versus the value of $B^{\max}$, respectively. Regarding the proposed approach, when $B^{\max}$ is small, each cluster gets only a handful of subcarriers. Hence, the chance of reusing the subcarriers is smaller, resulting in smaller frequency reuse ratio and system throughput. When $B^{\max}$ becomes larger, more subcarriers can be reused and so the system throughput increases greatly. However, when $B^{\max}$ reaches a certain value, both the frequency reuse ratio and system throughput start to drop. The reason is that too many subcarriers are allocated to a cluster, which causes some neighboring clusters to choose other available subcarriers and hence reduces the effectiveness of frequency reuse.

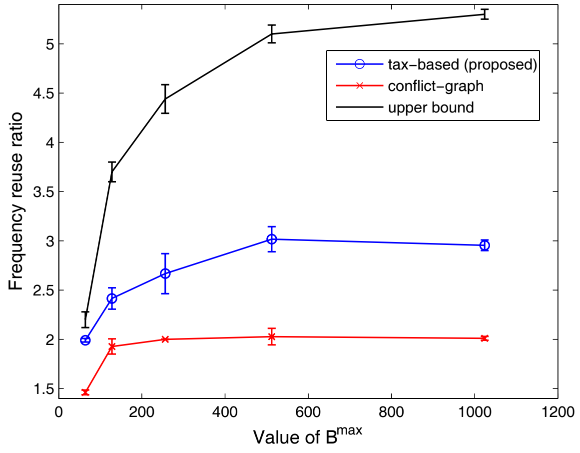

Fig. 8. Frequency reuse ratios of the proposed approach, the conflict-graph approach, and the upper bound vs. the value of B^{max} (where the number of mesh routers is 100 and $N = 1024$).

In fact, our results are comparable to the differences between fixed channel allocation (FCA) and dynamic channel allocation (DCA) in the context of cellular systems. Our proposed subcarrier allocation behaves like FCA when $B^{\max}$ is small and DCA when $B^{\max}$ is large. It is well-known that, in general, DCA exhibits superior performance compared to FCA in the case of non-uniform traffic distribution and/or low traffic load [18]. However, the performance of DCA degrades under heavy load conditions (e.g., large $B^{\max}$). Hybrid channel allocation (HCA) is shown to be the best performance compromise [18]. In our work, the traffic load is not evenly distributed and hence the system throughput improves when $B^{\max}$ increases. On the other hand, the traffic load in a cluster also increases with $B^{\max}$, as more clustermembers can be selected. When the traffic load reaches a certain threshold, the system throughput starts to decrease. Therefore, the value of $B^{\max}$ should be chosen carefully in order to achieve high system throughput. Concerning the system throughput obtained by the conflict-graph approach, it first goes up sharply as more subcarriers can be reused. As $B^{\max}$ increases, however, the system throughput of the conflict-graph approach decreases, although

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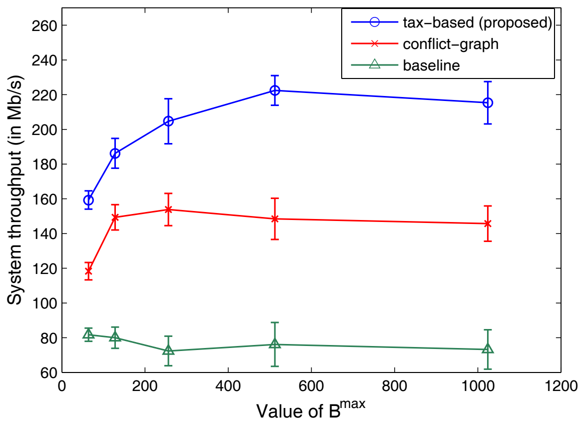

Fig. 9. System throughputs of the proposed approach, the conflict-graph approach, and the baseline approach vs. the value of B^{max} (where the number of mesh routers is 100 and $N = 1024$).

the frequency reuse ratio remains roughly the same from $B^{\max} = 128$ onward. That decline is based on the (large) aggregate interference generated from the transmissions outside the neighborhood. This result reasserts our claim discussed in Section I that the resource allocation solution deduced by a conflict-graph approach can reduce the system throughput in a large WMN. Thus, for the same frequency reuse ratio, in general, the system throughput obtained by the conflict-graph approach is less than that obtained by the proposed tax-based approach. An upper bound is also plotted for reference in Fig. 8. Since more subcarriers can be chosen in a cluster, the curve goes up with the value of $B^{\max}$, the idea of which is similar to the notion of *multi-user diversity*. On a different note, we observe that, when $B^{\max}$ is very small or very large, some clusters are “starved or almost starved", where no or very few subcarriers are allocated to those (lower priority) clusters. The value of $B^{\max}$, therefore, should be carefully chosen to ensure that a clustered WMN can operate efficiently.

VII. CONCLUSIONS AND FURTHER WORK

In this paper, we have proposed a novel resource allocation scheme for the problem of joint node clustering and subcarrier allocation in WMNs. The proposed node clustering algorithm is QoS-aware, and the proposed tax-based subcarrier allocation is shown to effectively enhance frequency reuse and ameliorate the system throughput. Our approach is also shown to provide a good performance balance between packet delay and end-to-end data rate for real-time traffic, leading to a viable candidate to support QoS. The proposed resource allocation solution is Pareto optimal and hence utilizes network resources efficiently. In addition, our analysis reveals that how to allocate resources in a sequential fashion affects a performance balance between QoS provisioning and throughput maximization. Simulation results demonstrate that the value of $B^{\max}$ should be determined carefully in order to achieve high system throughput.

For further work, the issue of routing should be taken into consideration, for resource allocation in the network layer affects that in the MAC layer and vice versa. Deployment of multiple gateways effectively and efficiently in WMNs is vital in practice. How to incorporate the gateway deployment problem into our proposed joint node clustering and subcarrier allocation approach is an open research problem. Besides, we will generalize the proposed node clustering algorithm to consider the case where a clusterhead can select nodes beyond 1 hop as its clustermembers. As discussed, the system performance of clustered WMNs is contingent on the value of $B^{\max}$. How to acquire the optimum value of $B^{\max}$ analytically is crucial but left for further work.

APPENDIX: TAX INTERPRETATION OF KKT CONDITIONS

Consider the following objective function of a system throughput maximization problem

$$\max_{\mathbf{a},\mathbf{p}} \left\{ \sum_m \sum_n \sum_l a^l_{m,n} r^l_{m,n} \right\} \tag{A-1}$$

$$\text{subject to } p^l_{m,n} \geq 0, \forall m, n, l \tag{A-2}$$

$$\sum_n p^l_{m,n} \leq P^{\max}_m, \forall m, l \tag{A-3}$$

$$a^l_{m,n} \in \{0, 1\}, \forall m, n, l. \tag{A-4}$$

By relaxing the constraint (A-4), i.e., $0 \leq a^l_{m,n} \leq 1, \forall m, n, l$, consider part of the KKT conditions of the relaxed problem with respect to $p^l_{m,n}$

$$\frac{\partial}{\partial p^l_{m,n}} \left(\sum_m \sum_n \sum_l a^l_{m,n} r^l_{m,n} \right) = \mu^l_m - \alpha^l_{m,n}, \forall m, n, l \tag{A-5}$$

$$\alpha^l_{m,n} p^l_{m,n} = 0, \forall m, n, l \tag{A-6}$$

$$\mu^l_m \left(\sum_n p^l_{m,n} - P^{\max}_m \right) = 0, \forall m, l \tag{A-7}$$

where $\alpha^l_{m,n} (\geq 0)$ and $\mu^l_m (\geq 0)$ are the Lagrange multipliers for the constraints (A-2) and (A-3), respectively. Condition (A-5) can be written as (A-8) and (A-9). Assuming $\sum_n \sum_l a^l_{k,n} r^l_{k,n} - R^d_k \geq \epsilon$, condition (A-9) can be written as

$$a^l_{m,n} \frac{\partial r^l_{m,n}}{\partial p^l_{m,n}} + \sum_{k \neq m} \frac{\partial}{\partial p^l_{m,n}} (U_k(\mathbf{a}, \mathbf{p}, R^d_k)) = \mu^l_m - \alpha^l_{m,n}, \forall m, n, l. \tag{A-10}$$

Let $T^l_{km,n} = -\frac{\partial U_k(\mathbf{a},\mathbf{p},R^d_k)}{\partial p^l_{m,n}}$. Viewing $T^l_{km,n}$ as tax paid by the m^{th} clusterhead for generating interference to the k^{th} clusterhead over the n^{th} subcarrier on the l^{th} timeslot, condition (A-10) is one of the (necessary) conditions for optimality for the relaxed problem. In other words, each clusterhead optimizes its power allocation and subcarrier allocation to maximize its payoff function, defined as

$$S^l_{m,n} \left(a^l_{m,n}, p^l_{m,n} \right) = a^l_{m,n} r^l_{m,n} - p^l_{m,n} \sum_{k \neq m}^{M} T^l_{km,n}, \forall m, n, l. \tag{A-11}$$

As a result, for each subcarrier and each timeslot, each clusterhead is to maximize the difference between its throughput obtained minus its lump-sum tax paid to the other clusterheads in the mesh backbone due to the induced interference.

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$$\frac{\partial}{\partial p^l_{m,n}}\Big(\sum_n \sum_l a^l_{m,n} r^l_{m,n}\Big) + \sum_{k\neq m} \frac{\partial}{\partial p^l_{m,n}}\Big(\sum_n \sum_l a^l_{k,n} r^l_{k,n}\Big) = \mu^l_m - \alpha^l_{m,n}, \forall m,n,l \tag{A-8}$$

$$\Rightarrow \qquad a^l_{m,n}\frac{\partial r^l_{m,n}}{\partial p^l_{m,n}} + \sum_{k\neq m} \frac{\partial}{\partial p^l_{m,n}}\Big(\sum_n \sum_l a^l_{k,n} r^l_{k,n} - R^d_k\Big) = \mu^l_m - \alpha^l_{m,n}, \forall m,n,l. \tag{A-9}$$

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