Joint QoS-aware Node Clustering and Tax-based Subcarrier Allocation for Wireless Mesh Networks

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Abstract—In this paper, we propose a novel node clustering algorithm with effective tax-based subcarrier allocation tailored for wireless mesh networks with quality-of-service support. With effective 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 performance tradeoff between packet delay and end-to-end transmission rate.

I. INTRODUCTION

Wireless mesh networking has emerged as a promising technology for future broadband wireless access [1,2]. 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 residential areas has been attracting a plethora of attentions, where mesh routers can be set up at premises in the neighborhood, rendering a resilient mesh backbone, and providing an all-wireless ambience.

Concerning the capacity of a wireless network, the throughput of a node decreases with the number of wireless nodes. The implication is that a node should only communicate with nearby nodes, thereby favoring clustering [3]. In fact, clustering is an effective way to manage a large wireless network [4]. Although clustering has been researched in the context of sensor networks and mobile ad hoc networks (MANETs) in recent 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 an all-wireless environment, rendering a high-speed and efficient mesh backbone offering broadband wireless access 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) [5]. 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 requisite of high efficiency of WMNs with QoS support. Thus, a new 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 [6]. In the literature, there exists a wide range of channel assignment schemes for wireless networks [7]–[10]. However, most of the existing approaches are not QoS-aware. An interference conflict graph is usually adopted to devise a collision-free scheduling in a two-hop neighborhood [8,9]. Yet, packet scheduling deduced by the interference conflict graph may not guarantee collision-free transmissions in a large-scale WMN, where the aggregate interference coming from the transmissions outside the neighborhood can be very large. Combining topology control with channel assignment is vital for better network management. TiMesh is proposed to avoid a ripple effect [10], but hampers the notion of frequency reuse, underutilizing the scarce radio resources. Therefore, a novel distributed channel allocation strategy tailored for a clustered mesh backbone is crucial.

With clustering, interference control and hence frequency reuse can be facilitated by channel allocation via clusterheads. 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) [6]. In this paper, we propose a QoS-aware clustering algorithm with tax-based subcarrier allocation tailored for WMNs. Our proposed approach is shown to achieve a high system throughput, and provide a good performance tradeoff between packet delay and end-to-end transmission rate for real-time traffic.

II. SYSTEM MODEL

Consider a WMN for suburban 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 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 at one side of the suburban residential area of interest. We assume that mesh routers are non-mobile and the channel gains can be estimated accurately. Traffic is assumed to be vertical, where traffic flows are traversed 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. Note that how to perform intra-cluster resource allocation to an individual node (e.g., packet scheduling [6]) is beyond the scope of this paper. 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.

III. JOINT QoS-AWARE CLUSTERING AND TAX-BASED SUBCARRIER ALLOCATION

We propose a QoS-aware 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 for the joint QoS-aware clustering and subcarrier allocation problem 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 [11]). However, the node clustering problem and the subcarrier allocation problem are coupled. To reduce the computational complexity, our approach is to solve the clustering problem and to allocate subcarriers in succession alternatively (as discussed in Section III-D).

Considering the factors of system capacity, QoS provisioning, burden on clusterheads, delay of packet delivery, and the austere suburban environment, we formulate the clustering problem by setting an upper bound on the subcarriers allocated to a cluster. Denote $B_{\text{max}}$ as the upper bound of allocated channels in a cluster. The bound caps the maximum traffic load in a cluster and hence the burden on a clusterhead, controls the cluster size to a certain extent, and facilitates packet scheduling assisted by clusterheads. The proposed approach for the joint node clustering and subcarrier allocation problem includes: 1) neighbor discovering; 2) initial route establishment; 3) traffic load estimation; 4) node clustering; and 5) subcarrier allocation.

A. Neighbor Discovering

A mesh router can discover its neighbor(s) via any routing protocol. 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 Route Establishment

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

$$\max_{m} \{ \min_{e} \{ \bar{R}_m(p_{\text{th}}^m) \} \}, \forall m \tag{1}$$

where $\bar{R}_m(y) = \ln \left( 1 + \frac{G_m(y)P_{\text{max}}}{\eta} \right)$ can be viewed as a data rate obtained at the $m^{th}$ node on the $y^{th}$ link with $G_m(y)$ being the (constant) channel gain on the link, $P_{\text{max}}$ being the maximum power constraint of the $m^{th}$ node, and $\eta$ being the noise power. The effect of co-channel interference is discussed in Section III-E. The objective given in (1) is to maximize the minimum of all link rates (i.e., maximize the end-to-end rate) along the shortest path of a node to the gateway. This initial path establishment criterion ends in a tree architecture for a WMN (See Fig. 1).

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. 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 crucial for supporting QoS in intra-cluster resource allocation [6].

D. Node Clustering Algorithm

We assume that clusterheads can operate in a dual-power mode [5], where higher power levels are reserved for inter-cluster signaling whereas lower power levels are for intra-cluster communications. Define an $I$-tier cluster as a cluster

\footnotetext[2]{In case direct inter-cluster transmissions fail (e.g., due to path loss), we assume that cooperative communications [12] are in place such that the inter-cluster signaling is always feasible.}
formed at the $I^{th}$ clustering level from the gateway. The proposed 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 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 III-E. If the QoS demand of the selected node cannot be satisfied, go to Step 6.

Step 4: If the total number of subcarriers acquired is less than or equal to $B_{\text{max}}$ 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 cluster 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 $B_{\text{max}}$.

Step 6: Repeat Steps 2-5 with another $I$-tier clusterhead elected randomly by the $(I-1)$-tier clusterhead(s), if any.

Step 7: The $I$-tier clusterhead(s) is/are to signal its/their closest unassigned neighbor(s) (e.g., 1-hop or 2-hop neighbors) and to elect the clusterhead(s) at the $(I+1)$-tier. If a clusterhead can be elected, set $I=I+1$ and go back to Step 2.

Step 8: 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 node that is a 1-hop neighbor of more than one clusterhead can be viewed as a clustergateway.

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. In this work, for simplicity, clusterheads only select their 1-hop nodes as their clustermembers. Thus, a clustered WMN will consist of 1- and/or 2-clusters, and different clusters may have different sizes. Further, clusterheads form a connected graph.

**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 clusters may have different sizes. Further, clusterheads form a connected graph.

3A $k$-cluster is defined as a subset of nodes which are mutually reachable by a path of length at most $k$-hops for an integer $k$. 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 system capacity. Hence, the above solution can be far from the optimal solution(s). In the following, we view a clusterhead as the representative of its cluster.

We propose a novel subcarrier allocation scheme motivated by Karush-Kuhn-Tucker (KKT) optimality conditions [13]. Denote $M$ as the number of clusterheads, $N$ as the number of available subcarriers (i.e., $B_{\text{max}} \leq N$), and $L$ as 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

$$S_{m,n}^l (a_{m,n,l}, p_{m,n}) = a_{m,n,l} - \sum_{k \neq m}^{M} a_{k,n,l} T_{km,n}^l$$

where $a_{m,n,l} = \ln(1 + \gamma_{m,n,l})$ represents the obtained 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) $\gamma_{m,n,l}$. $a_{m,n,l}$ is the indicator of allocating the $n^{th}$ subcarrier to the $m^{th}$ clusterhead on the $l^{th}$ timeslot, i.e., $a_{m,n,l} \in \{0,1\}$, $p_{m,n}$ is the transmit power, and $T_{km,n}^l$ is tax paid by the $m^{th}$ clusterhead for generating interference to the $k^{th}$ node over the $n^{th}$ subcarrier on the $l^{th}$ timeslot, defined as

$$T_{km,n}^l = -\frac{\partial U_k(a,p,R_k^l)}{\partial p_{m,n}}$$

where $U_k(a,p,R_k^l)$ is the utility function of the $k^{th}$ clusterhead with $R_k^l$ being the QoS demand of the $k^{th}$ clusterhead, $a = [a_{k,n,l}]_{M \times N \times L}$ and $p = [p_{k,n}]_{M \times N \times L}$. The SINR of the $m^{th}$ clusterhead over the $n^{th}$ subcarrier on the $l^{th}$ timeslot is given by $\gamma_{m,n,l} = \frac{\sigma^2 G_{m,n}T_{km,n}^l}{\sigma \sum_{k \neq m} G_{k,n} T_{km,n}^l + \eta}$, where $G_{m,n}$ is the channel gain from the $k^{th}$ clusterhead to the $m^{th}$ clusterhead over the $n^{th}$ subcarrier, $\varphi$ is a bit-error-rate measure, and $\sigma$ is the cross-correlation factor between any two signals. The utility function of the $k^{th}$ clusterhead is defined as

$$U_k(a,p,R_k^l) = \left\{ \begin{array}{ll} \sum_l \sum_n a_{k,n,l} p_{k,n,l} - R_k^l & R_k^l \geq \epsilon \\ 0, & \sum_l \sum_n a_{k,n,l} p_{k,n,l} - R_k^l < \epsilon \end{array} \right.$$
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 distributed 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 [6]. Thus, the criterion of subcarrier allocation can be deduced as follows: For the m<sup>th</sup> node on the t<sup>th</sup> timeslot, choose n<sup>*</sup> such that

\[ n^* = \arg \max_n \{ s_{m,n}^i (a_{m,n}^j) \} \] (5)

and set \( a_{m,n}^i = 1 \). Note that information exchange among clusterheads is triggered whenever there is any change in subcarrier allocation.

F. Complexity

Assume that message signaling among clusterheads is perfect such that they 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 clustering algorithm given in Section III-D is on the order of \( O(MNLB^{\text{max}}) \). With the help of effective data structure (e.g., binary tree implementation), the complexity can be further reduced to the order of \( O(MLB^{\text{max}} \log_2 N) \).

IV. PERFORMANCE EVALUATION

We consider a WMN with mesh routers randomly located in a 3km × 3km coverage area. A routing protocol is assumed in place such that the neighbors of each node can be identified in advance. Parameters for performance evaluation are chosen as follows: \( \varphi = 1 \), \( \sigma = 1 \), \( \eta \sim N(0, 10^{-12} \text{W}) \), \( P_{m,n}^{max} = 1 \text{W} \), \( \forall m, N = 25M, L = 4 \), and \( B^{\text{max}} = N/4 \). The maximum transmission rate of each subcarrier is 100Kbps. We adopt the channel model suggested in [14].

We use the traffic models for voice, video, and data, the MAC protocol, and CAC as described in [6]. Here, we use the 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, the 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 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.

The performance measurements are defined as follows:

- **System throughput** – the sum of the throughputs obtained in the entire 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 Clustering

We first study the performance of our proposed QoS-aware clustering algorithm. After discovering the neighbors, every node establishes an initial shortest route 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. An illustration of the cluster structure of a WMN with 24 mesh routers is depicted in Fig. 2. The WMN consists of 1- and 2-clusters, and different clusters may have different sizes.

We then compare the system performance in terms of packet delay and throughput of the proposed scheme for initial path establishment (named **proposed**) with the scheme for random shortest path establishment (named **random**) and the scheme for path establishment that gives the maximum end-to-end rate (named **max-rate**). The delay-throughput performance comparison of the three schemes for Node A and Node B shown in Fig. 2.

Fig. 2. An illustration of a clustered WMN with 24 mesh routers.

Fig. 3. Comparison of the real-time packet delay of the proposed scheme, the random scheme, and the max-rate scheme vs. the end-to-end throughput for Node A and Node B shown in Fig. 2.
Clearly, our proposed approach achieves a significantly higher frequency reuse ratio. Fig. 4 shows the approach where there is no frequency reuse and an approach based on subcarrier allocation in terms of system throughput and packet delay. For comparison, we consider a baseline approach conduces to a higher frequency reuse ratio than the conflict-graph approach (see Fig. 5). The results confirm the fact that employing the notion of frequency reuse is imperative for increasing the system throughput. Our proposed tax-based subcarrier allocation, therefore, can better utilize the network resources, giving rise to a radio spectrum efficient WMN.

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. For comparison, we consider a baseline approach where there is no frequency reuse and an approach using an interference conflict graph [9]. Fig. 4 shows the system throughput versus the number of clusterheads. The standard deviations of the results are also plotted for reference. Clearly, our proposed approach achieves a significantly higher system throughput than the other two approaches. The system throughput of all the approaches increases with the number of clusterheads, for the number of available subcarriers increases. The system throughput procured in our approach to subcarrier allocation, however, rises almost exponentially with the number of clusterheads. 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 over the same subcarrier(s). 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. 5). The results confirm the fact that employing the notion of frequency reuse is imperative for increasing the system throughput. Our proposed tax-based subcarrier allocation, therefore, can better utilize the network resources, giving rise to a radio spectrum efficient WMN.

V. CONCLUSION

In this paper, we have proposed a novel QoS-aware clustering algorithm with effective tax-based subcarrier allocation tailored for WMNs. The proposed taxation method is shown to be vital to bolster frequency reuse, effectively ameliorating the system throughput for a mesh backbone. In addition, our proposed scheme provides a good performance balance between packet delay and end-to-end data rate for real-time traffic, leading to a viable candidate for QoS provisioning. Further work includes study of multi-path transmissions and investigation of optimal $B_{\text{max}}$ value(s).

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