QoS-Driven Node Cooperative Resource Allocation for Wireless Mesh Networks with Service Differentiation

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Abstract—Node cooperation has been demonstrated promising in ameliorating system performance for wireless networks. To effectively and efficiently provision quality-of-service (QoS) at the packet level in wireless mesh networks (WMNs) supporting heterogeneous traffic, medium access control (MAC)-layer resource allocation and service differentiation are imperative. In this paper, we propose a low-complexity node cooperative resource allocation approach for WMNs, taking subcarrier allocation, partner allocation, QoS assurance, and service differentiation into account. With beneficial node cooperation, our proposed approach is shown to be promising in provisioning QoS and increasing system throughput. The proposed approach also achieves Pareto optimality, making efficient use of network resources.

I. INTRODUCTION

Wireless mesh networking has emerged as a promising solution for future broadband wireless access [1]. Wireless mesh networks (WMNs) generally comprise gateways, mesh routers, and mesh clients, organized in a three-tier hierarchical architecture [1]. Recently, wireless mesh networking for suburban and rural residential areas has been attracting a plethora of attentions (e.g., Wray WMNs [2]).

As ameliorating throughput in a WMN is the key to the success of providing an all-wireless ambience, different resource allocation strategies have been proposed to provide a high-speed mesh backbone with quality-of-service (QoS) assurance (e.g., [3]). To further enhance the system performance, cooperative diversity or node cooperation can be employed to realize spatial diversity gain by way of a virtual antenna array formed by multiple wireless nodes in a distributed fashion [4,5]. Compared to traditional co-located multi-antenna techniques, node cooperation can provide a comparable spatial diversity gain without imposing extra hardware complexity.

In the literature, there exists a rich body of research work on node cooperation [5]–[11]. Besides information-theoretic studies [6,7], most recent work on the topic of node cooperation can be classified into two groups. The first group focuses on the design and performance evaluation of distributed space-time coding (e.g., [5,8]). With appropriate detection techniques, an additional diversity order can be attained in time-varying wireless channels [9]. However, most node cooperation strategies based on distributed space-time coding conceive the existence of pure relay nodes, which is not always feasible in practical WMNs. The second group considers relay selection and resource allocation. Partner matching algorithms based on graph theory are proposed in [10], the objective of which is to optimize the energy efficiency; however, energy consumption is not a concern in WMNs. To achieve fairness in an orthogonal frequency division multiplexing (OFDM) system, a max-min cooperative subcarrier allocation approach is proposed in [11]. However, medium access control (MAC)-layer service differentiation is taken no notice of, for only a single class of traffic is considered in most of the existing work. Further, the issue of QoS support and provisioning is not addressed properly, and MAC-layer packet scheduling is mostly neglected, which stems from the fact that their research work only focuses on the issues related to the physical layer.

In this work, we propose an efficient and effective approach for the problem of node cooperative resource allocation for WMNs with QoS support and MAC-layer service differentiation. Instead of designing a node cooperation protocol for WMNs, we assume that there is an efficient cooperation protocol in place, and we study the impact of node cooperative resource allocation on the system performance. Simulation results show that our proposed approach achieves higher throughputs than a baseline approach. The proposed approach is also shown to be effective in packet-level QoS provisioning as compared to a throughput-oriented counterpart. Further, our approach achieves Pareto optimality, making efficient use of meager resources. Due to space limitations, most proofs are omitted in this paper.

II. SYSTEM MODEL

We consider an OFDM-based WMN for suburban or rural residential areas, consisting of wireline gateways attached to the Internet backbone and a number of mesh routers and mesh clients scattered around, rendering a hierarchical multi-hop network (see Fig. 1). Mesh routers are assumed non-mobile and hence the channel gains can be estimated accurately. We assume that traffic traverses from mesh clients to mesh routers to the gateway only. We consider that each mesh node is equipped with one transceiver having an omni-directional antenna, so that it cannot transmit and receive at the same time. To strive for a stable and scalable wireless network, node clustering is shown effective in providing network stability and system throughput increase. Here, we assume that there is an efficient node clustering algorithm in place for the wireless mesh backbone (e.g., [3]) so that the notion of frequency reuse is taken into consideration, the co-channel interference level is bounded, and each cluster is assigned a set of subcarriers. Two classes of traffic are considered, namely 1) rate-guaranteed (RG) traffic and 2) best-effort (BE) traffic. In particular, the RG traffic has a minimum data rate requirement and a delay bound, whereas the BE traffic has no QoS requirement.

As
regards aggregate traffic flows, a mesh node is treated as an RG node if any of its incoming traffic flows belongs to the RG traffic. We consider a synchronized WMN. Time is partitioned into frames, each of which is further divided into a beacon slot, a control slot, and $L$ DATA slots. Each RG node estimates the traffic load (i.e., both the local traffic load and the relay traffic load) by averaging the rate requirement over a fixed estimation window (e.g., 100ms) on a regular basis. In the control slot, a clusterhead collects the traffic demand from its clustermembers at the beginning of each active resource allocation interval (i.e., by polling periodically). Then, the clusterhead executes our proposed two-phase node cooperative resource allocation (to be discussed in Section IV) and announces a resource allocation decision in the next beacon slot. In the DATA slots, mesh nodes transmit their information according to the resource allocation decision. Call admission control (CAC) is assumed in place such that the QoS requirements of an admitted RG traffic flow can be met. We also assume that the transmission pairs among mesh nodes can be predetermined in advance. Since the OFDM technology is employed, simultaneous transmissions over different subcarriers are allowed in the WMN.

In this work, we consider non-altruistic non-reciprocal node cooperation, meaning that there is no pure relay node in the system and one node might assist its neighbor but not necessarily receive help from that neighbor. Node cooperation is triggered as long as it is feasible and beneficial for improving system performance. In the presence of multiple available partners, a node simply selects the one in which the achievable throughput is maximized, for choosing the (single) best partner is sufficient to achieve the full diversity order [12]. We employ the Cooperation Protocol I suggested in [4] as our node cooperation strategy throughout this paper: Consider a WMN consisting of three nodes, namely Node $S$, Node $R$, and Node $D$. Node $S$ is to transmit data to Node $D$, while Node $R$ is viewed as a relay to help Node $S$ forward the data to Node $D$. In the first timeslot, Node $S$ transmits a packet to both Node $R$ and Node $D$. In the second timeslot, Node $R$ forwards the packet received from Node $S$ to Node $D$, while Node $S$ transmits another packet to Node $D$. In this paper, we consider the decode-and-forward (DF) mode of cooperation (i.e., regenerative mesh nodes). In the case of non-altruistic node cooperation, however, power allocation is imperative as we envision that part of the transmit power of a node is dedicated to transmitting their own data and the rest of the transmit power is dedicated to relaying the data from other nodes, to be discussed in Section IV-B.

### III. QoS-driven Node Cooperative Resource Allocation

#### A. Problem Formulation

There are various system constraints associated with the node cooperative resource allocation problem for WMNs. Let $M$, $N$, and $L$ denote the number of mesh nodes, the number of subcarriers available, and the number of timeslots (i.e., DATA slots) in a frame, respectively. The sum of the (non-negative) transmit power of each mesh node on the (allocated) subcarriers is bounded by a maximum power level:

$$\sum_{n=1}^{N} v_{m,n}^l \leq P_{m}^{\text{max}}, \forall m, l \quad \text{and} \quad v_{m,n}^l \geq 0, \forall m, n, l$$

where $v_{m,n}^l$ is the transmit power of the $m$th node over the $n$th subcarrier on the $l$th timeslot and $P_{m}^{\text{max}}$ is the maximum power constraint of the $m$th node. With the help of node clustering, a number of subcarriers are allocated to each cluster. Here, we consider the case where each subcarrier can only be allocated to one transmission link without cooperation or at most two transmission links with node cooperation (i.e., a direct link and an assisted link) in a cluster. If node cooperation is employed, both a source node and its partner transmit data over the same subcarrier(s). In addition, as mentioned in Section II, since choosing the best partner is sufficient (in terms of outage performance), a node can have at most one partner at a time on condition that the node cooperation is favorable. The aforementioned constraints can be formulated as follows:

$$\sum_{m=1}^{M} c_{m,n}^l \leq 1 + \sum_{u=1, u \neq m}^{M} z_{mu}, \forall n, l$$

$$\sum_{m=1}^{M} z_{mu} \leq 1, \forall u \quad \text{and} \quad \sum_{u=1, u \neq m}^{M} z_{mu} \leq 1, \forall m$$

$$c_{m,n}^l = c_{m,n}, \quad \text{when} \quad z_{mu} = 1, \forall m, u, n, l$$

$$c_{m,n}^l \in \{0, 1\}, \forall m, n, l \quad \text{and} \quad z_{mu} \in \{0, 1\}, \forall m, u$$

where $c_{m,n}^l$ is the indicator of allocating the $n$th subcarrier to the $m$th node on the $l$th timeslot and $z_{mu}$ is the indicator of node cooperation offered to the $m$th node by the $u$th node. Notice that, in general, $z_{yx} \neq z_{xy}, \forall x, y$, as the node cooperation considered in this work is non-reciprocal (i.e., asymmetric). For the sake of notational convenience, we set $z_{mm} = 1, \forall m$. Providing node cooperation is in place, the transmit power of
a node will be split into two segments, where one segment is dedicated to its direct transmissions and the other is devoted to the assisted transmissions for its partner:

$$\sum_{m=1}^{M} z_{mu} a_{mu} = 1, \forall u \quad \text{and} \quad 0 \leq a_{mu} \leq 1, \forall m, u$$  \hspace{1cm} (6)$$

with $a_{mu}$ being the normalized portion of the total transmit power of the $u^{th}$ node allocated for the $m^{th}$ node’s transmissions. As mentioned in Section II, we consider two classes of traffic in this work, namely RG traffic and BE traffic. Let $\mathcal{M}_1$ and $\mathcal{M}_2$ be the set of RG nodes and that of BE nodes, respectively, i.e., $\mathcal{M} = |\mathcal{M}_1| + |\mathcal{M}_2|$. In our problem formulation, we take the minimum rate requirements of RG nodes in the current frame, if any, into account:

$$R_m (c, v, a, z) \geq R_m^d, \forall m$$  \hspace{1cm} (7)$$

where $p_m^d$ is the (instantaneous) transmission rate demand of the $m^{th}$ node, which can be computed by [5]

$$R_m (c, v, a, z) = \sum_{n=1}^{N} \sum_{l=1}^{L} c_{m,n} \log_2 \left( 1 + \frac{g_{m,n} v_{l,m,n}}{\sigma_n^2} \right)$$

$$+ \sum_{u=1, u \neq m}^{M} z_{mu} a_{mu} g_{m,n} v_{l,u,n}$$  \hspace{1cm} (8)$$

where $c_i = \left[ c_{m,n} \right]_{M \times N \times L}$, $v = \left[ v_{l,m,n} \right]_{M \times N \times L}$, $a = \left[ a_{mu} \right]_{M \times M}$, $z = \left[ z_{mu} \right]_{M \times M}$, and $g_{m,n} = G_{m,n}/\sigma_n^2$ with $G_{m,n}$ being the channel gain from the $u^{th}$ node to the receiver of the $m^{th}$ node’s transmissions over the $n^{th}$ subcarrier on the $l^{th}$ timeslot and $\sigma_n^2$ the aggregate noise-plus-co-channel interference power on the $n^{th}$ subcarrier. Notice that the constraints (2) and (4) are (implicitly) incorporated in (8). In order to facilitate QoS provisioning, resource reservation is indispensable [13], where partners, subcarriers, and timeslots allocated to mesh nodes are reserved for their transmissions in our MAC-layer packet scheduling, to be discussed in Section V-A. With the aforesaid system constraints, different objective functions can be considered. Here, we employ the well-known utility maximization framework to abstract our objective function. Denote $U_m (R_m (c, v, a, z) | \Theta)$ the utility function of the $m^{th}$ node and $\Theta$ the utility selector of the WMN of interest, $\Theta \in \{1, 2\}$. The objective function is given by

$$\max_{c,v,a,z} \left\{ \sum_{m=1}^{M} U_m (R_m (c, v, a, z) | \Theta) \right\}$$

$$= \begin{cases} \sum_{m=1}^{M} R_m (c, v, a, z), & \text{when } \Theta = 1 \\ \sum_{m=1}^{M} - \ln \left( \frac{R_m (c, v, a, z)}{A} \right)^{\kappa}, & \text{when } \Theta = 2 \end{cases}$$  \hspace{1cm} (9)$$

where $A$ is a sufficiently large constant such that $0 < R_m / A < 1, \forall m$. Thus, the objective function is to maximize the system throughput when $\Theta = 1$, to achieve max-min fairness when $\Theta = 2$ and $\kappa = 1$, and to achieve proportional fairness when $\Theta = 2$ and $\kappa \rightarrow \infty$, respectively.

Claim 1: The utility function of the $m^{th}$ node is an increasing function of its achievable data rate.

In practice, the choice of $\Theta$ is contingent on the purpose of the networking application of interest and/or the prerogative of a system designer. Other system performance can also be optimized by means of utility functions (e.g., a tradeoff between throughput and fairness [14]).

Consider the following node cooperative resource allocation optimization problem (NCRAOP)

$$\max_{c,v,a,z} \left\{ \sum_{m=1}^{M} U_m (R_m (c, v, a, z) | \Theta) \right\}$$

subject to

$$1, (3), (5), (6), \text{ and } \sum_{m=1}^{M} c_{m,n} \leq 1, \forall n,l$$

where $c, v, a$, and $z$ are the optimization variables. By reducing the NP-complete number partitioning problem to the NCRAOP, it can be proved that the NCRAOP is an NP-hard problem.

**Proposition 1:** The NCRAOP is an NP-hard problem.

**B. KKT Interpretations**

In general, solving the NP-hard NCRAOP requires exponential time complexity [15]. To design an efficient and effective resource allocation approach to solve the NCRAOP, we first investigate the relationships among different optimization variables by means of the Karush-Kuhn-Tucker (KKT) interpretations [15]. By relaxing the integer constraints and interpreting the KKT conditions with respect to $c_{m,n}$ and $z_{mu}$, we can obtain the subcarrier allocation criterion and the partner allocation criterion as follows:

**Proposition 2:** (Subcarrier Allocation Criterion) For the $n^{th}$ subcarrier and the $l^{th}$ timeslot, the necessary condition for $c_{m,n}^l$ being positive is

$$m = \arg \max_{m} \left\{ U_m^l (R_m (c, v, a, z) | \Theta) \right\}$$

subject to

$$\sum_{m=1}^{M} c_{m,n} \leq 1, \forall n,l$$

where $R_m (c, v, a, z) | \Theta$ and $z_{mu}$ are the Lagrange multipliers for constraints (7).

**Proposition 3:** (Partner Allocation Criterion) The necessary condition for $z_{mu}$ being positive is

$$m = \arg \max_{m} \left\{ U_m^l (R_m (c, v, a, z) | \Theta) \right\}$$

subject to

$$\sum_{m=1}^{M} c_{m,n} \leq 1, \forall n,l$$

**IV. PROPOSED RESOURCE ALLOCATION APPROACH**

Clearly, to obtain the global optimal solutions to the NCRAOP, subcarrier allocation, partner allocation, and power allocation should be jointly considered, which brings about very high computational cost. To devise an efficient yet effective resource allocation strategy for WMNs with node cooperation, in this work, we propose a two-phase resource allocation approach with QoS assurance and MAC-layer service differentiation by fixing the power allocation (i.e., uniform power allocation). Specifically, in Phase 1, we solve the NCRAOP without considering node cooperation. In Phase 2, we allow node cooperation, if feasible and favorable, so as to further meliorate the system performance.
A. Phase-1 Resource Allocation

With uniform power allocation (i.e., $\rho_{m,n}^l = P_{m}^{\max}/N, \forall m,l$) and no node cooperation (i.e., $z_{mu} = 0$ and $a_{um} = 0, \forall m,u$), the NCRAOP can be reduced to the following resource allocation optimization problem

$$\max_{\mathbf{c}} \left\{ \sum_{m=1}^{M} U_m (R_m (\mathbf{c}) | \Theta) \right\}$$

subject to

$$(7), \sum_{m=1}^{M} I_m, n \leq l, \forall n,l, \text{ and } I_m, n \in (0,1), \forall m,n,l.$$  

Thus, the subcarrier allocation criterion given in (11) is as follows: for the $n^{th}$ subcarrier and the $l^{th}$ timeslot, choose $m^*$ such that

$$m^* = \arg \max_m \left\{ \left( I_m^l \right) + \zeta_m \right\} \log \left( 1 + \gamma_{mm,n} \right) = 1, \forall n,l,$$

where $\zeta_m$ is updated iteratively as follows: $\zeta_m = \max \left\{ 0, \zeta_m - a_{km} \right\}$ with $a_{km}$ being the step size at the $k^{th}$ iteration for the $m^{th}$ node and $a_{km} = R_m (c) - R_m$. Since CAC is assumed to be in place, the approach terminates when all the subcarriers are allocated and all the rate requirements are met (i.e., $\zeta_m = 0, \forall m$, and the subcarrier allocation solution $c^*$ is obtained such that $\sum_{m=1}^{M} I_m^l = 1, \forall n,l$.

B. Phase-2 Resource Allocation

We investigate the performance gain due to feasible and favorable node cooperations in this phase. With the subcarrier allocation solution obtained in Phase 1, the NCRAOP becomes

$$\max_{\mathbf{a}, \mathbf{z}} \left\{ \sum_{m=1}^{M} U_m (R_m (\mathbf{a}, \mathbf{z}) | \Theta) \right\}$$

subject to

$$(3), (6), (7), \text{ and } z_{mu} \in \{0,1\}, \forall m,u.$$  

Denote $\rho(\geq 0)$ as a tunable system parameter to balance node cooperation and node non-cooperation, i.e., $a_{um} = \rho a_{mm}, \forall m,u$. In fact, $\rho$ indicates the willingness of a node to assist another mesh node’s transmissions. Here, we consider that for the $m^{th}$ node, if $\sum_{i \neq j} z_{im} = 1$, then $a_{mm} = \rho a_{mm}(>0), \forall i \neq m$; otherwise, $a_{mm} = 1$ and $a_{im} = 0, \forall i \neq m$. Suppose the $u^{th}$ node is to help assist the $m^{th}$ node, i.e., $z_{mu} = 1$. Then, the transmit power of the $u^{th}$ node left for cooperation, denoted by $\rho_{ul}^l$, is given by $\rho_{ul}^l = P_{m}^{\max} - U_{u} \sum_{n=1}^{N} I_{u,n}^l$. In the assisted transmissions, the $u^{th}$ node is to help relay the $m^{th}$ node’s data over the set of subcarriers allocated to the $m^{th}$ node. Let $N_u^l$ be the set of subcarriers allocated to the $m^{th}$ node on the $l^{th}$ timeslot. Here, we consider that the transmit power of the $u^{th}$ node dedicated to node cooperation is uniformly distributed over the subcarriers allocated to the $m^{th}$ node on the $l^{th}$ timeslot, i.e., $\hat{c}_{u,n} = P_{m}^{\max}/N, \forall n \in N_u^l, \forall u \in N_u^l$. Thus, the portion of the transmit power of the $u^{th}$ node in assisting the $m^{th}$ node’s transmissions is $a_{um} \sum_{n \in N_u^l} \hat{c}_{u,n}$. Regarding the node cooperation in our specific system model with two classes of traffic, MAC-layer service differentiation is indispensable for effective packet-level QoS provisioning, where RG nodes are assigned higher priority and BE nodes are assigned lower priority. As a consequence, node cooperation should also be prioritized. In particular, we consider that only RG nodes can receive assistance from BE nodes whenever favorable. Let $A = \{ m | m \in M_1, \sum_{j \neq m} z_{mj} = 0 \}$ and $B = \{ u | u \in M_2, \sum_{j \neq u} z_{ju} = 0 \}$. The set $A$ consists of RG nodes which do not receive any assistance from any other nodes, whereas the set $B$ consists of BE nodes which do not offer any assistance to any nodes. The partner allocation criterion is as follows: for the $u^{th}$ node, $u \in B$, choose $m^*$ such that

$$m^* = \arg \max_{m \in A} \left\{ \frac{U_{m}^u (R_m (\mathbf{a}, \mathbf{z}) | \Theta) \partial R_m (\mathbf{a}, \mathbf{z})}{a_{mu} \sigma_{mu}^2} \right\}.$$  

Then, we check if this partner allocation process can help enhance the total utilities. Let $R_m (\mathbf{a}, \mathbf{z})$ and $R_m (\tilde{\mathbf{a}}, \tilde{\mathbf{z}})$ be the achievable data rate obtained of the $m^{th}$ node without node cooperation and that with node cooperation, respectively. We have

$$R_m (\mathbf{a}, \mathbf{z}) = \sum_{n=1}^{N} \sum_{l=1}^{L} I_{m,n}^l \log (1 + g_{m,n}^l \gamma_{mm,n}^l) \geq \sum_{n=1}^{N} \sum_{l=1}^{L} I_{m,n}^l \log (1 + g_{m,n}^l \gamma_{mm,n}^l) = R_m (\tilde{\mathbf{a}}, \tilde{\mathbf{z}}),$$

$$R_u (\mathbf{a}, \mathbf{z}) = \sum_{n=1}^{N} \sum_{l=1}^{L} I_{u,n}^l \log (1 + g_{u,n}^l \gamma_{uu,n}^l) < R_u (\tilde{\mathbf{a}}, \tilde{\mathbf{z}}).$$

Since $R_{u}^0 = 0, u \in M_2$, the solutions obtained by considering node cooperation will also be feasible to the NCRAOP. Setting $z_{mu} = 1$, we remove the $m^{th}$ node from $A$ (i.e., $A \leftarrow A \{ m^* \}$) if the following condition is valid:

$$U_m^* (R_m (\tilde{\mathbf{a}}, \tilde{\mathbf{z}}) | \Theta) + U_u (R_u (\tilde{\mathbf{a}}, \tilde{\mathbf{z}}) | \Theta) > U_m^* (R_m (\mathbf{a}, \mathbf{z}) | \Theta) + U_u (R_u (\mathbf{a}, \mathbf{z}) | \Theta).$$

If the condition (21) is satisfied, assigning the $u^{th}$ node to the $m^{th}$ node as its partner can increase the total utilities, thereby improving the network-wise system performance. The $u^{th}$ node is removed from $B$ (i.e., $B \leftarrow B \{ u \}$), and the process repeats until $A = \{ \phi \}$ or $B = \{ \phi \}$.

With effective node cooperation, Phase-2 resource allocation improves the Phase-1 resource allocation solutions, thereby giving rise to higher total utilities. Notice that the time complexity of the proposed two-phase node cooperative resource allocation approach is on the order of $O(bMN + |M_1||M_2|)$, where $b$ is a constant. Compared to the well-known Hungarian approach, the complexity of which is on the order of $O(|M_1| M_2^2 + MN^2 L^2)$, our proposed approach is of low complexity and more suitable for the WMNs with affordable off-the-shelf mesh nodes.

Proposition 4: With fixed subcarrier allocation and power allocation, the partner allocation solution obtained from our proposed node cooperative resource allocation approach is Pareto optimal [16].
Proof: Let \( S_j(z^*) \) denote the payoff function of the \( j^{th} \) node with the partner allocation solution \( z^* \) obtained from the proposed approach, where the payoff function indicates the utility gain when the \( j^{th} \) node is chosen to be the partner of some source node. Consider \( \tilde{z} \) is another solution. If \( S_j(\tilde{z}) > S_j(z^*) \), then \( Su(\tilde{z}) < Su(z^*) \), \( \exists u \), as \( z_{mj}^* = 1 \) and \( z_{mu}^* = 0 \). Since the \( m^{th} \) node is the best source node for the \( u^{th} \) node to assist in \( z^* \), changing the partner allocation solution will decrease the payoff function (i.e., the utility gain) of the \( u^{th} \) node and, therefore, \( Su(\tilde{z}) < Su(z^*) \), \( \exists u \). Notice that the case of \( z_{mj}^* = 1 \) and \( \sum_{u \neq m} z_{mu}^* = 0 \), \( \exists m \), is not possible because, should the \( j^{th} \) node be the partner of the \( m^{th} \) node in \( z^* \), the \( j^{th} \) node can be the partner of the \( m^{th} \) node based on the notion of our partner allocation criterion. Therefore, according to the definition of Pareto optimality [16], with fixed subcarrier allocation and power allocation, the partner allocation solution \( z^* \) obtained from our proposed approach achieves the Pareto optimality.

V. PERFORMANCE EVALUATION

A. Packet-Level QoS Provisioning

In the MAC layer, packet-level QoS provisioning is vital in WMNs supporting heterogeneous traffic. To streamline QoS provisioning and provide service differentiation, packet prioritization is essential. We conceive that priority of RG traffic (packets) is related to the performance of their packet dropping rates. In this work, we only take the packet dropping due to the delay bound violation into account. The higher the packet dropping rate that an RG traffic flow suffers from, the higher the priority of the packets associated with that flow.

In the proposed approach, after gathering the transmission requests in the control slot, a clusterhead will grant the requests of transmitting higher-priority packets first, facilitating QoS provisioning. In other words, our QoS provisioning strategy for the RG traffic hinges upon the packet dropping rate. The resources allocated to a particular mesh node are reserved for transmissions until the next active resource allocation interval (i.e., next polling).

B. Simulation Environment

We consider a cluster with a number of wireless nodes randomly located in a 1km x 1km coverage area. We adopt the path-loss model suggested in [17]. Simulation parameters are chosen as follows: \( P_m^{\text{max}} = 1\, \text{W} \), \( \sigma_n^2 = 10^{-10}\, \text{W} \), \( N = 100 \), \( L = 4 \), \( \rho = 1/3 \), \( |M_2| = 2|M_1| \), and \( \Theta = 1 \). The carrier frequency and the maximum transmission rate over each subcarrier are assumed to be 1.9GHz and 200kbps, respectively. As regards the parameters for medium access, we consider that the duration of a DATA slot is 5ms. We consider that the polling is done in every 150ms, meaning that the node cooperative resource allocation solution is updated every 150ms. Here, both the polling and the beacon packet transmissions are assumed to be error-free. We perform the simulations for 1,000 runs and average the results, where each simulation run sustains 5,000 frames.

Concerning the traffic models, RG traffic is generated according to a two-state ON-OFF model. In the ON state, a fixed-size packet arrives at a constant rate of 384kbps, whereas in the OFF state, no packet is generated. The packet inter-arrival time is 5ms in the ON state. We consider that the duration of an ON period and that of an OFF period both follow an exponential distribution, where the mean ON period and the mean OFF period are 1s and 1.2s, respectively. The delay bound of RG traffic is assumed to be 20ms. The desired packet dropping rate is less than 1%. On the other hand, BE traffic does not have any QoS requirements, and packet arrivals follow a Poisson process with mean rate 50 packets/second, where the packet size follows a Weibull distribution (i.e., Weibull(2,2)).

Regarding node cooperation, mesh nodes that can successfully decode some mesh node’s transmissions become their potential partners. In the simulations, we consider that if the rate achieved by a source-partner link is larger than that by a cooperative transmission given in (8), the partner of interest can reliably decode the source node’s data and become one of its potential partners [5].

C. Simulation Results

Here, we study the impact of the number of mesh nodes on the system performance in terms of throughput, resource utilization, packet dropping rate, and node cooperation gain (NCG) (i.e., the normalized throughput gain due to node cooperation). For comparison, we consider a baseline approach and an approach suggested in [18]. The baseline approach is the same as the proposed approach without Phase-2 resource allocation, while the Zhang’s approach proposed in [18] first allocates the subcarriers with no QoS consideration and then re-allocates the subcarriers trying to satisfy the QoS demands of the nodes without considering node cooperation. Fig. 2 shows the throughput performance versus the number of mesh nodes. The standard deviations of the results are also plotted for reference. Since the network is not saturated, the throughputs of all considered approaches increase with \( M \). As seen, without considering node cooperation, the Zhang’s approach performs better than the baseline approach. Due to bandwidth reservation, the throughput obtained in the baseline approach is smaller than the Zhang’s approach, for QoS provisioning and throughput increment are conflicting performance measures [14]. However, our proposed approach outperforms the baseline approach, which stems from an additional performance gain due to beneficial node cooperation. The performance difference between the Zhang’s approach and the proposed approach is about 10%. The NCG is given in Table I. As expected, in general, the more the mesh nodes, the higher the NCG; however, the gain is roughly leveled off from \( M = 30 \) onward, which is ascribed to the limited available subcarriers (and resource reservation for the RG traffic). We expect that the NCG can be higher with a larger value of \( N \). The slight fluctuation of the curves is partly because of the random arrivals of RG packets. We observe that the resource utilizations of the baseline approach, the Zhang’s approach, and the proposed approach increase from 8% to
effectively provision QoS and achieve an enhanced throughput.

Zhang’s approach [18], the proposed approach is shown to provide effective QoS provisioning for RG traffic requirements of RG traffic at the packet level. Nonetheless, the Zhang’s approach is ineffective in supporting the QoS as the number of mesh nodes increases from 6 to 48. The rationale for low resource utilizations is due to low traffic load and resource reservation. We note that the resource utilization (and throughput) for the proposed approach can be improved when the traffic load increases and the RG traffic demand is less stringent. In Fig. 3, the RG packet dropping rates are depicted. The standard deviations of the results are also plotted for reference. The packet dropping rates for RG traffic in the proposed approach and the baseline approach are well below 1% due to effective packet-level QoS provisioning. On the other hand, the RG packet dropping rates of the Zhang’s approach increase and reach 20% as \( M \) increases. Fig. 3 shows that the Zhang’s approach is ineffective in supporting the QoS requirements of RG traffic at the packet level. Nonetheless, the Zhang’s approach aims at maximizing the throughput in lieu of focusing on QoS satisfaction. Based on the results shown in Figs. 2 and 3, the fact that there is a tradeoff between (packet-level) QoS provisioning and throughput maximization can be further re-assured [14]. Simulation results show that the proposed two-phase node cooperative resource allocation approach provides effective QoS provisioning for RG traffic and achieves satisfactory throughput and resource utilization.

VI. CONCLUSION

A two-phase node cooperative resource allocation approach is proposed, tailored for WMNs with MAC-layer service differentiation. Compared to a baseline approach and the Zhang’s approach [18], the proposed approach is shown to effectively provision QoS and achieve an enhanced throughput performance. Our approach is also Pareto optimal, utilizing scarce network resources efficiently. Further, with low computational complexity, the proposed approach can be a viable candidate for practical implementation. Further work includes developing a distributed node cooperative resource allocation approach for WMNs with decentralized control and study of various cooperation scenarios in WMNs.

TABLE I

<table>
<thead>
<tr>
<th>( M )</th>
<th>6</th>
<th>12</th>
<th>18</th>
<th>24</th>
<th>30</th>
<th>36</th>
<th>42</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCG (in %)</td>
<td>4.2</td>
<td>10.1</td>
<td>16.9</td>
<td>21.8</td>
<td>25.1</td>
<td>23.7</td>
<td>25.4</td>
<td>24.2</td>
</tr>
</tbody>
</table>

The authors wish to thank Professor Kuang-Hao Liu for his helpful suggestions which improved the quality of this paper.

REFERENCES