VCG-Based Time-Slot Auctioning in IEEE 802.16 OFDM/TDMA Wireless Mesh Networks

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***Abstract*—In this paper, we study the problem of bandwidth resource allocation in a non-cooperative IEEE 802.16 OFDM/TDMA based wireless mesh network, and propose an auction based framework in which the gateway, equipped with the precious high speed Internet connection, serves as the auctioneer while the first-level mesh routers (MRs) (i.e., those with direct wireless connections to the gateway) act as bidders competing resources among each other. We then present Vickrey-Clarke-Groves (VCG) based auction approaches to allocate time-slots among MRs. Through simulations, we find that the proposed VCG algorithms can achieve much better throughput and connection blocking probability performance than traditional resource allocation approaches in a non-cooperative environment.**

***Index Terms*—wireless mesh networks, IEEE 802.16, OFDM/TDMA, resource allocation, Vickrey-Clarke-Groves auction.**

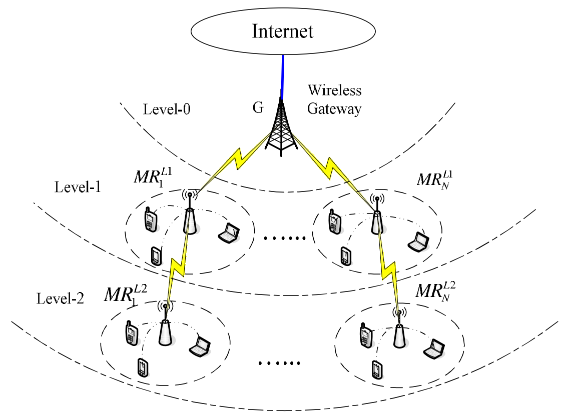

Fig. 1: Structure of a hierarchical wireless mesh network.

I. Introduction

The research of IEEE 802.16-based wireless mesh networks (WMNs) [1], [8] have gained enormous popularity recently due to its capability to improve the capacity and coverage for wireless broadband services at affordable costs in rural areas. A typical WMN consists of mesh routers (MRs) that not only provide wireless access for mesh clients (MCs) but also form the backbone of the network. To provide broadband out-bound access, gateways are usually installed between the mesh backbone and the Internet. Consequently, as shown in Fig. 1, to provide broadband Internet services to a remote area, the MRs close to the gateway can work as relay nodes transmitting traffic between the Internet and the MRs far away from the gateway.

One of the key enabling features behind such a hierarchical WMN is that a MR should not only serve the MCs in its own local cell, but also relay traffic for outer level MRs. Unfortunately, this kind of cooperation among MRs is not always practical in reality, especially when these MRs are owned by different profit-maximizing entities so that they have to compete with each other for radio resource. In such a non-cooperative environment, a MR will rationally exhibit selfish behaviors driven by self-interests in that the MR may report a bogus channel information or valuation so as to improve its own benefit [5], or refuse to relay other MRs' traffic because relaying traffic will inevitably consume its own resource and consequently degrade the performance of its local cell. Though these non-cooperative behaviors could improve the performance for the selfish MR itself, they may lead to inefficient or unfair resource utilization for the whole system. Several recent works [3], [8] have addressed the problem of resource allocation in WMNs, but they are either based on a cooperative situation or the assumption that the relay node itself does not have local connections to serve, which are different from our model where a relay MR should serve both local and relay connections in a non-cooperative environment.

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The resource allocation problem in a competitive environment can be effectively addressed by means of auction theory [6], which is widely known to be efficient in allocating resources in a non-cooperative situation, and is the focus of our study. Specifically, in this hierarchical mesh infrastructure, we assume using an IEEE 802.16 WirelessMAN-OFDM air interface, where the physical layer is based on orthogonal frequency-division multiplexing (OFDM), and the media access control (MAC) scheme is based on time-division multiple access (TDMA). With OFDM/TDMA, all subchannels are allocated to one connection at a time. Thus, in our model, the auction goods are time-slots, the auctioneer is the gateway who has radio resource, i.e., time-slots, to allocate, and the bidders are MRs who need to request time-slots from the gateway and use them for local or relay traffic transmissions.

To implement an auction approach in WMNs, two challenging problems must be tackled. First, a succinct and expressive bidding language is necessary. Here, we define a bidder's valuation function by quantifying its valuation on the allocated resource under the current state, and then fully characterize it simply by a single scalar parameter. Thus, each bidder can submit the scalar as its bid, thereby leading to an efficient and practical bidding process. Second, how should we define "payment"? In some auction-based algorithms [3], [9], payments are expressed in terms of money or some kinds of virtual parameters, and thus, suffer from a lack of practical meanings and significance. Here we consider associating payment with the time-slots used by an MR to relay other MR's packets. Specifically, to win time-slots allocated by the gateway, a bidder must "pay" some wireless resources, i.e., time-slots, and use them to forward an outer level MR's traffic.

Our contributions are as follows. We first define a linear valuation function based on time-slots. Consequently, a bidder's utility is just the value it receives minus the assigned payment. The auction approach based on VCG auction [6] can then be used to solve this model with linear utility [2]. On the other hand, we find that a concave valuation function is more suitable to represent bidder's valuation and the corresponding utility because it can represent the saturation of user QoS satisfaction as the received resource increases. Thus, we further define a family of concave valuation and utility functions, and derive a Quasi-VCG (QVCG) method, which employs the VCG allocation and payment policies under this non-linear environment. Then we compare the performance of these two VCG-based auction algorithms with some traditional resource allocation algorithms through simulations, and find that the proposed VCG algorithms can achieve much better throughput and connection blocking probability (CBP) performance in a non-cooperative WMN.

The rest of this paper is organized as follows. We present the system model and auction model in Section II. Section III presents and analyzes our proposed VCG auction algorithms. Section IV gives simulation results. We conclude in Section V.

II. Model

A. System Model

In this paper, we consider an IEEE 802.16 OFDM/TDMA-based WMN with three hierarchical levels as shown in Fig. 1 and focus on downlink resource allocation. Such a hierarchical network structure is highly practical and can be used to model a WMN in a rural area, where at Level-0, there is a wireless gateway that has direct connection to the Internet. There are N Level-1 MRs, denoted by $MR_i^{L_1}, i \in \mathbb{N} = \{1, 2, \ldots, N\}$, surrounding the gateway and providing wireless access for their clients. Each MR and its corresponding clients form a cell. Outside Level-1, to cover a wide geographical area (a necessary condition in a rural area), there are N other MRs, denoted by $MR_i^{L_2}$, which are located far from the central gateway. As a result, each $MR_i^{L_2}$ does not have direct wireless connections with the gateway, and it can only get broadband Internet services through the relaying services provided by $MR_i^{L_1}$. We also assume that $MR_i^{L_1}$ in Level-1 just relays traffics to $MR_i^{L_2}$ in Level-2. Every Level-1 $MR_i^{L_1}$ competes with each other for the bandwidth resource provided by the gateway.

We assume all cells operate under IEEE 802.16 OFDM/TDMA-TDD mode, and each adjacent cell uses a different frequency band. The MAC frame is composed of downlink and uplink subframes. Each downlink subframe is composed of T_d time-slots, each of which is used for transmission of packets corresponding to one connection. For uplink and downlink transmission using OFDM, each MR uses M subchannels with total bandwidth of B MHz. There are $R_i^{GL_1}$ packets per time-slot transmitted from the gateway to $MR_i^{L_1}$. We use $PER_i^{L_1}$ and $PER_i^{L_2}$ to denote the average packet error rates in the downlink of $MR_i^{L_1}$'s and $MR_i^{L_2}$'s local cell, respectively. These PERs depend on the PHY layer packet transmission error rate and MAC layer packet dropping rate. Then we can get the average number of packets that can be transmitted successfully per time-slot from $MR_i^{L_1}$ and $MR_i^{L_2}$ as $a_i^{L_1}$ and $a_i^{L_2}$, respectively, i.e.,

$$a_i^{L_1} = R_i^{GL_1} \cdot (1 - PER_i^{L_1}) \tag{1}$$

$$a_i^{L_2} = a_i^{L_1} \cdot (1 - PER_i^{L_2}) \tag{2}$$

We also assume that there are $N_i^{L_1}$ MCs served by $MR_i^{L_1}$, and $N_i^{L_2}$ MCs served by $MR_i^{L_2}$. Thus, when $T_i^{L_1}$ time-slots are allocated to $MR_i^{L_1}$ for its local usage and $T_i^{L_2}$ time-slots are used to relay Level-2 MR's traffic, the average received packets per frame by a Level-1 MC and a Level-2 MC are then given by:

$$\overline{Q}_i^{L_1}(T_i^{L_1}) = \frac{a_i^{L_1}}{N_i^{L_1}} \cdot T_i^{L_1} \tag{3}$$

$$\overline{Q}_i^{L_2}(T_i^{L_2}) = \frac{a_i^{L_2}}{N_i^{L_2}} \cdot T_i^{L_2} \tag{4}$$

B. Auction Framework

In our proposed auction framework, each $MR_i^{L_1}$ needs to compete for time-slots through auction, and the valuation function can be fully characterized by a scalar valuation parameter. Specifically, every $MR_i^{L_1}$ calculates the valuation parameter $a_i^{L_1}$ and then submits a bid $b_i = \mu_i(a_i^{L_1})$ to the gateway according to a rationally selfish strategy. For $MR_i^{L_2}$, because $a_i^{L_2}$ depends on $PER_i^{L_2}$ and $MR_i^{L_1}$'s reported valuation parameter, we assume that every $MR_i^{L_2}$ can send $PER_i^{L_2}$ to the gateway via a secure out-of-band control channel through $MR_i^{L_1}$. After receiving the announced bidding profile $B = \{b_1, b_2, \ldots, b_N\}$ from every $MR_i^{L_1}$, and all level-2 $PER_i^{L_2}$, the gateway will know each MR's reported valuation, and then calculate the allocation $T = T(B) = \{T_1, T_2, \ldots, T_i, \ldots, T_N\}$, which represents the number of time-slots allocated to each $MR_i^{L_1}$, as well as the payment $P = P(B) = \{T_1^{L_2}, T_2^{L_2}, \ldots, T_i^{L_2}, \ldots, T_N^{L_2}\}$, which represents the number of time-slots that should be used by $MR_i^{L_1}$ to relay $MR_i^{L_2}$'s traffic. Subsequently, the allocation and payment results are transmitted to each $MR_i^{L_1}$. Upon receiving them, each $MR_i^{L_1}$ gets to know $T_i^{L_1} = T_i - T_i^{L_2}$ and payment $T_i^{L_2}$.

In a typical auction, the utility of a bidder is the value received by this bidder minus the payment assigned by the auctioneer. However, in our model, to provide practical meanings for payment, we associate the payment with the practical radio resource, i.e., time-slots. Thus, when $MR_i^{L_1}$ receives T_i

time-slots and accept $T_i^{L_2}$ time-slots as payment, its ultimate utility is its true valuation when getting $T_i^{L_1} = T_i - T_i^{L_2}$, i.e.,

$$U_i^{L_1}(T_i, T_i^{L_2}) = V_i^{L_1}(T_i - T_i^{L_2}) = V_i^{L_1}(T_i^{L_1}) \tag{5}$$

For Level-2 $MR_i^{L_2}$, its utility is just its valuation with $T_i^{L_2}$ time-slots, i.e.,

$$U_i^{L_2}(T_i^{L_2}) = V_i^{L_2}(T_i^{L_2}) \tag{6}$$

III. VCG Auction

A. Classical VCG Based on a Linear Utility Function

Vickrey-Clarke-Groves (VCG) auction has been regarded as one of the most effective mechanisms to induce truth-revealing strategies [2], i.e., every bidder truthfully declares their resource requirements. The VCG theory relies on the restrictive assumption that bidders' utility functions are quasi-linear, i.e., the utility can be expressed as the value of the goods received minus the payment made. To fulfill this requirement, we first design a VCG auction-based algorithm using a linear utility function, called a Classical-VCG (CVCG) algorithm, where the valuation function is given by the maximal feasible received packets per time-slot as discussed in Section I, i.e.,

$$V_i^{L_1}(T_i^{L_1}) = \overline{Q}_i^{L_1}(T_i^{L_1}) \cdot N_i^{L_1} = a_i^{L_1} \cdot T_i^{L_1} \tag{7}$$

$$V_i^{L_2}(T_i^{L_2}) = \overline{Q}_i^{L_2}(T_i^{L_2}) \cdot N_i^{L_2} = a_i^{L_2} \cdot T_i^{L_2} \tag{8}$$

Thus, their utilities can be expressed as:

$$U_i^{L_1}(T_i, T_i^{L_2}) = a_i^{L_1} \cdot T_i - a_i^{L_1} \cdot T_i^{L_2} \tag{9}$$

$$U_i^{L_2}(T_i^{L_2}) = a_i^{L_2} \cdot T_i^{L_2} \tag{10}$$

Based on the above linear model, we design an auction mechanism based on the classic VCG theory as follows.

1) Each bidder $MR_i^{L_1}$ submits its true valuation parameter $a_i^{L_1}$ as bid b_i to the gateway, i.e., $b_i = \mu_i(a_i^{L_1}) = a_i^{L_1}$.
2) The gateway computes an outcome that maximizes the declared social welfare, i.e.,

$$\begin{aligned} T^* &= \{T_1^*, T_2^*, \cdots, T_N^*\} \\ &= \arg\max_{\{T_i\}} \sum_i V_i(T_i) = \arg\max_{\{T_i\}} \sum_i a_i^{L_1} \cdot T_i \end{aligned} \tag{11}$$

subject to:

$$(I)\ \sum_i T_i = T_d \quad (II)\ 0 \le T_i \le T_d$$

3) The price paid by each bidder corresponds to the loss of declared welfare it imposes to the others through its presence, which is further converted to the number of time-slots used by $MR_i^{L_1}$ to forward the traffic to $MR_i^{L_2}$, i.e.,

$$T_i^{L_2} = (V_i^{L_2})^{-1}(P_i) \tag{12}$$

where $P_i = \max_i \sum_{j \neq i} V_j(T_j) - \sum_{j \neq i} V_j(T_j^*)$.

B. Quasi-VCG Based on a Concave Utility Function

While the above CVCG algorithm based on classical VCG model is very easy to implement, the linear utility function has a drawback in that it cannot capture the "diminishing return" effects in satisfying the QoS requirements of wireless service users. Specifically, we consider the following logarithmic function to express a level-1 MC's valuation on its average received packets per frame, i.e.,

$$v_i^{L_1}(a_i^{L_1}, T_i^{L_1}) = \log(\overline{Q}_i^{L_1}(T_i^{L_1}) + 1) = \log(\frac{a_i^{L_1}}{N_i} \cdot T_i^{L_1} + 1) \tag{13}$$

Thus, when there are $N_i^{L_1}$ MCs served by $MR_i^{L_1}$, its valuation on $T_i^{L_1}$ time-slots can be defined as:

$$V_i^{L_1}(a_i^{L_1}, T_i^{L_1}) = N_i^{L_1} \cdot v_i^{L_1}(a_i^1, T_i^{L_1}) = N_i^{L_1} \cdot \log(\frac{a_i^{L_1}}{N_i^{L_1}} \cdot T_i^{L_1} + 1) \tag{14}$$

Similarly, $MR_i^{L_2}$'s valuation on $T_i^{L_2}$ time-slots is:

$$V_i^{L_2}(a_i^{L_2}, T_i^{L_2}) = N_i^{L_2} \cdot \log(\frac{a_i^{L_2}}{N_i^{L_2}} \cdot T_i^{L_2} + 1) \tag{15}$$

Thus, according to (8) and (9), their utilities are:

$$U_i^{L_1}(T_i, T_i^{L_2}) = V_i^{L_1}(a_i^{L_1}, T_i - T_i^{L_2}) \tag{16}$$

$$U_i^{L_2}(T_i^{L_2}) = V_i^{L_2}(a_i^{L_2}, T_i^{L_2}) \tag{17}$$

Obviously, $U_i^{L_1}$ is concave on both valuation parameter $a_i^{L_1}$ and allocated resource $T_i^{L_1}$, while $U_i^{L_2}$ is also concave on both $a_i^{L_2}$ and $T_i^{L_2}$. These utility functions are not quasi-linear, implying that they cannot be simply expressed as the difference between the valuation and payment. Thus, the classical VCG method cannot be applied directly. In the following, based on the concave utility function in a non-linear setting, we propose a novel auction approach employing the VCG allocation and payment policies.

1) Each $MR_i^{L_1}$ submits its bid $b_i = a_i^{L_1}$ to the gateway.
2) The gateway computes an outcome that maximizes the declared social welfare, i.e.,

$$\begin{aligned} T_* &= \{T_1^*, \cdots, T_i^*, \cdots, T_N^*\} \\ &= \arg\max_{\{T_i\}} \sum_i V_i^{L_1}(a_i^{L_1}, T_i) \\ &= \arg\max_{\{T_i\}} \sum_i N_i^{L_1} \cdot \log(\frac{a_i^{L_1}}{N_i^{L_1}} \cdot T_i + 1) \end{aligned} \tag{18}$$

subject to:

$$(I)\ \sum_i T_i = T_d \quad (II)\ 0 \le T_i \le T_d$$

3) To determine the payment, the gateway first calculates the loss of social welfare due to $MR_i^{L_1}$'s presence, i.e.,

$$P_i = \max_i \sum_{j \neq i} V_j(T_j) - \sum_{j \neq i} V_j(T_j^*) \tag{19}$$

P_i is further converted to the number of time-slots $T_i^{L_2}$ used by $MR_i^{L_1}$ to relay the traffic to $MR_i^{L_2}$, i.e.,

$$T_i^{L_2} = (V_i^{L_2})^{-1}(P_i) \tag{20}$$

Here, our proposed auction mechanism applies the VCG allocation and payment policies to a non-linear environment, and thus we refer it to as Quasi-VCG (QVCG) algorithm.

IV. Simulations

The simulation topology is shown in Fig. 1, where $N = 4$ and the frequency bands for adjacent MRs are non-coverlapping. Each MR has 64 subchannels, and total bandwidth is 10 MHz. We further group 25 OFDM symbols into a slot, and let one downlink-subframe have 10 time-slots. There are 10 MCs in each cell. The wireless channel is modeled as frequency-selective Rayleigh fading channel.

We then compare our proposed VCG algorithms with two traditional cooperative resource allocation methods in our non-cooperative environment: (1) proportional fairness (PF) [4], and (2) a global optimization method (GLB) which maximizes the following function:

$$\begin{aligned} \widetilde{T} &= \{\widetilde{T_1^{L_1}}, \widetilde{T_1^{L_2}}, \cdots, \widetilde{T_N^{L_1}}, \widetilde{T_N^{L_2}}\} \\ &= \arg \max_{\{T_i^{L_1}, T_i^{L_2}\}} \sum_i U_i^{L_1}(T_i^{L_1}) + U_i^{L_2}(T_i^{L_2}) \end{aligned} \tag{21}$$

subject to:

$$(I) \sum_i T_i = T_d \quad (II)\, T_i = T_i^{L_1} + T_i^{L_2}$$

Notice that in a cooperative situation which is unrealistic in the environment considered in this paper, all MRs report their true valuations to the gateway, which then allocates resource based on these true information. However, in a non-cooperative environment, a selfish MR may report a bogus valuation to gain a high payoff without regard to the overall system performance [5]. In our simulations, we assume $MR_1^{L_1}$ always reports a higher valuation under the PF and GLB algorithms.

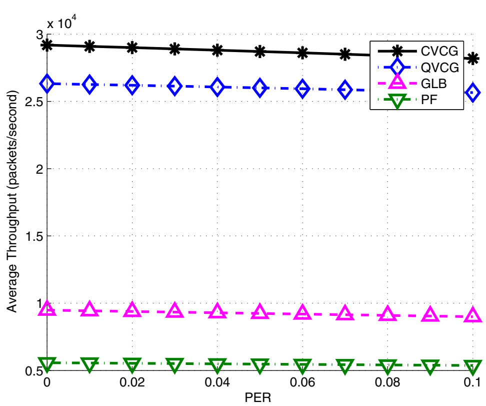

Fig. 2: System aggregate throughput vs. Level-2 PER.

As can be seen from Fig. 2, the system average throughputs of PF and GLB are much lower than those of the VCG-based algorithms. To quantify the service dependability for Level-2 MRs in the system, we assume that each local connection generates 2500 packets per second in the downlink, and calculate the Level-2 MR's connection blocking probability (CBP) according to Engset formula [7]. As shown in Fig. 3,

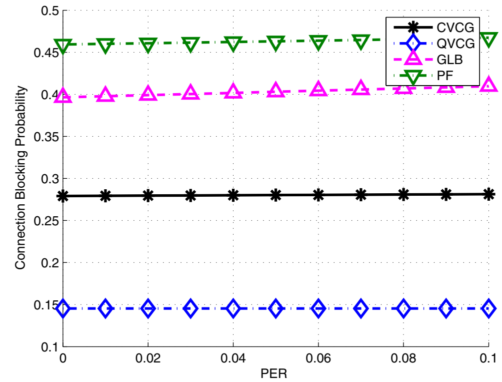

Fig. 3: CBP vs. Level-2 PER.

the CBP performance of PF and GLB are worse than those of the VCG algorithms. Thus, it is quite clear that the traditional resource allocation algorithms are not suitable for a non-cooperative WMN.

V. Conclusions

In this paper, we study the downlink bandwidth allocation problem in a non-cooperative IEEE 802.16 OFDM/TDMA-based hierarchical wireless mesh network. We design an auction framework to let rationally selfish mesh routers request time-slots actively and motivate them to forward an outer level MR's traffic. We also propose two Vickrey-Clarke-Groves (VCG) based auction approaches according to different valuation functions, and compare their performance with traditional proportional fair and global optimization algorithms through simulations. We find that the proposed VCG auction algorithms can achieve much better performance in terms of efficiency and service dependability than traditional resource allocation algorithms in a non-cooperative environment.

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