Auction-Based Bandwidth Allocation and Scheduling in Noncooperative Wireless Networks

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***Abstract*—We investigate bandwidth allocation and scheduling in non-cooperative wireless networks as a mixed integer programming problem. Fast Vickrey-Clarke-Groves (VCG) auction-based bandwidth allocation (FABA), incorporating relaxation-based greedy algorithm (RGA) and split-flow-based algorithm (SFA), is proposed by modifying the traditional VCG auction to make it computationally feasible. With incentives provided by FABA, the dominant strategy of any selfish node in the network is to be cooperative so that the system cost is minimized. We implement FABA via a batching-based mechanism which allocates bandwidth for all call routing requests arriving in a certain batching period simultaneously. Our simulation evaluates the performance in terms of system cost, payment-cost ratio, and setup time.**

***Index Terms*—Auction-Based Routing, Bandwidth Allocation, Scheduling, Non-cooperative Wireless Network.**

I. Introduction

Some networks, such as ad hoc networks, inter-domain networks, and cellular networks, consist of devices owned by different individual users [1], [4], [10]. Due to the limited communication resources (*e.g.,* energy or bandwidth), these users may only be interested in maximizing their own utilities, and not willing to forward data packets for others. Such networks are called non-cooperative networks. The network performance and availability may be adversely affected by the non-cooperative users [5].

Credit/payment is an incentive for selfish nodes to cooperate [9]. In [9], a cheating detection system is developed based on a statistical analysis of the payment information in activity reports to prevent cheating in multi-hop wireless networks. In [17], the receivers monitor whether intermediate nodes are cooperative to relay the flows, and report to a credit center, which makes the payments to the intermediate nodes. A charging policy is proposed for multihop cellular networks in [10], in which payments are secured via a low-overhead implementation of payment checks.

Transmission payment determination is a critical issue in a monetary transfer system. The bandwidth allocation and pricing in an overlay network with respect to one-hop flows is studied in [13]. Xi *et al.* studied a pricing game in which nodes price their services selfishly and strategically in multihop networks [16]. However, strategy-proofness is not guaranteed in their schemes. An optimal scheme for multipath traffic assignment (OSMA) was proposed in [14] to handle the routing requests sequentially in the order of their arrivals. A more general analytical model was proposed in [17] with a strategy-proof scheme for multiple requests. Unfortunately, these work cannot handle the bandwidth allocation and scheduling for multi-hop routing in non-cooperative wireless network, since the interferences among wireless nodes are not considered.

The available transmission bandwidth of every link is assumed to be given and fixed in most work [14], [15], [16]. In fact, the transmission bandwidth available for each link in a wireless network depends on how the communication resources, such as time slots in time-division duplexing (TDD) system and frequency channels in frequency-division duplexing (FDD) system, are shared. In this work, we study the joint auction-based bandwidth allocation and scheduling in noncooperative wireless networks.

A. Our Contribution

In this paper, an analytical model for bandwidth allocation and scheduling in non-cooperative wireless networks is proposed. To the best of our knowledge, this is the first work considering bandwidth allocation and scheduling in non-cooperative wireless networks. Referring to the analogy between the bandwidth allocation problem (BAP) and the procurement problem in economics, BAP is formulated as a mixed integer programming (MIP) problem. Since BAP is NP-hard, the traditional VCG auction is computationally infeasible [11]. We have proposed a computationally feasible scheme, fast VCG auction-based bandwidth allocation (FABA), to allocate bandwidth and to determine the corresponding payments. FABA can also guarantee strategy-proofness and system cost efficiency. FABA is implemented with a batching mechanism which allocates bandwidth and determines prices of resources for all routing requests arriving in a batching period simultaneously.

B. Organization

The rest of the paper is organized as follows. In Section II, we model the problem of bandwidth allocation and scheduling in non-cooperative wireless networks. We present and analyze FABA in Section III. Section IV discusses simulation results. Section V concludes with possible extensions of our work.

II. System Model

Assume that there is a directed wireless network $G = (V, E)$. $V = \{v_0, v_1, v_2, \ldots, v_n\}$ is the set of $n+1$ nodes in which v_0 is the access point (AP) connected to the wired network (or Internet) and the remaining n nodes are non-AP nodes. Node $u \in V$ can communicate to any node $v \in N_u$ within the transmission range r_u of Node u, i.e., $N_u = \{v \in V \setminus \{u\} | \parallel v - u \parallel \leq r_u\}$ [12]. $E_u^{out} = \{(u,v)|v \in N_u\}$ is the set of outgoing links originated from Node u. $E_u^{in} = \{(w,u)|u \in N_w, w \in V \setminus \{u\}\}$ is the set of incoming links terminated at Node u. Denote the maximum achievable data transmission rate on Link (u,v) as C_{uv}, which quantifies the capacity of Link (u,v) if the wireless radio is dedicated only to transmissions from Node u to Node v.

We adopt the *Interference Range Model* [8] for modelling wireless channel interferences. The emission of Node u interferes with data reception of Node $v \in I_u$, where I_u is the set of nodes within the interference range R_u of Node u, i.e., $I_u = \{v \in V \setminus \{u\} | \parallel v - u \parallel \leq R_u\}$. Link (u,v) is said to be interfered by Link (w,e), if the receiver of Link (u,v) is situated within the interference range of the sender of Link (w,e), namely, $v \in I_w$. Let $L_{uv} = \{(w,e) \in E | v \in I_w, w \in V \setminus \{u\}\}$ be the link interference set of Link (u,v), i.e., data transmissions on the links in L_{uv} would interfere with the transmissions on Link (u,v).

A set of M senders is represented as $S = \{s_1, s_2, \ldots, s_M\}$. These senders request bandwidth to communicate with the AP in the form of a bandwidth requirement vector $\mathbf{b} = (b_s | s \in S)$. Each Link $(u,v) \in E_u^{out}$ originated from Node u has a marginal cost function $f_{uv}(x)$, which is private and only known to Node u. $f_{uv}(x)$ is an increasing function, which represents the cost of forwarding one additional unit of traffic when x units of bandwidth have been used. Indeed, the higher the traffic load on a link, the longer the queueing delay, and the higher the packet dropping probability. Thus, the cost for Node u to forward a flow occupying y_{uv} units of bandwidth on Link (u,v) is a convex function $c_{uv}(y_{uv}) = \int_0^{y_{uv}} f_{uv}(x)dx$.

Assume that all nodes in the network are non-cooperative. Node u reports $\hat{\mathbf{f}}_u = (\hat{f}_{uv}(x)|v \in N_u)$ instead of $\mathbf{f}_u = (f_{uv}(x)|v \in N_u)$. Here, Node u cheats when $\mathbf{f}_u \neq \hat{\mathbf{f}}_u$. The source node of an SD pair must pay for the intermediate nodes to carry its flows, and this payment must at least cover the forwarding costs of the intermediate nodes. Let p_u be the total revenue received by Node u in forwarding traffic for other nodes when the allocated bandwidth on its outgoing links in E_u^{out} is $\mathbf{y}_u = (y_{uv}|v \in N_u)$. Let $c_u(\mathbf{y}_u) = \sum_{v \in N_u} c_{uv}(y_{uv})$ be the total cost of Node u. A non-cooperative intermediate node u in the network aims to maximize its utility, U_u, where

$$U_u = p_u - c_u(\mathbf{y}_u) \tag{1}$$

III. Fast VCG Auction-Based Bandwidth Allocation (FABA)

We formulate BAP for finding the feasible bandwidth allocation and scheduling as a mixed integer program (MIP). AP collects the routing requests in a batching period $T \cdot \Delta T$, where T is the number of time slots in a batching period and ΔT is the duration of a time slot. The routing requests are scheduled simultaneously at the end of the batching period. Unsatisfied requests due to lack of bandwidths are postponed to the next batching period. Then, FABA is developed to determine the payment to stimulate selfish nodes to relay flows of others so that the system cost is minimized according to truthfully reported information.

A. Bandwidth Allocation

The notation *Transmission Mode (TM)* [12] is employed to demonstrate the transmission states of links. Each state of a link in a TM indicates whether data can be transmitted on it. Let the state of Link (u,v) in TM γ_i be denoted by $\gamma_{i,uv}$. If the link $(u,v) \in E$ is utilized, $\gamma_{i,uv} = 1$; otherwise, $\gamma_{i,uv} = 0$. A TM $\gamma_i = (\gamma_{i,uv}|(u,v) \in E)$ is said to be feasible if and only if γ_i satisfies the following conditions:

$$\forall \gamma_{i,uv}, \text{if } \gamma_{i,uv} = 1, \quad \sum_{(w,e) \in L_{uv} \cup E_u^{out} \cup E_v^{out}} \gamma_{i,we} = 1 \tag{2}$$

With a feasible transmission mode (FTM), data can be transmitted on the employed links simultaneously without any interferences. These O FTMs consist of the feasible transmission mode set Γ, where O is the number of FTMs.

Assume that routing requests require cumulative bandwidth $\mathbf{b} = (b_s | s \in S)$ in a certain batching period. Let $\mathbf{y}_u = (y_{uv}|(u,v) \in E_u^{out})$ be the occupied bandwidth on the outgoing links of Node u. If one time slot is allocated to Link (u,v), $\frac{C_{uv}}{T}$ units of bandwidth are available on Link (u,v). Let h_i be the number of time slots assigned to FTM γ_i. The total number of time slots allocated to Link (u,v) is $\sum_{i=1}^{O} h_i \gamma_{i,uv}$. Thus, total available bandwidth is $\frac{C_{uv}}{T} \sum_{i=1}^{O} h_i \gamma_{i,uv}$. BAP can be formulated as a mixed integer program (MIP) to minimize the total system cost as follows:

$$\min W = \sum_{u \in V} \hat{c}_u(\mathbf{y}_u) \tag{3}$$

$$s.t. \quad \sum_{(s,v) \in E_s^{out}} y_{sv} - \sum_{(w,s) \in E_s^{in}} y_{ws} = b_s, \forall s \in S \tag{4}$$

$$\sum_{(u,v) \in E_u^{out}} y_{uv} - \sum_{(w,u) \in E_u^{in}} y_{wu} = 0, \forall u \in V \setminus \{S \cup \{v_0\}\} \tag{5}$$

$$y_{uv} \leq \frac{C_{uv}}{T} \sum_{i=1}^{O} h_i \gamma_{i,uv}, \forall (u,v) \in E \tag{6}$$

$$\sum_{i=1}^{O} h_i \leq T \tag{7}$$

$$0 \leq h_i \leq T, h_i \in \mathbb{Z} \ (i = 1, 2, \ldots, O) \tag{8}$$

$$y_{uv} \geq 0 \ ((u,v) \in E) \tag{9}$$

In BAP, Constraint (4) ensures that the difference between the total outgoing flow and incoming flow equals the required bandwidth so that the bandwidth requirement of Sender s is satisfied. Constraint (5) ensures the flow balance at the intermediate nodes such that all data packets will be forwarded by intermediate nodes. Constraint (6) is the capacity constraint. Constraint (7) is the time slot constraint.

B. Relaxation-Based Greedy Approximation

BAP is a mixed integer program, which is an NP-hard problem [3]. We propose RGA to solve BAP. The relaxation of BAP (RBAP) is the problem obtained by replacing the integer constraints of $h_i \in \mathbb{Z}$ $(i = 1, 2, \ldots, O)$ in BAP by constraints $h_i \in \mathbb{R}$ $(i = 1, 2, \ldots, O)$, where $\mathbb{R}$ is the set of real numbers. Then, RBAP is a convex optimization problem, which can be solved via the interior-point algorithm in polynomial time. Assume that $(\mathbf{y}^r, \mathbf{h}^r)$ is the optimal solution to RBAP, where $\mathbf{h}^r = (h_i^r | i = 1, \ldots, O)$ is the time slot allocation vector. The following relaxation-based greedy algorithm (RGA) is developed to obtain the solution $(\mathbf{y}^a, \mathbf{h}^a)$ to BAP.

Algorithm 1: Relaxation-based greedy algorithm (RGA)

Input: FTMs $\gamma_i \in \Gamma$, network graph G, bandwidth request $\mathbf{b}$
Output: The approximate solution $(\mathbf{y}^a, \mathbf{h}^a)$ to BAP

```
1  begin
2      Compute optimal solution (y^r, h^r) to RBAP;
3      y^a ← y^r;
4      h_i^a ← ⌊h_i^r⌋ (i = 1, 2, ..., O), where ⌊h_i^r⌋ is the integer
       part of h_i^r;
5      g_uv ← max (y_uv^a − C_uv Σ_{i=1}^{O} h_i^a γ_{i,uv} / T, 0), ∀(u,v) ∈ E;
6      while Σ_{(u,v)∈E} g_uv > 0 do
7          if Σ_{i=1}^{O} h_i^a ≤ T then
8              ψ_i ← Σ_{(u,v)∈E} Φ(g_uv) C_uv γ_{i,uv} / T, where
               Φ(g_uv) = 0, if g_uv = 0; Φ(g_uv) = 1, otherwise;
9              i* ← arg max{ψ_i | i = 1, 2, ..., O};
10             g_uv ← max(g_uv − C_uv γ_{i*,uv} / T, 0);
11             h_{i*}^a ← h_{i*}^a + 1;
12         else
13             Network cannot support the request;
14             STOP;
15         end
16     end
17 end
```

Intuitively, RGA uses the bandwidth allocation result $\mathbf{y}^a$ as the target allocation to adjust the time slot assignment vector $\mathbf{h}^a = (h_i^a | i = 1, \ldots, O)$ to satisfy Constraints (6)-(8) in BAP. Line 4 in Algorithm 1 removes the decimal part of the elements of $\mathbf{h}^a$ so that any h_i^a is an integer and $\sum_{i=1}^{O} h_i^a = \sum_{i=1}^{O} \lfloor h_i^r \rfloor \le \sum_{i=1}^{O} h_i^r \le T$ satisfies Constraints (7)-(8) in BAP. In Line 5, $\{g_{uv} | (u, v) \in E\}$ indicates the rate gaps between the target bandwidth $\mathbf{y}^a$ and the available bandwidth with the current time slot assignment vector $\mathbf{h}^a$. From Line 6 to Line 16, RGA iteratively assigns the remaining time slots one by one to FTMs to increase the available bandwidth until the rate gaps g_{uv} $(\forall (u, v) \in E)$ are reduced to zero. In each iteration, the time slot is greedily assigned to an FTM so that the total reduced rate gap is maximized (Line 9).

Theorem 1: Any feasible solution found by RGA is a global optimal for BAP.

Proof: According to Algorithm 1, $\sum_{i=1}^{O} h_i^a \le T$ and $\mathbf{g} = (g_{uv} | (u, v) \in E) = \mathbf{0}$. That is, for each Link (u, v), $g_{uv} = \max(y_{uv}^a - C_{uv} \sum_{i=1}^{O} \frac{h_i^a \gamma_{i,uv}}{0}, 0) = 0$. Thus,

$$y_{uv}^a \le C_{uv} \sum_{i=1}^{O} \frac{h_i^a \gamma_{i,uv}}{T} \tag{10}$$

As a result, $(\mathbf{y}^a, \mathbf{h}^a)$ is a feasible solution to both RBAP and BAP. For any other feasible solution $(\mathbf{y}', \mathbf{h}')$ to BAP, $W' = \sum_{u \in V} \hat{c}_u(\mathbf{y}'_u) \ge W^r = \sum_{u \in V} \hat{c}_u(\mathbf{y}^r_u) = W^a = \sum_{u \in V} \hat{c}_u(\mathbf{y}^a_u)$. Therefore, $\mathbf{y}^a$ is the optimal solution to BAP. ■

From Theorem 1, the feasible solution found by RGA in polynomial time is globally optimal. However, RGA may not find a feasible solution while a feasible solution to BAP exists. The price to lower the computational complexity in RGA is that some feasible solutions may be missed.

C. FVCG-Based Pricing Scheme

Revenues will be received by those nodes who participate in data forwarding. A pricing scheme of FABA is proposed to reduce the computational complexity. The total revenue received in FABA by Node u is p_u, which is

$$p_u = W'_{-u} - W^a + \hat{c}_u(\mathbf{y}^a_u) \tag{11}$$

where $\mathbf{y}^a_u$ is the bandwidth allocation of Node u computed by RGA, W^a is the optimal system cost calculated in RGA, and W'_{-u} is the system cost of BAP without Node u computed by any approximate algorithm. Thus, the unit price of the bandwidth in Node u is $q_u = \frac{p_u}{\sum_{(u,v) \in E_u^{out}} y^a_{uv}}$.

The following theorem shows that, with this payment scheme, each selfish node will report its truthful information to AP in order to maximize its utility, i.e., $\hat{\mathbf{c}}_u = \mathbf{c}_u$, where $\hat{\mathbf{c}}_u = (\mathbf{c}_{uv} | v \in N_u)$.

Theorem 2: If FABA is used, truthful reporting is the dominant strategy for each node, irrespective of the bids of other nodes.

Proof: Consider an arbitrary Node u, fix the set of bids of cost functions for the other nodes as $\hat{\mathbf{c}}_{-u} = \{\hat{\mathbf{c}}_v | v \in V \setminus \{u\}\}$. If Node u reports its true information, i.e., $\hat{\mathbf{c}}_u = \mathbf{c}_u$, the utility of Node u is:

$$\begin{aligned} U_u &= p_u - c_u(\mathbf{y}^a_u) \\ &= W'_{-u} - W^a \\ &\ge W^*_{-u} - W^* \ge 0 \end{aligned} \tag{12}$$

where $W^* = W^a$ is the minimal system cost of BAP according to Theorem 1 and W^*_{-u} is the minimal system cost of BAP without Node u.

Let $\mathbf{y}'$ be the bandwidth allocation vector with respect to $(\hat{\mathbf{c}}_{-u}, \hat{\mathbf{c}}_u | u \in V)$, where $\hat{\mathbf{c}}_u \ne \mathbf{c}_u$. The utility of Node u is:

$$\begin{aligned} U'_u &= p_u - c_u(\mathbf{y}'_u) \\ &= W'_{-u} - (\sum_{\substack{v \in V \\ v \ne u}} \hat{c}_v(\mathbf{y}'_v) + \hat{c}_u(\mathbf{y}'_u)) + \hat{c}_u(\mathbf{y}'_u) - c_u(\mathbf{y}'_u) \end{aligned}$$

$$= W'_{-u} - \sum_{\substack{v \in V \\ v \neq u}} \hat{c}_v(\mathbf{y}'_v) - c_u(\mathbf{y}'_u) \tag{13}$$

Since $\mathbf{y}'$ is not an optimal allocation with respect to the set of the reported costs $(\hat{\mathbf{c}}_{-u}, \mathbf{c}_u | u \in V)$, $\sum_{v \in V, v \neq u} \hat{c}_v(\mathbf{y}'_v) + c_u(\mathbf{y}'_u) \geq W^*$. Thus, $0 \leq U'_u \leq U_u$, and truthful reporting always maximizes the bidder's utility. As a result, reporting true information is the dominant strategy. ■

From Theorem 2, FABA has the property of incentive compatibility (IC). Since $U_u \geq 0$ for all selfish nodes, participations result in a non-negative utility. Thus, FABA possesses individual rationality (IR). FABA is strategy-proof, because FABA has both properties of IC and IR.

Algorithm 2: Split-Flow-Based Algorithm (SFA)

Input: Available path set $\mathcal{P} = \{\mathcal{P}_i | s_i \in S\}$, cost functions $\hat{\mathbf{c}} = (c_{uv}(x) | (u,v) \in E)$, and bandwidth requirements $\mathbf{b} = (b_s | s \in S)$.

Output: Bandwidth allocation $\mathbf{x}^*$ among path set $\mathcal{P}$ and scheduling vector $\mathbf{h}^*$.

1 **begin**
2 Initialize: $S_A \leftarrow S$;
3 $\mathbf{x}^* \leftarrow \mathbf{0}$ and $\mathbf{h}^* \leftarrow \mathbf{0}$, where $\mathbf{0}$ is a zero vector;
4 **while** $S_A \neq \emptyset$ **do**
5 $\omega = (\omega_{uv} | (u,v) \in E) \leftarrow \mathbf{0}$;
6 $\nu = (C^a_{uv} | (u,v) \in E)$;
7 **for** *each* $s_i \in S_A$ **do**
8 $P^t = \arg\min_{P_i^k \in \mathcal{P}_i} \ c_i^k(\delta, \mathbf{x}^*)$;
9 **for** *each Link* (u,v) *on Path* $\mathcal{P}^t$ **do**
10 $\omega_{uv} = \omega_{uv} + \delta$;
11 **end**
12 **end**
13 $\omega \leftarrow \max\{\mathbf{0}, \omega - \nu\}$;
14 **while** $\sum_{(u,v) \in E} \omega_{uv} \neq 0$ **do**
15 $i^* =$ $\arg\max_{\gamma_i \in \Gamma} \ \sum_{(u,v) \in E} \max\{0, \omega_{uv} - \gamma_{i,uv} \frac{C_{uv}}{T}\}$;
16 $h_{i^*} \leftarrow h_{i^*} + 1$;
17 $\omega_{uv} \leftarrow \max\{0, \omega_{uv} - \gamma_{i^*,uv} \frac{C_{uv}}{T}\}$;
18 **end**
19 **for** *each* $s_i \in S_A$ **do**
20 $P_i^l = arg\min_{P_i^k} c_i^k(\delta_l, \mathbf{x}^*)$, where $\delta_{il} = \min\{b_i, \delta, C_{il}^{max}\}$;
21 $x_{il}^* \leftarrow x_{il}^* + \delta_{il}$;
22 $b_i \leftarrow b_i - \delta_l$;
23 **if** $b_i = 0$ **then**
24 Remove s_i from S_A;
25 **end**
26 **end**
27 **end**
28 **end**

D. Split-Flow-Based Algorithm (SFA)

Although RBAP in RGA can be solved in polynomial time, payment determination in (11) still requires a terribly long time to compute $W'_{-u}, \forall u \in V$ using RGA [17]. SFA is developed to make it computationally feasible to compute $W'_{-u}, \forall u \in V$.

Let $\mathcal{P}_i = \{P_i^1, \ldots, P_i^{K_i}\}$ be the available path set connecting sender s_i and AP, where K_i is the number of paths in $\mathcal{P}_i$. Denote bandwidth allocation among $\mathcal{P}_i$ as $\mathbf{x}_i^* = (x_{ik}^* | k = 1, \ldots, K_i)$. Each path consists of several links. Let $\theta_{ik}^{uv} = 1$, if $(u,v) \in P_i^k$. Otherwise, $\theta_{ik}^{uv} = 0$. Thus, given the currently allocated bandwidth vector $\mathbf{x}^* = (\mathbf{x}_i^* | s_i \in S)$, the additional cost for assigning δ units of traffic to path P_i^k is $c_i^k(\delta, \mathbf{x}^*) = \sum_{(u,v) \in P_i^k} (c_{uv}(y_{uv}^* + \delta) - c_{uv}(y_{uv}^*))$, where $y_{uv}^* = \sum_{s_i \in S} \sum_{k=1}^{K_i} \theta_{ik}^{uv} x_{ik}^*$ is the aggregated flow rate on Link (u,v). Furthermore, given the time slot assignment vector $\mathbf{h}^*$, the available bandwidth on Link (u,v) is

$$C_{uv}^a = \frac{C_{uv}}{T} \sum_{i=1}^{O} h_i^* \gamma_{i,uv} - y_{uv}^* \tag{14}$$

Therefore, the available bandwidth on Path P_i^k is $C_{ik}^{max} = \min_{(u,v) \in P_i^k} C_{uv}^a$.

In SFA, bandwidth requirements from different senders are split into small pieces whose sizes are capped at δ. These pieces are assigned to the least-cost paths one after another sequentially until all bandwidth requirements are met. The algorithm contains two adjustment processes, namely, production adjustment and consumption adjustment. In production adjustment, the algorithm assigns the time slot to FTMs in Γ to increase the available bandwidth in the least-cost paths of different senders so that the pieces of bandwidth can be distributed to these least-cost paths. In consumption adjustment, the pieces of bandwidth requirements from unmet senders are assigned to the least-cost path so that the system cost is minimized. These two adjustment processes are alternately executed to assign time slots and distribute bandwidth.

In Algorithm 2, Line 2 initializes the active sender set S_A which contains the senders with unmet bandwidth requirements. From Line 4 to Line 28, SFA iteratively allocates the time slots to different links that are out of available bandwidth, and the split traffic demands, capped at δ, of different senders are assigned to the least-cost paths one after another. The process is repeated until all requests are satisfied, i.e., $S_A = \emptyset$. Lines 5-18 are for the production adjustment. Line 5 initializes the variable ω for predicting the bandwidth requirement on links for the following bandwidth allocation. Line 6 initializes the variable ν which denotes the current available bandwidth. For each unsatisfied sender in S_A, the split bandwidth is assigned to the least-cost paths in Line 8 so that the required bandwidth ω_{uv} for the next bandwidth allocation are determined. Line 13 computes the bandwidth shortage which is the difference between the bandwidth requirement and the available bandwidth on all links. Lines 14-18 iteratively assign time slots one by one to FTMs until the bandwidth shortages are reduced to zero. At each step, the time slot is assigned to an FTM in Γ which can maximally reduce the bandwidth shortage in Line 15. After the production adjustment process, the bandwidth pieces from senders in S_A are distributed in turns from Line 19 to Line 26 (consumption adjustment). In particular, Lines 20-22 assign pieces of bandwidth to the least-cost path for each sender in S_A. If the bandwidth requirement of a sender is satisfied, the sender is removed from S_A.

A total of $O(\frac{1}{\delta})$ times are required for the while-loop from

Line 4 to Line 28. In each while-loop, there are three for-loops. The time complexities of these three for-loops are $O(M)$, $O(MO)$, and $O(M)$, respectively, where M is the number of senders and O is the number of FTMs in Γ. As a result, the time complexity of SFA is $O(\frac{MO}{\delta})$.

IV. Performance Evaluation

We evaluate FABA-20, FABA-220, and FABA-420, where FABA-δ is the FABA using parameter δ Kbps in SFA. FABA is implemented via a batching mechanism [17]. In particular, AP acting as the control center allocates the bandwidth and determines the payments for all routing requests of calls at the end of each batching period. The duration of a batching period BP has three different configurations, namely, 3, 7, and 11 seconds. The convex optimization solver used in RGA is the Interior Point OPTimizer (Ipopt). We use dynamic source routing (DSR) as the routing discovery protocol.

The routing schemes are evaluated via a simulation program in C++. We simulate a random wireless network with node density 100 nodes/km^2 in a 400 metres by 400 metres area. The access point is deployed at the centre of the area. Following the IEEE 802.11 standards, the time slot length is selected as 20 μs. Each node has a fixed transmission range of 140 metres and interference range of 280 metres [12]. The maximum transmission rate of each node is set to be $C = 54$ Mbps. Three convex link cost functions, namely, x, x^2, and $e^{x/C}$, where x is the occupied bandwidth, are considered in the simulation.

For a routing request, the sender is randomly selected from the network. The duration time follows a general pareto distribution with shape parameter 0.78 and scale parameter 31 [2]. The bandwidth requirement follows a lognormal distribution whose mean is 175 Kbps [7]. The interarrival time between two successive requests follows the exponential distribution with arrival rate λ which can be 80, 90, 100, 110, and 120 (in min^{-1}).

The algorithms are compared via the following metrics:

1) *System cost:* The sum of costs measured by virtual money at the participant nodes to meet routing requests in a batching period is called the system cost.
2) *Payment-cost ratio:* The payment-cost ratio is defined as the total payment over the system cost in a batching period. Here, the total payment is the sum of the payments to intermediate nodes.
3) *Setup time:* The setup time of a routing request is the period from when the request is sent to AP to when the bandwidth allocation result is received by the sender.

A. Simulation Results

There are three sets of simulation results. The first set demonstrates the system costs of different batching periods and link cost functions for different values of the arrival rate λ. Fig. 1 shows the system cost of different batching periods with the link cost function of x^2. The system costs of all cases increase when the arrival rates of routing requests increase. Since FABA equipped with a lower batching period allocates the bandwidth and time slots more frequently, given the same arrival rate, the total batched bandwidth requirements of different senders to be satisfied at the end of the batching period is relatively less than that of the FABA with a longer batching period. As a result, FABA with lower batching period results in a smaller system cost. The results in other cases with different batching periods and link cost functions are similar.

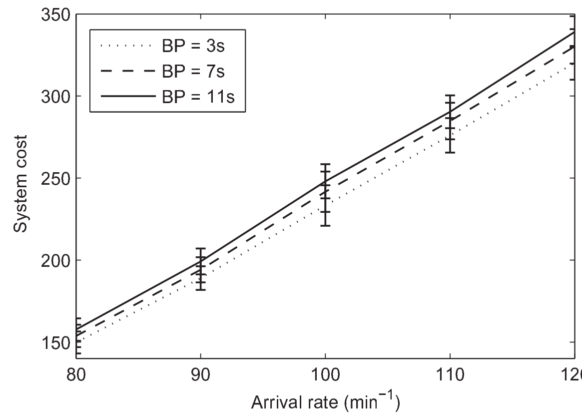

Fig. 1. Comparison of system costs for different batching periods.

The second set of simulation results examines the payment-cost ratios of different batching periods and routing algorithms. It is expected that the intermediate nodes can be cooperative when the payment-cost ratio is smaller. The payment-cost ratios of different algorithms and batching periods with the link cost function of x^2 are shown in Fig. 2. The payment-cost ratios of different algorithms and batching periods grow dramatically with the increase of arrival rate λ, because the difference between W'_{-u} and W^a, which evaluates the reduction of system cost via the cooperation of Node u, becomes larger with the increase of the cumulative bandwidth $\mathbf{b}$. In particular, FABA-δ with a larger batching period results in a larger payment-cost ratio, since the cumulative bandwidth $\mathbf{b}$ will be larger. In addition, SFA distributes the traffic more uniformly into the network with a smaller δ resulting in a smaller W'_{-u} in (11). As a result, given the batching period, the payment-cost ratio becomes larger with the increase of δ in FABA. Similar trends have been observed for other cases of different link cost functions.

Our batching mechanism delays the unsatisfied requests to the next batching period until the requests are satisfied. As a result, the blocking probabilities of our proposed batching algorithms are zero. However, the requests may need to wait until the next batching period with a certain setup time. The third set of simulation results shows the setup times of our proposed batching algorithms for different arrival rates. Fig. 3 illustrates the setup time among the cases of different BPs. Generally, the setup time is about half of the batching period, when the arrival rate is small. There is a sharp jump when the arrival rate increases from 110 min^{-1} to 120 min^{-1}, since the

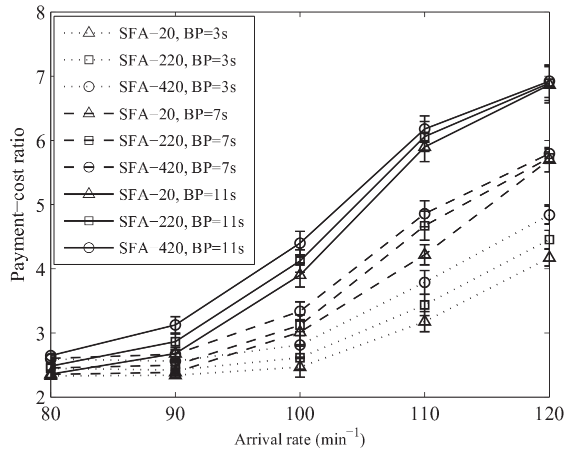

Fig. 2. Comparison of payment-cost ratios for different algorithms.

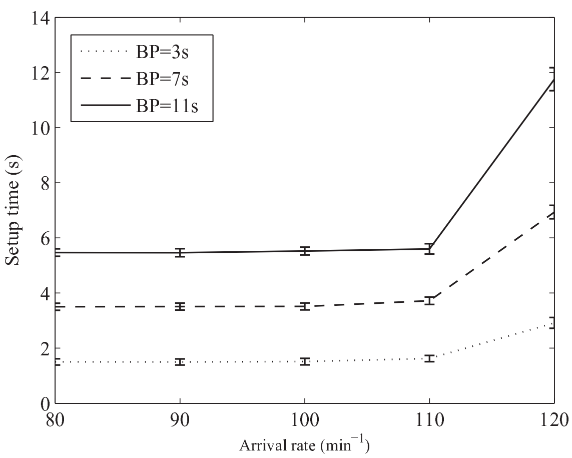

Fig. 3. Comparison of setup time for different algorithms.

scheduling of time slots in a batching period cannot support all batched bandwidth requirements and, hence, more routing requests are delayed. Furthermore, a setup time not more than five seconds is acceptable to certain data transmission applications in wireless networks [6].

Finally, we can summarize the relationships among batching period, system cost, payment-cost ratio, setup time, and δ in FABA. A longer batching period results in a larger system cost, payment-cost ratio, and setup time. Moreover, smaller δ results in a smaller payment-cost ratio but increases the computational complexity. We expect both batching period and δ to be small. However, a batching period and δ are selected so that the payment calculation by SFA-δ can be finished within a batching period.

V. Conclusion

We have constructed an analytical model of bandwidth allocation and scheduling in a non-cooperative wireless network. Traditional VCG cannot be applied in bandwidth allocation and scheduling because of its high computational complexity. Based on fast VCG auction, FABA, which still guarantees strategy-proofness and efficiency, dramatically reduces the computational time with only a small sacrifice in the payment-cost ratio. The distributed version of FABA can be devised so as to further improve the scalability of the allocation mechanism.

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