QoS-Aware Cooperative and Opportunistic Scheduling Exploiting Multiuser Diversity for Rate-Adaptive *Ad Hoc* Networks

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***Abstract*—The recent research works in wireless networks prompt the opportunistic transmission that exploits channel fluctuations to improve the overall system performance. In wireless *ad hoc* networks, nodes may have packets destined to multiple neighboring nodes. We consider an opportunistic scheduling that takes advantage of a time-varying channel among different receivers to improve system performance. Maximizing the overall throughput and satisfying the QoS requirements for the transmission flows are two important objectives that need to be considered. In literature, many opportunistic scheduling policies for *ad hoc* networks have been proposed, in which each transmitter independently schedules the transmission. However, due to cochannel interference, the decisions of neighboring transmitters are highly correlated. Moreover, to achieve the QoS requirements, the nodes have to be cooperative to share the common wireless channel. In this paper, we formulate the opportunistic scheduling problem, taking the interaction among the neighboring transmitters into account. We present an optimal scheduling policy which maximizes the overall network performance while satisfying the QoS requirements of the individual flows. We also propose a distributed cooperative and opportunistic scheduling algorithm that modifies the IEEE 802.11 protocol to implement the optimal scheduling policy. Simulation results indicate that our implementation achieves higher network throughput and provides better QoS support than the existing solutions.**

***Index Terms*—*Ad hoc* networks, IEEE 802.11, multiuser diversity, opportunistic scheduling, QoS requirement.**

I. Introduction

The mobile *ad hoc* network (MANET) has emerged as a key technology for next-generation wireless networking. Due to the high availability and low cost of the 802.11 wireless networking products, the IEEE 802.11 protocol has been widely used in the deployment of MANETs. In such networks, a node sends or forwards packets to its neighboring nodes by accessing the shared and time-varying wireless channel. To achieve high utilization of the scarce wireless resource, the opportunistic transmission exploits the variations in channel conditions to improve the overall network throughput by preferring to serve the links in strong channel quality and by setting the highest feasible data rate that the channel condition permits.

In MANETs, there are two main classes of opportunistic transmission. The first one is to exploit time diversity of the individual links by adapting the transmit rate to the time-varying channel condition [1]–[3]. In [3], the authors proposed the opportunistic auto-rate (OAR) scheme in which a flow transmits with higher data rate, and more back-to-back packets are sent when the channel condition is better. It is shown that the auto-rate schemes achieve a significant throughput gain compared with the fixed-rate schemes. Exploiting a multiuser diversity is another class of opportunistic transmissions, which jointly leverages the time and spatial heterogeneity of channels and thus further exploits the benefits of rate-adaptation schemes. In wireless networks, a node may have packets destined to multiple neighboring nodes. It is first observed, in the context of cellular networks, that selecting an instantaneous "on-peak" receiver with the best channel condition improves the system performance [4]–[6]. Motivated by this effect, practical opportunistic scheduling schemes have been implemented in Qualcomm's high data-rate (HDR) system [7].

However, to exploit multiuser diversity in 802.11-based MANETs, there are at least three unique issues due to the substantially different physical and medium-access-control (MAC) characteristics. First, due to the shared media in *ad hoc* networks, the cochannel interference has a deep impact on the flow scheduling. Two links that contend with each other cannot concurrently be scheduled. Hence, the neighboring transmitters should jointly determine the "on-peak" flows. Without the help of any infrastructure node, such cooperation should be executed in a distributed way. Second, while selecting the "on-peak" receivers, it is also important to consider the QoS requirements of each flow. To favor a flow which has not achieved its requirement, the transmitter should offer more transmission opportunities to that flow. Moreover, the neighboring transmitters should be coordinated to reserve the shared wireless bandwidth to reduce the potential collision to that flow. Finally, estimating the channel conditions is an essential process before scheduling. However, no dedicated channel-probing mechanism exists in the IEEE 802.11 protocols. Thus, a complemental scheme

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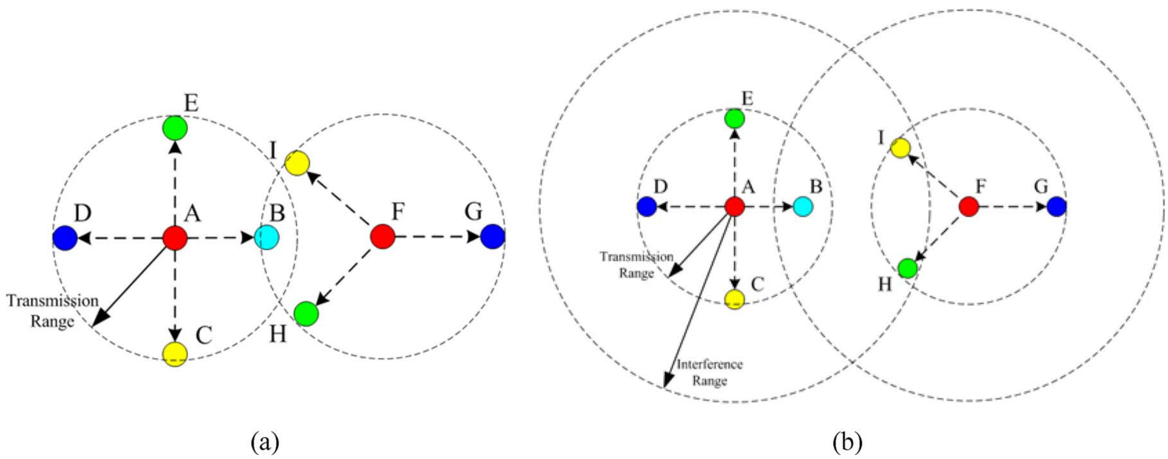

Fig. 1. Two examples with two transmitters, which both have several candidate receivers. In the second example, transmitter F is a hidden terminal to link A–B. (a) Example I. (b) Example II.

needs to be designed, which has to avoid collisions and to have an acceptable overhead during the probing process.

Recently, the opportunistic packet-scheduling and auto-rate (OSAR) [13] and medium-access-diversity (MAD) [12] schemes have been proposed to exploit multiuser diversity for 802.11-based wireless networks. In these schemes, two similar channel-probing mechanisms are introduced: multicast request-to-send (RTS) in OSAR and group RTS (GRTS) method in MAD. Herein, a sender broadcasts a probing RTS packet, then its receivers measure the signal-to-interference-plus-noise ratio (SINR) as their current channel conditions and send back the result by the clear-to-send (CTS) packets. To avoid collisions, receivers reply to the same sender in a predefined order. After probing, the sender schedules the rate-adapted transmission to the receiver which experiences the best channel condition. In [14], based on the OSAR, the authors proposed contention-based prioritized opportunistic (CBPO) scheme to reduce the probing overhead, in which the channel conditions can be simultaneously replied by using black-burst contention method. However, the existing schemes do not consider the interaction among neighboring transmitters, i.e., a sender individually makes its local decision to maximize its own performance. Intuitively, the local selection may not be the globally optimal one which maximizes the network performance due to the potential contention among neighboring transmissions. In addition, through the existing works, the QoS requirements are difficult to achieve since no mechanism is presented to coordinate the neighboring senders' transmissions.

In this paper, we propose a cooperative scheduling to exploit multiuser diversity for *ad hoc* networks. By exchanging the interference information, average channel conditions, and QoS factors among neighboring nodes in two-hop transmission range, the cooperative scheduling aims to find out the globally optimal set of simultaneously transmitting flows. In addition, through cooperation, some transmitters are deferred to favor some other links which have not yet achieved their QoS requirements. The key contributions of this paper are the following: 1) An interference-dependent multiuser diversity model is given for the *ad hoc* networks while considering the QoS requirement of each flow. 2) An optimal criterion is presented to find the globally optimal set of simultaneously transmitting flows. 3) An IEEE 802.11-based QoS-aware distributed cooperative and opportunistic scheduling (COS) is designed, which obtains higher network throughput and better QoS support than the existing schemes with limited local information.

The rest of this paper is organized as follows. Section II presents the motivation of our research, and the analytic model of the COS is formulated in Section III. Section IV discusses the optimal criteria of scheduling. Section V describes the distributed implementation of the optimal scheduling. Section VI introduces our simulation platform and presents the numerical results. Section VII reviews some related works. Section VIII concludes this paper.

II. Motivation

In this section, we give two examples, as shown in Fig. 1, to show that the prior schemes (e.g., OSAR) may not schedule the globally optimal transmitting link set. Moreover, we also show that the QoS requirements are not easily satisfied without the cooperation among neighboring transmitters.

As Fig. 1(a) shows, transmitter A has four candidate receivers: B, C, D, and E. At the same time, transmitter F is going to communicate with G, H, and I. Here, we assume a sender's transmission range as the area in which another node is able to successfully receive packets from this sender. Meanwhile, a node's interference range is the area in which the transmission of any other node can interrupt its receiving. In the first example, node B is in the transmission range of both A and F. Therefore, F can overhear node B's packets destined to A. Suppose that there is no ongoing communication at the beginning and that node A sends first its GRTS. As OSAR suggests, the transmitter A may select B as its data receiver and sends the data packets since B is the nearest neighbor to A. In this case, node F cannot access the channel, which has been held by node B's CTS. Flow A→D and flow F→G can simultaneously transmit. In other words, OSAR does not fully exploit the spatial reuse.

In another even worse case shown by Fig. 1(b), the distance between A and F increases; thus, B is out of node F's transmission range but in its interference range. In this example, node F is a hidden terminal to node B, i.e., node F cannot decode node B's CTS packets, but its transmission interrupts node B's receiving. As OSAR suggests, node A chooses B as its data receiver and starts the data transmission. During this period, node F sends its own GRTS. Since I and H suffer the interference from the ongoing transmission A→B, node F chooses node G for data transmission. By OSAR, we obtain the two flows A→B and F→G which are arranged to simultaneously transmit. However, due to the hidden terminal effect, at node B, the data packets transmitted by node A collide with the ones sent by node F. Therefore, the transmission of flow A→B fails once node F transmits. In this example, link contention occurs by using OSAR. In fact, the flow A→D and flow F→G are still the optimal choice from the global networking point of view.

Let us further look at the case wherein a certain QoS requirement needs to be provided for data transmission. We reuse the network topology which is shown by Fig. 1(b), whereas a bandwidth requirement is assigned to the flow A→B or we want to keep a certain fairness among node A's outgoing links. By OSAR, node A should offer this flow with more transmission opportunities since such a link suffers a high collision probability induced by the hidden terminal F. However, more opportunities are given, and more packets are lost due to collisions. It means that, without coordination among transmitters, the QoS requirements may lead to more packet collisions and degradation of the network throughput. If node F can cooperatively defer its transmission, or, for example, keep silence for a while, the QoS requirement of flow A→B may be achieved while the overall throughput increases.

In this paper, we present the optimal scheduling policy to find the globally best set of flows which can simultaneously transmit while maximizing the overall system performance. In addition, we introduce the cooperation among neighboring transmitters to favor the flows, which are assigned with certain QoS requirements, by deferring the transmissions of the other neighboring flows. A certain level of information sharing is needed for scheduling decision making. As proposed in the literature [16]–[18], one- and two-hop information of neighboring transmission is helpful for the contention resolution. In the following two sections, we will first discuss the problem formulation and then present the optimal scheduling policy.

III. Problem Formulation

Consider an *ad hoc* network with N nodes. The loaded links (single-hop flows) are node pairs and indexed by i (where $i \in \mathcal{N}$). We assume that all of the flows have saturated traffic, i.e., the transmitters always have packets to send. Several flows may have a common transmitter, i.e., a transmitter may have multiple candidate receivers. In this paper, we consider the system with fixed transmit power. Due to the fading phenomenon, the feasible data rate of each flow is also time-varying. Suppose that time is divided into timeslots, whose time width is fixed and in which back-to-back data packets are sent. Hence, a throughput that is achieved in a timeslot is linearly proportional to the used data rate. It is reasonable to assume that the channel conditions do not vary during a timeslot since the channel coherence time typically exceeds the duration of multiple packet transmissions [13]. The highest data rate that the ith link supports, i.e., the feasible data rate, in timeslot t is denoted by $\mu_i(t)$.

The contention relationship among flows can be represented by a contention graph (CG) [22] in which vertices are flows and an edge exists between two flows if they contend with each other. Any two flows can transmit in the same timeslot if and only if both the transmitter and the receiver of any flow are outside of the interference range of another flow's transmitter and receiver. Due to the fading phenomenon, the path gain between any two nodes varies from time to time, which leads to the time-varying $CG(t)$. We introduce a contention indication function $c(i,j,t)$, which equals one if links i and j are edged in $CG(t)$; otherwise, it equals zero. Moreover, by coloring vertices, we can obtain several independent subsets (ISs) in which the flows can simultaneously transmit. A maximal IS (MIS) $(S_m(t))$ is an IS that is not a subset of any other IS. Let $\Omega(t) = \{S_m(t)\}$ denote the MIS set.

Thus far, we can formulate the problem of cooperative scheduling that exploits multiuser diversity for *ad hoc* networks. We aim to find out a scheduling policy which maximizes the average system performance while satisfying the generalized QoS requirements of individual flows. Q denotes a certain scheduling policy, and $Q(t)$ denotes the scheduled transmitting link set in timeslot t. The $i \in Q(t)$ means that link i transmits at this moment. We also introduce an indicator function I_X, which equals one if X is true; otherwise, it is zero. If the ith flow transmits in timeslot t, it obtains a positive utility $f_i(\mu_i(t))$ which is a nondecreasing function of the used data rate; otherwise, the obtained utility in this timeslot is zero. For the best effort data traffic, the utility function can be simply set as $f_i(\mu_i) = \mu_i$, which implies that the utility is linearly proportional to the achieved throughput. To maximize the expectation system performance, we formulate the objective function as the sum of each flow's expectation utility: $\sum_{i\in\mathcal{N}} E\{f_i(\mu_i(t))I_{i\in Q(t)}\}$, where E denotes the expectation value over time.

The problem should have two sets of constraints: One is the contention restriction, and the other is the QoS constraint of each flow. In this paper, we only consider the long-term QoS requirements and use a generalized function $g_i(\mu_i(t))$ to describe different constraints. For instance, $g_i(\mu_i(t)) = 1$ denotes the time-sharing constraint, and $g_i(\mu_i(t)) = \mu_i(t)$ denotes the minimal bandwidth constraint. Finally, the opportunistic scheduling for *ad hoc* networks can be formulated as

$$\begin{aligned} \max_{Q} \quad & \sum_{i\in\mathcal{N}} E\left\{f_i\left(\mu_i(t)\right) I_{i\in Q(t)}\right\} \\ \text{s.t.} \quad & E\left\{g_i\left(\mu_i(t)\right) I_{i\in Q(t)}\right\} \geq G_i \quad \forall i \in \mathcal{N} \\ & c(i,j,t) = 0 \quad \forall i, \quad j \in Q(t), \quad i \neq j \end{aligned} \tag{1}$$

where G_i denotes the ith flow's long-term QoS requirement.

IV. Optimal Criteria of Scheduling

Let us denote an optimal solution/policy of (1) by Q^*. Then, we have the following propositions.

Proposition 1: The optimal solution of opportunistic scheduling (1), if one exists, satisfies $Q^*(t) \in \Omega(t)$ in any timeslot t, i.e., the link set selected by optimal scheduling should be a MIS.

Proof: In any timeslot t, supposing that the link set selected by an optimal policy $Q^*(t)$ is not a MIS, there exists a MIS $S_m(t)$ which satisfies $Q^*(t) \subset S_m(t)$. We have $g_i(\mu_i)I_{i\in S_m} \geq g_i(\mu_i)I_{i\in Q^*}$ $\forall i \in \mathcal{N}$, and $\sum_i f_i(\mu_i)I_{i\in S_m} \geq \sum_i f_i(\mu_i)I_{i\in Q^*}$. Moreover, $f_i(\mu_i)I_{i\in S_m} > f_i(\mu_i)I_{i\in Q^*} = 0$ $\forall i \in S_m - Q^*$. Therefore, another policy Q^{**}, whose selection in timeslot t is $Q^{**}(t) = S_m(t)$, outperforms Q^*, whereas the constraints still hold. This conflicts with the assumption that $Q^*(t)$ is the optimal solution. ■

By Proposition 1, we show that every selection of the optimal policy in timeslot t is a MIS. Then, we solve the problem (1) and present the optimal policy Q^* as the following proposition.

Proposition 2: The optimal solution of the aforementioned QoS-constrained opportunistic scheduling problem, if one exists, is of the following form:

$$Q^*(t) = S_{m^*}(t), \quad \text{where}$$
$$m^* = \arg\max_m \left\{ \sum_{i\in S_m(t)} [f_i(\mu_i) + \lambda_i g_i(\mu_i)] \right\} \tag{2}$$

where λ_i's are the Karush–Kuhn–Tucker (KKT) multipliers, and the Kuhn–Tucker conditions hold as

$$\forall i, \quad \lambda_i \geq 0, \quad E\{g_i(\mu_i)I_{i\in Q^*}\} \geq G_i$$
$$\text{and} \quad \lambda_i \left(E\{g_i(\mu_i)I_{i\in Q^*}\} - G_i\right) = 0. \tag{3}$$

Proof: Consider any feasible policy Q (feasible means that the QoS and contention constraints are satisfied). Then, there exist nonnegative constants λ_i's such that the following holds:

$$\begin{aligned}
&\sum_{i\in\mathcal{N}} E\{f_i(\mu_i)I_{i\in Q}\} \\
&\quad \leq \sum_{i\in\mathcal{N}} E\{f_i(\mu_i)I_{i\in Q}\} + \sum_{i\in\mathcal{N}} \lambda_i \left[E\{g_i(\mu_i)I_{i\in Q}\} - G_i\right] \\
&\quad = \sum_{i\in\mathcal{N}} E\{[f_i(\mu_i) + \lambda_i g_i(\mu_i)]\, I_{i\in Q}\} - \sum_{i\in\mathcal{N}} \lambda_i G_i \\
&\quad \leq E\left\{ \sum_{i\in S_{m^*}} [f_i(\mu_i) + \lambda_i g_i(\mu_i)] \right\} - \sum_{i\in\mathcal{N}} \lambda_i G_i \\
&\quad = E\left\{ \sum_{i\in\mathcal{N}} [f_i(\mu_i) + \lambda_i g_i(\mu_i)]\, I_{i\in Q^*} \right\} - \sum_{i\in\mathcal{N}} \lambda_i G_i \\
&\quad = \sum_{i\in\mathcal{N}} E\{f_i(\mu_i)I_{i\in Q^*}\}.
\end{aligned}$$

Therefore, the average system performance achieved by the policy (2) is greater than or equal to that of any other policies. ■

In this paper, we focus on the minimum bandwidth constraints and the network throughput maximization; thus, we set $g_i(\mu_i) = f_i(\mu_i) = \mu_i$. Therefore, the optimal criteria can be written as

$$Q^*(t) = S_{m^*}(t), m^* = \arg\max_m \left\{ \sum_{i\in S_m} \mu_i(1+\lambda_i) \right\}. \tag{4}$$

The KKT multipliers λ_i's depend on the multidimensional distribution of $\mu_i(t)$'s. In practice, the λ_i's can similarly be calculated by stochastic approximation algorithm as in [19]. We give an iterative algorithm as follows:

$$\lambda_i^{k+1} = \begin{cases} \lambda_i^k + a^k \left(G_i - C_i^k\right), & \text{if } G_i > C_i^k \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where the C_i^k is the throughput achieved until timeslot k, and for the stationary case, we can set $a^k = 1/k$; otherwise, we set a^k to a small constant to track the system variation [19].

The policy maximizes the average system performance even if the flows' performance values are arbitrarily correlated both in time and across the flows. The following proposition establishes, under a more restrictive assumption, that our scheme improves every flow's average performance relative to the nonopportunistic scheduling policies.

Proposition 3: If the utility values of each flow $f_i(\mu_i)$ (denoted by U_i) are independent, then we have

$$E\{U_i I_{i\in Q^*}\} \geq r_i E\{U_i\} \qquad \forall i \tag{6}$$

where $U_i = f_i(\mu_i)$, and $r_i = E\{I_{i\in Q^*}\}$.

Proof: For the ith flow that $i \in Q^*(t)$, the optimal scheduling (2) implies that

$$\begin{aligned}
i \in S_{m^*} \Rightarrow &\sum_{j\in S_{m^*}} f_j(\mu_j) \\
&\geq \max_{k\neq m} \left\{ \sum_{j\in S_k} [f_j(\mu_j) + \lambda_j g_j(\mu_j)] \right\} - \sum_{j\in S_m} g_j(\mu_j)\lambda_j.
\end{aligned}$$

Since we consider the scheduling in a connected CG, there should exist at least one MIS S_n wherein flow i is not in. Therefore, we have

$$\begin{aligned}
i \in S_{m^*} \Rightarrow U_i \geq &\sum_{k\in S_n} U_k + \sum_{k\in S_n} g_k(\mu_k)\lambda_k \\
&- \sum_{k\in S_m} g_k(\mu_k)\lambda_k - \sum_{k\in S_m, k\neq i} U_k \equiv Y.
\end{aligned}$$

Here, the defined Y is independent of U_i; thus, we have

$$\begin{aligned}
E\{U_i | i \in S_{m^*}\} &\geq E\{U_i | U_i \geq Y\} \\
&= E\{U_i | U_i \geq Y\} P(U_i \geq Y) \\
&\quad + E\{U_i | U_i \geq Y\} P(U_i < Y) \\
&\geq E\{U_i | U_i \geq Y\} P(U_i \geq Y) \\
&\quad + E\{U_i | U_i < Y\} P(U_i < Y) \\
&= E\{U_i\}.
\end{aligned}$$

Hence, the average performance of the ith flow obtained by the opportunistic scheduling policy satisfies the following equation:

$$\begin{aligned} E\{U_i I_{i\in Q^*}\} &= E\{U_i I_{i\in S_{m^*}}\} \\ &= E\{U_i | i \in S_{m^*}\} \cdot P\{i \in Q^*\} \\ &\geq E\{U_i\} \cdot P\{i \in Q^*\} \\ &= E\{U_i\} \cdot r_i. \end{aligned} \tag{7}$$

■

So far, we solve the opportunistic scheduling problem and present the optimal scheduling criteria by (2). For a special case which maximizes the network throughput under minimal bandwidth constraints, the optimal scheduling criteria are given by (4). Moreover, we prove that our scheme not only maximizes the network performance but also improves each flow's performance compared with the nonopportunistic policies.

A. Multihop Extension

In this paper, we mainly focus on the opportunistic scheduling for single-hop flows. However, for multihop flows, the performance of each flow depends on the end-to-end throughput which is upper bounded by a link with the minimal throughput along this flow. Herein, we try to formulate the scheduling problem for the multihop flows.

We formulate the multihop flows as M link sets: L_m, where $m \in \mathcal{M}$. For the ith link, $i \in L_m$ means that the mth multihop flow traverses the ith link. We assume that one link belongs to at most one multihop flow.[1] Thus, we have $L_m \cap L_{m'} = \Phi$ $\forall m$, where $m' \in \mathcal{M}$, and $m \neq m'$ (Φ denotes an empty set). Let b_i denote the expectation throughput of each link $b_i = E\{\mu_i(t) I_{i\in Q(t)}\}$, where $i \in \mathcal{N}$. Therefore, the throughput of a multihop flow can be given as

$$B_m = \min_i \{b_i | i \in L_m\}. \tag{8}$$

The link scheduling with minimal bandwidth requirements can be formulated as

$$\begin{aligned} \max_Q \quad & \sum_{m\in\mathcal{M}} U_m(B_m) \\ \text{s.t.} \quad & E\left\{\mu_i(t) I_{i\in Q(t)}\right\} \geq G_m \qquad \forall m \in \mathcal{M} \text{ and } i \in L_m \\ & c(i,j,t) = 0 \quad \forall i, \quad j \in Q(t), \quad i \neq j \end{aligned} \tag{9}$$

where U_m is the utility function, and G_m denotes the mth multihop flow's long-term bandwidth requirement. Compared with the optimization problem with single-hop flows, the solution of (9) turns out to be much more complicated, and this will be our future work.

[1]This assumption may not be true in every multihop scenario, and it will be dropped in our future work.

V. Heuristic Scheduling

Next, we focus on the design for a practical algorithm based on the optimal scheduling policy (4). Let $\mathrm{CR}(X)$ be a credit function which returns the credit of entity X. We define a MIS S_m's credit as $\mathrm{CR}(S_m) = \sum_{i\in S_m} \mu_i(1+\lambda_i)$, and the ith flow's QoS factor as λ_i. By the optimal criteria, a scheduler should gather the following instantaneous parameters for each timeslot: the CG, the flows' feasible data rate, and their QoS factors. Then, a set of flows, in one MIS with the largest credit, is scheduled to simultaneously transmit. After the transmissions, each flow updates its QoS factor according to (5).

The aforesaid optimal scheduling cannot directly be implemented into the IEEE 802.11-based *ad hoc* networks due to the following challenges: 1) Exchanging the feasible data rates and QoS factors all over the network is impractical since such a flooding consumes a lot of bandwidths, and some instantaneous values become outdated after a several-hop transmission. 2) It is difficult to track the time-varying CG which is needed in the optimal scheduling. 3) To schedule a set of links in a deterministic order, as time-division multiple access in cellular networks, is not trivial because of the distributed nature of the IEEE 802.11-based *ad hoc* network. In this section, we propose the COS which aims to approach the optimal scheduling but with the following reasonable and practical approximations.

First, to avoid the potential flooding overhead, we introduce a two-hop transmission-range information exchanging. In [22], the authors proved that the two-hop information is sufficient to build a local CG (LCG) for a certain link. The LCG is able to reveal the completed contention relationship among this link and its contending links since twice of the transmission range is a conservative approximation of the interference range. Second, our COS does not track the time-varying LCG. Instead, to reduce the system complexity and the bandwidth cost, we use an average LCG in which two links are assumed to be contended if and only if one node of a flow is in the two-hop average transmission range of any node of another flow. Finally, as previously mentioned, a transmitter that has no flows to be scheduled should be deferred. In COS, we propose to insert an extra interval into the consecutive data transmissions to defer the transmission of such a transmitter. The length of such an interval is dynamically adjusted according to the scheme introduced later.

Table I describes the several basic procedures of COS, and the typical time line on the frame format is shown by Fig. 2. We describe in detail the several important parts of our COS in the following sections.

A. Channel Probing and Information Exchanging

In our scheme, each node maintains a credit table for the links in its LCG. An entity in a table includes one link's identifier, the feasible data rate, and the QoS factor. A node updates its table in two ways: channel probing mechanism and overhearing other links' control packets. The probing process is based on the group RTS mechanism [12]. We modified the group RTS mechanism to facilitate the information exchanging. In COS, more information, including the average feasible data rates and

TABLE I
BASIC PROCEDURES OF COS

No.	Procedure Name	Description
I	Channel Probing	Use GRTS and CTS to measure the channel conditions and to exchange information.
II	Credit Calculation & Flow Scheduling (I)	The transmitter selects one receiver from candidate receivers.
III	DATA Transmission	The transmitter sends back-to-back data packets to the selected receiver.
IV	Flow scheduling (II)	The transmitter holds for some interval before starting the next transmission.

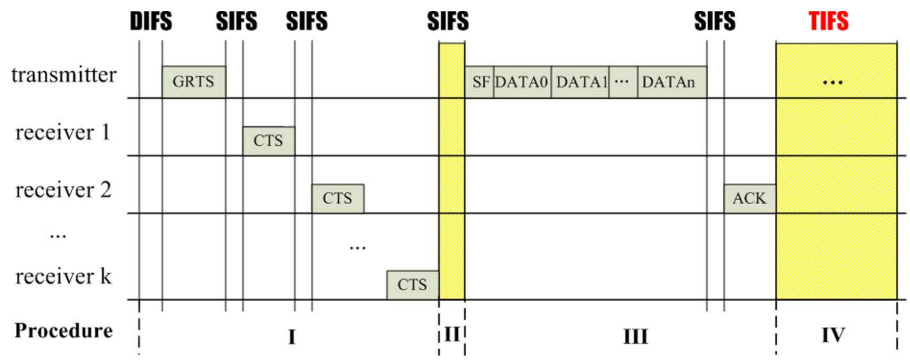

Fig. 2. Illustration of the COS on the frame format.

the QoS factors of the flows which are in the node's LCG, is piggybacked on the outgoing GRTS and CTS packets. Since each node maintains the information of the flows in its LCG, the parameters are actually propagated in a two-hop transmission range. Compared with OSAR, COS does not induce any more control packets. However, the number of packet makes difference of the network throughput rather than the packet length. In conclusion, a transmitter receives the instantaneously feasible data rate of its originating flows by the channel probing mechanism, whereas it obtains the average data rates and QoS factors of the other neighboring flows through the two-hop information exchanging.

B. Credit Calculation

In order to select the flows which maximize the network throughput, each transmitter should calculate the credit of each MIS before the data transmission. Through the information exchanging during the channel probing and LCG building process, a transmitter can gather all of the parameters needed in (4). After the calculation of the credits of the MISs, the credit of flows and transmitters can also be determined. Herein, a flow's credit is set to the largest credit of the MISs that include this flow, i.e., $\text{CR}(l_i) = \max_m\{\text{CR}(S_m)|i \in S_m\}$. A transmitter's credit is set to the largest credit of the flows originated by this transmitter, i.e., $\text{CR}(T_A) = \max_i\{CR(l_i)|l_i$ is originated by transmitter A$\}$.

C. Flow Scheduling

The flow scheduling executed by a transmitter can be divided into two phases. The first phase is to select the transmitter's outgoing flow which has the highest credit among its candidate flows. The transmitter sends back-to-back packets on this flow with the packet concatenation (PAC) mechanism [12], by which nodes will transmit more data during epochs of high-quality channels. The second phase is to approximate the optimal time scheduling, by which it means that only part of the links transmit and that other flows keep silence. To achieve this target, we propose a priority-based scheduling policy: An adaptive interval is inserted into a transmitter's two consecutive data transmissions. Here, we call the inserted interval as the traffic-control interframe space (TIFS) (see Fig. 2). The length of the TIFS is set according to the transmitter's credit. In other words, a link with a smaller credit implies that it experiences worse channel quality or achieves lower spatial diversity and that it should be assigned with a lower priority to access the channel at this moment. Thus, a longer interval (TIFS) is inserted between such a link's consecutive transmissions. Intuitively, the optimal length of the TIFS of a transmitter should be the duration from now until the transmitter credit turns out to be the largest. Hence, the optimal value depends on several factors of the network, such as the number of the neighboring transmitters, the coherent time of the varying channel, and the QoS requirements of the contending flows. In order to adaptively set the TIFS, we imitate the IEEE 802.11 contention-window (CW) updating algorithm in which a transmitter doubles its CW size if a collision occurs

$$\text{TIFS} = \begin{cases} 0, & \text{if seq} = 1 \\ \text{TIFS}_{\min}, & \text{if TIFS} = 0 \text{ and seq} > 1 \\ \min(\text{TIFS} \cdot \text{seq}, & \\ \qquad \text{TIFS}_{\max}), & \text{otherwise} \end{cases} \tag{10}$$

where seq denotes one transmitter's credit order among all the transmitters in its LCG. The seq $= 1$ means that this transmitter has the largest credit. The exponential increase (multiply by the factor seq) leads to quick convergence to the optimal value, whereas TIFS is reset to zero as soon as the credit appears to be the largest.

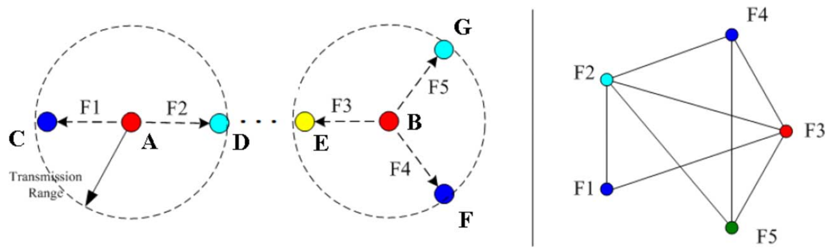

Fig. 3. Two-transmitter scenario and its contention graph. There are four MISs: $\Omega = \{S_m\} = \{\{F_2\}, \{F_3\}, \{F_1, F_4\}, \{F_1, F_5\}\}$.

Finally, in this section, we give an example to demonstrate our link scheduling process. The illustration network topology is shown in Fig. 3 with two transmitters, five flows, and four MISs: $\Omega=\{S_m\}=\{S_1, S_2, S_3, S_4\}=\{\{F_2\}, \{F_3\}, \{F_1, F_4\}, \{F_1, F_5\}\}$. Suppose that the network has been run for a sufficient long time. In other words, transmitters A and B have constructed their own LCGs and credit tables. In timeslot t_0, transmitter A sends a GRTS packet; its two receivers C and D reply CTSs one by one. In the meantime, the data rates and QoS factors of the other three flows (F_3, F_4, and F_5) are piggybacked on node D's CTS. Node D gets such information by overhearing node E's outgoing control packets. After receiving two CTSs, node A updates its credit table and computes the credits for all of the MISs, flows, and transmitters in its LCG. Here, we consider two typical computation results. The first one is that, in node A's credit table, the $\mu_i(1 + \lambda_i)$, $i = 1, 2, \ldots, 5$, for the five flows are $\{2, 4, 5, 4, 5\}$. Therefore, the credits of the four MISs $S_1(t)$, $S_2(t)$, $S_3(t)$, and $S_4(t)$ are 4, 5, 6, and 7, respectively. In this case, $S_4(t)$ has the largest credit; the credits of flows $F_1 - F_5$ are $\{7, 4, 5, 6, 7\}$; the credits of transmitters A and B are both 7. Thus, node A would send back-to-back data packets on F_1 and then receives an acknowledgment (ACK) from node C. Since F_1 is in $S_4(t)$, transmitter A sets its TIFS as 0, which means that node A can start a DIFS and CW backoff at once if there is another data packet queuing in node A's buffer. Consider another case in which the $\mu_i(1 + \lambda_i)$, $i = 1, 2, \ldots, 5$, for the five flows are $\{2, 4, 10, 4, 5\}$. Thus, the credits of the four MISs are $\{4, 10, 6, 7\}$, and the credits of flows $F_1 - F_5$ are $\{7, 4, 10, 6, 7\}$. The result shows that the MIS with the largest credit is $S_2 = \{F_3\}$. Node A sends back-to-back data packets on F_1 (F_1 is associated with a higher credit than F_2) and sets a nonzero TIFS according to (10). After receiving an ACK from node C, transmitter A would start a TIFS backoff process, during which node A would not try to access the channel.

VI. Simulation Result

In this section, we show the performance evaluation of the COS. The simulation experiments are conducted by ns-2 (version 2.29). We compare COS with OAR, OSAR,[2] and the optimal scheduling (described in Section IV). The available transmit rates of data packets are set to 1, 2, 5.5, and 11 Mb/s based on the IEEE 802.11b standard. The numbers of packets in one back-to-back transmission, i.e., a timeslot, are set according to the selected data rate: one for 1 Mb/s, two for 2 Mb/s, five for 5.5 Mb/s, and 11 for 11 Mb/s. All of the control packets (GRTS, CTS, and ACK) are transmitted with the basic data rate (1 Mb/s). The values of receiver sensitivities for different data rates are chosen based on the settings of ORiNOCO 802.11b card.[3] Under such setting, the corresponding simulation parameters in ns-2 are given by Table II. The average transmission and carrier sensing ranges can be computed by the two-ray ground reflection model, and the result is shown in Table III.

TABLE II
NS-2 Simulation Parameters

Frequency	2.4 G
Transmit Power	15 dBm
11.0 Mbps Sensitivity	-82 dBm
5.5 Mbps Sensitivity	-87 dBm
2.0 Mbps Sensitivity	-91 dBm
1.0 Mbps Sensitivity	-94 dBm
Carrier Sense Threshold	-108 dBm
1.0 Mbps Capture Threshold	10
Propagation Model	Two Ray Ground & Ricean Fading

TABLE III
Average Transmission and Carrier Sensing Ranges

Rates (Mbps)	11.0	5.5	2.0	1.0	CS
Range (m)	399	531	669	796	1783

In OAR, we use the standard FIFO queue (PriQueue) defined in ns-2, whereas in OSAR and COS, we implement a separate queue for each active neighbor and schedule the data packets according to the corresponding policies. The maximum length of the candidate receiver list is set to four. The Ricean fading channel model that we use is the same as the one used in OAR and OSAR. To evaluate the performance of OSAR with QoS constraints, we combine OSAR with the single-cell optimal scheduling criteria given by Kulkarni and Rosenberg [10]. Through that criteria, a transmitter activates the flow whose credit $\mu_i(1 + \lambda_i)$ is the largest among all of its originating flows.

The data packet size is set to 1000 B in all simulations. We use the fixed-route policy and report the end-to-end effective

[2]For comparison, we modify the rate adaptation part of OSAR to PAC, which is also used in COS.

[3]For 802.11b, we use the specifications for the ORiNOCO 11b Client PC Card, which can be found at http://www.proxim.com/.

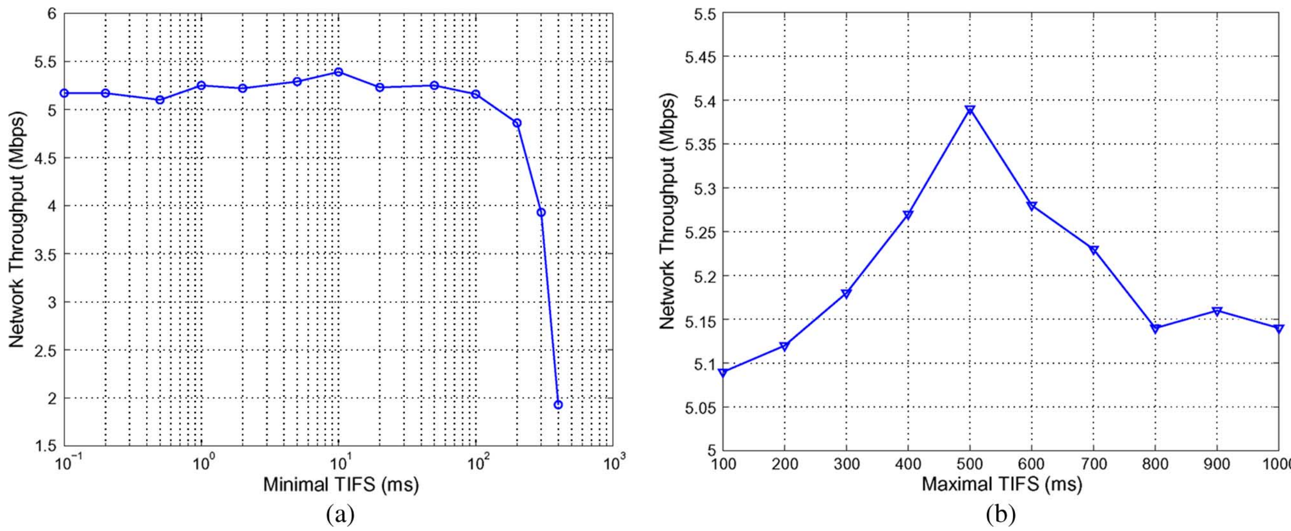

Fig. 4. Network throughput versus minimal and maximal TIFS. It shows that COS is not sensitive with the minimal TIFS. (a) Maximal TIFS is fixed at 500 ms. (b) Minimal TIFS is fixed at 1 ms.

throughput, in which the bandwidth overhead of MAC and routing layer is not included.

A. Two-Transmitter Scenario

First, we simulate a two-transmitter scenario, as shown in Fig. 3. In this scenario, each of the five constant bit-rate flows is originated from one of the two transmitters and destined to different receivers. The distance between a sender and a receiver of each flow is 450 m. Meanwhile, the distance between the two transmitters is 1800 m, which is larger than the average carrier sensing range.

Fig. 4 shows the relationship between the network throughput and $\text{TIFS}_{\min}$ ($\text{TIFS}_{\max}$). It is shown in Fig. 4(a) that the network throughput remains nearly the same when the $\text{TIFS}_{\min}$ varies from hundreds of microseconds to tens of milliseconds. This validates that our exponential increase algorithm is not sensitive to the setting of $\text{TIFS}_{\min}$. In the following simulation, we set the $\text{TIFS}_{\min}$ as 1 ms. Under such setting, as Fig. 5(b) shows, the network throughput reaches its peak when $\text{TIFS}_{\max}$ equals 500 ms. Intuitively, the value of the optimal $\text{TIFS}_{\max}$ depends on many network factors, such as the $\text{TIFS}_{\min}$, the network topology, and the packet length. To simplify our protocol, we set the $\text{TIFS}_{\max}$ as 500 ms in the following simulations. The design of the adaptive $\text{TIFS}_{\max}$ algorithm will be our future work.

Fig. 5 shows the throughput of each flow in the two-transmitter scenario, which is achieved by OAR, OSAR, COS and the optimal scheduling, with or without the different QoS requirements. As Fig. 5(a) shows, if there is no QoS requirement for each link, COS prefers to transmit on links 1, 4, and 5 since they maximize spatial reuse of a channel. Compared with OSAR, COS reduces the throughput of links 2 and 3 but improves that of links 1, 4, and 5 by almost 100%. Totally, the network throughput of COS is 35% higher than that of OSAR. Furthermore, our COS achieves about 90% of the network throughput achieved by the optimal scheduling, in which there is no overhead of the information exchanging and that the flows are scheduled in a collision-free way.

Giving links 2 and 3's QoS requirements as $G_2 = G_3 = 1.5$ Mb/s, the simulation result is shown by Fig. 5(b). Both OSAR and COS can achieve the requirements, and COS achieves much higher individual throughput gain: about 90% for links 4 and 5, and 250% for link 1. In Fig. 5(c), as the requirements increase to $G_2 = G_3 = 2.0$ Mb/s, OSAR fails to achieve the targets, whereas COS satisfies the requirements. Moreover, COS can also achieve more than 70% of the optimal network throughput. The performance gap exists due to the overhead of information exchanging, the usage of average but not instantaneous channel condition, the retransmissions due to packet collisions, etc.

In our simulation, we also vary the mobile speed[4] and Ricean parameter K to evaluate the impact of the channel variation on the network throughput. Fig. 6 compares the network throughput obtained by OAR, OSAR, and COS under different parameter settings. It is shown that, as the mobile speed increases or the parameter K decreases, the network throughput of all the three algorithms drops due to the channel-coherence-time decreases and, thus, more packet losses. Among all the examined mechanisms, COS performs the best and improves the network throughput by up to 40% with respect to OSAR and 100% to OAR.

B. Random Flows in Grid Topology

We also set up an 8×8 grid topology in which 64 nodes are located at the vertices. The transmitter and the receiver of each loaded flow are the neighboring nodes selected from such 64 nodes. The side length of each unit grid is 450 m; thus, the distance between each flow's transmitter and receiver is 450 m.

[4]Here, we assume that the mobile speed influences the Ricean channel condition but does not change the network topology. It can be seen as the mobile node is moving around a certain location or as the environment is continuously changing.

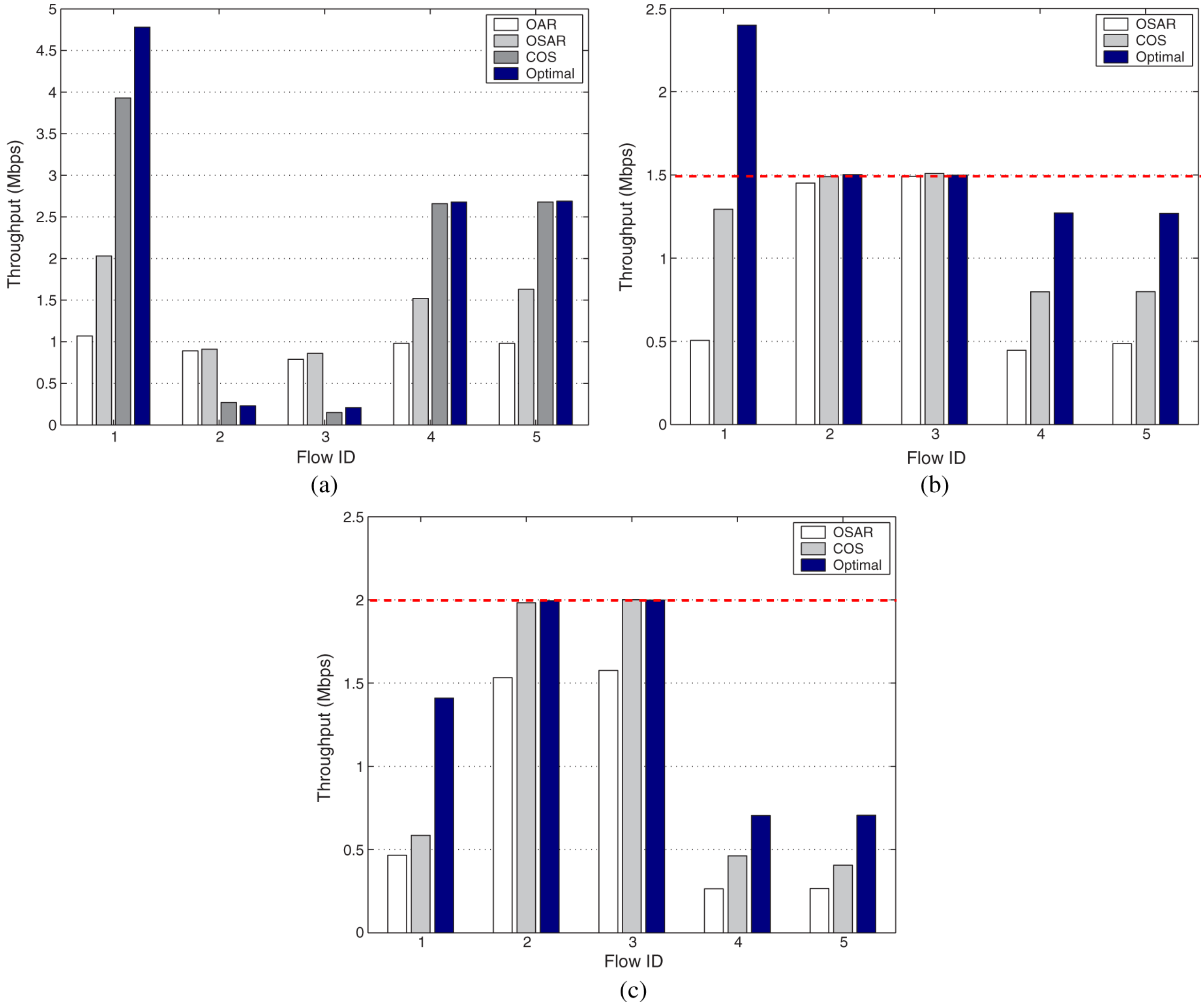

Fig. 5. Throughput of each flow in the two-transmitter scenario with or without QoS requirements. (a) Without QoS requirements. (b) Without QoS requirements: $G_2 = G_3 = 1.5$ Mb/s. (c) Without QoS requirements: $G_2 = G_3 = 2.0$ Mb/s.

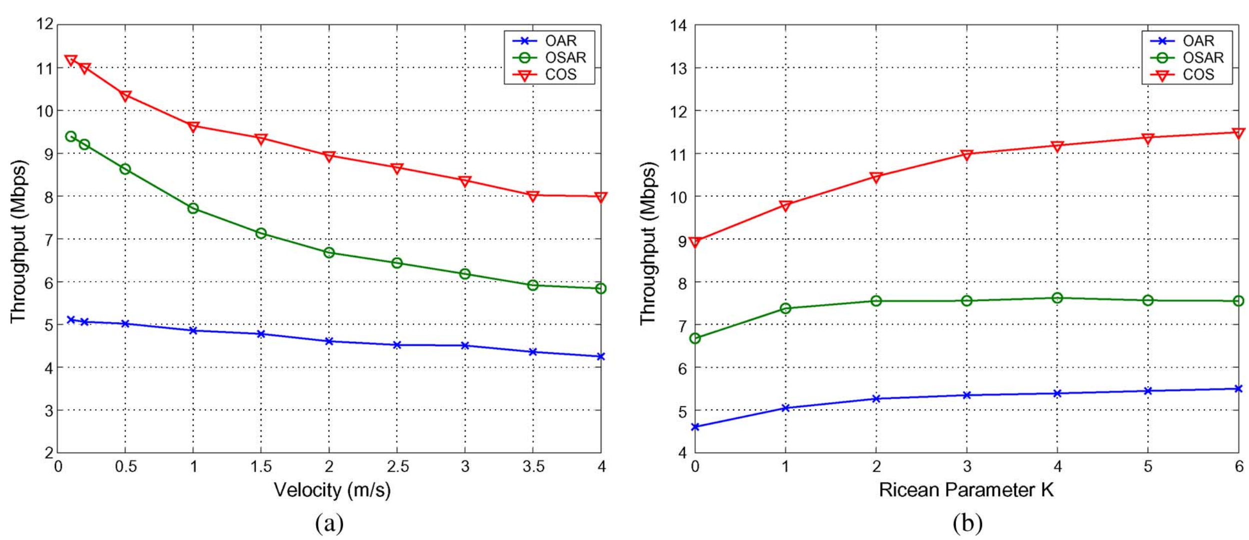

Fig. 6. Network throughput as a function of mobile speed and Ricean Parameter K in the two-transmitter scenario. (a) Ricean parameter $K = 0$. (b) Mobile speed $v = 2$ m/s.

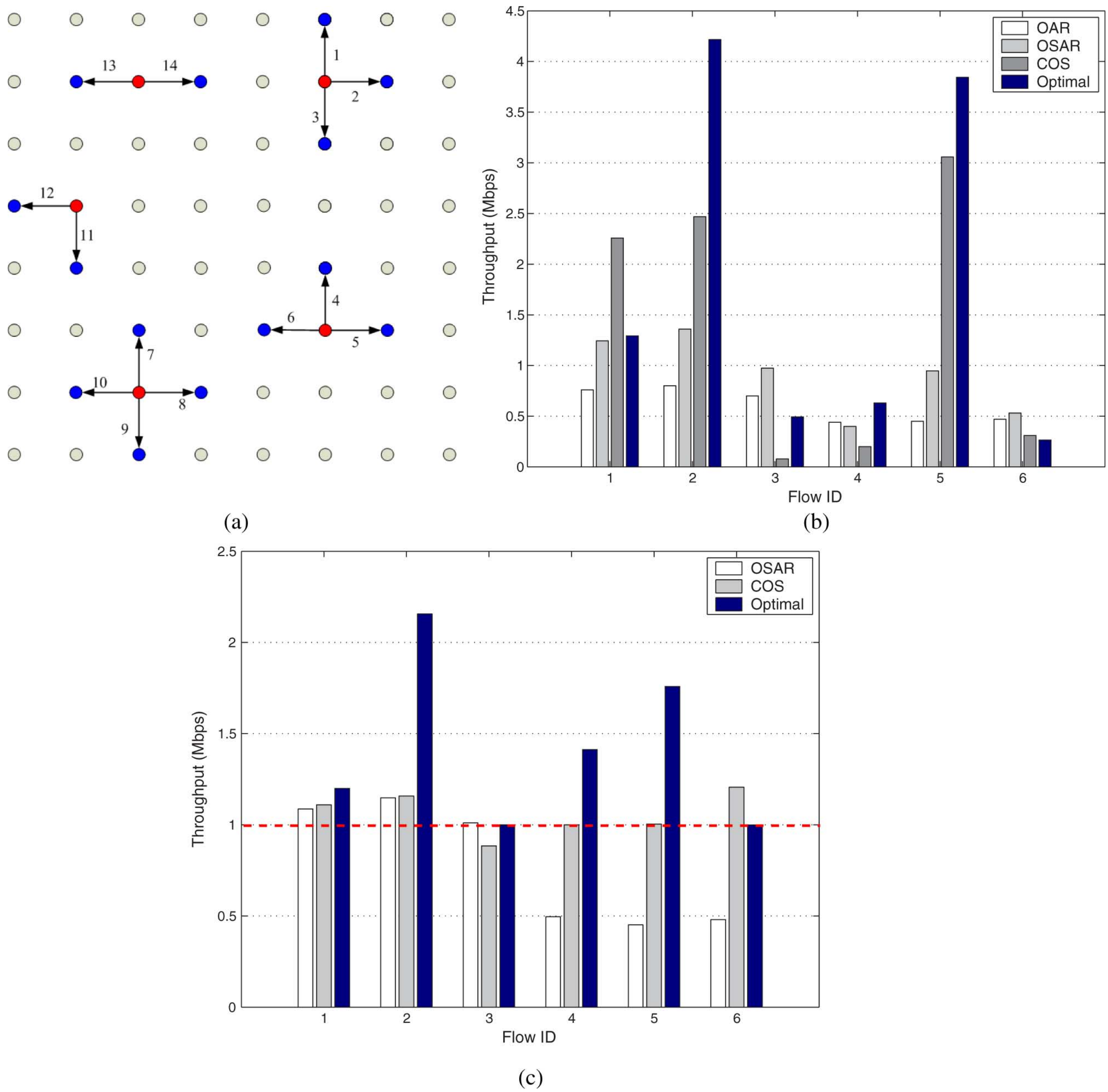

Fig. 7. Example of 14 flows generated in a grid topology with flow ID marked on. The first six flows' throughput of this example is shown. (a) Some 14 flows in a grid topology. (b) Without QoS requirements. (c) Without QoS requirements: $G_1 = G_2 = \cdots = G_6 = 1.0$ Mb/s.

First, we show a 14-flow example by Fig. 7(a). Without any QoS constraint, the simulation results on the network throughput are the following: 8.70 Mb/s with OAR, 10.16 Mb/s with OSAR, 13.72 Mb/s with COS, and 22.12 Mb/s with the optimal scheduling. In other words, COS achieves 35% performance gain over OSAR and 60% over OAR. The reason can be found in Fig. 7(b) in which the throughput of flows 1, 2, and 5 intensely increases. COS favors these flows since to serve them increases the spatial reuse and hence enhances the network throughput. For this complicated scenario, our COS obtains only 65% of the throughput obtained by the optimal scheduling. Compared with the two-transmitter example, there is one more reason for the performance gap: Each transmitter uses its local information, i.e., the LCG to determine its transmit priority which may not be the globally optimal choice. Given the QoS requirements of the first six flows as $G_1 = G_2 = \cdots = G_6 = 1.0$ Mb/s, Fig. 7(c) shows that COS successfully achieves the requirements by cooperatively reducing the throughput of the surrounding transmitters. However, without cooperation, OSAR fails to reach the targets.

Moreover, we simulate random scenarios in which 10–16 flows are randomly generated. The transmitters are randomly selected from the 64 nodes in the grid topology. Each transmitter has two-to-four single-hop flows to deliver, each of which destined to a randomly chosen neighboring receiver. We totally generate 80 different scenarios and show the result of the average network throughput, as shown in Fig. 8. It can be seen that COS outperforms OSAR by 15% and OAR by 30% on average. The average performance gain of the random scenarios is lower than those obtained in the

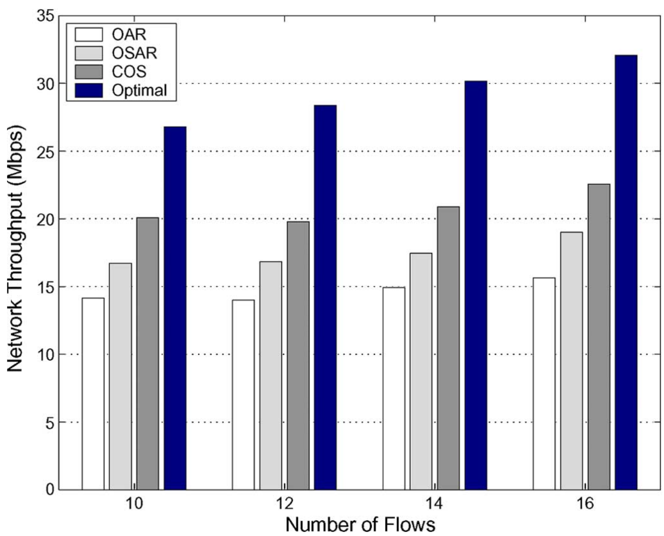

Fig. 8. Average network throughput versus the number of random flows in a grid topology.

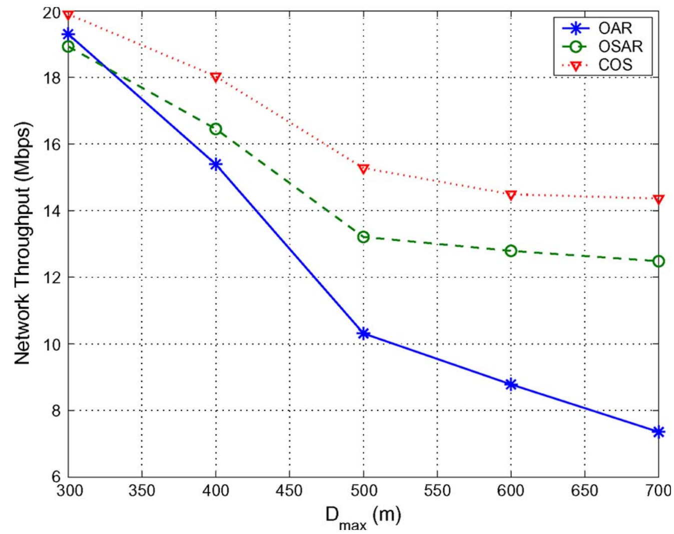

Fig. 9. Network throughput versus the maximal distance between a transmitter and its intended receiver in random scenarios.

two-transmitter scenario and the 14-flow example in Fig. 7(a). This is because, in some scenarios, several transmitters are located quite close and thus do not have the opportunity to be concurrently scheduled to increase the spatial reuse.

C. Random Topologies

In this paper, we simulate random topologies in which four transmitters are uniformly distributed in a 3 × 3-km square area. Each transmitter has three candidate receivers which are uniformly distributed in a round area with a radius of $D_{\max}$ from the transmitter. In our simulation, $D_{\max}$ is varied from 300 to 700 m. By simulating 30 random scenarios for each $D_{\max}$, the average network throughput versus $D_{\max}$ is shown by Fig. 9. Similarly, as before, our COS performs best in all the settings of $D_{\max}$. The network throughput of all the schemes drops as $D_{\max}$ increases since the probability of a transmitter that transmits with high data rates declines. Fig. 9 shows another noteworthy thing that, when $D_{\max}$ is small as 300 m, OSAR obtains a lower throughput than OAR. The reason is that, with small $D_{\max}$, all flows support the highest data rate (11 Mb/s) with high probability, and thus, the probing process becomes useless and a waste of network bandwidth.

VII. Related Works

Exploiting multiuser diversity is first studied by Knopp and Humblet for cellular networks. These authors showed in [4] that the total uplink capacity can be maximized by choosing the user with the best channel to transmit. Tse extended the study of [4] to downlink cases in [5], which showed that the same access scheme is also valid. The aforementioned scheduling algorithms independently work in individual cells. In the literature [8], [9], the authors extended the aforesaid work to multicell optimization and proposed the coordinated scheduling in which base stations in a cluster jointly schedule the users to be served. Numerical results verified that the coordinated scheduling improves the overall performance.

In contention-based wireless networks, a challenge to the exploitation of multiuser diversity is that no infrastructural node can behave as a central scheduler. A channel-aware ALOHA protocol is proposed in [11] to exploit multiuser diversity in a distributed fashion. In this work, each flow adjusts its transmission probability based on its channel gain, assuming that each flow knows its own channel gain as well as the distribution of other flows' channel gains. For 802.11-based *ad hoc* networks, OSAR [13] and MAD [12] are proposed. The difference between OSAR and MAD is that the rate adaptation part of OSAR is OAR, whereas, in MAD, the authors proposed a new rate adaptation scheme: the PAC. The PAC eliminates the ACKs and short-interval frame space between consecutive back-to-back data packets, which exist in OAR, and hence further exploits the channel variation. Simulation results indicated that OSAR and MAD obtain much higher network throughput as compared with the barely rate adaptation protocols such as OAR. Meanwhile, MAD outperforms OSAR due to the usage of PAC. However, none of the above opportunistic policies for *ad hoc* networks takes the contention among neighboring transmitters into account, which intuitively influences the network performance.

Purely exploiting multiuser diversity shows preference to flows with good channel conditions. In order to support fairness or QoS requirements, the criteria of the opportunistic scheduling should not merely depend on the channel conditions but also on the QoS requirement of each flow. For cellular networks, the scheduling criterion of the Qualcomm's HDR [7] system is to select the link which maximizes the ratio of the instantaneously feasible data rate over the average throughput. It is proved in [6] that HDR exploits multiuser diversity while maintaining proportional fairness among users. In [19], the authors consider resource-sharing constraints and propose a water-filling algorithm that selects the link with the highest feasible data rate added by a bias value. Kulkarni and Rosenberg extended the water-filling method to a more generalized solution in [10] for multiple long-term QoS constrains. For *ad hoc* networks, many schemes [20]–[22] are presented to provide fair scheduling, whereas none of them takes the fading phenomenon into account. For 802.11-based networks with fading channels, to keep fairness among multiple flows, MAD [12] uses a k-set round robin and the revenue-based scheduling to make sure that each receiver can be served according to its QoS requirement. However, all the previous analyses are based on single-cell/transmitter model. In *ad hoc* networks, the scheduling decisions of neighboring transmitters are highly correlated due to the cochannel interference. To the best of our knowledge, we are the first to address the opportunistic scheduling problem with the consideration of interaction among the transmitters for *ad hoc* networks with QoS constraints.

VIII. Conclusion

Exploiting multiuser diversity has emerged as an essential way to utilize the variation of the wireless channel. In this paper, we formulate opportunistic scheduling which exploits multiuser diversity in wireless *ad hoc* networks. Considering the cochannel interference caused by neighboring transmissions is essential for *ad hoc* networks; in our analysis, the interaction among neighboring transmitters is included. We present the optimal scheduling policy, which finds out the globally best set of simultaneously transmitting flows, to maximize network throughput while satisfying each link's QoS requirement. Moreover, we propose a distributed algorithm, called the COS, which is based on the IEEE 802.11 MAC protocols, in which two aspects of cooperation are introduced to approximate the optimal scheduling. The first aspect is to exchange the supported average data rates, the QoS factors, and the contention relationship among the two-hop neighboring nodes for scheduling decision making, and another aspect coordinates the transmissions of neighboring flows by deferring the unscheduled transmitters. The simulation results show that our proposed COS achieves higher network throughput and provides better QoS support than the existing solutions, such as OSAR.

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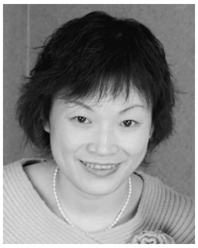

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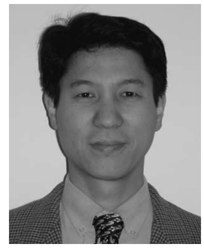

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