Opportunistic Link Scheduling with QoS Requirements in Wireless Ad Hoc Networks

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Abstract—In this paper, we study the link layer scheduling problem in wireless ad hoc networks. In such a network, the communication links compete for the scarce and time-varying wireless channels. Recently, opportunistic scheduling that exploits variation of channel conditions at each link has drawn great attention to improve system performance. Taking advantage of the multiuser diversity and being aware of the potential contention among neighboring transmissions, we formulate the opportunistic scheduling problems with QoS requirements and present the optimal scheduling policies for both single- and multi-hop ad hoc networks. We also proposed COS, a distributed Cooperative and Opportunistic Scheduling algorithm, which realizes the optimal scheduling policies by introducing the cooperation among neighboring transmitters. Simulation results indicate that our implementation achieves higher network throughput and provides better QoS support than existing solutions.

I. INTRODUCTION

Wireless ad hoc networks receive growing interest due to user’s provisioning of mobility, usability of services, and seamless communications. In ad hoc networks, a node sends or forwards packets to its neighboring nodes by accessing the shared and time-varying wireless channel. Although traditionally viewed as a source of unreliability that the fading needs to be mitigated, recent research suggests exploiting the channel fluctuations opportunistically when and where the channel is strong.

There are two main classes of opportunistic transmission policies for wireless ad hoc networks. The first is to exploit time diversity of individual links by adapting the transmit rate to the time-varying channel condition [1], [2]. In [2], the authors proposed the Opportunistic Auto Rate (OAR) scheme, in which a flow transmits with higher data rate and more back-to-back packets when its channel condition is better. Exploiting multi-user diversity is another class of opportunistic transmission, which jointly leverages the time and spatial heterogeneity of channels to adjust rates. In wireless networks, a node may have packets destined to several neighboring nodes. Selecting instantaneously an “on-peak” receiver with the best channel improves the channel utilization efficiency [3]–[6]. For IEEE 802.11 based wireless ad hoc networks, Opportunistic packet Scheduling and Auto Rate (OSAR) scheme [4] and Medium Access Diversity (MAD) scheme [5] are proposed to exploit multiuser diversity, in which a sender multicasts a channel probing message (e.g. Group RTS in MAD) before the data transmissions. Each receiver replies the current channel condition and then the sender schedules the rate adapted transmission to the receiver with the best channel quality. However, the existing algorithms do not consider the interaction among neighboring transmitters, i.e. a sender individually makes its local decision to maximize its own performance. Actually, the contention between the links which do not have a common sender has deep impact on the link scheduling. For instance, Fig. 1 shows a two-transmitter scenario, in which the link 2 contends with link 3, 4 and 5. Therefore, if sender A selects link 2, sender B should keep silence. Whereas, sender A selecting link 1 and B selecting link 4 or 5 may be the optimal choice which maximizes the network performance.

Purely exploiting multiuser diversity shows preference to flows with good channel conditions. For ad hoc networks, many schemes [8], [9] are presented to provide fair scheduling, whereas none of them takes the time-varying channels into account. For 802.11 based wireless LAN with fading channels, MAD [5] use a k-set round robin and the revenue based scheduling to provide the fairness. Whereas, by existing work, QoS requirements are difficult to achieve in wireless ad hoc networks, 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, neighboring transmitters jointly determine the “on-peak” links. In addition, through a priority based policy, some transmitters are deferred so as to favor the scheduled links. The key contributions of this paper are: 1) a multiuser diversity model is given for both single- and multi-hop ad hoc networks, while considering two types of QoS criteria: deterministic QoS constraints (etc., the minimal bandwidth requests) and fairness requirements; 2) we present the optimal criteria to choose the globally optimal set of simultaneously transmitting links; 3) an distributed Cooperative and Opportunistic Scheduling (COS) is designed, which can be easily implemented into IEEE 802.11 based ad hoc networks.

The rest of this paper is organized as follows. Problem formulation for single-hop ad hoc networks is given in Section II. Section III represents the optimal solution. Section IV gives the multihop extension. Section V describes the distributed implementation of the optimal scheduling and Section VI gives the numerical results. This paper is concluded in Section VII.
II. PROBLEM FORMULATION

In the following two sections, we discuss single-hop flow scenarios and we assume that all the links (single-hop flows) have saturated traffic. Consider an ad hoc network with $N$ links $(f_i, i \in N)$. In this paper, we consider the system with fixed transmit power. Due to the fading phenomenon, the possible data rate supported by each link is also time-varying. Suppose that time is divided into timeslots with fixed time width. Hence, throughput achieved by a link in a timeslot is linear proportional to its transmit 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 [4]. The highest data rate that the $i$th link supports in timeslot $t$ is denoted by $\mu_i(t)$.

The contention relationship of links can be represented by a Contention Graph (CG) [8], in which vertexes are links and an edge exists between two links if they contend with each other. Due to the fading phenomenon, the path gain between any two nodes varies from time to time, which leads to the time-varying contention relationship $CG(t)$. We introduce a contention indication function $c(i, j, t)$, which equals 1 if link $i$ and link $j$ are edged in the contention graph $CG(t)$, otherwise zero. Moreover, by coloring vertexes we can obtain several Independent Subsets (IS), in which the flows can transmit simultaneously. A Maximal Independent Subset (MIS) $(S_m(t))$ is an IS that is not subset of any other IS. $\Omega(t) = \{S_m(t)\}$ denotes the MIS set. Similarly, we can define Maximal Clique (MC) $(C_m(t))$ as the link set in which all the links contend with each other.

We formulate any link scheduler as $\Omega$, in which $Q(t)$ denotes the scheduled transmitting link set in timeslot $t$. $i \in Q(t)$ means that link $i$ transmits at this moment. We also introduce an indicator function $I_X$, which equals 1 if $X$ is true, otherwise zero.

A. Deterministic QoS constraints

For deterministic requirements such as the minimal bandwidth or time-sharing constraints, we aim to find out a scheduling policy which maximizes the network performance while satisfying the deterministic QoS constraints of individual flows. We formulate the network performance as the sum of each link’s expectation throughput: $\sum_{i \in N} \mathbb{E}[\mu_i(t) I_{i \in Q(t)}]$, in which $\mathbb{E}$ denotes the expectation value over time: $\mathbb{E}[x(t)] = \lim_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} x(t)$.

The problem should have two sets of constraints, one is contention restriction and the other is QoS constraint of each link. We use a generalized function $g_i(x)$ to describe different constraints. For instance, $g_i(x) = 1$ denotes the time sharing constraint and $g_i(x) = x$ denotes the minimal bandwidth constraint. The opportunistic scheduling for deterministic QoS constraints can be formulated as

$$\begin{align*}
\max_{Q} & \quad \sum_{i \in N} \mathbb{E}[\mu_i(t) I_{i \in Q(t)}] \\
\text{s.t.} & \quad \mathbb{E}[g_i(\mu_i(t)) I_{i \in Q(t)}] \geq G_i, \forall i \in N, \\
& \quad c(i, j, t) = 0, \quad \forall i, j \in Q(t), i \neq j,
\end{align*}$$

in which $G_i$ denotes the $i$th link’s QoS requirement.

B. Fairness requirements

We treat the fairness as another kind of QoS requirements, by which no deterministic/hard constraints is given. We introduce utility functions $U_i(\cdot)$, which are non-decreasing, concave and differentiable. By maximizing the network utility, i.e. the sum of all user utilities $\sum_i U_i(x)$, we can control the tradeoff between efficiency and fairness. Different shapes of utility functions lead to different types of fairness. For example, a family of utility functions parameterized by $\alpha \geq 0$ is proposed in [10]:

$$U_\alpha(x) = \begin{cases} 
\log x, & \text{if } \alpha = 1 \\
x^{1-\alpha}, & \text{otherwise}
\end{cases}$$

by which the proportional fairness is achieved as $\alpha = 1$ and the max-min fairness as $\alpha \to \infty$. If we set $\alpha = 0$, the problem reduces to system throughput maximization.

Thus we present the link scheduling problem with fairness requirements as

$$\begin{align*}
\max_{Q} & \quad \sum_{i \in N} U_\alpha(\mathbb{E}[\mu_i(t) I_{i \in Q(t)}]) \\
\text{s.t.} & \quad c(i, j, t) = 0, \quad \forall i, j \in Q(t), i \neq j.
\end{align*}$$

III. OPTIMAL CRITERIA OF SCHEDULING

Let us denote the optimal solution/policy of problem (1) by $Q^*$ and problem (2) by $Q^{**}$. Then we have following propositions.

Proposition 1: The optimal solution of opportunistic scheduling (1) and (2) satisfies $Q^*(t) \in \Omega(t) (Q^{**}(t) \in \Omega(t))$ in any timeslot $t$.

By Proposition 1, we show that every selection of the optimal policy in timeslot $t$ is an MIS. This can be easily proved by contradiction.

Then, we solve the problem (1) and present the optimal policy $Q^*$ as following Proposition 2.

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

$$Q^*(t) = S_m(t),$$

in which

$$m^* = \arg \max_m \sum_{i \in S_m(t)} [\mu_i + \lambda_i g_i(\mu_i)]$$

(3)
in which \( \lambda_i \)'s are the Karush-Kuhn-Tucker (KKT) multipliers and the Kuhn-Tucker conditions hold as

\[
\forall i, \quad \lambda_i \geq 0, \quad E\{g_i(\mu_i)I_{i\in Q}\} \geq G_i \quad \text{and} \quad \lambda_i (E\{g_i(\mu_i)I_{i\in Q}\} - G_i) = 0.
\]

Due to space limitation, we omit the proof here. The detailed proof can be found in our technical report [11].

In the case of the minimum bandwidth constraints, the optimal criteria (3) can be written as

\[
Q^*(t) = S_m^*(t), \quad m^* = \arg \max_m \{ \sum_{i \in S_m} \mu_i (1 + \lambda_i) \}. \quad (4)
\]

The KKT multipliers \( \lambda_i \)'s depend on the multidimensional distribution of \( \mu_i(t) \)'s. In practice, the \( \lambda_i \)'s can be calculated by stochastic approximation algorithm similarly as in reference [7]. We give an iterative algorithm as follow.

\[
\lambda_{i}^{k+1} = \begin{cases} 
\lambda_{i}^{k} + a^k(G_i - b_i^k), & \text{if } G_i > b_i^k \\
0, & \text{otherwise},
\end{cases} \quad (5)
\]

where the \( b_i^k \) is the throughput achieved until time slot \( k \):

\[
b_i^k = \frac{1}{k} \sum_{t=1}^{k} \mu_i(t) I_{i \in Q(t)}. \quad (6)
\]

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 [7].

Nextly, we give Proposition 3 to present the optimal policy \( Q^{**} \) which maximizes the network utility.

**Proposition 3:** The optimal solution of the network utility maximization problem (2) is of the following form.

\[
Q^{**}(t) = S_{m^*}(t), \quad \text{in which} \quad m^* = \arg \max_m \{ \sum_{i \in S_{m}(t)} U_i'(b_i^{(t-1)}) \mu_i(t) \}, \quad (7)
\]

in which \( U_i'() \) is the differential function of \( U_i() \) and \( b_i^{(t-1)} \) is average throughput until timeslot \( t-1 \) (see equation (6)).

**Proof:** Due to the space limitation, we only give the sketch of the proof.

We start our analysis from a sufficient long timeslot \( T \) and the scheduling policy before \( T \) is given, i.e., \( Q(t), t = 1, 2, \cdots, T - 1 \) are fixed. Under this assumption, we try to find the optimal policy \( Q(T) \).

\[
\sum_{i \in N} U_i(b_i^T) = \sum_{i \in N} U_i' \left( \frac{T}{T-1} \sum_{t=1}^{T-1} \mu_i(t) I_{i \in Q(t)} + \frac{1}{T} \mu_i(T) I_{i \in Q(T)} \right) = \sum_{i \in N} \left[ U_i(c_i^T) + \frac{1}{T} U_i' \left( c_i^T \right) \mu_i(T) I_{i \in Q(T)} + \alpha \left( \frac{\mu_i(T)}{T} \right) \right] \leq \sum_{i \in N} \left[ U_i(c_i^T) + \alpha \left( \frac{\mu_i(T)}{T} \right) \right] + \sum_{i \in S_{m^*}} \left[ \frac{1}{T} U_i' \left( c_i^T \right) \mu_i(T) \right]
\]

in which \( c_i^T = \frac{T-1}{T} b_i^{(T-1)} \approx b_i^{(T-1)} \) and \( m^* = \arg \max_m \{ \sum_{i \in S_m(T)} U_i'(b_i^{(T-1)}) \mu_i(T) \} \).

The above inequation reveals that by using the scheduling policy (7) the network utility can be maximized.

The differential function of \( \alpha \)-family utility is \( x^{-\alpha} \). Therefore, for the proportional fairness, the optimal scheduling is given by

\[
Q^{**}(t) = S_{m^*}(t), \quad m^* = \arg \max_m \{ \sum_{i \in S_m(t)} \mu_i(t) \beta_i(t-1) \}, \quad (8)
\]

**IV. MULTIHOP EXTENSION**

In the previous sections, we formulate the opportunistic scheduling for single-hop ad hoc networks. 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. In time-varying ad hoc networks, the scheduling aiming to maximize the sum of the multihop flows’ utility turns to be much more complicated. In this section, we try to formulate the problem and solve it in some special scenarios.

We formulate multihop flows as \( M \) link sets: \( F_m, m \in M \).

For the \( i \)th link, \( i \in F_m \) if and only if the \( m \)th flow traverses the \( i \)th link. We assume that one link belongs to at most one multihop flow, thus we have \( F_m \cap F_{m'} = \Phi, \forall m, m' \in M, m \neq m' \) (\( \Phi \) denotes an empty set). As in previous sections, \( b_i \) denotes the throughput of each link \( b_i = E\{\mu_i(t) I_{i \in Q(t)}\}, i \in N \). Therefore, the throughput of a multihop flow can be given as

\[
B_m = \min_{i \in I} \{b_i | i \in F_m\}. \quad (9)
\]

The link scheduling with fairness QoS requirements can be formulated as

\[
\max \sum_{m \in M} U_m(B_m) \quad \text{s.t.} \quad c(i, j, t) = 0, \quad \forall i, j \in Q(t), i \neq j,
\]

where \( U_m \) is the concave utility function.

To solve the above optimization problem, we first give several definitions.

**Definition 1:** The \( i \)th link is defined to be strongly contented by the \( j \)th link if and only if there is no clique that contains link \( i \) but does not contain link \( j \), i.e., \( \forall C_m, i \in C_m \Rightarrow j \notin C_m \).

**Definition 2:** A link in a multihop flow is congested if and only if it strongly contends with any other links in this flow.

Then, we have the following proposition.

**Proposition 4:** By using the scheduling which is the optimal solution to problem (10), the end-to-end throughput of each
flow is equal to the congested link along its path. In other words, by the optimal scheduling, the congested links within the same flow have equal throughput which is the smallest among all the links in this flow.

This proposition can be proved by contradiction. Thus, we can solve some special cases that each flow has at least one congested link. For instance, we can find in our example scenario (see Fig. 6) that $f_1$ and $f_2$ are the congested links for $F_1$, while $f_4$ congests $F_2$. We have $B_1 = b_1 = b_2$, $b_1 \leq b_3$ and $B_2 = b_4$. Therefore, the example problem can be written as

$$\max \log E\{\mu_1 I_1\} + \log E\{\mu_4 I_4\}$$

s.t. $E\{\mu_1 I_1\} = E\{\mu_2 I_2\}$

$$E\{\mu_1 I_1\} \leq E\{\mu_3 I_3\}$$

$$I_{Q(t)} = \{3, 4\} + I_{Q(t)} = \{1\} + I_{Q(t)} = \{2\} \leq 1$$

Using the same analysis in the previous sections, the optimal scheduling $Q^*$ can be given by

$$Q^*(t) = \begin{cases} \{1\}, & \text{if } i^* = 1 \\ \{2\}, & \text{if } i^* = 2 \\ \{3, 4\}, & \text{if } i^* = 3 \end{cases}$$

(12)

$$i^* = \arg \max_i (1 / p_i - \lambda_2 - \lambda_3 \mu_1 + \lambda_2 \mu_2 + \lambda_3 \mu_3 + \mu_4 / b_4)$$

(13)

in which the $\lambda_i$’s are the KKT values, which can also be computed by stochastic approximation algorithm.

V. COS: A HEURISTIC FOR COOPERATIVE AND OPPORTUNISTIC SCHEDULING

Next, we focus on the design for a practical algorithm based on the optimal scheduling policies. Let $CR(X)$ be a credit function which returns the credit of entity $X$. For deterministic QoS constrained problems, we define an MIS $S_m$’s credit as $CR(S_m) = \sum_{i \in S_m} \mu_i(1 + \lambda_i)$, and the i th flow’s QoS factor as $\lambda_i$. Whereas, for proportional fairness problems, $CR(S_m) = \mu_i / b_i$. By the optimal criteria, a scheduler should gather following instantaneous parameters for each timeslot: the contention graph, the links’ feasible data rate (divided by achieved throughput for fairness problems) and their QoS factors. Then a set of flows, in one MIS with the largest credit, are scheduled to transmit simultaneously. After the transmissions, each flow updates its QoS factor according to equation (5).

Due to the lack of infrastructure nodes, the above optimal scheduling cannot be directly implemented into IEEE 802.11 based ad hoc networks. In this section, we propose a Cooperative and Opportunistic Scheduling (COS) which aims to approach the optimal scheduling but with the following reasonable and practical approximations. Firstly, to avoid the potential flooding overhead, we introduce a two-hop transmission range information exchanging. In [8], the authors proved that the Local Contention Graph (LCG), which includes only the flows in one node’s two-hop transmission range, is sufficient for revealing the contention relationship. Secondly, our COS does not track the time-varying LCG. Instead, we use an average LCG, in which two links are assumed to be contended iff any node of a link is in the average interference range of any node of another link. The average LCG can be built with the help the FLOID scheme (see [8] for details). Lastly, we propose a priority based transmission policy to approximate the optimal scheduling which is TDMA-like. By inserting extra intervals into consecutive data transmissions of the unscheduled transmitters, the scheduled links would be associated with higher priority to access the wireless channels.

Fig. 3 shows a typical time line of COS. Before a data transmission, we also use the Group RTS (GRTS) [5] to achieve the channel probing: a sender multicasts a RTS packets and its candidate receivers reply with CTS packets which contain channel conditions. To exchange the information among the links which have no common sender, more information, including the average data rates and the QoS factors of the links which are recorded in a node’s LCG, is piggyback on its out-going GRTS and CTS packets. Since each node maintains the information of links in its LCG, the parameters actually are propagated in a 2-hop transmission range. As soon as a node receives any updated information, it runs a credit calculation procedure to compute the credits for all the MIS’s, links and senders in its LCG. Here the i th link’s credit is given by

$$CR(f_i) = \max_{m} \{CR(S_m) \mid f_i \in S_m\} \text{, and a sender’s credit equals } \max_{m} \{CR(f_i) \mid f_i \text{ is originated by this sender}\}$$

After a sender receives all the CTS’s, it runs the first phase of link scheduling to find the link with largest credit among the candidate links and then sends back-to-back packets on it. When a sequence of data transmission is finished, i.e, ACK is received, the sender executes another phase of the link scheduling, which determines the length of the inserted interval before starting the next transmission. We call the inserted interval as the Traffic-control InterFrame Space (TIFS). The length of TIFS is set according to the order of its credit. The optimal length of TIFS is the duration from now till the transmitter’s credit turns to be the largest. In order to adaptively set TIFS, we imitate the IEEE 802.11 Contention Window (CW) updating algorithm in which a transmitter doubles its CW size if a collision occurs:

$$TIFS = \begin{cases} 0, & \text{if } seq = 1 \\ \min(TIFS_{\text{min}}, \text{TIFS}_0), & \text{if } seq = 0 \text{ and } seq > 1 \end{cases}$$

min(TIFS_{\text{max}}), \text{otherwise}$$

(14)
in which the \textit{seq} denotes one transmitter’s credit order among all the transmitters in its local contention graph. \textit{seq} = 1 means that this transmitter has the largest credit.

VI. SIMULATION RESULT

Our simulation experiments are conducted by ns-2 (version 2.29). Under minimal bandwidth constraints, we compare COS with OAR, OSAR, and the optimal scheduling. Moreover, three schemes with proportional fairness requirements: COS\_prop, OSAR\_prop and Optimal\_prop are compared. In all schemes, the data packet size is set to 1000 bytes, of which the available transmit rates of data packets are set to 1Mbps, 2Mbps, 5.5Mbps and 11Mbps according to IEEE 802.11b standard. The number of packets in one back-to-back transmission is set according to the data rate selected: 1 for 1Mbps, 2 for 2Mbps, 5 for 5.5Mbps and 11 for 11Mbps. All the control packets (GRTS, CTS and ACK) are transmitted with the basic data rate, 1Mbps. The values of receiver sensitivities for different data rates are chosen based on the settings of ORiNOCO 802.11b card\(^1\). Thus, the average transmission and carrier sensing ranges can be computed by the two-ray ground reflection model and the result is shown in Table I.

In our simulation, the Ricean fading channel model we use is the same as the one used in literature [2], [4]. To evaluate the performance of OSAR with QoS requirements, we modify OSAR’s scheduling criteria as: Each sender selects the link with maximal \(\mu_i(1 + \lambda_i) \ (\mu_i/b_i \text{ in OSAR\_prop})\) among its own outgoing links.

We use the fixed route policy and report the end-to-end effective throughput, in which the bandwidth overhead of MAC and routing layer is not included. Meanwhile, we set the \(TIFS_{\text{min}} = 1\)ms and \(TIFS_{\text{max}} = 500\)ms. Intuitively, the value of the optimal \(TIFS_{\text{min}}\) or \(TIFS_{\text{max}}\) depends on many network factors, such as the network topology and the packet length. The design of adaptive algorithm will be our future work.

A. Two-Transmitter Scenario

Firstly, we simulate a two-transmitter scenario with five CBR flows as illustrated in Fig. 1. The distance between any sender and its receiver of each flow is 450m. Meanwhile, the

\(^1\)For 802.11b, we use the specifications for the ORiNOCO 11b Client PC Card which can be found at http://www.proxim.com/.
distance between two transmitters is 1800m, which is larger than the average carrier sensing range.

Fig. 4 shows the throughput of each flow in the two-transmitter scenario without or with different deterministic QoS (minimal bandwidth) constraints. As Fig. 4(a) depicts, if there is no deterministic QoS constraint for each link, COS prefers to transmit on link 1, 4 and 5, since they maximize the spatial reuse of channel. Comparing with OSAR, COS reduces throughput of link 2 and 3, but improves link 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. Giving link 2’s and 3’s constraints as $G_2 = G_3 = 1.5$ Mbps, we provide the simulation result by Fig. 4(b). Both OSAR and COS can satisfy the requirements, but COS achieves much higher individual throughput gain: about 90% for link 4 and 5, 250% for link 1. In Fig. 4(c), as the requirements increase to $G_2 = G_3 = 2.0$ Mbps, OSAR fails to achieve the targets whereas COS satisfies the requirements. In addition, COS can also obtain more than 70% of the optimal network throughput.

We also simulate the COS_prop, OSAR_prop and Optimal_prop. Fig. 7 shows the each link’s normalized throughput, i.e. $b_i/b_i^*$, in which $b_i^*$ is the throughput obtained by the Optimal_prop. Our policy COS_prop achieves well fairness among links and its network throughput is about 75% of the optimal one.

C. A Multihop Scenario

We simulate the example scenario in Fig. 2 with multihop transmissions. By using the optimal scheduling policy (13) which maximizes the sum of flows’ log utility, Fig. 6(a) shows that the throughput of these links converge to constant values as the iteration/timeslot goes on. As our Proposition 4 describes, $f_1$ and $f_2$ are the congested links in $F_1$, thus they obtain the same bandwidth which is lower than $f_3$ obtains. The KKT values updated by stochastic approximation algorithm are shown in Fig. 6(b), in which the $\lambda_3$ is oscillating to track the time-varying channel and keep that link 1 and link 2 obtain the equal throughput: $b_1 = b_2$. Under proportional fairness requirements, $F_1$ and $F_2$ obtain 1.45 and 2.00 Mbps end-to-end throughput respectively.

VII. CONCLUSION

Exploiting multiuser diversity has emerged as an essential way to utilize the variation of the wireless channel. In this paper, we formulate the opportunistic scheduling which exploits the multiuser diversity for both single- and multi-hop ad hoc networks with deterministic QoS constraints or fairness requirements. We present optimal scheduling policies to maximize overall end-to-end throughput of each flow while satisfying their QoS requirements. Moreover, we propose the cooperative and opportunistic scheduling scheme, COS, based on IEEE 802.11 MAC protocols. The numerical result shows that our COS achieves higher network throughput and provides better QoS support than existing work.

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