Link Scheduling With Power Control for Throughput Enhancement in Multihop Wireless Networks

Jian Tang, Guoliang Xue, *Senior Member, IEEE*, Christopher Chandler, and Weiyi Zhang

***Abstract*—Joint scheduling and power control schemes have previously been proposed to reduce power dissipation in wireless *ad hoc* networks. However, instead of power consumption, throughput is a more important performance concern for some emerging multihop wireless networks, such as wireless mesh networks. This paper examines joint link scheduling and power control with the objective of throughput improvement. The MAximum THroughput link Scheduling with Power Control (MATH-SPC) problem is first formulated and then a mixed integer linear programming (MILP) formulation is presented to provide optimal solutions. However, simply maximizing the throughput may lead to a severe bias on bandwidth allocation among links. To achieve a good tradeoff between throughput and fairness, a new parameter called the demand satisfaction factor (DSF) to characterize the fairness of bandwidth allocation and formulate the MAximum Throughput fAir link Scheduling with Power Control (MATA-SPC) problem is defined. An MILP formulation and an effective polynomial-time heuristic algorithm, namely, the serial linear programming rounding (SLPR) heuristic, to solve the MATA-SPC problem are also presented. Numerical results show that bandwidth can be fairly allocated among all links/flows by solving the MILP formulation or by using the heuristic algorithm at the cost of a minor reduction of network throughput. In addition, extensions to end-to-end throughput and fairness and multiradio wireless multihop networks are discussed.**

***Index Terms*—Cross-layer optimization, fairness, link scheduling, power control, QoS, throughput maximization.**

I. Introduction

IN A MULTIHOP wireless network, power control and link scheduling are typical issues in the physical layer and the link layer, respectively. However, scheduling transmissions without careful consideration for physical layer constraints may end up with the following two situations.

1) Spatially close wireless nodes are scheduled to transmit simultaneously.
2) When a node begins to transmit, all other nodes in its neighborhood are forced to become silent (e.g., 802.11 DCF).

In the first situation, more wireless nodes may be scheduled to transmit simultaneously so that the channel spatial reuse can be improved, which eventually leads to high network throughput. However, wireless nodes need to increase the transmission power to guarantee the required signal-to-interference-plus-noise ratio (SINR) for each receiver, which will result in high energy dissipation or sometimes even the infeasibility of power assignment due to the strong interference and maximum power level limit of each transmitter. On the contrary, in the second situation, the transmission power can be saved at the cost of poor network throughput. Therefore, researchers have begun to study cross-layer approaches, i.e., joint link scheduling and power control schemes.

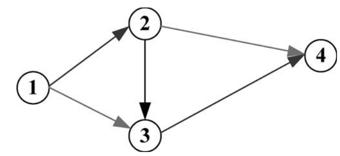


Fig. 1. Throughput maximization and fairness.

Most of the previous works on joint link scheduling and power control focus on minimizing the power dissipation [6], [27]. The schemes proposed in those papers are useful for wireless *ad hoc* networks and wireless sensor networks in which power consumption and network lifetime are the primary concerns. However, they cannot be applied to some emerging multihop wireless networks such as wireless mesh networks (WMNs) [1], in which network throughput and fairness are the most critical issues. WMN is envisioned to provide the community with many attractive applications such as broadband Internet access, distributed information sharing and storage, and various real-time multimedia applications. A WMN is usually composed of wireless mesh routers and mesh clients. Wireless mesh routers form a multihop wireless network that serves as the backbone to provide network access for mesh clients. In such networks, wireless mesh routers are usually stationary and connected with a fixed alternating current power, which makes WMNs quite different from the well-studied wireless *ad hoc* networks and wireless sensor networks. In WMNs, a high volume of traffic is expected to be efficiently delivered on the bandwidth-limited wireless channels, and a large number of users must be fairly served.

In this paper, we study joint link scheduling and power control in a time-division-multiple-access (TDMA)-based multihop wireless network with the objective of maximizing network throughput. We seek feasible transmission schedules along with power assignments that may not lead to a minimum power consumption but can provide high throughput. However, scheduling with only throughput maximization in mind may cause a severe bias on the bandwidth allocation among the flows, which can be shown by a simple example in Fig. 1. Throughout this

Manuscript received November 13, 2005; revised January 6, 2006 and January 14, 2006. This work was supported in part by ARO under Grant W911NF-04-1-0385 and NSF under Grants CCF-0431167 and CNS-0524736. The information reported here does not reflect the position or the policy of the federal government. The review of this paper was coordinated by Prof. X. Shen.

The authors are with the Department of Computer Science and Engineering, Arizona State University, Tempe, AZ 85287-8809 USA (e-mail: jian.tang@asu.edu; xue@asu.edu; cchandler@asu.edu; weiyi.zhang@asu.edu).

Digital Object Identifier 10.1109/TVT.2006.873836

paper, we always use a link (i, j) to model transmissions from node i to j, which is also called flow (i, j) in some papers on packet scheduling [14]. In this figure, we assume that all nodes transmit at a constant rate of c, and there are always packets waiting for transmission on each link/flow. We also assume that link pair (1,2)/(3,4) or (1,3)/(2,4) can be active for transmission at the same time if power is assigned appropriately for each transmitting node. However, once link (2,3) becomes active, no other transmission can happen simultaneously due to the primary interference. By forbidding the transmissions from two to three all the time, we can achieve a throughput of $2c$. If this link receives nonzero bandwidth allocation, the network throughput will be reduced. From this example, we can see that throughput and fairness conflict with each other. In other words, the goal of throughput maximization may force some links to receive very low bandwidth allocation or even to remain silent all the time to prevent interference.

In this paper, we consider a nonuniform traffic model [26] in which traffic demands, i.e., mean packet arrival rates, for different links/flows are not assumed to be the same or all equal to infinity. Compared with its counterpart, i.e., uniform traffic model, this model is more general and practical because network layer routing algorithms normally cannot achieve perfect load balancing and the traffic load may not be very heavy for all flows. To enhance fairness, every link should obtain a piece of share of the channel. However, if the bandwidth is equally allocated to all links with traffic, bandwidth may be wasted on some links that only carry very light traffic.

We first present a mixed integer linear programming (MILP) solution for the formulated problem, i.e., the MAximum THroughput link Scheduling with Power Control (MATH-SPC) problem, which seeks a transmission schedule and power assignment leading to a maximum throughput subject to the maximum power and interference constraints in each time slot. The solution to the MATH-SPC problem can serve as a benchmark of the maximum achievable throughput. Based on the nonuniform traffic model, we define a new parameter for each link/flow to address fairness, i.e., the demand satisfaction factor (DSF), which is the ratio between the amount of successfully transmitted traffic and the traffic demand. We formulate the MAximum Throughput fAir link Scheduling with Power Control (MATA-SPC) problem, seeking a solution with maximum throughput among all feasible solutions with maximum minimum DSF values. On one hand, improving network throughput is still our optimization goal. On the other hand, a max–min fairness constraint enforces limited bandwidth to be fairly allocated for links/flows according to their demands. For the MATA-SPC problem, we present an MILP formulation and an effective polynomial-time heuristic named serial linear programming rounding (SLPR) heuristic. To the best of our knowledge, this is the first paper addressing joint link scheduling and power control for throughput and fairness enhancement in TDMA-based multihop wireless networks.

The rest of this paper is organized as follows. We discuss related work in Section II. We describe the system model and define the optimization problems in Section III. We present the MILP formulations and our heuristic algorithm in Sections IV and V, respectively. The numerical results are presented in Section VI. We discuss the extensions in Section VII and conclude this paper in Section VIII.

II. Related Work

Joint link scheduling and power control as a cross-layer design problem in multihop wireless networks has recently attracted research attention. As a first attempt, ElBatt and Ephremides [6] proposed a simple two-phase heuristic to minimize the total power consumption via two alternating phases. In the first phase, the scheduling algorithm is responsible for coordinating independent users' transmissions to eliminate primary interference. In the second phase, power control is executed to determine the admissible set of power levels that could be used by the scheduled nodes, if one exists. If no such set of positive power levels can be found, control is transferred back to the scheduling phase to reduce interference via deferring the transmissions of one or more users participating in this scenario. Wang *et al.* extended their work to support multicast traffic in [27]. In [3], Behzad and Rubin studied a similar problem as ElBatt and Ephremides [6], but focusing on minimizing the schedule length. The joint link scheduling and power control problem has also been studied in wireless access networks [2] and ultrawideband (UWB) networks [4]. A distributed fair scheduling and power control algorithm was proposed in [28]. Different from [6], our major concerns here are throughput and fairness. The algorithms proposed in [3] are not suitable for the nonuniform traffic model because every given link will be allocated exactly one time slot in one frame. In addition, we consider a commonly used multihop wireless network model with homogeneous wireless nodes and TDMA-based medium access control (MAC) layer, which is quite different from the code-division multiple-access (CDMA)-based system studied in [28], wireless access network in [2], and UWB network in [4].

Transmission scheduling in TDMA-based multihop wireless networks has been well studied in the literature [5], [21], [24]. In almost all of those works, the authors used the protocol interference model [8], assuming no interference exists out of a limited transmission/interference range, and solved the problems by transferring them to some corresponding graph-coloring problems. Power control is also a well-addressed topic. Several power-controlled MAC protocols have been proposed for wireless *ad hoc* networks to reduce power dissipation [16], [17]. Their basic idea was to exchange ready-to-send (RTS)/clear-to-send (CTS) packets using the maximum power, but transmit their data and acknowledgment (ACK) packets with the minimum power required for correct reception. Different from these, throughput-oriented power-controlled MAC protocols [18]–[20] can improve spatial channel utilization by allowing more concurrent interference-limited transmissions in the same vicinity of a receiver at the cost of a reasonable increase of power consumption.

Fairness has been taken into consideration in an algorithm/protocol design for multihop wireless networks before. The max–min fair scheduling was studied in [7], [9], and [26]. In [10], Hou *et al.* advocated the use of lexicographical max–min (LMM) fair rate allocation for the nodes in a wireless sensor network. They developed an elegant polynomial-time optimal algorithm, i.e., serial LP with parametric analysis (SLP-PA), to calculate the LMM fair rate allocation. In [29], Zhai *et al.* proposed a novel rate-based end-to-end congestion control (RBCC) scheme, which was shown to outperform the traditional transmission control protocol (TCP) in terms of fairness, channel utilization, and delay. Several fair packet scheduling algorithms were proposed to improve both channel spatial reuse and fairness in [13]–[15].

III. Problem Definition

In this section, we will first describe our system model and notations and then formally define the optimization problems to be studied.

We consider a single-channel TDMA-based multihop wireless network as in [3] and [6]. We assume that each wireless node has only one transceiver and a single common channel is shared by all nodes in the network. The multiradio case will be discussed in Section VII. The TDMA scheme is used at the MAC layer for multiple access, i.e., the time domain is divided into time slots with equal constant duration, and these time slots are further grouped into frames of T time slots each. The duration of a time slot is considered a time unit. We assume that each wireless node is equipped with an omnidirectional antenna and is able to adjust its transmission power within a given range $[0, P_{\max}]$. However, the transmission power level of a node will remain the same within one time slot. Changing the transmission power of a wireless node will only change its transmission range, not its transmission rate. Each node transmits at a fixed rate, i.e., c bits/time unit. We also assume that all wireless nodes are stationary.

Like in all other related works, half-duplex operation is assumed to prevent self-interference, i.e., one node can only transmit or receive at one time. Moreover, we assume unicast communication, i.e., a single transmission is intended for exactly one receiver. In addition, any two transmissions with a common receiver are not allowed to be made simultaneously because a collision will corrupt the packet reception. Let τ be the set of transmissions simultaneously transmitting at some time instant over a certain channel. Then a transmission from node i is successfully received by node j if

$$\frac{G_{ij}P_{ij}}{N_0 + \sum_{(p,q)\in\tau\setminus\{(i,j)\}} G_{pj}P_{pq}} \geq \beta \tag{1}$$

where G_{ij} is the channel gain for node pair (i, j) that depends on path loss, channel fading, and shadowing; P_{ij} is the power set at the transmitter of node i for transmission (i, j); and N_0 is the thermal noise power at the receiver of node j, which is normally considered to be a constant. Note that the left-hand side of the inequality is called the SINR at the receiver of node j, and β is a given threshold determined by some quality-of-service (QoS) requirements such as bit error rate (BER). This is introduced in [8] as the physical model for successful wireless transmission.

We use a directed graph $G(V, E)$ to model the considered multihop wireless network, where V is the set of vertices and E is the set of edges. Each vertex $i \in V$ corresponds to a wireless node in the network with a known location. By abusing the notation a little bit without confusion, we also use i to denote its corresponding wireless node or even the location of the corresponding wireless node. There is a directed edge $(i, j) \in E$ connecting vertex i and vertex j if there exists a power level $P \in [0, P_{\max}]$ such that $G_{ij}P/N_0 \geq \beta$. Note that if there is a link (i, j) in G, we can conclude that a transmission from node i to j can be successfully made without any interference from other transmissions at the same time instant. However, we need to consider the SINR constraint in (1) to determine if a set of links can be active simultaneously. Specifically, we say that there exists a primary interference between two links if they are incident in a common node. In this case, they cannot be active at the same time due to half duplexing, unicasting, or collision. For a set of links, in which no two links share a common node, inequality (1) can be applied to check if concurrent transmissions are allowed.

A traffic demand B_{ij} is associated with each link/flow (i, j), indicating the number of time slots in which link (i, j) is required to be active for transmission, which can be determined by the mean packet arrival rate and transmission rate. Let the set of links $L(m = |L|, L \subseteq E)$ and the frame length T be given. We are interested in computing a schedule assigning these m links into T time slots without violating any power or interference constraint. We use V_L to denote the set of nodes that are end nodes of links in L. A 3-tuple (i, j, t) $((i, j) \in L, t \in [1, T])$ can uniquely define a channel. Note that there are mT possible channels, T channels associated with each link. We use Γ_{LT} to denote the complete set of possible channels corresponding to link set L and the set of T time slots. Scheduling is performed on a per frame basis. We define a transmission schedule Γ to be a set of channels. If a channel (i, j, t) is in Γ, then link (i, j) will be active in time slot t, i.e., node i will transmit to node j in time slot t in every frame. According to Γ, we denote the complete set of corresponding links and the set of corresponding active links in time slot t as L^Γ and L_t^Γ, respectively. A specific link may appear several times in a schedule, and r_{ij}^Γ is used to denote the number of channels whose corresponding link is (i, j) in schedule Γ. r_{ij}^Γ actually specifies the number of time slots (bandwidth) allocated to link/flow (i, j) in one frame, which should never be larger than the demand B_{ij}. Note that some demands may not be satisfied due to limited network resources. The DSF of a link $(i, j)(\alpha_{ij}^\Gamma)$ can be computed as r_{ij}^Γ/B_{ij}, which indicates how much demand has been satisfied. Obviously, if a link in L is not included in L^Γ, then its DSF is 0. We use $\alpha_{\min}^\Gamma$ to denote the minimum link DSF value among all links in L according to Γ. In addition, we use P to denote a power assignment corresponding to a schedule Γ, which is a table indexed by a 3-tuple (i, j, t). Each entry in P corresponds to a channel in schedule Γ, whose value, denoted as P_{ij}^t, represents the power level set for channel (i, j, t), i.e., for transmission from node i to node j at time slot t.

Definition 1 (Feasible Schedule): A schedule Γ is said to be a feasible schedule if the followingconditions are satisfied.

1) Any two links in L_t^Γ are not incident with each other $\forall t \in [1, T]$.
2) Inequality (1) is satisfied $\forall (i, j, t) \in \Gamma$.

3) $0 \leq P_{ij}^t \leq P_{\max} \quad \forall (i,j,t) \in \Gamma$.
4) $r_{ij}^{\Gamma} \leq B_{ij} \quad \forall (i,j) \in L^{\Gamma}$.

The throughput given by a feasible schedule Γ is defined as $c(\sum_{(i,j)\in L^{\Gamma}} r_{ij}^{\Gamma})/T$. It actually specifies how much traffic can be successfully transmitted per time unit based on this schedule. We can factor out the constant c/T and simply use $\sum_{(i,j)\in L^{\Gamma}} r_{ij}^{\Gamma}$ to represent the network throughput.

We address the fairness according to DSF and consider a simplified max–min fairness model.

Definition 2 (Feasible Fair Schedule): A schedule Γ is said to be a feasible fair schedule if Γ is a feasible schedule and the minimum link DSF value according to Γ, i.e., $\alpha_{\min}^{\Gamma}$, is maximum among all feasible schedules.

Now we are ready to define our optimization problems. Let link set L, frame length T, and the traffic demand B_{ij} for each link/flow be given.

Definition 3 (MATH-SPC): The MATH-SPC problem seeks a feasible schedule Γ along with a power assignment such that the throughput given by Γ is maximum among all feasible schedules.

As discussed before, simply maximizing throughput may starve some links/flows. On the other hand, equally allocating bandwidth to flows may lead to poor throughput. To achieve a tradeoff between fairness and throughput, we formulate the following optimization problem.

Definition 4 (MATA-SPC): The MATA-SPC problem seeks a feasible fair schedule Γ along with a power assignment such that the throughput given by Γ is maximum among all feasible fair schedules.

IV. MILP Formulations

In this section, we present MILP formulations to solve the proposed problems. First, we need to define the variables and introduce several notations that will be used in the MILP formulations.

1) X_{ij}^t (scheduling variable): a binary variable that is equal to 1 if link (i,j) is active for transmission in time slot t. Otherwise, it is 0.
2) P_{ij}^t (power assignment variable): can take any real number between $[0, P_{\max}]$ and specifies the power level for link (i,j) in time slot t.

Our MILP formulation for the MATH-SPC problem is presented as

MILP1 : MATH-SPC

$$\text{maximize} \quad \sum_{(i,j)\in L} \sum_{t=1}^{T} X_{ij}^t \tag{2}$$

subject to

$$\sum_{t=1}^{T} X_{ij}^t \leq B_{ij} \qquad \forall (i,j) \in L \tag{3}$$

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,l)\in L} X_{jl}^t \leq 1 \qquad \forall t \in [1,T]; \quad \forall j \in V_L \tag{4}$$

$$G_{ij} P_{ij}^t - \beta \sum_{(p,q)\in L\backslash\{(i,j)\}} G_{pj} P_{pq}^t - \beta N_0 \geq \Phi\left(X_{ij}^t - 1\right) \tag{5}$$

$$\forall t \in [1,T]; \quad \forall (i,j) \in L \tag{6}$$

$$X_{ij}^t \in \{0,1\} \qquad \forall t \in [1,T]; \quad \forall (i,j) \in L \tag{7}$$

$$0 \leq P_{ij}^t \leq P_{\max} X_{ij}^t \qquad \forall t \in [1,T]; \quad \forall (i,j) \in L. \tag{8}$$

The objective function in MILP1 is the network throughput. Constraint (3) is the traffic demand constraint, ensuring that the bandwidth allocated to each link is no more than the given traffic demand. Constraint (4) takes care of the primary interference: any two links sharing some common node will not be scheduled in the same time slot. Constraint (5) makes sure that the SINR requirement is satisfied: if a link (i,j) is scheduled to be active in time slot t, then the SINR at the receiver of node j must not be less than the given threshold β. Here, Φ is a big positive number. This constraint is automatically satisfied if link (i,j) is inactive in time slot t. Constraint (8) is the power constraint: if a link (i,j) is scheduled for time slot t ($X_{ij}^t = 1$), then the corresponding power value P_{ij}^t must be some real number in the interval $[0, P_{\max}]$. Otherwise, its value will be zero. Obviously, once we obtain the values of X_{ij}^t and P_{ij}^t for each possible channel (i,j,t), we can easily figure out the corresponding schedule and power assignment.

Actually, we can have a much simpler parameterized MILP formulation MILP2(t,r) whose decision variables are exactly the same as those in MILP1 except that r is a bandwidth allocation table, in which each entry (r_{ij}) corresponds to a link and its value shows how much bandwidth has been allocated to that link so far. MILP2(t,r) can be used to compute a set of links along with a power assignment that can maximize the throughput in a specific time slot t under the current bandwidth allocation condition given by table r, i.e.,

MILP2(t,r) :

$$\text{maximize} \quad \sum_{(i,j)\in L} X_{ij}^t \tag{9}$$

subject to

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,l)\in L} X_{jl}^t \leq 1 \qquad \forall j \in V_L \tag{10}$$

$$G_{ij} P_{ij}^t - \beta \sum_{(p,q)\in L\backslash\{(i,j)\}} G_{pj} P_{pq}^t - \beta N_0 \geq \Phi\left(X_{ij}^t - 1\right) \qquad \forall (i,j) \in L \tag{11}$$

$$0 \leq P_{ij}^t \leq P_{\max} X_{ij}^t \qquad \forall (i,j) \in L \tag{12}$$

$$X_{ij}^t \begin{cases} = 0, & \text{if } r_{ij} \geq B_{ij} \\ \in \{0,1\}, & \text{otherwise} \end{cases} \qquad \forall (i,j) \in L. \tag{13}$$

In a special case where fairness is not a concern and the traffic demand for each link is large enough, i.e., not less than T, when we make a decision whether a link (i,j) should be active for time slot t, we do not need to consider whether it has been scheduled to any other time slots. In this case, we can obtain the maximum throughput by solving MILP2$(1,r)$ once instead of solving MILP1, where the link bandwidth values in r are all set to 0. We always schedule those links whose corresponding

X value is equal to 1 for transmission and set its transmission power based on its P value in all T time slots. The obtained throughput is maximum because we can achieve the maximum throughput in each time slot.

Moreover, a suboptimal solution can be provided for the MATH-SPC problem by solving T MILP2(t, r) sequentially. More specifically, we solve MILP2$(1, r)$ first, where all entry values in r are initialized to 0. We schedule those links whose X value is 1 for transmission and set its transmission power accordingly in time slot 1. We do this slot by slot until we reach slot T. During the execution, we update the table r in each step. We call those links whose traffic demands have been satisfied $(r_{ij} = B_{ij})$ as saturated links. Once a link becomes a saturated link, it will not be considered for scheduling in later steps, which can be implemented by simply fixing its corresponding X value to be 0 in MILP2(t, r) (13). The total network throughput is computed as the summation of all objective function values. We will call it the serial MILP2 heuristic in the following sections.

We use MILP3 to find out the maximum minimum DSF value α. Then we can obtain the optimal solution of the MATA-SPC problem by solving MILP4(α), i.e.,

MILP3 :

$$\text{maximize} \quad \alpha \tag{14}$$

subject to

$$\begin{aligned}
&\alpha B_{ij} \leq \sum_{t=1}^{T} X_{ij}^t \leq B_{ij} && \forall (i,j) \in L \\
&\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,l)\in L} X_{jl}^t \leq 1 && \forall t \in [1,T]; \quad \forall j \in V_L \\
&G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\setminus\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \geq \Phi\left(X_{ij}^t - 1\right) && \\
& && \forall t \in [1,T]; \quad \forall (i,j) \in L \\
&X_{ij}^t \in \{0,1\} && \forall t \in [1,T]; \quad \forall (i,j) \in L \\
&0 \leq P_{ij}^t \leq P_{\max} X_{ij}^t && \forall t \in [1,T]; \quad \forall (i,j) \in L
\end{aligned} \tag{15}$$

MILP4(α) : MATA-SPC

$$\text{maximize} \quad \sum_{(i,j)\in L} \sum_{t=1}^{T} X_{ij}^t$$

subject to

$$\begin{aligned}
&\alpha B_{ij} \leq \sum_{t=1}^{T} X_{ij}^t \leq B_{ij} && \forall (i,j) \in L \\
&\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,l)\in L} X_{jl}^t \leq 1 && \forall t \in [1,T]; \quad \forall j \in V_L \\
&G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\setminus\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \geq \Phi(X_{ij}^t - 1) && \\
& && \forall t \in [1,T]; \quad \forall (i,j) \in L \\
&X_{ij}^t \in \{0,1\} && \forall t \in [1,T]; \quad \forall (i,j) \in L \\
&0 \leq P_{ij}^t \leq P_{\max} X_{ij}^t && \forall t \in [1,T]; \quad \forall (i,j) \in L.
\end{aligned}$$

It is well known that solving MILP may take a long time especially for large-size cases. Therefore, we present our polynomial-time heuristic algorithm in the following section.

V. LP-Based Heuristic

The basic idea of our heuristic algorithm, i.e., the SLPR heuristic, is to solve serial relaxed LPs instead of solving an MILP. By relaxing the integer constraint for decision variables X_{ij}^t in MILP1, we can obtain a corresponding LP formulation LP1. Once the relaxed LP is solved, we can use the solutions to the LP as guidelines to schedule some channel. We then solve another LP (with X values of the given channels fixed, whereas allowing the power levels to be adjusted) and schedule more channels. The process is repeated until no more channels can be scheduled in this way. The SLPR heuristic is formally presented as Algorithm 1. LP formulation takes Y as the only parameter, which is a table and will be updated during the execution of the algorithm. Y is indexed by a 3-tuple (i, j, t), and every entry corresponds to a possible channel. We use Y_{ij}^t to denote the entry (i, j, t) in Y. If its value is 1, it means the corresponding channel has been selected into the schedule. By setting its value to be 0, we can forbid the corresponding channel to be selected by LP1. Initially, all the entry values are set to -1.

LP1(Y) :

$$\text{maximize} \quad \sum_{(i,j)\in L} \sum_{t=1}^{T} X_{ij}^t$$

subject to

$$\begin{aligned}
&\sum_{t=1}^{T} X_{ij}^t \leq B_{ij} && \forall (i,j) \in L \\
&\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,l)\in L} X_{jl}^t \leq 1 && \\
& && \forall t \in [1,T]; \quad \forall j \in V_L \\
&G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\setminus\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \geq \Phi\left(X_{ij}^t - 1\right) && \\
& && \forall t \in [1,T]; \quad \forall (i,j) \in L \\
&0 \leq P_{ij}^t \leq P_{\max} X_{ij}^t && \forall t \in [1,T]; \quad \forall (i,j) \in L \\
&X_{ij}^t \begin{cases} = Y_{ij}^t, & \text{if } Y_{ij}^t \geq 0 \\ \in [0,1], & \text{otherwise} \end{cases} && \forall t \in [1,T]; \quad \forall (i,j) \in L.
\end{aligned} \tag{16}$$

In the algorithm, Γ (the set of scheduled channels) and Γ_L (the set of channels not yet scheduled) are initialized to $\oslash$ and the complete channel set Γ_{LT}, respectively. They are dynamically updated during the execution of the algorithm. The algorithm eventually outputs Γ as the schedule. We use the LP relaxation of MILP1, i.e., LP1(Y), as the guidance of channel selection. In Step_3, the feasibility of a channel (i, j, t) can be checked by solving LP2(i, j, t, L_t^Γ). In the formulation, L_t^Γ denotes the set of links that have been scheduled in time slot t so far. If LP2(i, j, t, L_t^Γ) can return a feasible solution, we can conclude that link (i, j) can be scheduled in time slot t, i.e., channel (i, j, t) is selectable based on the current schedule Γ. The algorithm will also output a table P as the power assignment whose entry values are updated in each iteration based on the results of LP2, i.e.,

LP2 $\left(i, j, t, L_t^{\Gamma}\right)$:

$$\text{minimize} \quad \sum_{(h,l)\in L_t^{\Gamma} \bigcup \{(i,j)\}} P_{hl} \tag{17}$$

subject to

$$G_{hl}P_{hl} - \beta \sum_{(p,q)\in L_t^{\Gamma} \bigcup \{(i,j)\}\setminus\{(h,l)\}} G_{pl}P_{pq} - \beta N_0 \geq 0 \qquad \forall (h,l) \in L_t^{\Gamma} \bigcup \{(i,j)\} \tag{18}$$

$$0 \leq P_{hl} \leq P_{\max} \qquad \forall (h,l) \in L_t^{\Gamma} \bigcup \{(i,j)\}. \tag{19}$$

Algorithm 1 SLPR Heuristic

Step_1 $\Gamma := \emptyset;\ \Gamma_L := \Gamma_{LT};\ num_B := 0;$
  FOR $t := 1$ TO T
    $L_t^{\Gamma} := \emptyset;$
  ENDFOR
  FORALL $(i, j, t) \in \Gamma_L$
    $Y_{ij}^t := -1;$
  ENDFORALL

Step_2 Solve LP1(Y);
  IF LP1(Y) is infeasible
    OUTPUT Γ and P; STOP;
  ENDIF

Step_3 Examine the nonnegative variables X_{ij}^t in the optimal solution of LP1(Y) in decreasing order of their values. Solve LP2(i, j, t, L_t^{Γ}) to check whether channel (i, j, t) can be selected into Γ;
  IF no channel can be selected
    OUTPUT Γ and P; STOP;
  ELSE
    Let (p, q, s) be the first selectable channel;
    $\Gamma := \Gamma \bigcup \{(p, q, s)\};$
    $\Gamma_L := \Gamma_L \setminus \{(p, q, s)\};$
    $L_s^{\Gamma} := L_s^{\Gamma} \bigcup \{(p, q)\};$
    $Y_{pq}^s := 1;$
    Update P according to the results of LP2(p, q, s, L_s^{Γ});
  ENDIF

Step_4 $r_{pq} := r_{pq} + 1;$
  IF $(r_{pq} := B_{pq})$
    $\alpha_{pq} := -1;$
    $num_B := num_B + 1;$
  ELSE $\alpha_{pq} := r_{pq}/B_{pq};$
  ENDIF
  $\alpha := max_{(i,j)\in L}\alpha_{ij};$
  $num_{\alpha} = 0;$
  FORALL $(i, j, t) \in \Gamma_L$
    $Y_{ij}^t := -1;$
    IF $\alpha_{ij} := \alpha\ num_{\alpha} := num_{\alpha} + 1;$
    ENDIF
  ENDFORALL
  FORALL $(i, j, t) \in \Gamma_L$
    IF $[(r_{ij} = B_{ij})$ or $(\alpha_{ij} = \alpha$ and $num_{\alpha} < |\Gamma_L| - num_B)]$
      $Y_{ij}^t := 0;$
    ENDIF

Step_5 GOTO Step_2;

After a channel (p, q, s) is selected, we will update its bandwidth allocation B_{pq} and DSF α_{pq}. For fairness consideration, we will forbid all channels corresponding to those saturated links $(r_{ij} = B_{ij})$ and the links whose DSF is maximum among all unsaturated links to be selected in the next iteration by Step_4. However, in the special case where the current bandwidth allocated to every unsaturated link is the same, all of the unsaturated links will be considered in the next iteration. The design philosophy behind it is to give chances for those links with relatively smaller DSFs to be scheduled in each iteration. In this way, the fairness can be enhanced.

It is obvious that the running time in Algorithm 1 is dominated by solving LPs in Step_2 and Step_3. Step_2 solves an LP with both the number of variables and constraints bounded by $O(mT)$. Therefore, the running time of Step_2 is bounded by $O(m^3T^3M_{\mathrm{LP1}})$, where M_{LP1} is the number of binary bits required to store the data. In Step_3, we may have to solve $O(mT)$ LP2s, each with variables and constraints bounded by $O(m)$. Therefore, the running time of Step_3 is bounded by $O(m^4TM_{\mathrm{LP2}})$. In addition, there are $O(mT)$ iterations. As a result, the worst case running of the algorithm is bounded by $O(m^4T^2(T^2M_{\mathrm{LP1}} + mM_{\mathrm{LP2}}))$. Hence, Algorithm 1 is a polynomial-time algorithm. The algorithm runs very fast in practice because the LPs can be efficiently solved even for large cases.

VI. Numerical Results

In our simulations, we consider wireless networks with static nodes randomly located in a region measuring 1000×1000 m^2. The thermal noise power $N_0 = -90$ dB $\cdot$ m. The SINR threshold $\beta = 10$ dB, and the maximum transmission power $P_{\max} = 300$ mW. The channel gain G_{ij} is simply set to d_{ij}^4, where d_{ij} is the Euclidean distance between node i and node j. We randomly choose m links from the network into our link set L in each run. The traffic demand B_{ij} for each link/flow is a random integer uniformly distributed in $[1, T]$. We compute optimal solutions by solving MILP formulations using CPLEX9.0. We compare our heuristic algorithm and optimal solutions with regard to network throughput and DSFs. For simplicity, we use $\sum_{(i,j)\in L^{\Gamma}} r_{ij}^{\Gamma}$ to represent the network throughput by factoring out c/T.

In the first scenario, we randomly select eight links and set the frame length to ten time slots. We randomly place ten nodes in the given region at the first trial and 15 nodes at the second trial. The network throughput, the DSF of each link/flow, and the variances of DSFs given by solving MILP1 (maximum throughput), serial MILP2 heuristic, solving MILP4(α) (optimal solution of MATA-SPC), and the SLPR heuristic (Algorithm 1) are presented in Tables I and II.

In the tables, α_i is the DSF of the ith link. In the results obtained by solving MILP1 and by serial MILP2 heuristic, the

TABLE I
TRIAL 1: NETWORK THROUGHPUT AND DSFS

	MILP1	MILP2	MILP4	SLPR
Thru	20	20	15	16
α_1	1.000	0.250	0.500	0.500
α_2	1.000	0.571	0.286	0.143
α_3	0.000	1.000	0.333	0.333
α_4	0.000	0.857	0.286	0.286
α_5	0.000	0.000	0.333	0.000
α_6	1.000	0.000	0.333	0.500
α_7	0.300	0.000	0.300	0.500
α_8	0.000	0.000	0.500	0.500
Var	0.216	0.096	0.007	0.032

TABLE II
TRIAL 2: NETWORK THROUGHPUT AND DSFS

	MILP1	MILP2	MILP4	SLPR
Thru	20	20	14	15
α_1	0.500	0.000	0.250	0.500
α_2	0.857	1.000	0.286	0.429
α_3	0.000	0.000	0.333	0.333
α_4	0.667	1.000	0.333	0.000
α_5	0.000	0.000	0.333	0.167
α_6	0.000	0.000	0.333	0.333
α_7	1.000	0.600	0.400	0.800
α_8	0.714	1.000	0.286	0.143
Var	0.149	0.218	0.002	0.054

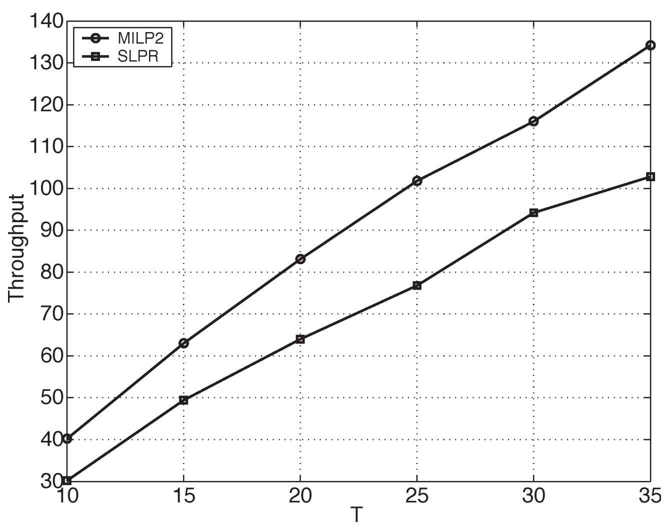


Fig. 2. Network throughput with $m = 30$.

DSFs of almost half of the links are equal to 0, i.e., half of the links do not obtain any chance to deliver their packets. This verifies that simply maximizing throughput results in a severe bias on bandwidth allocation among all links/flows. By solving MILP4(α) or using our SLPR heuristic, the fairness is improved, i.e., the DSFs are more evenly distributed, with a reasonable reduction of network throughput.

In the following scenarios, we randomly place 20 nodes in the region. In the second scenario, we fix the number of selected links to 30 and change the frame length from 10 to 35 time slots. In the last scenario, we fix the frame length to 20 time slots and change the number of selected links from 10 to 60. Similarly, we use the variance of the DSFs of all chosen links to show fairness. The smaller the value, the better the fairness. Each value presented in Figs. 2–5 is the average of over 20 runs.

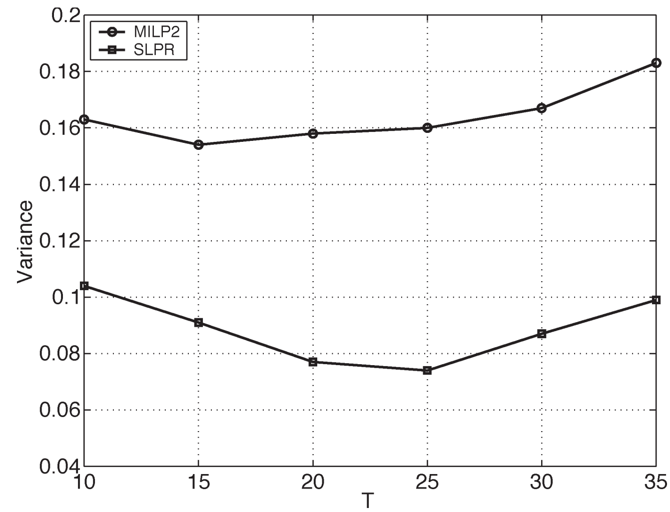


Fig. 3. DSF variance with $m = 30$.

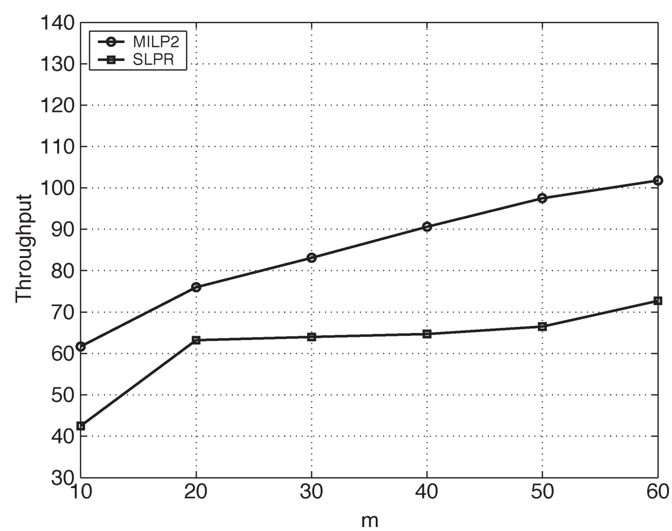


Fig. 4. Network throughput with $T = 20$.

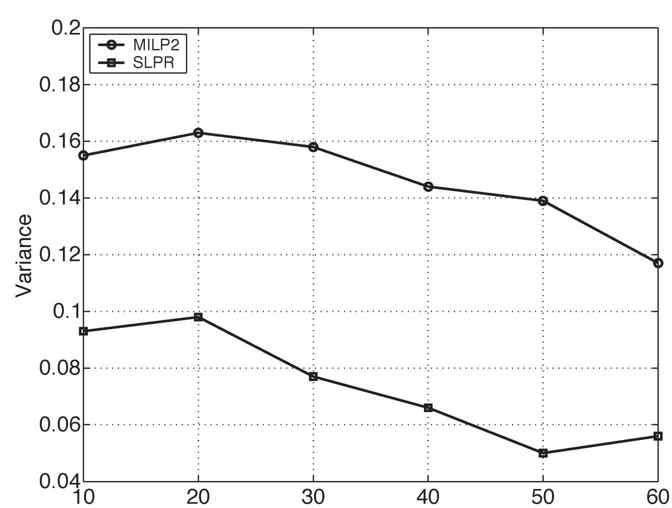


Fig. 5. DSF variance with $T = 20$.

In each run, we generate a network with 20 nodes randomly distributed in the region.

We make the following observations from our simulation results. On average, the network throughput given by our SLPR algorithm is close to the throughput given by the serial MILP2 heuristic. However, in terms of fairness, the SLPR heuristic achieves much smaller DSF variances in all cases. Compared with the average DSF variance given by the serial MILP2 heuristic, i.e., 0.155, our scheme decreases it to 0.081, which is a 47.7% reduction.

VII. Extensions

In the previous sections, we have focused on MAC layer throughput and fairness as [3] and [28]. In this case, we essentially assume that the routes for all end-to-end communication sessions have been predetermined and the traffic load on each link is known *a priori*. However, route selection may also have a substantial impact on network throughput. In this section, we extend our work to the end-to-end case. In addition, we also discuss how to extend our work to emerging multiradio multihop wireless networks.

A. End-to-End Throughput and Fairness

From the end-to-end point of view, we consider a joint rate control, routing, scheduling, and power control problem. Suppose that we are given the source (s_k), destination nodes (t_k), and traffic demands (D_k) of K communication sessions. Similarly, we say that a feasible end-to-end rate allocation vector $r = [r_1, r_2, \ldots, r_k]$ for all sessions is fair if for any other feasible rate allocation vector $r' = [r'_1, r'_2, \ldots, r'_k]$, $\min\{r_k/D_k | 1 \leq k \leq K\} \geq \min\{r'_k/D_k | 1 \leq k \leq K\}$. Note here that r_k/D_k is actually the DSF of communication session k. We seek a fair feasible rate allocation vector r along with a flow allocation, transmission schedule, and power assignment such that its throughput is maximum among all feasible fair rate allocations. In the following, we define two more variables for routing and rate control, respectively, and present MILP formulations for this end-to-end fairness problem.

1) f_{ij}^k (flow variable): any nonnegative real number and specifies the amount of flow going through link (i, j) for session k.
2) r_k (rate variable): any nonnegative real number and specifies the end-to-end rate of session k.

MILP5 :

$$\text{maximize} \quad \alpha \tag{20}$$

subject to

$$\sum_{(s_k,j)\in E} f_{s_k j}^k - \sum_{(i,s_k)\in E} f_{is_k}^k = r_k, \quad 1 \leq k \leq K \tag{21}$$

$$\sum_{(i,j)\in E} f_{ij}^k - \sum_{(j,l)\in E} f_{jl}^k = 0, \quad 1 \leq k \leq K; \quad \forall j \in V\backslash\{s_k, t_k\} \tag{22}$$

$$r_k/D_k \geq \alpha, \quad 1 \leq k \leq K \tag{23}$$

$$f_{ij}^k \geq 0, \quad 1 \leq k \leq K; \quad \forall (i,j) \in E \tag{24}$$

$$0 \leq \alpha \leq 1 \tag{25}$$

$$\begin{aligned}
&\sum_{k=1}^{k} f_{ij}^k \leq (c/T) * \left(\sum_{t=1}^{T} X_{ij}^t\right) && \forall (i,j) \in E\\
&\sum_{(i,j)\in E} X_{ij}^t + \sum_{(j,l)\in E} X_{jl}^t \leq 1 && \forall t \in [1,T]; \quad \forall j \in V\\
&G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\backslash\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \geq \Phi\left(X_{ij}^t - 1\right)\\
& && \forall t \in [1,T]; \quad \forall (i,j) \in E\\
&X_{ij}^t \in \{0,1\} && \forall t \in [1,T]; \quad \forall (i,j) \in E\\
&0 \leq P_{ij}^t \leq P_{\max} X_{ij}^t && \forall t \in [1,T]; \quad \forall (i,j) \in E
\end{aligned} \tag{26}$$

MILP6(α) :

$$\text{maximize} \quad \sum_{k=1}^{k} r_k \tag{27}$$

subject to (4)–(8) and (21)–(26).

In the preceding formulations, (21) makes sure that the net amount of flow going out from the source node of a session is equal to the corresponding end-to-end session rate. For each session, the flow conservation constraint is satisfied at every node except at the source and the destination nodes, which are enforced by (22). Constraint (26) connects the MAC layer and the network layer. It requires that each link has allocated enough bandwidth to deliver the aggregated flow allocated to it. Similar to MILP3 and MILP4, MILP5 is used to compute the maximum minimum DSF value α. Then, we use MILP6 to find out the fair rate allocation with a maximum throughput. Obviously, this problem is much more complicated than the formulated MATA-SPC problem. A fast and efficient algorithm for solving it will be of our future interest.

B. Multiradio Multihop Wireless Network

As mentioned before, we expect the proposed scheme to be used in emerging WMNs. It has been shown that network throughput can be improved substantially by equipping every wireless mesh node with multiple network interface cards (NICs), i.e., transceivers, and tuning them to different frequency channels [22], [23]. Fortunately, the dominating protocols for wireless networking such as IEEE 802.11 specify multiple nonoverlapping frequency channels, e.g., 12 channels specified in 802.11a standard [12] and three channels in 802.11b standard [11]. Two NICs can communicate with each other if they work on the same channel and their Euclidean distance is not larger than the sender's transmission range. Moreover, concurrent transmissions within a common neighborhood are allowed as long as they work on different channels. To make full use of network resources, every NIC should be assigned to a particular channel and every two NICs in one node should be assigned to different channels. How to compute a channel assignment is out of the scope of this paper. Existing static channel assignment algorithms such as the interference-aware scheme in [25] or the approaches proposed in [22] and [23] may be applied here. Once a channel assignment is given, the network topology can be easily determined. There is a directed edge (i, j) in the topology $G_A(V, E_A)$ connecting nodes i and j if there exists a power level $P \in [0, P_{\max}]$ such that $G_{ij}P/N_0 \geq \beta$ and one of the NICs in node i and one of the NICs in node j are assigned to a common channel w. In this case, we say that link (i,j) works on channel w. It is possible that two neighboring nodes share more than one channel. We use $A(i)$ to denote the set of channels assigned to node i and $C(i,j)$ to denote the set of channels that link (i,j) works on.

To formulate the corresponding MILPs to solve the defined optimization problems in a multiradio multihop wireless network, we need to define two new variables.

1) X^t_{ijw} (scheduling variable): a binary variable that is equal to 1 if link (i,j) is active for transmission in time slot t using channel w. Otherwise, it is 0.
2) P^t_{ijw} (power assignment variable): any real number between $[0, P_{\max}]$ and specifies the power level for link (i,j) in time slot t and channel w.

The MILP for the MATA-SPC problem can be reformulated as

MILP7 :

maximize α

subject to

$$\alpha B_{ij} \leq \sum_{w \in C(i,j)} \sum_{t=1}^{T} X^t_{ijw} \leq B_{ij} \quad \forall (i,j) \in L \tag{28}$$

$$\sum_{(i,j)\in L} X^t_{ijw} + \sum_{(j,l)\in L} X^t_{jlw} \leq 1 \qquad \forall t \in [1,T]; \quad \forall j \in V_L; \qquad \forall w \in A(j) \tag{29}$$

$$G_{ij}P^t_{ijw} - \beta \sum_{(p,q)\in L\setminus\{(i,j)\}: w\in C(p,q)} G_{pj}P^t_{pqw} - \beta N_0 \geq \Phi\left(X^t_{ijw} - 1\right) \qquad \forall t \in [1,T]; \quad \forall (i,j) \in L; \quad \forall w \in C(i,j) \tag{30}$$

$$X^t_{ijw} \in \{0,1\} \qquad \forall t \in [1,T]; \quad \forall (i,j) \in L; \quad \forall w \in C(i,j) \tag{31}$$

$$0 \leq P^t_{ijw} \leq P_{\max} X^t_{ijw} \qquad \forall t \in [1,T]; \quad \forall (i,j) \in L; \quad \forall w \in C(i,j) \tag{32}$$

MILP4(α) : MATA-SPC

$$\text{maximize} \quad \sum_{(i,j)\in L} \sum_{w\in C(i,j)} \sum_{t=1}^{T} X^t_{ijw} \tag{33}$$

subject to (28)–(32).

VIII. CONCLUSION

In this paper, we studied the joint link scheduling and power control problem with the objective of maximizing the network throughput. We formulated a novel MATH-SPC problem and presented an MILP to provide optimal solutions. For fairness considerations, we defined a new parameter, i.e., the DSF, to characterize the fairness of bandwidth allocation. Based on this definition, we formulated and presented an MILP formulation for the MATA-SPC problem. We also proposed a polynomial-time heuristic, namely, the SLPR heuristic. Our numerical results showed that a good tradeoff between fairness and throughput can be achieved by solving our MILP formulation or by using our SLPR algorithm. In addition, we discussed extensions to end-to-end rate allocation for throughput enhancement and multiradio multihop wireless networks.

REFERENCES

[1] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: A survey," *Comput. Netw.*, vol. 47, no. 4, pp. 445–487, Mar. 2005.

[2] A. Behzad and I. Rubin, "Multiple access protocol for power controlled wireless access nets," *IEEE Trans. Mobile Comput.*, vol. 3, no. 4, pp. 307–316, Oct.–Dec. 2004.

[3] ——. (2004). "Optimum integrated link scheduling and power control for *ad hoc* wireless networks," *IEEE Trans. Veh. Technol.*, Submitted for publication. [Online]. Available: http://www.ee.ucla.edu/~abehzad

[4] J. Cai, K.-H. Liu, X. Shen, J. W. Mark, and T. D. Todd, "Power allocation and scheduling for MAC layer design in UWB networks," in *Proc. IEEE QShine*, 2005, pp. 9–16.

[5] I. Chlamtac and S. Kutten, "A spatial reuse TDMA/FDMA for mobile multihop radio nertworks," in *Proc. IEEE INFOCOM*, 1985, pp. 389–394.

[6] T. ElBatt and A. Ephremides, "Joint scheduling and power control for wireless *ad hoc* networks," in *Proc. IEEE INFOCOM*, 2002, pp. 976–984.

[7] Z. Y. Fang and B. Bensaou, "Fair bandwidth sharing algorithms based on game theory frameworks for wireless *ad hoc* networks," in *Proc. IEEE INFOCOM*, 2004, pp. 1284–1295.

[8] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[9] X. L. Huang and B. Bensaou, "On max-min fairness and scheduling in wireless *ad hoc* networks: Analytical framework and implementation," in *Proc. MobiHoc*, 2001, pp. 221–231.

[10] Y. T. Hou, Y. Shi, and H. D. Sherali, "Rate allocation in wireless sensor networks with network lifetime requirement," in *Proc. ACM MobiHoc*, 2004, pp. 67–77.

[11] IEEE 802.11 Working Group, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 1997.

[12] IEEE 802.11a Working Group, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 1: High-Speed Physical Layer in the 5 GHz Band*, 1999.

[13] H. Luo and S. Lu, "A topology-independent fair queueing model in *ad hoc* wireless networks," in *Proc. IEEE ICNP*, 2000, pp. 325–335.

[14] H. Luo, S. Lu, and V. Bharghavan, "A new model for packet scheduling in multihop wireless networks," in *Proc. ACM MobiCom*, 2000, pp. 76–86.

[15] H. Luo, P. Medvedev, J. Cheng, and S. Lu, "A self-coordinating approach to distributed fair queueing in *ad hoc* wireless networks," in *Proc. IEEE INFOCOM*, 2001, pp. 1370–1379.

[16] E. S. Jung and N. H. Vaidya, "A power control MAC protocol for *ad hoc* networks," in *Proc. ACM MobiCom*, 2002, pp. 36–47.

[17] P. Karn, "MACA—A new channel access method for packet radio," in *Proc. ARRL Comput. Netw. Conf.*, 1990, pp. 134–140.

[18] J. Monks, V. Bharghavan, and W. M. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proc. IEEE INFOCOM*, 2001, pp. 219–228.

[19] A. Muqattash and M. Krunz, "Power controlled dual channel (PCDC) medium access protocol for wireless *ad hoc* networks," in *Proc. IEEE INFOCOM*, 2003, pp. 470–480.

[20] ——, "A single-channel solution for transmission power control in wireless *ad hoc* networks," in *Proc. ACM MobiHoc*, 2004, pp. 210–221.

[21] S. Ramanathan and E. L. Lloyd, "Scheduling algorithms for multihop radio networks," *IEEE/ACM Trans. Netw.*, vol. 1, no. 2, pp. 167–177, Apr. 1993.

[22] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *Proc. IEEE INFOCOM*, 2005, pp. 2223–2234.

[23] A. Raniwala, K. Gopalan, and T. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM Mobile Comput. Commun. Rev. (MC2R)*, vol. 8, no. 2, pp. 50–65, Apr. 2004.

[24] A. Sen and M. L. Huson, "A new model for scheduling packet radio networks," *ACM/Baltzer J. Wireless Netw.*, vol. 3, no. 1, pp. 71–82, 1997.

[25] J. Tang, G. Xue, and W. Zhang, "Interference-aware topology control and QoS routing in multi-channel wireless mesh networks," in *Proc. ACM MobiHoc*, 2005, pp. 68–77.

[26] L. Tassiulas and S. Sarkar, "Maxmin fair scheduling in wireless networks," in *Proc. IEEE INFOCOM*, 2002, pp. 763–772.

[27] K. Wang, C. F. Chiasserini, R. R. Rao, and J. G. Proakis, "A distributed joint scheduling and power control algorithm for multicasting in wireless *ad hoc* networks," in *Proc. IEEE ICC*, 2003, pp. 725–731.

[28] K. Wang, J. G. Proakis, and R. R. Rao, "Distributed fair scheduling and power control in wireless *ad hoc* networks," in *Proc. IEEE GLOBECOM*, 2004, pp. 3557–3562.

[29] H. Zhai, X. Chen, and Y. Fang, "Rate-based transport control for mobile *ad hoc* networks," in *Proc. IEEE WCNC*, 2005, pp. 2264–2269.

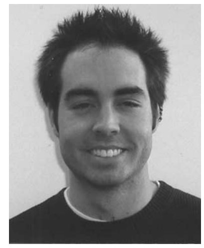
Jian Tang received the B.E. and M.E. degrees from Beijing University of Posts and Telecommunications, Beijing, China, in 1998 and 2001, respectively. He is currently working toward the Ph.D. degree at the Department of Computer Science and Engineering, Arizona State University, Tempe.

His research interest is in the area of wireless networking and mobile computing with emphases on routing, scheduling, and cross-layer design in wireless networks.

Guoliang Xue (M'98–SM'99) received the Ph.D. degree in computer science from the University of Minnesota, Minneapolis, in 1991.

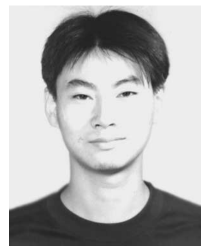
He has held previous positions at the Army High Performance Computing Research Center and at the University of Vermont, Burlington. He is a Full Professor at the Department of Computer Science and Engineering, Arizona State University, Tempe. He has published over 130 papers in these areas. His research has been continuously supported by federal agencies including NSF and ARO. His research interests include efficient algorithms for optimization problems in networking with applications to fault tolerance, robustness, and privacy issues in networks ranging from wavelength-division multiplexing optical networks to wireless *ad hoc* and sensor networks.

Dr. Xue has served on the executive/program committees of many IEEE conferences, including Infocom, Secon, ICC, Globecom, and QShine. He served as the General Chair of *IEEE International Performance, Computing, and Communications Conference* in 2005 and will serve as a TPC Cochair of *IEEE Globecom'2006 Symposium on Wireless Ad Hoc and Sensor Networks* and *IEEE ICC'2007 Symposium on Wireless Ad Hoc and Sensor Networks*. He is the Associate Editor of *Computer Networks*, the *IEEE Network Magazine*, and the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—PART I: REGULAR PAPERS. He was the recipient of an NSF Research Initiation Award in 1994 and an NSF-ITR Award in 2003.



Christopher Chandler is currently working toward the B.S. degree in computer science at the Arizona State University, Tempe.

He has been involved with research in wireless networks for approximately a year as an undergraduate. His other research interests are primarily in information assurance.



Weiyi Zhang received the M.E. degree from the Southeast University, Nanjing, China, in 1999 and is currently working toward the Ph.D. degree at the Department of Computer Science and Engineering, Arizona State University, Tempe.

His research interests include reliable communication in networking, protection and restoration in wavelength-division multiplexing networks, and quality-of-service provisioning in communication networks.