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

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Abstract— **Throughput is an important performance consideration for multihop wireless networks. In this paper, we study the joint link scheduling and power control problem, focusing on maximizing the network throughput. We formulate the *MAximum THroughput link Scheduling with Power Control (MATH-SPC)* problem, and present a Mixed Integer Linear Programming (MILP) formulation to provide optimal solutions. However, simply maximizing the throughput leads to a severe bias on bandwidth allocation among all links. In order to enhance both throughput and fairness, we define a new parameter, the *Demand Satisfaction Factor (DSF)*, to characterize the fairness of bandwidth allocation. We formulate the *MAximum Throughput fAir link Scheduling with Power Control (MATA-SPC)* problem and present an MILP formulation for this problem. We also present an effective polynomial time heuristic algorithm, namely, the Serial LP Rounding (SLPR) heuristic. Our numerical results show that bandwidth can be fairly allocated among all links/flows by solving our MATA-SPC formulation or using our heuristic algorithm at the cost of a minor reduction of network throughput.**

Keywords: Cross-layer optimization, link scheduling, power control, fairness, QoS.

I. Introduction

In a multihop wireless network, power control and link scheduling are typical problems in the physical layer and the link layer, respectively. However, scheduling transmissions without careful considerations of physical layer constraints may end up with two situations:

1) Spatially close wireless nodes are scheduled to transmit simultaneously.
2) When a node begins to transmit, all other nodes in the 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 and Noise Ratio (SINR), which will result in high energy dissipation or sometime even the infeasibility of power assignment due to maximum power level limits and strong interference. In the second situation, transmission power can be saved at the cost of poor network throughput. Therefore, researchers have begun to seek solutions for joint link scheduling and power control problems with different optimization goals, such as power consumption minimization [5] or frame length minimization [3].

Different from previous work, we study the joint problem in TDMA-based multihop wireless network with the objective of maximizing the network throughput. We 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 ([11]).

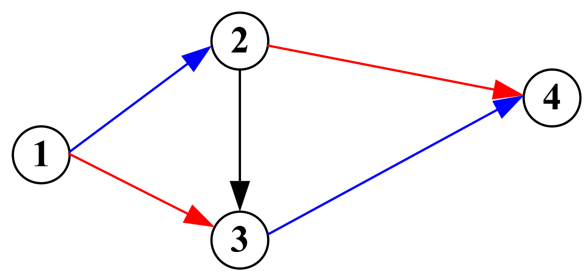

Fig. 1. Throughput maximization and fairness

We present a Mixed Integer Linear Programming (MILP) solution for a new optimization problem, *MAximum THroughput link Scheduling with Power Control (MATH-SPC)* problem which seeks a transmission schedule and power assignment leading to maximum throughput subject to the maximum power and interference constraints in each time slot. However, scheduling with only throughput maximization in mind may cause a severe bias on bandwidth allocation among all links, which can be shown by Fig. 1. In this figure, suppose the transmission rates of all nodes are equal to c and there are always packets waiting for transmission on each link/flow. 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 2 to 3 all the time, we can achieve a throughput of $2c$. If this link receives non-zero 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

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some links to receive very low bandwidth allocation or even to remain silent all the time to prevent strong interference.

In this paper, we consider a non-uniform traffic model in which traffic demands ([20]), i.e., mean packet arrival rates, for different wireless links/flows are not assumed to be the same. Compared with its counterpart, uniform traffic model, this model is more practical because the network layer routing algorithms normally cannot achieve perfect load balancing. In order to enhance fairness, every link should obtain a piece of share of the channel. However, if the bandwidth is equally allocated to all links having traffic, bandwidth may be wasted on some links which only carry on very light traffic.

Based on the non-uniform traffic model, we define a new parameter for each link/flow, the *Demand Satisfaction Factor (DSF)*, which is the ratio between the amount of successfully transmitted traffic and the traffic demand. We define the *MAximum Throughput fAir link Scheduling with Power Control (MATA-SPC)* problem, seeking a solution such that network throughput is maximized and the DSF of each link is no less than a given threshold. A method is presented in Section III to choose a fairly good threshold. On one hand, improving network throughput is still our optimization goal. On the other hand, limited bandwidth is required to be fairly allocated for links/flows according to their demands. For the MATA-SPC porblem, we present an MILP formulation and a polynomial time heuristic named the Serial LP Rounding (SLPR) heuristic. To our best knowledge, this is the first paper addressing link scheduling and power control for both throughput and fairness enhancement in TDMA-based multihop wireless networks.

We expect our results to be applicable to multihop wireless networks where the network throughput and fairness are the most critical issues, such as Wireless Mesh Networks (WMN) ([1]), in which wireless nodes are normally stationary and do not rely on batteries. Therefore, mobility and power efficiency are not primary concerns. They are designed to provide commercial applications like last-mile broadband Internet access, distributed file backup, neighborhood gaming and so on. Hence, in such networks, a high volume of traffic is expected to be efficiently delivered on the bandwidth limited wireless channels and a large number of users are required to be fairly served.

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 Section IV and Section V, respectively. We present the numerical results in Section VI and conclude the paper in Section VII.

II. Related Work

Transmission scheduling in TDMA-based multihop wireless networks has been well studied in the literature ([4], [18], [19]). In almost all those works, the authors use the protocol interference model ([7]) assuming no interference exists out of a limited transmission/interference range, and solve 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 ([13], [14]). Their basic idea is to exchange RTS/CTS packets using the maximum power, but transmit their data and ACK packets at the minimum power required for correct reception. Different from these, the so called throughput-oriented power-controlled MAC protocols ([15], [16], [17]) can improve spatial channel utilization by allowing concurrent interference-limited transmissions in the same vicinity of a receiver at the cost of a reasonable increase of power consumption.

The most related works are several recent papers studying the joint link scheduling and power control problems in TDMA-based multihop wireless networks. In the first attempt, the authors in [5] propose 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 set of positive power levels can be found, control is transferred again to the scheduling phase to reduce interference via deferring the transmissions of one or more users participating in this scenario. Wang *et al.* extend their work to support multicast traffic in [21]. In [3], Behzad and Rubin study the similar problem as [5] but focusing on minimizing the schedule length. They present both an MILP formulation and a polynomial time heuristic. They also study the joint link scheduling and power control for wireless access networks in [2]. A distributed fair scheduling and power control algorithm is proposed in [22]. Different from [5], our major concerns here are throughput and fairness. The algorithms proposed in [3] are not suitable for the non-uniform traffic model, since every given link will be allocated one time slot in one frame. In addition, we consider a commonly used TDMA-based multihop wireless network model with homogeneous wireless nodes, which is quite different from the CDMA-based system studied by [22] and wireless access network in [2].

Fair scheduling in wireless ad hoc networks has also attracted substantial attention in the past several years. The well known maxmin fair scheduling is studied in [6], [8], [20]. The authors in [20] formalize the maxmin fair objective under scheduling constraints for a CDMA-over-TDMA based wireless system. They propose a fair scheduling algorithm which is proved to attain the maxmin fair rates. In [9], Hou *et al.* advocate the use of Lexicographical Max-Min (LMM) rate allocation for the nodes in a wireless sensor network. They develop a polynomial time algorithm, Serial LP with Parametric Analysis (SLP-PA) to calculate the LMM rate allocation. Several fair packet scheduling algorithms are proposed to improve both channel spatial reuse and fairness in [10], [11], [12].

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 use a similar system model as described in [3], [5]. A single channel is assumed to be shared by all nodes in the network. Time Division Multiple Access (TDMA) scheme is used at the MAC layer for multiple access, i.e., the time domain is divided into many 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 each wireless node is equipped with an omni-directional antenna and is able to adjust its transmission power in 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. Every node transmits at a fixed rate, 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 ([3], [5]). In addition, any two transmissions with a common receiver are not allowed to be made simultaneously since a collision will corrupt the packet reception. Because the transmission power of a node is variable, we adopt the physical model in [7] to model interference. According to this model, 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

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

where G_{ij} is the channel gain for node pair (i, j) which depends on pass loss, channel fading and shadowing; P_{ij} is the transmission power at the transmitting node i; N_0 is the thermal noise power at receiving node j which is normally considered to be a constant. Note that the left hand side of the inequality is called the *Signal to Interference and Noise Ratio* (SINR) for transmission (i, j) and β is a given threshold determined by some QoS requirements such as *Bit Error Rate* (BER).

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 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 *primary interference* between two links if they are incident on a common node. In this case, they can not 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 used to check if concurrent transmissions are allowed.

There is a traffic demand B_{ij} 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 computed 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 which 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 T time slots. The 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. A specific link may appear several times in a schedule and r^{Γ}_{ij} is used to denote the number of channels whose corresponding link is (i, j) in schedule Γ. r^{Γ}_{ij} actually indicates the bandwidth allocated to link/flow (i, j), which should never be larger than the demand B_{ij}. Note here that some demands may not be satisfied due to limited network resource. The Demand Satisfaction Factor (DSF) of a link (i, j) can be computed as r^{Γ}_{ij}/B_{ij}. Furthermore, according to schedule Γ, we use L^{Γ} and L^{Γ}_t to denote the complete set of corresponding links and the set of corresponding active links in time slot t, respectively. In addition, we use P to denote a power assignment. A power assignment P is a table which is indexed by 3-tuples (i, j, t). P^t_{ij} is used to represent the entry in P corresponding to channel (i, j, t). Γ^P is used to denote the set of channels having a corresponding entry in P.

Definition 1 (Feasible Power Assignment): A power assignment P is said to be a **feasible power assignment** if the following two conditions are satisfied.

1) $0 \leq P^t_{ij} \leq P_{max}$, $\forall(i, j, t) \in \Gamma^P$.
2) Inequality (1) is satisfied, $\forall(i, j, t) \in \Gamma^P$.

Definition 2 (Feasible Schedule): A schedule Γ is said to be a **feasible schedule** if the following conditions are satisfied.

1) Any two links in L^{Γ}_t are not incident with each other, $\forall t \in [1, T]$.
2) There exists at least one feasible power assignment P, s.t. $\Gamma = \Gamma^P$.
3) $r^{\Gamma}_{ij} \leq B_{ij}, \ \forall(i, j) \in L^{\Gamma}$.

A schedule Γ is said to be a **feasible fair schedule** if Γ is a feasible schedule and DSF of each link based on Γ is no less than the given threshold α.

Definition 3 (Throughput): The **throughput** of the network provided by a feasible schedule Γ, is $Z(\Gamma) = c(\sum_{(i,j)\in L^{\Gamma}} r^{\Gamma}_{ij})/T$.

Note that the throughput of a feasible schedule actually specifies how much traffic can be successfully transmitted per time unit based on this schedule. Since T and c are constants, we can simply use $(\sum_{(i,j)\in L^{\Gamma}} r^{\Gamma}_{ij})$ to represent the network throughput.

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 4 (MATH-SPC): The **MAximum THroughput link Scheduling with Power Control (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 the throughput may starve some links/flows. Therefore, we formulate the following problem to seek a schedule which maximizes the throughput subject to a fairness constraint. Let the DSF threshold be given as α.

Definition 5 (MATA-SPC): The **MAximum Throughput fAir link Scheduling with Power Control (MATA-SPC)** problem seeks a feasible schedule Γ along with a power assignment such that the throughput given by Γ is maximum among all feasible fair schedules with threshold α.

We prefer α to be as large as possible. However, if α is too large, it may be impossible to find a feasible solution. We define an auxiliary problem named MDSF. By solving it, we can find out an achievable and large enough DSF threshold.

Definition 6 (MDSF): The **Maximum DSF threshold** problem seeks a DSF threshold α such that α is maximum among all possible thresholds and there exists at least one feasible fair schedule with threshold α.

IV. MILP Formulation

In this section, we present a Mixed Integer Linear Programming (MILP) formulation for solving the proposed problems. Firstly, we need to define some decision variables and introduce several notations that will be used in the MILP formulation.

(i) X_{ij}^t is a binary variable which is equal to 1 if link (i,j) is active for transmission in time slot t. Otherwise, it is 0.

(ii) P_{ij}^t is a variable which can take any positive real number between $[0, P_{max}]$ and indicates the power level for link (i,j) in time slot t.

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

$MILP1$: MATH-SPC

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

subject to:

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

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,k)\in L} X_{jk}^t \le 1; \quad \forall t\in[1,T], \forall j\in V_L \tag{4}$$

$$G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\setminus\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \ge \Phi(X_{ij}^t - 1); \quad \forall t\in[1,T], \forall (i,j)\in L \tag{5}$$

$$X_{ij}^t \in \{0,1\}; \quad \forall t\in[1,T], \forall (i,j)\in L \tag{6}$$

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

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 the SINR requirement is satisfied: if a link (i,j) is scheduled to be active in time slot t, then the SINR at receiving node j must be larger 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 (7) 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.

Actually, we can obtain a much simpler parameterized MILP formulation $MILP2(t,r)$ whose decision variables are exactly the same as those in $MILP1$ except that r is the 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. $MILP2(t,r)$ can be used to compute a set of links along with a power assignment which can maximize the throughput in time slot t under the bandwidth allocation condition given by the table r.

$MILP2(t,r)$:

$$\text{maximize} \quad \sum_{(i,j)\in L} X_{ij}^t \tag{8}$$

subject to:

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,k)\in L} X_{jk}^t \le 1; \quad \forall j\in V_L \tag{9}$$

$$G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\setminus\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \ge \Phi(X_{ij}^t - 1); \quad \forall (i,j)\in L \tag{10}$$

$$0 \le P_{ij}^t \le P_{max}X_{ij}^t; \quad \forall (i,j)\in L \tag{11}$$

$$X_{ij}^t \begin{cases} = 0, & \text{if } r_{ij} \ge B_{ij} \\ \in \{0,1\}, & \text{otherwise} \end{cases} \quad \forall (i,j)\in L \tag{12}$$

In a special case where fairness is not a concern and the traffic demand for each link is large enough, i.e., no less than T, when we make a decision whether a link (i,j) should be active for some 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 $MILP2(1, r_0)$ once instead of solving $MILP1$, where the bandwidth allocated to each link in r_0 is 0. Specifically, 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 achieve the maximum throughput in each time slot.

Moreover, a suboptimal solution can be provided for MATH-SPC problem by solving T $MILP2(t,r)$ sequentially.

More specifically, we solve $MILP2(1,r)$ first. We schedule those links with X value of 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 ($r_{ij} = B_{ij}$) the *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 $MILP2(t,r)$ (Constraint 12). 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.

We use $MILP3$ to find out the maximum DSF threshold α. Then we can obtain the optimal solution of the MATA-SPC problem with threshold α by solving $MILP4(\alpha)$.

$MILP3$: MDSF

$$\text{maximize} \quad \alpha \tag{13}$$

subject to:

$$\alpha B_{ij} \le \sum_{t=1}^{T} X_{ij}^t \le B_{ij}; \quad \forall (i,j) \in L \tag{14}$$

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,k)\in L} X_{jk}^t \le 1; \quad \forall t \in [1,T], \forall j \in V_L$$

$$G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\backslash\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \ge \Phi(X_{ij}^t - 1); \quad \forall t \in [1,T], \forall (i,j) \in L$$

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

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

$MILP4(\alpha)$: MATA-SPC

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

subject to:

$$\alpha B_{ij} \le \sum_{t=1}^{T} X_{ij}^t \le B_{ij}; \quad \forall (i,j) \in L$$

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,k)\in L} X_{jk}^t \le 1; \quad \forall t \in [1,T], \forall j \in V_L$$

$$G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\backslash\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \ge \Phi(X_{ij}^t - 1); \quad \forall t \in [1,T], \forall (i,j) \in L$$

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

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

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, the Serial LP Rounding (SLPR) heuristic, is to solve serial relaxed LPs instead of solving the MILP. By relaxing the integer constraint for decision variables X_{ij}^ts 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 a guideline to schedule some channels. We then solve another LP (with X values of the given channels fixed, while allowing the power levels to be adjusted) and schedule some 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. The 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 3-tuples (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, the values of all entries are set to -1.

$LP1(Y)$:

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

subject to:

$$\sum_{t=1}^{T} X_{ij}^t \le B_{ij}; \quad \forall (i,j) \in L$$

$$\sum_{(i,j)\in L} X_{ij}^t + \sum_{(j,k)\in L} X_{jk}^t \le 1; \quad \forall t \in [1,T], \forall j \in V_L$$

$$G_{ij}P_{ij}^t - \beta \sum_{(p,q)\in L\backslash\{(i,j)\}} G_{pj}P_{pq}^t - \beta N_0 \ge \Phi(X_{ij}^t - 1); \quad \forall t \in [1,T], \forall (i,j) \in L$$

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

$$X_{ij}^t \begin{cases} = Y_{ij}^t, & \text{if } Y_{ij}^t \ge 0 \\ \in [0,1], & \text{otherwise} \end{cases} \quad \forall t \in [1,T], \forall (i,j) \in L \tag{15}$$

In the algorithm, Γ and Γ_L are initialized to $\emptyset$ 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 $MILP1$ as the guidance of channel selection. In **Step_3**, the feasibility of a channel (i,j,t) can be checked by solving $LP2(i,j,t,L_t^\Gamma)$. In the formulation, L_t^Γ denotes the set of links which have been scheduled in time slot t so far. If $LP2(i,j,t,L_t^\Gamma)$ can return a feasible solution, we can conclude that link (i,j) can be scheduled in time slot t. 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 $LP2$.

$LP2(i,j,t,L_t^\Gamma)$:

$$\text{minimize} \sum_{(h,l)\in L_t^\Gamma \bigcup\{(i,j)\}} P_{hl} \quad (16)$$

subject to:

$$G_{hl}P_{hl} - \beta \sum_{(p,q)\in L_t^\Gamma \bigcup\{(i,j)\}\setminus\{(h,l)\}} G_{pl}P_{pq} - \beta N_0 \geq 0$$
$$\forall (h,l) \in L_t^\Gamma \bigcup\{(i,j)\} \quad (17)$$

$$0 \leq P_{hl} \leq P_{max}; \quad \forall (h,l) \in L_t^\Gamma \bigcup\{(i,j)\} \quad (18)$$

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 and the links whose DSF is maximum among all unsaturated links to be selected in the next iteration by **Step_4**. The design philosophy behind it is to give chances for those links with relatively smaller DSFs to be scheduled. In this way, the fairness can be enhanced.

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

VI. Numerical Results

In our simulations, we consider static wireless networks with nodes randomly located in a $1000 \times 1000\ m^2$ region. The thermal noise power $N_0 = -90dBm$. The SINR threshold $\beta = 10dB$ and the maximum transmission power $P_{max} = 300mW$. The channel gain, G_{ij} is set to be 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 for each link/flow (B_{ij}) 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 regards 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 choose 8 links and set the frame length to be 10 time slots. We randomly place 10 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 variance of DSFs given by solving $MILP1$ (Maximum Throughput), serial $MILP2$ heuristic, solving $MILP4(\alpha)$ (OPT of MATA-SPC) and SLPR heuristic are presented in Table I and Table 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, DSF of almost half of 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 the throughput results in a severe bias on bandwidth allocation among all links/flows. By solving $MILP4(\alpha)$ or using our SLPR heuristic, the fairness

Algorithm 1 Serial LP Rounding (SLPR) Heuristic

```
Step_1  Γ = Ø; Γ_L = Γ_LT;
        for t = 1 to T
          L_t^Γ = Ø
        endfor
        forall (i,j,t) ∈ Γ_L
          Y_ij^t = −1;
        endforall
Step_2  Solve the LP1(Y).
        if LP1(Y) is infeasible
          output Γ and P; stop;
        endif
Step_3  Examining the positive 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 selected
          output Γ and P; stop;
        else
          Let (p,q,s) be the first channel that can be selected.
          Γ = Γ + {(p,q,s)};
          Γ_L = Γ_L − {(p,q,s)};
          L_s^Γ = L_s^Γ + {(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 + +;
        if (r_pq == B_pq) α_pq = −1;
        else α_pq = r_pq/B_pq;
        endif
        α = max_{(i,j)∈L} α_ij;
        num_α = 0;
        num_B = 0;
        forall (i,j,t) ∈ Γ_L
          Y_ij^t = −1;
          if (α_ij == α) num_α + +;
          if (r_ij == B_ij) num_B + +;
        endforall
        forall (i,j,t) ∈ Γ_L
          if ((r_ij == B_ij) or (α_ij == α and
              num_α < |Γ_L| − num_B))
              Y_ij^t = 0;
          endif
Step_5  Goto Step_2;
```

TABLE I

TRIAL1: 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

TRIAL2: 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

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 chosen links to be 30 and change the frame length from 10 to 35 time slots. In the last scenario, we fix the frame length to be 20 time slots and change the number of chosen links from 10 to 60. Similarly, we use the variance of the DSFs of all chosen links to show the fairness. The smaller this value, the better the fairness. Each value presented in Fig. 2–5 is the average over 20 runs.

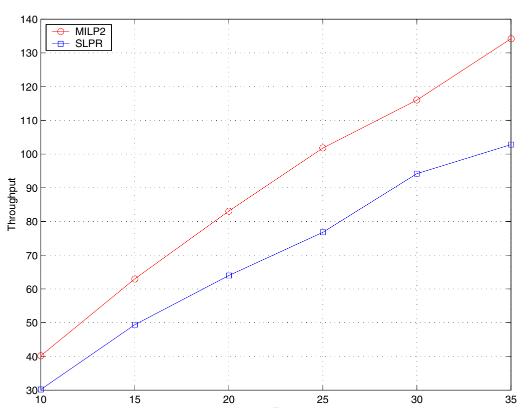

Fig. 2. Network Throughput with $m = 30$

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 serial $MILP2$ heuristic. However, in terms of fairness, SLPR heuristic achieves much smaller DSF variances in all cases.

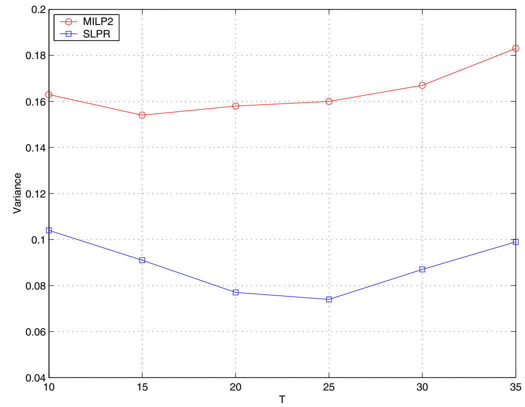

Fig. 3. The DSF Variance with $m = 30$

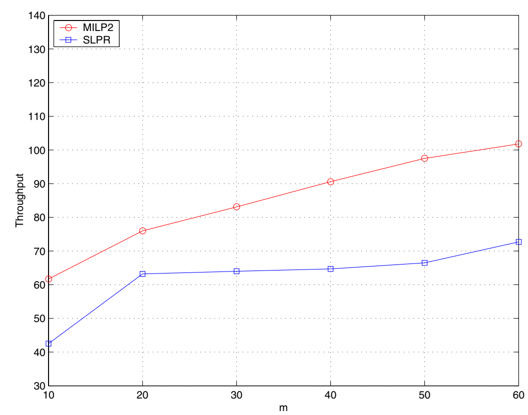

Fig. 4. Network Throughput with $T = 20$

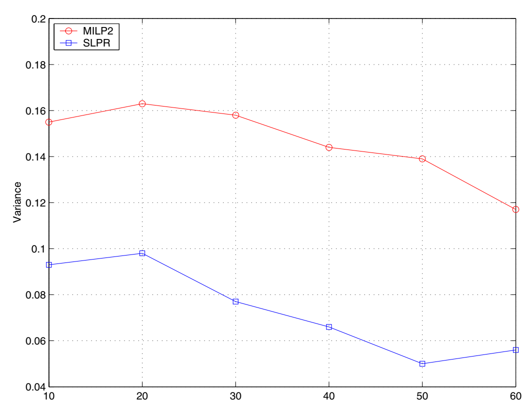

Fig. 5. The DSF Variance with $T = 20$

Compared with the average DSF variance given by serial $MILP2$ heuristic, 0.155, our scheme decreases it to 0.081, which is a 47.7% reduction.

VII. CONCLUSIONS

In this paper, we have studied the joint link scheduling and power control problem with the objective of maximiz-

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ing the network throughput. We have formulated a novel *MAximum THroughput link Scheduling with Power Control (MATH-SPC)* problem, and presented a Mixed Integer Linear Programming (MILP) to provide optimal solutions. For the fairness consideration, we have defined a new parameter, the *Demand Satisfaction Factor (DSF)*, to characterize the fairness of bandwidth allocation. Based on this definition, we have formulated and presented an MILP formulation for the *MAximum Throughput fAir link Scheduling with Power Control (MATA-SPC)* problem. We have also proposed a polynomial time heuristic, namely, SLPR heuristic. Our numerical results have shown that bandwidth can be fairly allocated among all links/flows by solving our MATA-SPC formulation or by using our SLPR algorithm at the cost of a reasonable throughput reduction.

As future research, we intend to design distributed algorithms and implementations for the proposed problem. Extending our research to multichannel wireless mesh networks will also be of interest.

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