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Power control and scheduling with minimum rate constraints in clustered multihop TD/CDMA wireless ad hoc networks

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Summary

In order to achieve high end-to-end throughput in a multihop wireless ad hoc network, TD/CDMA has been chosen as the Medium Access Control (MAC) scheme due to its support for high network throughput in a multihop environment. The associated power control and scheduling problem needs to be addressed to optimize the operations of TD/CDMA. In this paper, cluster-based architecture is introduced to provide centralized control within clusters, and the corresponding power control and scheduling schemes are derived to maximize a network utility function and guarantee the minimum rate required by each traffic session, given routes for multiple end-to-end multihop traffic sessions. Because the resulted optimal power control reveals bang-bang characteristics, that is, scheduled nodes transmit with full power while other nodes remain silent, the joint power control and scheduling problem is reduced to a scheduling problem. The multi-link version of the throughput-optimal and the proportional fair scheduling algorithms for multihop wireless ad hoc networks are proposed. In addition, a generic token counter mechanism is employed to satisfy the minimum rate requirements. By ensuring different minimum rate for different traffic sessions, service differentiation is also achieved. Approximation algorithms are suggested to reduce the computational complexity. In networks that are lack of centralized control, distributed scheduling algorithms are also derived and fully distributed implementation is provided. Simulation results demonstrate the effectiveness of the proposed schemes. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: power control; scheduling; TD/CDMA; multihop wireless ad hoc network

1. Introduction

Wireless ad hoc networks have been the topic of extensive research recently. The interests in such networks are due to their ability to provide wireless networking capability in scenarios where no fixed wired infrastructure is available (e.g., disaster relief efforts, battlefields, etc.). The lack of fixed infrastructure introduces great design challenges. One way to reduce the difficulty is by organizing nodes into clusters and assigning certain

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nodes management functions [1], such as transmission coordination. These nodes are called cluster heads. It has been shown that proper clustering in wireless ad hoc networks reduces the complexity of link-layer and routing protocol design significantly and improves the scalability of the protocols [2]. In addition, clustering increases the network capability of supporting Quality-of-Service (QoS) [3]. Clustering is also desirable because of practical reasons. For instance, in a battlefield deployment, a cluster may be naturally formed by a set of soldiers equipped with wireless communication devices and a tank serving as cluster head.

In order to resolve the issue of low end-to-end throughput in a multihop ad hoc network, innovative Medium Access Control (MAC) protocols are indispensable. In wireless ad hoc networks, MAC protocols play a critical role in optimizing bandwidth efficiency and ensuring QoS due to the broadcast nature of wireless channels. There are mainly three types of MAC protocols, namely random access with collision resolution based schemes (such as CSMA/CA), reservation based schemes (such as D-PRMA [4]), and signal orthogonalization based schemes (such as TDMA or CDMA). For a thorough review of the MAC protocols for wireless ad hoc networks, see for example Reference [5] and the references therein. Due to their poor scalability in a multihop ad hoc network, random access protocols are not an efficient solution [6]. In Reference [7], it is demonstrated that CDMA-based MAC protocols achieve a significant increase in network throughput at no additional cost in energy consumption compared to 802.11x MAC protocols.

In this research work, we restrict our interests in clustered TD/CDMA wireless ad hoc networks. It is assumed that the wireless ad hoc network is organized into clusters and each cluster has a cluster head with higher than average network resources such as power. All users/nodes within the cluster share the same frequency band and each user/node is assigned a randomly generated orthogonal code. On top of that, time is split into equal-sized slots where only scheduled users/nodes are allowed to transmit in each slot. The cluster head functions as a manager and is responsible for scheduling the transmissions within the cluster. It is assumed that the communication links among cluster heads (inter-cluster communications) have sufficient bandwidth such that the bottleneck of end-to-end traffic between nodes in different clusters resides within clusters. Hence, scheduling intra-cluster transmissions is the main concern in this paper.

An example of a clustered TD/CDMA wireless ad hoc network is shown in Figure 1. There are two clusters with cluster heads $CH1$ and $CH2$, respectively. It is assumed that the intra-cluster route is given for a traffic session: $r_I = A \rightarrow E \rightarrow G \rightarrow F \rightarrow CH1$. Data traffic is forwarded in a multihop fashion. Figure 1 also shows a schedule for intra-cluster traffic transmissions.

Power control is employed in a wireless ad hoc network to control transmission range and keep the network fully connected [8]. It is a physical layer function. However, transmission power has a direct impact on multiple access of nodes by affecting received signal-to-interference ratio (SIR) at receivers. Hence, power control is strongly coupled with scheduling

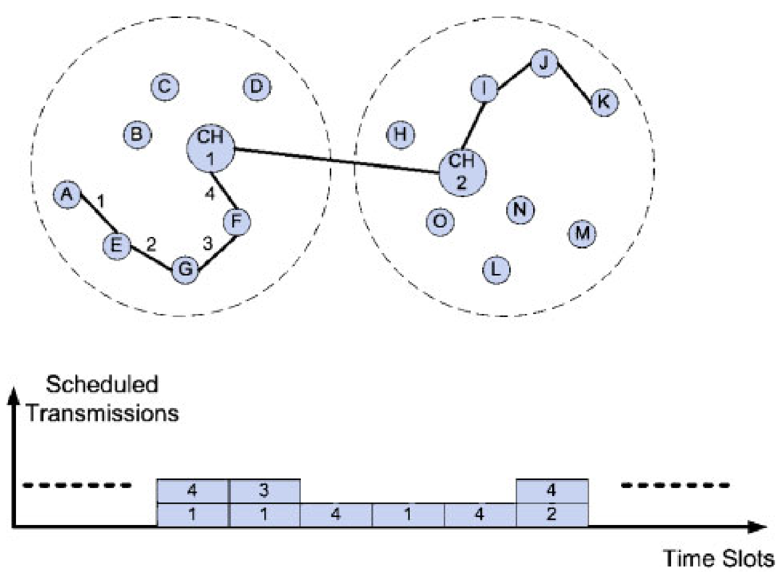

Fig. 1. A clustered TD/CDMA wireless ad hoc network. CH, cluster head.

and has additional functions of reducing unnecessary interference among concurrent transmissions in TD/CDMA-based systems [9]. Power control and scheduling is of paramount importance for ensuring the success of multiple simultaneous transmissions and maximizing network utility in TD/CDMA wireless ad hoc networks, and is the focus of this paper. In this work, we are interested in traffic sessions with minimum rate constraints. The goal is to study power control and scheduling schemes that maximize certain network utility functions while guarantee minimum rate of traffic sessions, given the routes and minimum rate constraints of those sessions. Although the proposed power control and scheduling schemes focus on intra-cluster traffic transmissions where a central controller (cluster head) is available, fully distributed versions of schemes are also developed for scenarios where no central controller is available.

The rest of the paper is organized as follows: Section 2 presents an overview of the works that are closely related to our problem. Section 3 states the wireless network model and formulates the joint power control and scheduling problem with QoS constraints. Both optimal solution and low complexity approximations are proposed, together with several algorithms that serve as lower bounds. The proposed algorithms are evaluated by extensive discrete-event simulations in Section 4. Distributed schemes and other various implementation issues are discussed in Section 5. Section 6 contains the concluding remarks.

2. Related Works

A power control and scheduling problem has been solved in Reference [10] for TDMA ad hoc networks on a per frame basis and each link is assigned to a number of slots in a given frame. The authors assume that each slot has *fixed* data rate. Using the concept of virtual links, assigning one slot to each virtual link satisfies the end-to-end session rate requirements. The joint feasibility problem is proven to be NP-complete and centralized approximation algorithms are provided. In our study, we assume variable data rate from slot to slot due to channel fluctuations.

A centralized joint routing, scheduling, and power control problem is formulated for TD/CDMA ad hoc networks and an approximation algorithm is derived in Reference [11]. However, a simplified interference model is adopted, where no interference is assumed among different links. In Reference [12], a centralized joint routing, scheduling and power control problem is solved for multihop base stations where data rate is assumed to be a linear function of SIR (in low SIR regime). In our work, a general interference model is adopted, where each transmitting node in the network is assumed to cause interference at any receiving nodes, even if they are far apart. The data rate is calculated as a concave function of the SIR, which covers the entire range of SIR.

The authors in Reference [13] proposed a joint power control and scheduling scheme based on a utility function of *instantaneous* power or *instantaneous* data rate. A degree-based greedy scheduling and an iterative power control algorithm using a penalty function approach are suggested to maximize the utility function while guarantee minimum and maximum link data rates. The algorithm in Reference [13] focused on a *snapshot* of a set of wireless links. Another work on *instantaneous* power control in wireless ad hoc networks is Reference [9]. In this study, we focus on *long-term average data rate* and minimum average data rate requirements for traffic sessions in a routed wireless ad hoc network.

A randomized policy is given to solve the multi-commodity flow problem given the long-term link capacity as weight in wireless networks [14]. Then a dynamic policy (throughput-optimal policy) is proposed for unknown arrival and channel statistics and is proven to perform better than the randomized policy. The dynamic policy is a non-linear and non-convex optimization problem that is very difficult to solve. A steepest ascent search is suggested as a sub-optimal centralized solution. As pointed out later in this paper, throughput-optimal policies maximize the effective rate of data flows. However, no fairness among users/flows is addressed in such policies. In addition, no minimum rate constraint is considered in Reference [14]. In this paper, both throughput-optimal and proportional-fair (PF) scheduling algorithms are taken into consideration. Furthermore, a token counter mechanism is introduced to maintain minimum rate of traffic flows whenever feasible. A distributed approximation is also proposed in Reference [14] assuming that the link gains between a node and its neighbors are known. Our proposed distributed algorithm uses control channel to exchange link gain information. In the simulation of Reference [14], the link gains are calculated only based on distances between nodes. No fading is considered and the locations of nodes are assumed to be known. In our simulation study, channel is modeled to have both shadowing and rayleigh fading.

Power allocation and scheduling has been extensively studied for WLAN. In Reference [15], a fully distributed algorithm for scheduling packet transmissions is proposed such that different flows are allocated bandwidth in proportion of their weights. The paper proposes a distributed fair scheduling (DFS) approach obtained by modifying the distributed coordination function (DCF) in IEEE 802.11 standard. A fair scheduling mechanism, distributed elastic round robin (DERR) is proposed in Reference [16]. DERR is suitable for IEEE 802.11 wireless LANs operated in the ad hoc mode and capable of avoiding collisions through a random mapping between allowance and IFS. DERR outperforms 802.11e in terms of delay and throughput. In Reference [17], an enhanced timer-based scheduling control algorithm is proposed to effectively manage the delay budget in IEEE 802.11e. Simulation results show that the proposed algorithm outperforms the simple scheduler control algorithm in delay and jitter in infrastructure mode. Although there are a lot of work on power allocation and scheduling for WLAN, most of them studied infrastructure mode and focused on random access part (DCF) in 802.11. Furthermore, to our best knowledge, very few of the papers considered ad hoc mode and none of them considered multihop scenarios.

3. Joint Power Control and Scheduling With Minimum Rate Constraints

In this paper, we assume that the routes for the multiple end-to-end traffic sessions are given. All the links contained in the routes form the set of 'active links.' Each active link is uniquely identified by its transmitter and receiver. In other words, transmitter i and receiver i are the transmitter and receiver of active link i. The received SIR at the ith receiver from the ith transmitter (received SIR of the ith active link) is defined by

$$\gamma_i = \frac{h_{ii} p_i}{\frac{1}{L} \sum_{j \neq i} h_{ij} p_j + \sigma^2} \tag{1}$$

where h_{ii} is the link gain from transmitter i to its designated receiver i. h_{ij} is the link gain from transmitter j to receiver i (active link i's designated receiver). p_i and p_j are the transmission power of transmitters i and j, respectively. σ^2 is the background (receiver) noise. L is the spreading gain for spread spectrum systems.

In this paper, we assume that each link has variable rate. This rate is bounded by the feasible rate region. The link gains (channel quality) may fluctuate dramatically from one slot to another slot. In other words, the data rates of the active links are different from slot to slot during the traffic sessions. A scheduling scheme should take advantage of channel fluctuations, that is, it should be 'channel-aware.'

The instantaneous data rate of each active link can be evaluated by Shannon capacity formula (for AWGN channel)

$$R_i = W_i \log_2(1 + \gamma_i) \tag{2}$$

where W_i is the bandwidth occupied by the transmission from the ith transmitter to its designated receiver. Note that this formula gives the achievable rate (upper bound) of the AWGN channel. However, it is justified by the fact that with the current modulation and coding technology it can be closely approximated in most practical scenarios [18].

The interference model adopted here assumes that each transmitting node in the network causes interference at any receiving nodes, even if they are far apart. This model is considered more realistic than the one which assumes that transmitting nodes only cause interference to their neighbors. This is because the aggregate interference from a large number of nodes may not be negligible even if interference from each of them is small. The instantaneous data rate will be determined solely by the received SIR.

3.1. Problem Formulation

In this work, we will focus on end-to-end traffic sessions with QoS constraints. Specifically, we are interested in traffic sessions with minimum rate constraints. The goal of this research work is to study joint power control and scheduling schemes that maximize certain utility functions while guarantee minimum rate of traffic sessions, given the routes and minimum rate constraints of those sessions. A guarantee on minimum rate is arguably the simplest possible QoS guarantee. Therefore, we believe it is natural that mobile users would expect such an assurance. Other reasons of ensuring minimum rate are

(1) Some applications need a minimum rate in order to perform well. For example, streaming audio and video can become unusable if the data rate is too low.
(2) Even for static TCP-based applications such as web browsing, if the data rate is too low then we typically get a large queue buildup which can lead to TCP timeouts and poor performance. Such effects were discussed by Chakravorty *et al.* in Reference [19].
(3) Providing a minimum rate guarantee can help to smooth out the effects of a variable wireless channel.

(4) Providing a minimum rate can allow us to ensure that a slot-based TD/CDMA service is no worse than circuit-based data systems such as wireline dialup or 3G1X wireless service.
(5) By setting minimum data rate differently for different users we can ensure service differentiation.

Given the routes of multiple end-to-end traffic sessions with minimum rate constraints, our approach follows the Gradient algorithm with Minimum/Maximum Rate constraints (GMR) developed in Reference [20]. Let's define the long-term average rate vector $\bar{\boldsymbol{R}} = (\bar{R}_1, \ldots, \bar{R}_N)$ assuming that there are N active links resulted from routing, and each of the active link has minimum rate constraint $(\bar{R}_i{}^{\min})$. The joint power control and scheduling problem is formulated as the following optimization problem
(P.1)

$$\max_{\boldsymbol{R} \in \mathcal{R}, \boldsymbol{p} \in \mathcal{P}} U(\bar{\boldsymbol{R}}) \tag{3}$$

subject to

$$\bar{R}_i \geq \bar{R}_i{}^{\min} \tag{4}$$

where the instantaneous rate is determined by Equations (1) and (2). $\mathcal{R}$ is the rate region, which is the set of long-term service rate vectors which the system is capable of providing. $\mathcal{P}$ is the set of allowable power vector defined by

$$p_i \leq p_i^{\max} \quad \forall\, i \tag{5}$$

where $p_i^{\max}$ is the maximum allowable transmission power of transmitter i. The utility function is of the form

$$U(\bar{\boldsymbol{R}}) = \sum_i U_i(\bar{R}_i) \tag{6}$$

where each $U_i(x)$ is an increasing concave continuously differentiable function defined for $x \geq 0$.

A node cannot transmit and receive simultaneously. This primary conflict [11] is resolved by setting the link gain matrix appropriately. For example, if node i is selected to transmit in the current slot, the corresponding link gains where node i is the receiver will be set to zero.

The multihop nature of the problem (P.1) will be included in the choices of the utility functions as well. For example, queue backlog weighted average rate at each node will be included in the utility function for throughput optimal criterion, which is directly related to the paths resulted from routing [14,21]. In other words, the order of the transmissions is implicitly included in the problem formulation. It also reflects in the fact that the links on the same route require the same minimum rate whereas links on different routes typically have different minimum rate requirements.

3.2. Centralized Solution

Before introducing the Multi-link Gradient algorithm with Minimum Rate constraints (MGMR) to solve the optimization problem (P.1), we observe some useful properties of the optimal solution.

3.2.1. Optimal power control

Theorem 1. *The optimal scheme has the property that each transmitting node transmits at full power, that is, $p_i = p_i^{\max}$ for some subset $\mathcal{S}$ of the nodes and $p_i = 0$ for the complementary set $\bar{\mathcal{S}}$.*

Proof. Assume that there are N active links (transmitter-receiver pairs) in the network. Let p_{ii}^{rcv} and p_{ij}^{rcv} be the instantaneous received power at receiver i from transmitter i and j, respectively. For simplicity, we express p_{ii}^{rcv} and p_{ij}^{rcv} in units of the background noise σ^2. In order to meet the minimum rate constraints of all active links, we must have for each active link i

$$\frac{p_{ii}^{\text{rcv}}}{\frac{1}{L}\sum_{j \in \{1,2,\ldots,N\}, j \neq i} p_{ij}^{\text{rcv}} + 1} \geq \gamma_i^{\text{tar}} \tag{7}$$

where γ_i^{tar} is the required SIR of link i. If a desired data flow rate is specified by a certain application, say, R_i^{tar}, then γ_i^{tar} can be expressed as

$$\gamma_i^{\text{tar}} \geq 2^{\frac{R_i^{\text{tar}}}{W_i}} - 1, \qquad i = 1, 2, \ldots, N \tag{8}$$

The feasible SIR vectors specified in Equation (7) is adapted from that in the cellular wireless networks to multihop wireless networks. Given the peak received power $p_{ii}^{\text{rcv,max}} = h_{ii} p_i^{\max}$ and $p_{ij}^{\text{rcv,max}} = h_{ij} p_j^{\max}$, we may change variables to $\theta_{ii} = \frac{p_{ii}^{\text{rcv}}}{p_{ii}^{\text{rcv,max}}}$ and $\theta_{ij} = \frac{p_{ij}^{\text{rcv}}}{p_{ij}^{\text{rcv,max}}}$ to rewrite Equation (7) as

$$\frac{\theta_{ii} p_{ii}^{\text{rcv,max}}}{\frac{1}{L}\sum_{j \in \{1,2,\ldots,N\}, j \neq i} \theta_{ij} p_{ij}^{\text{rcv,max}} + 1} \geq \gamma_i^{\text{tar}} \tag{9}$$

A given SIR vector is feasible if Equation (9) can be satisfied with equality with $0 \leq \theta_{ij} \leq 1$ for all i and j. We hence examine the solution to the set of linear equations

$$\frac{\theta_{ii} p_{ii}^{\mathrm{rcv,max}}}{\gamma_i^{\mathrm{tar}}} = \frac{1}{L} \sum_{j \in \{1,2,\ldots,N\}, j \neq i} \theta_{ij} p_{ij}^{\mathrm{rcv,max}} + 1 \quad (10)$$

which can be further rewritten as

$$\theta_{ii} p_{ii}^{\mathrm{rcv,max}} \left(1 + \frac{L}{\gamma_i^{\mathrm{tar}}}\right) = \sum_{j \in \{1,2,\cdots,N\}} \theta_{ij} p_{ij}^{\mathrm{rcv,max}} + L \quad (11)$$

It can be seen by inspection that the solution is of the form $\theta_{ii} p_{ii}^{\mathrm{rcv,max}}(1 + \frac{L}{\gamma_i^{\mathrm{tar}}}) = C$ where C is a global parameter. The value of C can be obtained by substituting the postulated solution in Equation (11) to obtain $C = C \sum_j \frac{\gamma_j^{\mathrm{tar}}}{\gamma_j^{\mathrm{tar}}+L} + L$ which gives the final solution

$$\theta_{ii} = \frac{\gamma_i^{\mathrm{tar}}}{(L + \gamma_i^{\mathrm{tar}}) p_{ii}^{\mathrm{rcv,max}}} \frac{L}{\left[1 - \sum_{j \in \{1,2,\cdots,N\}} \frac{\gamma_j^{\mathrm{tar}}}{\gamma_j^{\mathrm{tar}}+L}\right]} \quad (12)$$

Define $\alpha_i = \frac{\gamma_i^{\mathrm{tar}}}{\gamma_i^{\mathrm{tar}}+L}$ we see that

$$\theta_{ii} = \frac{L\alpha_i / p_{ii}^{\mathrm{rcv,max}}}{1 - \sum_j \alpha_j} \quad (13)$$

Clearly, $0 \leq \alpha_i < 1$. Since we require $0 \leq \theta_{ii} \leq 1$, Equation (13) results in the following feasibility conditions to meet the required SIRs.

$$\sum_j \alpha_j + \frac{L\alpha_i}{p_{ii}^{\mathrm{rcv,max}}} \leq 1 \quad \forall i \quad (14)$$

Note the simple linear form of the feasible SIRs in terms of the α_i.

Note that the utility function $U_i(\bar{R}_i)$ is a concave function and $\bar{R}_i$ is a linear combination of the instantaneous data rate R_i. The instantaneous data rate is again a concave function of the SIR. Since Equation (14) is linear in α_i, it is more convenient to consider the R, α relationship which is now convex. The optimization problem (P.1) becomes

$$\max_{\boldsymbol{R} \in \mathcal{R}, \boldsymbol{p} \in \mathcal{P}} \sum_i U_i(\bar{R}_i) \quad (15)$$

subject to

$$\sum_j \alpha_j + \frac{L\alpha_i}{p_{ii}^{\mathrm{rcv,max}}} \leq 1, \quad \alpha_i > 0 \quad \forall i \quad (16)$$

Equation (16) specifies $2N$ constraints on the feasible α_i. From standard theorems on convex maximization with linear constraints, it is easy to see that the optimum occurs at *corner point* of Equation (16) due to the joint-convexity of Equation (15) in the α_i. Corner points of Equation (16) have exactly N of the $2N$ constraints binding, that is, some subset of the α_i are null, while the complementary set saturate their respective constraints in the first equation of (16). Combining this observation with Equation (13) results in $\theta_{ii} = 1$ for the complementary set, thus proving the theorem. ■

Note that similar observations are obtained under various different contexts and assumptions [12,14,22,23]. Specifically, the results reported in Reference [12] may be viewed as a special case of the above theorem where the data rate is assumed a linear function of SIR instead of the more general form that adopted in this paper. Theorem 1 reveals the bang-bang characteristics of the nodes' transmission power in order to maximize the network's utility. In each time slot, selected transmitting nodes will use the maximum transmission power, while other nodes remain silent.

3.2.2. Scheduling algorithms

As highlighted by Theorem 1, the joint power control and scheduling problem is reduced to a scheduling problem given the bang-bang characteristics of the optimal transmission power. We address the scheduling problem by first reviewing two important types of scheduling algorithms. Then the Multi-link Gradient scheduling algorithm with Minimum Rate constraints (MGMR) will be proposed to solve the optimization problem (P.1).

One type of scheduling algorithm considered in this paper is the throughput-optimal scheduling, such as the scheduling algorithms proposed in References [14,21,24,25], where a weighted sum of user rates is maximized for each scheduling interval. This choice has provable stability properties shown in much previous work in various contexts involving data scheduling and resource allocation. The weights may be chosen to optimize one of many possible performance measures, including average queue length, delay, or corresponding percentiles, and other similar criteria. A version of this type of algorithms that guarantees *queue stability*, that is, boundedness of queue lengths when feasible, is specified as the rate choice that satisfies

$$\boldsymbol{R}^* = \arg\max_{\boldsymbol{R}\in\mathcal{R}} \boldsymbol{Q}\cdot\boldsymbol{R}$$

where $\boldsymbol{R}$, $\boldsymbol{Q}$ are rate and queue vectors of the user set respectively, and $\mathcal{R}$ is the *rate region*, or the set of feasible rate vectors. Minimum/maximum instantaneous rate guarantees may be satisfied by restricting the rate region $\mathcal{R}$ appropriately.

Another type of scheduling algorithms considered in this paper is the fair scheduling, such as the proportional fair scheduling proposed in References [26,27] and further analyzed in References [28,29]. PF scheduling algorithm was proposed and implemented by QualComm for 3G1X EVDO (HDR) downlink. PF algorithm provides fairness among users such that in the long run each user receives the same number of time slots of services. At the same time, PF also takes advantage of channel variations (user diversity). However, since PF schedules users one-at-a-time, it needs to be modified for a multihop scenario.

A review of throughput-optimal and proportional fair scheduling is given in Reference [30]. The authors also proposed a combination of throughput-optimal scheduling and congestion control for cellular systems.

In this paper, we are interested in proposing and studying the multi-link version of the throughput-optimal and the PF algorithms for multihop wireless ad hoc networks, called multi-link throughput optimal (MQR) and multi-link proportional fair (MPF), respectively. We are particularly interested in their modified versions that accommodate QoS constraints required by multiple traffic sessions. MQR and MPF are modified to satisfy minimum rate constraints using a token counter mechanism inspired by the scheme developed for cellular systems [20], thus they are named multi-link throughput optimal with minimum rate (MQRMR) and multi-link proportional fair with minimum rate (MPFMR), respectively.

We now formulate the MGMR, which seeks to solve the optimization problem (P.1).

MGMR. In a time slot k, select the active links

$$\arg\max_{\boldsymbol{R}\in\mathcal{R}} \sum_i \mathrm{e}^{a_i T_i(k)} U_i'(\bar{R}_i(k)) R_i(k) \tag{17}$$

where $\bar{R}_i(k)$ is the current average service rate received by link i, $T_i(k)$ is a 'token counter' for link i, and $a_i > 0$ is a parameter. The values of average rate $\bar{R}_i$ are updated as in the PF algorithm [26,27]:

$$\bar{R}_i(k+1) = (1-\beta)\bar{R}_i(k) + \beta R_i(k)$$

where $\beta > 0$ is a small fixed parameter, and $R_i(k)$ is the instantaneous data rate if link i was actually served in slot k and $R_i(k) = 0$ otherwise. The token counter T_i is updated as follows:

$$T_i(k+1) = \max\left\{0, T_i(k) + \bar{R}_i^{\min} - R_i(k)\right\} \tag{18}$$

We prove the optimality of the MGMR algorithm by studying the dynamics of user throughputs and token counters under the MGMR algorithm when parameters β and a_i are small. Namely, we consider the asymptotic regime such that β converges to 0, and each $a_i = \beta\alpha_i$ with some fixed $\alpha_i > 0$. We study the dynamics of *fluid sample paths* (FSP), which are possible trajectories $(r(t), \tau(t))$ of a random process which is a limit of the process $(\bar{R}(t/\beta), \beta T(t/\beta))$ as $\beta \to 0$. (Thus, $r(t)$ approximates the behavior of the vector of throughputs $\bar{R}(t)$ when β is small and we 'speed-up' time by the factor $1/\beta$; $\tau(t)$ approximates the vector $\boldsymbol{T}(t)$ scaled down by factor β, and with $1/\beta$ time speed-up.) The main result is a 'necessary throughput convergence' condition stated in the following theorem:

Theorem 2. *Suppose FSP (r, τ) is such that*

$$r(t) \to \bar{R}^* \quad \text{as } t \to \infty$$

and $\tau(t)$ remains uniformly bounded for all $t \geq 0$. Then, $\bar{R}^*$ is a solution to the problem (P.1) and, moreover, $\bar{R}^* \in \mathcal{R}^{\text{cond}} \cap \mathcal{R}^* \neq \emptyset$.

Rate region $\mathcal{R}$ is a convex closed bounded polyhedron in the positive orthant. By $\mathcal{R}^*$ we denote the subset of maximal elements of $\mathcal{R}$: namely, $v \in \mathcal{R}^*$ if conditions $v \leq u$ (component wise) and $u \in \mathcal{R}$ imply $u = v$. Clearly, $\mathcal{R}^*$ is a part of the outer boundary of $\mathcal{R}$. The subset $\mathcal{R}^{\text{cond}} \subseteq \mathcal{R}$ of elements $v \in \mathcal{R}$ satisfying conditions $\bar{R}_i^{\min} \leq v_i \leq \bar{R}_i^{\max}$ for all i, is also a convex closed bounded set.

The proof of Theorem 2 follows that in Reference [20], and it is given in Reference [31]. Theorem 2 says that if FSP is such that the vector of throughputs $r(t)$ converges to some vector $\bar{\boldsymbol{R}}^*$ as $t \to \infty$, then $\bar{\boldsymbol{R}}^*$ is necessarily a solution to the problem (P.1). This implies that if the user throughputs converge, then the corresponding stationary throughputs do in fact maximize the desired utility function, subject to the minimum rate constraints.

The token counter T_i provides the key mechanism trying to ensure that the active link i received (long term) service rate stays above $\bar{R}_i^{\min}$. The dynamics of the token counter process $T_i(k)$ (see Equation (18)) is briefly described and interpreted as follows. There is a virtual 'token queue' corresponding to each flow i. The tokens 'arrive in the (token) queue' (i.e., T_i is incremented) at the rate $\bar{R}_i^{\min}$ per slot. If active link i is served in slot k, then $R_i(k)$ tokens are 'removed from the queue' (i.e., T_i is decremented). Thus, if in a certain time interval, the average service rate of flow i is less than $\bar{R}_i^{\min}$, the token queue size T_i has 'positive drift,' and therefore, the chances of flow i being served in each time slot *gradually* increase. If the average service rate of flow i stays close to $\bar{R}_i^{\min}$, T_i will stay around zero and will not affect scheduling decisions.

The special cases of the MGMR algorithm (based on different choices of the utility function, $U(\bar{\mathbf{R}})$) include the following

(1) MPFMR algorithm: The multi-link proportional fair with minimum rate (MPFMR) algorithm corresponding to utility functions $U(\bar{\mathbf{R}}) = \sum_i \log(\bar{R}_i)$, and the scheduling rule is

$$\arg\max_{\boldsymbol{R}\in\mathcal{R}} \sum_i \mathrm{e}^{a_i T_i(k)} \frac{R_i(k)}{\bar{R}_i(k)} \tag{19}$$

(2) MMTMR algorithm: The multi-link maximum throughput with minimum rate (MMTMR) algorithm corresponding to utility functions $U(\bar{\mathbf{R}}) = \sum_i \bar{R}_i$, and the scheduling rule is

$$\arg\max_{\boldsymbol{R}\in\mathcal{R}} \sum_i \mathrm{e}^{a_i T_i(k)} R_i(k) \tag{20}$$

(3) MQRMR algorithm: The multi-link throughput optimal with minimum rate (MQRMR) algorithm corresponding to utility functions $U(\bar{\mathbf{R}}) = \sum_i Q_i \bar{R}_i$, where Q_i is the queue backlog at the transmitter of link i, and the scheduling rule is

$$\arg\max_{\boldsymbol{R}\in\mathcal{R}} \sum_i \mathrm{e}^{a_i T_i(k)} Q_i R_i(k) \tag{21}$$

In this study, we also considered a set of scheduling algorithms that solve a similar optimization problem as (P.1), however, *without* the minimum rate constraint (Equation (4)). The resulted special cases are

(1) MPF algorithm: The multi-link proportional fair (MPF) algorithm corresponding to utility functions $U(\bar{\mathbf{R}}) = \sum_i \log(\bar{R}_i)$, and the scheduling rule is

$$\arg\max_{\boldsymbol{R}\in\mathcal{R}} \sum_i \frac{R_i(k)}{\bar{R}_i(k)} \tag{22}$$

(2) MMT algorithm: The multi-link maximum throughput (MMT) algorithm corresponding to utility functions $U(\bar{\mathbf{R}}) = \sum_i \bar{R}_i$, and the scheduling rule is

$$\arg\max_{\mathbf{R}\in\mathcal{R}} \sum_i R_i(k) \tag{23}$$

(3) MQR algorithm: The multi-link throughput optimal (MQR) algorithm corresponding to utility functions $U(\bar{\mathbf{R}}) = \sum_i Q_i \bar{R}_i$, where Q_i is the queue backlog at the transmitter of link i, and the scheduling rule is

$$\arg\max_{\boldsymbol{R}\in\mathcal{R}} \sum_i Q_i R_i(k) \tag{24}$$

3.3. Low Complexity Approximations

In this part, we attempt to provide a greedy, low-complexity, approximate solution to the optimization problem (P.1) discussed before. The optimal solution needs to sort all the possible combinations of active links. In order to run the scheduler in real-time, low complexity approximations are needed. We hence propose the following simple scheduling scheme (greedy algorithms that rank active links by their respective measure) that may be more suitable for practical implementation.

3.3.1. Greedy algorithms

In each time slot

(1) Create a list by sorting active links in decreasing order of the measure v_i assuming no interference from other active links while computing R_i^0.
(2) Add active link j, in order starting from the top of the list, while maintaining and updating the value of $\Phi = \sum_{i\leq j} v_i$, where R_i now takes into account interference from all added active links.
(3) Stop if adding the next active link reduces Φ, and allow transmission of all added active links at their peak powers and rates as computed.

Table I. Scheduling algorithms for TD/CDMA wireless ad hoc networks.

		Throughput-optimal	Proportional fair
Multi-link algorithms	Without min rate	MQR	MPF
	With min rate	MQRMR	MPFMR
One-at-a-time algorithms	Without min rate	QR	PF
	With min rate	QRMR	PFMR
Implementation		Queue backlog needed	Average rate needed
Comments		Session rates maximized. No fairness considered	Take advantage of diversity and guarantee long-term fairness

The measure v_i for different algorithms are $v_i = \mathrm{e}^{a_i T_i} \frac{R_i^0}{\bar{R}_i}$, for MPFMR; $v_i = \mathrm{e}^{a_i T_i} R_i^0$, for MMTMR; $v_i = \mathrm{e}^{a_i T_i} Q_i R_i^0$, for MQRMR; $v_i = \frac{R_i^0}{\bar{R}_i}$, for MPF; $v_i = R_i^0$, for MMT; $v_i = Q_i R_i^0$, for MQR.

We also considered several algorithms that will serve *one* active link in each time slot. These algorithms serve as the lower bound for performance comparison.

3.3.2. One-at-a-time algorithms

Create a list by sorting active links in decreasing order of the measure v_i assuming no interference from other active links while computing R_i^0. Serve the top on the list. $v_i = \frac{R_i^0}{\bar{R}_i}$, for PF; $v_i = R_i^0$, for MT; $v_i = Q_i R_i^0$, for QR; $v_i = \mathrm{e}^{a_i T_i} \frac{R_i^0}{\bar{R}_i}$, for PFMR; $v_i = \mathrm{e}^{a_i T_i} R_i^0$, for MTMR; $v_i = \mathrm{e}^{a_i T_i} Q_i R_i^0$, for QRMR.

The various scheduling algorithms considered in this paper are summarized in Table I.

4. Performance Evaluation

One benchmark algorithm is the optimal (centralized) MGMR algorithm given in the previous section. It gives the best possible performance. Other benchmark algorithms are the one-at-a-time algorithms, which will serve as lower bounds. We will compare with these algorithms to evaluate the gains of different optimal/sub-optimal multi-link algorithms. Round Robin and fully simultaneous transmission are considered too far from optimal and perform very poorly in most of the cases, and are thus ignored here.

4.1. Simulation Setup

In order to quantify the performance gain by applying optimal/sub-optimal scheduling algorithms, discrete-event simulations using OPNET have been performed to evaluate them in multihop TD/CDMA wireless ad hoc networks. Networks of two types of topologies and corresponding routing configurations are tested, see Figures 2 (linear topology) and 3 (network with crossover traffic). It is assumed that routes are given for fixed destinations and marked with arrows in the Figures. There is one route (r_I) for destination node F in the linear network. There are three routes (r_{II}, r_{III}, and r_{IV}) for destination nodes L, J, K, respectively. The links on the routes are indexed with numerical numbers.

The routing setups represent important scenarios in multihop wireless ad hoc networks. The linear model is considered as the simplest case of relaying traffic sequentially and represents intra-cluster traffic to a fixed destination (cluster head). Figure 3 shows a general model where there are multiple data collection nodes such as cluster heads or data gathering gateways in wireless sensor networks.

In order to quantify the performance of different algorithms, all the nodes generate traffic such that the network is fully loaded, that is, each node will have enough data to transmit at any time slot. It is also assumed that the traffic sources are Poisson with different

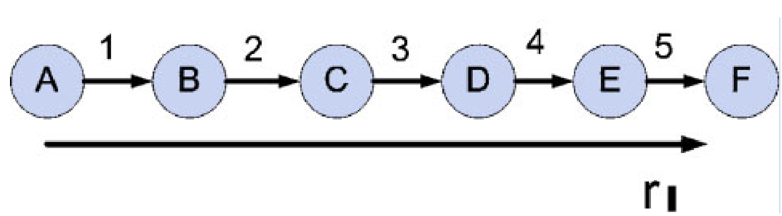

Fig. 2. A Linear TD/CDMA wireless ad hoc network.

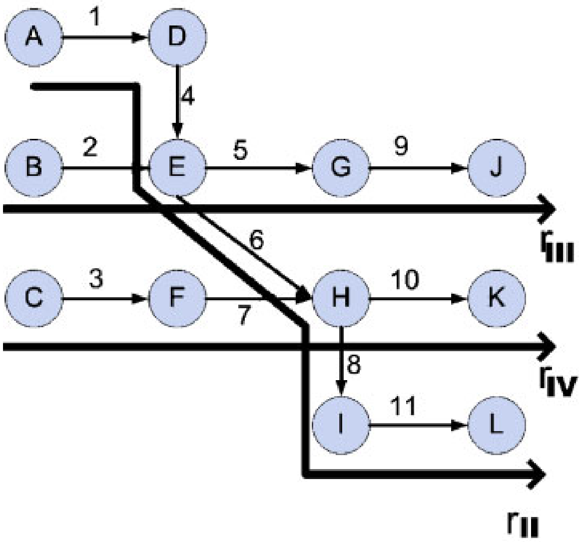

Fig. 3. A TD/CDMA wireless ad hoc network with crossover traffic.

inter-arrival time for different traffic sessions. Packet length is exponentially distributed with mean 1024 bits.

In this simulation study, we will use the time-averaged service rate as the criterion to compare different algorithms for fully loaded networks. Individual as well as total average rates are considered for comparison. It will quantify the traffic carrying capability of the entire network.

In order to measure the QoS-support capability for specific traffic sessions, we also define the *effective rate along a route/path* ($\bar{R}_r^{\text{eff}}$) as the minimum average rate among all the links in the path r, that is,

$$\bar{R}_r^{\text{eff}} = \min_{i \in r} \bar{R}_i. \tag{25}$$

Higher effective rate of a path implies higher QoS-support capability.

Four routes/paths are of interests here. There is route one (r_I) from node A to node F in the linear network, whereas there are three routes traversing through the network in Figure 3 with crossover traffic, namely, $r_{II} : A \rightarrow D \rightarrow E \rightarrow H \rightarrow I \rightarrow L$, $r_{III} : B \rightarrow E \rightarrow G \rightarrow J$, and $r_{IV} : C \rightarrow F \rightarrow H \rightarrow K$. Suppose there are each traffic session along each route, and their respective minimum rate requirements are $\bar{R}_I^{\min} = 160$ kbps, $\bar{R}_{II}^{\min} = 90$ kbps, $\bar{R}_{III}^{\min} = 190$ kbps, and $\bar{R}_{IV}^{\min} = 100$ kbps. The goal is to examine various algorithms and decide whether they could support the required minimum rate.

In the simulation, we further make the following assumptions:

(1) The scheduling decision is made by a central controller in every time slot. We use 1.6667 ms time slot as defined in 3G1xEV-DO (HDR) [32].
(2) It is assumed that the link gains have the following form

$$h_{ij}(k) = d_{ij}^{-4}(k) A_{ij}(k) B_{ij}(k) \tag{26}$$

where $d_{ij}(k)$ is the distance from the jth transmitter to the ith receiver at time instant k, A_{ij} is a log-normal distributed stochastic process (shadowing). B_{ij} is a fast fading factor (Rayleigh distributed).
(3) It is assumed that $d_{ij}(k)$ is a uniformly distributed random variable between 150 and 250 m.
(4) It is assumed that the standard deviation of A_{ij} is 8 dB [[33].
(5) It is assumed that the Doppler frequency is 8 Hz, corresponding to pedestrian mobile users [33].
(6) It is assumed that all users share 1.25 MHz bandwidth.
(7) It is assumed that the maximum allowable transmission power $p^{\max} = 200$ mW for all nodes.
(8) Simulation time = 40 000 slots.

In order to study the detailed behavior of each algorithm, the slot occupancy rate of each link i (η_i) is also an important quantity. It is defined as the percentage of slots assigned to link i. Note that in Multi-link algorithms, one slot may be assigned to multiple links simultaneously.

4.2. Linear Network

The results of the linear network are summarized in Table II. We observe that the throughput-optimal family of algorithms (QR, MQR, MQRMR) have achieved better effective rates ($\bar{R}_{r_I}^{\text{eff}}$) than that of the proportional fair family of algorithms (PF, MPF, PFMR, MPFMR) for a single traffic session. In general, the

Table II. Effective rate and total average rate (both in kbps) in the linear network.

Algorithms	$\bar{R}_{r_I}^{\text{eff}}$	$\bar{\boldsymbol{R}}$	support $\bar{R}_I^{\min} = 160$ kbps?
PF	95.5	314.1	No
MPF (G)	123.7	436.1	No
PFMR	155.8	204.2	No
MPFMR (G)	170.1	301.2	Yes
QR	261.9	272	Yes
MQR (G)	266.6	279.8	Yes
MQR (O)	268.2	281.2	Yes
MQRMR (G)	245.3	262.2	Yes
MMTMR (G)	186.9	474.5	Yes

(G), Greedy algorithm; (O), Optimal algorithm.

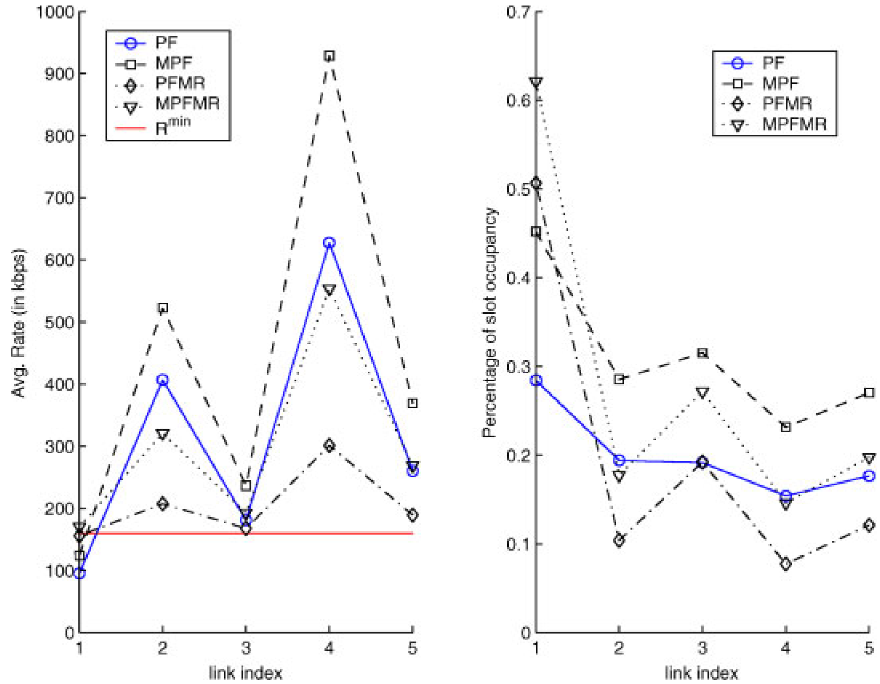

Fig. 4. Comparison of PF-family of algorithms in a linear TD/CDMA wireless ad hoc network.

throughput-optimal family of algorithms tend to balance the average rate along each traffic session/flow as long as the system is feasible because the optimization criterion (network utility function) address the queue backlog together with the average data rate. On the other hand, the proportional fair family of algorithms try to assign each link similar amount of slots (in the long-term) and thus, will not balance the average rate along the routes. However, they tend to achieve higher total average data rate ($\bar{\mathbf{R}}$) because they take advantage of the wireless channel fluctuations and give more slots to links with better channel quality than that of the throughput-optimal family of algorithms.

We also observe that the multi-link algorithms outperform the one-at-a-time counterparts as expected. For example, the MPF outperform PF 30% in effective rate and 39% in total average rate, respectively. The results also show that the greedy algorithm (for example, MQR (G)) performs very closely to the optimal algorithm (MQR (O)).

The proposed token counter mechanism helps to lift the minimum rate, and hence the effective rate. PFMR has lifted the minimum rate from PF's 95.5 kbps to 155.8 kbps, while MPFMR has lifted the minimum rate from MPF's 123.7 kbps to 170.1 kbps. Of course, this is achieved by assigning more slots to links that violate the minimum rate constraints. As a result, the links that may get higher service rates will be assigned less slots, which result in lower total average data rate. This effect can be better observed in Figure 4.

In Figure 4, the average rate (in kbps) and percentage of slot occupancy of all five links in the linear network are plotted when PF-family of algorithms are employed. It is clear that multi-link algorithms (MPF and MPFMR) outperform their one-at-a-time counterpart (PF and PFMR) by allowing multiple links transmit at the same slot. The plot also show that link 1 needs help to achieve the minimum rate. PFMR and MPFMR use the token counter mechanism to assign more slots to link 1 than PF and MPF, from 29% to 51% and from 45% to 62%, respectively. As a result, other links will receive less slots assignments and thus less average rates.

Figure 5 shows the average rate (in kbps) and percentage of slot occupancy of all five links in the linear network when throughput-optimal family of algorithms are employed. They tend to balance the average rate along the route as discussed before.

4.3. Network With Balanced Crossover Traffic

The simulations of network with crossover traffic reveals similar observations as those obtained in the linear network. Figures 6 and 7 show the average rate (in kbps) of all the links along each of the three routes of the PF-family of algorithms and the

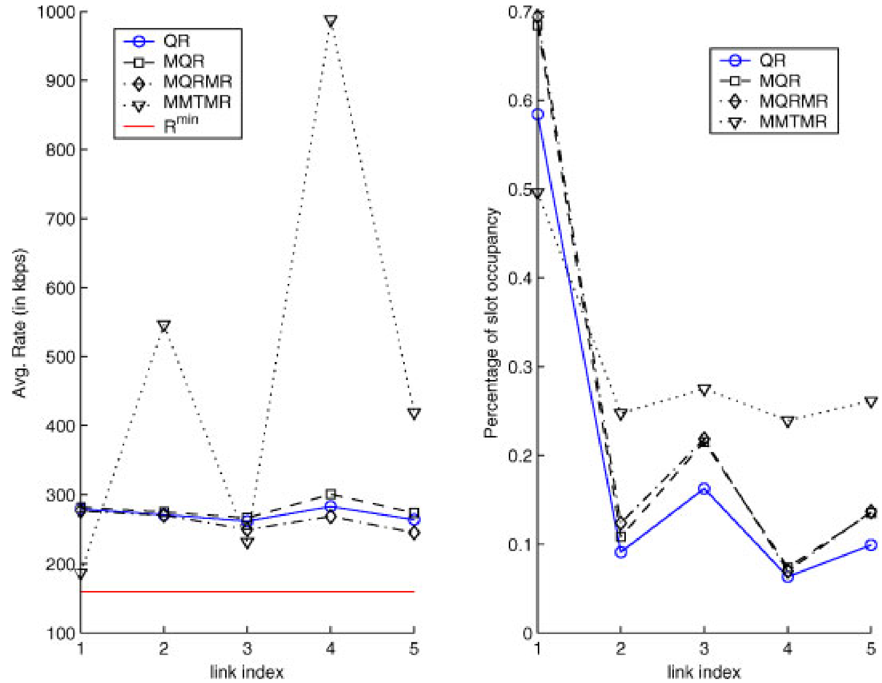

Fig. 5. Comparison of throughput-optimal family of algorithms in a linear TD/CDMA wireless ad hoc network.

throughput-optimal family of algorithms, respectively. As long as the network load is feasible, the throughput-optimal family of algorithms provide higher effective rate than the PF-family of algorithms. On the other hand, the PF-family of algorithms provide higher total average rate than the throughput-optimal family of algorithms. Note that if the total average rate is the only concern, then the MMT and MMTMR algorithms

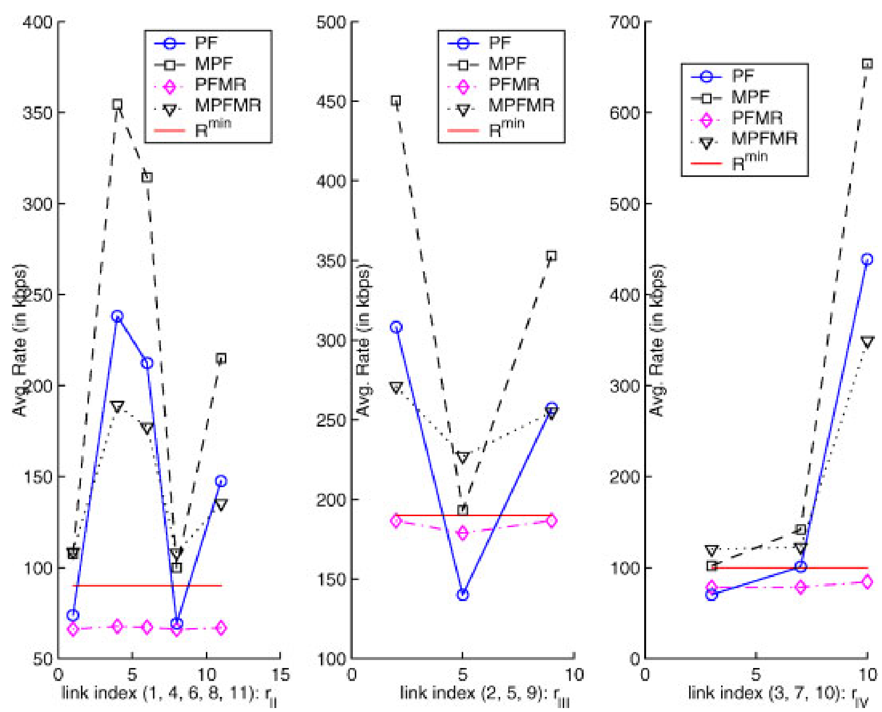

Fig. 6. Comparison of PF-family of algorithms with balanced crossover traffic sessions.

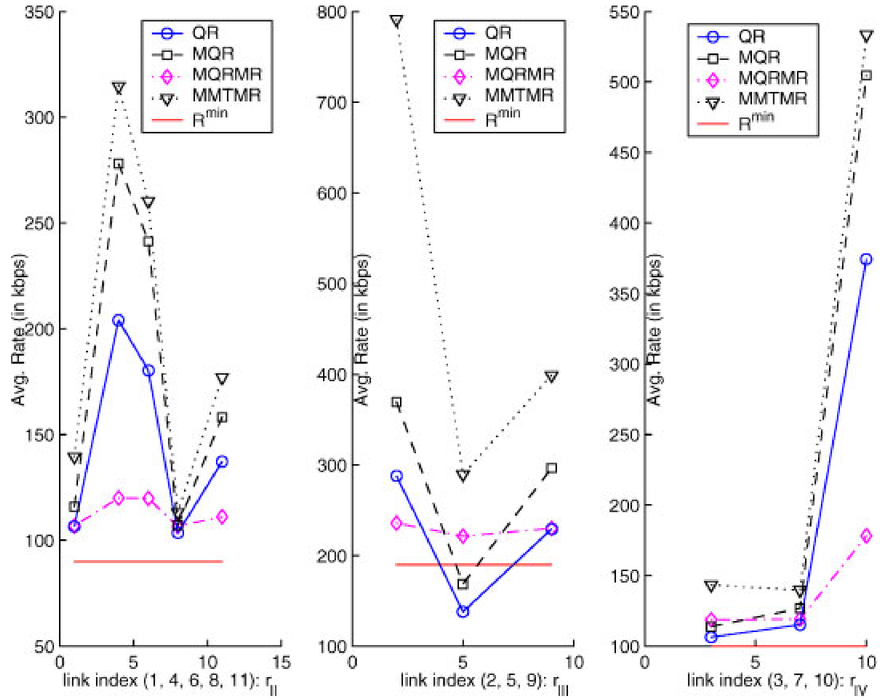

Fig. 7. Comparison of throughput-optimal family of algorithms with balanced crossover traffic sessions.

should be used. However, these algorithms consider neither queue occupancy nor fairness among nodes.

In order to verify the feasibility of the network load, all the queues at all the nodes have to be bounded. A sample of the queue occupancy of all five nodes along r_{II} using algorithms MQR in the network with crossover traffic is given in Figure 8. All queue lengths are bounded below 10^5 bits through the entire

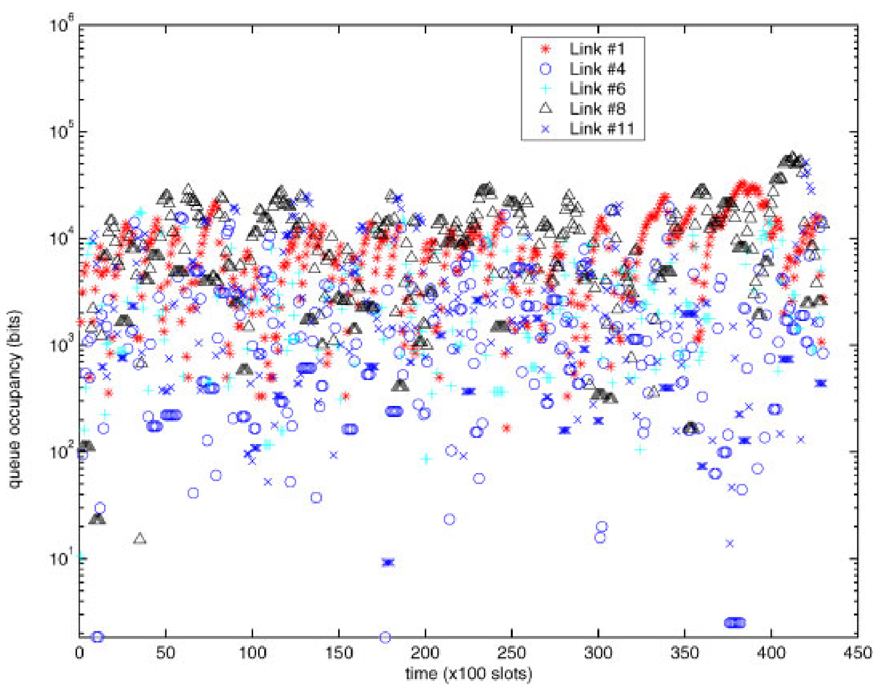

Fig. 8. Queue occupancy of all links of r_{II} using algorithms MQR in a TD/CDMA wireless ad hoc network with crossover traffic.

simulation, which demonstrate the feasibility of the network load and the throughput-optimal nature of the MQR algorithm.

4.4. Network With Unbalanced Crossover Traffic

The above experiments show that the throughput-optimal family of algorithms outperforms the PF-family of algorithms in terms of effective rate of traffic sessions. However, it is noticeable that the throughput-optimal family of algorithms provide no fairness among the nodes, and thus may have serious unhealthy behavior when some malicious nodes take advantage of that and send large amount of data into the network.

A simple example is created to demonstrate this damaging effect. Instead of balanced traffic loads along the three routes (r_{II}, r_{III}, and r_{IV}), node A injected a lot of traffic into the network, to be exact, an order of magnitude higher than the other traffic sessions. The results are listed in Table III. It is obvious that because no fairness has been considered by the throughput-optimal family of algorithms, they perform poorly with the effective rate of r_{III} and r_{IV} far below the required minimum rate. On the other hand, the PF-family of algorithms still provides required minimum rate for all the traffic sessions and suppresses the disturbance caused by the malicious node. All the multi-link PF-family of algorithms are able to support all the minimum rate requirements. However, in the throughput-optimal family of algorithms, only MQRMR is able to support all the minimum rate requirements because of the token counter mechanism. This result also indicates that the token counter mechanism indeed can help maintain the fair share of the traffic sessions specified by their minimum rate requirements.

Table III. Effective rates of route II, III and IV and total average rate (all in kbps) in the network with unbalanced traffic.

Algorithms	$\bar{R}^{\text{eff}}_{r_{II}}$	$\bar{R}^{\text{eff}}_{r_{III}}$	$\bar{R}^{\text{eff}}_{r_{IV}}$	$\bar{\boldsymbol{R}}$	Support $\bar{R}^{\min}_{II}$, $\bar{R}^{\min}_{III}$, $\bar{R}^{\min}_{IV}$?
PF	69.4	140.1	70.3	187.1	No
MPF (G)	101.8	191.8	101.1	271.6	Yes
PFMR	66.1	179.1	78.5	102.5	No
MPFMR (G)	108.9	226.2	122.3	188.3	Yes
QR	277.2	58.1	30.7	233.3	No
MQR (G)	371.3	66.4	44.9	256.9	No
MQRMR (G)	106.9	220.8	117.1	170.2	Yes
MMTMR (G)	150.2	281.7	135.5	303.9	Yes

(G), Greedy algorithm.

5. Implementation Issues

The centralized solution needs a central controller and *global* information of all the link gains. It may be implemented, for example, in a clustered wireless ad hoc network with 'strong' cluster heads where centralized control is not far-fetched. However, it is very difficult to obtain the knowledge of all the link gains in many other cases and thus, it is impractical to implement a centralized solution.

5.1. Distributed Implementation

A distributed implementation is proposed in this section where only local information is used to perform the power control and scheduling decisions at each transmitting node individually. At the start of each time slot, neighboring nodes will exchange information using control/signaling channel. The procedures are as follows:

(1) At the beginning of each time slot, each node i in the potential transmitter set $\mathcal{S}$ select to transmit or not by flipping a coin. (This is motivated by the work of References [14] and [34].)
(2) Each node that decide to transmit will send a probe packet using power equal to the maximum transmission power $p^{\max}$.
(3) Each receiver detects the probe packets from all transmitting nodes nearby, and estimates the corresponding channel gain. The receiver then sends a packet including information of all the estimated link gains using power equal to the maximum transmission power $p^{\max}$.
(4) Each node i in the potential transmitter set S detects the packets from the receivers within its transmission range. From each of these receivers, node i obtains the list of all possible interfering transmitters and their link gains toward the receiver.
(5) Each node i in the potential transmitter set $\mathcal{S}$ will transmit to one of the neighboring receivers where v_i (e.g., $v_i = R_i/\bar{R}_i$ for MPF) is maximized.
(6) Update the token counter according to Equation (18) for the algorithms using the token counter mechanism.

Note that each node need to keep a table of all the token queue length (for MGMR algorithms) and average rate for all outgoing active links.

5.2. Simulation Results

In this simulation study, only local information is available to each node by exchanging control messages with

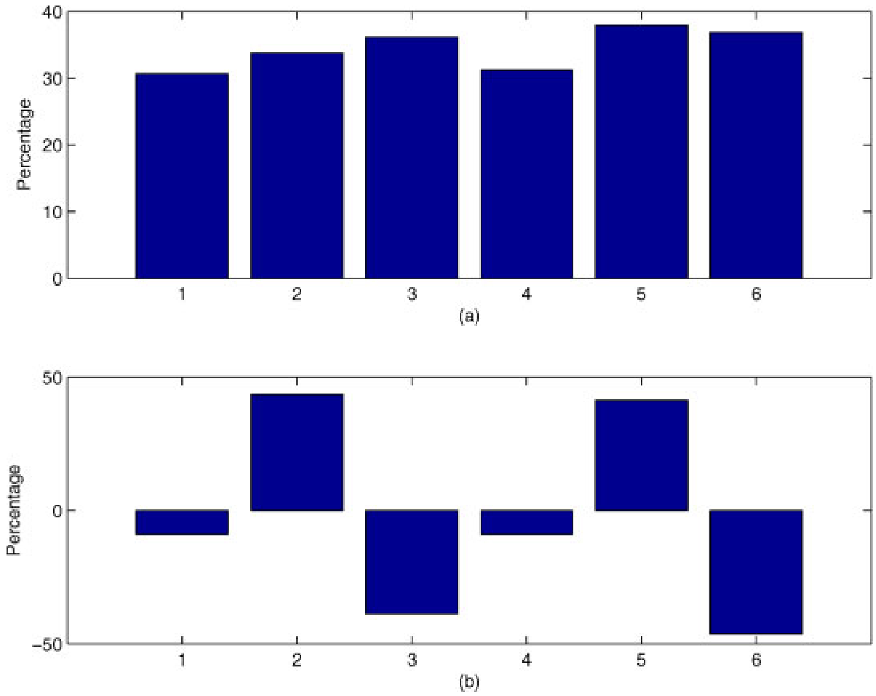

Fig. 9. Gain/loss of distributed algorithms over their centralized counterparts: (a) Total average rate, (b) Effective rate. 1, MPFMR (r_{II}); 2, MQRMR (r_{II}); 3, MPFMR (r_{III}); 4, MQRMR (r_{III}); 5, MPFMR (r_{IV}); 6, MQRMR (r_{IV}).

its neighbors as described above. The overhead of the information exchange includes a 1-byte (8 bits) probe packet and the reply from the receiver (which may contain multiple bytes). The exact size of the reply depends on the number of probes that the receiver get. Each link gain in the reply is counted as 1 byte assuming that the link gain is quantized using a 256-level quantizer. The other parameters of the simulation are the same as in Section 4. MPFMR and MQRMR algorithms are selected for comparison in the network with balanced crossover traffic.

The percentage of rate gain/loss of distributed algorithms over their centralized counterparts is shown in Figure 9. The experiment reveals somewhat surprising results. The total average rate achieved by the distributed algorithms is about 30% higher than their centralized counterparts in spite of lack of centralized control and global information. This surprising result is mainly due to the greedy nature of local decisions made by each transmitting node. Because there is no global information about queue backlogs or average rate, neither throughput-optimal nor fairness can be guaranteed in the distributed algorithm. The same greedy nature of local decisions also results in the reductions in most of the effective rates. The centralized algorithm still outperforms the distributed schemes in terms of the minimum rate requirements (which is not directly shown in Figure 9). The goal of the scheduling is not just maximize the utilities, but also satisfy *all* minimum rate constraints. In this specific scenario, route II contains links with good channel conditions whereas route III and route IV need help to satisfy the minimum rate constraints along the routes. The centralized MPFMR and MQRMR are able to satisfy all minimum rate requirements. The distributed algorithms perform poorly in this respect, the effective rate along route III (MPFMR) and the effective rate along route IV (MQRMR) are far below requirements. Of course, the total average rates gain due to the sacrifice in effective rates.

The overhead in all the cases is roughly the same 16%. This simple experiment demonstrates that the proposed distributed implementation achieves acceptable performance (in terms of total average rate and effective rate comparing to the corresponding centralized algorithms) while keeps the overhead low.

6. Conclusions

In this paper, the joint power control and scheduling problem for TD/CDMA wireless ad hoc networks is formulated using a utility function approach. Because the resulted optimal power control reveals bang-bang characteristics, that is, scheduled nodes transmit with full power while other nodes remain silent, the joint power control and scheduling problem is reduced to a scheduling problem. The MGMR is proposed to solve the constrained optimization problem (P.1). Two special cases of MGMR are highlighted, namely, the multi-link version of the throughput-optimal and the proportional fair algorithms with a generic token counter mechanism to satisfy the minimum rate requirements. By ensuring different minimum rate for different traffic sessions, service differentiation is also achieved.

If there is an admission control in the network to monitor different traffic sessions and prevent malicious nodes to occupy the network capacity, the throughput-optimal family of algorithms will be ideal for maximizing session rates. However, such an admission control mechanism may be very difficult to implement in reality, thus the PF-family of algorithms will be desirable to distribute the network resources fairly.

Note that the MGMR algorithm may be modified to accommodate the maximum data rate constraints, by modifying the way that the token counter updated. The token counter T_i is updated as follows:

$$T_i(k+1) = T_i(k) + \bar{R}_i^{\text{token}} - R_i(k) \qquad (27)$$

where $\bar{R}_i^{token} = \bar{R}_i^{\min}$ if $T_i(k) \geq 0$, and $\bar{R}_i^{\text{token}} = \bar{R}_i^{\max}$ if $T_i(k) < 0$. If $\bar{R}_i^{\max} = \infty$ for some i, the token counter update rule becomes Equation (18). If $\bar{R}_i^{\min} = 0$ for some i, the rule is simplified for this i to:

$$T_i(k+1) = \min\{0, T_i(k) + \bar{R}_i^{\max} - R_i(k)\} \qquad (28)$$

Maximum data rate constraints may be necessary for mobile device that has limited memory for buffering.

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Authors' Biographies

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