Power Control and Proportional Fair Scheduling with Minimum Rate Constraints in Clustered Multihop TD/CDMA Wireless Ad Hoc Networks

Lijun Qian, Ning Song and Dhadesugoor R. Vaman
CeBCom Research Center
Prairie View A&M University
Prairie View, Texas 77446
Email: liqian, nsong, drvaman@pvamu.edu

Xiangfang Li and Zoran Gajic
WINLAB
Rutgers University
Piscataway, NJ 08854
Email: xfli, gajic@winlab.rutgers.edu

***Abstract*— 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. Because the resulted optimal power control reveals bang-bang characteristics, i.e., scheduled nodes transmit with full power while other nodes remain silent, the joint power control and scheduling problem is reduced to a scheduling problem. In order to achieve a balance between throughput and fairness, proportional fair scheduling is considered. The multi-link version of 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. 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.**

I. 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 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. Due to their poor scalability in a multihop ad hoc network, random access protocols are not an efficient solution [5]. In [4], it is demonstrated that CDMA-based MAC protocols achieves 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 TD/CDMA is chosen as the medium access scheme. Each user/node is assigned a randomly generated orthogonal code. On top of that, time is splited 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 a 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 Fig 1. One of the clusters is shown with cluster head CH. It is assumed that the intra-cluster route is given for a traffic session: $r_I = A \rightarrow B \rightarrow C \rightarrow D \rightarrow CH$. Data traffic is forwarded in a multihop fashion. Fig 1 also shows a possible 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 [6]. 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 and has additional functions of reducing unnecessary interference among concurrent transmissions in TD/CDMA based systems [8]. Power control and scheduling

1-4244-0270-0/06/$20.00 (c)2006 IEEE
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.

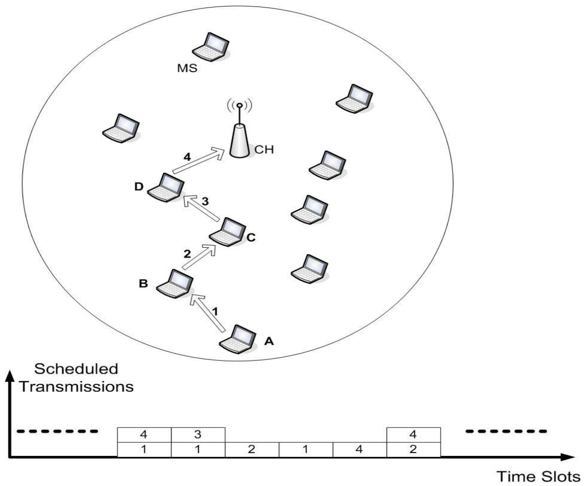

Fig. 1. A Clustered TD/CDMA wireless ad hoc network. CH: cluster head.

is of paramount importance of ensuring the success of multiple simultaneous transmissions and is the focus of this paper. The goal is to study power control and proportional fair scheduling schemes that maximize network utility, maintain fairness among links and guarantee minimum rate of traffic 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 II presents an overview of the works that are closely related to our problem. Section III states the wireless network model and formulate 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 IV. Distributed schemes and other various implementation issues are discussed in Section V. Section VI contains the concluding remarks.

II. Related Works

A power control and scheduling problem has been solved in [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 [14]. However, a simplified interference model is adopted, where no interference is assumed among different links. In [7], 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 [9] 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 panelty function approach are suggested to maximize the utility function while guarantee minimum and maximum link data rates. The algorithm in [9] focused on a *snapshot* of a set of wireless links. Another work on *instantaneous* power control in wireless ad hoc networks is [8]. 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 [13]. 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. As pointed out in [23], 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 [13]. In this paper, a family of proportional fair scheduling algorithms are considered to maintain fairness among nodes and take advantage of wireless channel fluctuations. Furthermore, a token counter mechanism is introduced to maintain minimum rate of traffic flows whenever feasible. A distributed approximation is also proposed in [13] 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 [13], 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.

III. 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 i^{th} receiver from the i^{th} transmitter (received SIR of the i^{th} active link) is defined by

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

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, i.e., 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 i^{th} 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 approoximated in most practical scenarios [16].

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.

A. Problem Formulation

In this work, we will focus on end-to-end traffic sessions with minimum rate constraints. 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 [22].
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, let's define the long-term average rate vector $\bar{\mathbf{R}} = (\bar{R}_1, \ldots, \bar{R}_N)$ 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)

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

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. $\mathcal{P}$ is the set of allowable power vector defined by

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

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

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

where each $U_i(x)$ is an increasing concave continuously differentiable function defined for $x \geq 0$. In this work, the network utility function is chosen as $U(\bar{\mathbf{R}}) = \sum_i \log(\bar{R}_i)$ to achieve the balance between network throughput and fairness.

B. Centralized Solution

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

1) Optimal Power Control:

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

The proof can be found in [23]. Note that similar observations are obtained under various different contexts and assumptions [13], [7], [11]. Specifically, the results reported in [7] 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.

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. The scheduling algorithm considered in this paper is the proportional fair scheduling proposed in [17], [18] and further analyzed in [19], [20]. Proportional Fair (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). As pointed out in [21], PF scheduling maintains a balance between fairness and efficiency. However, since PF schedules users one-at-a-time, it needs to be modified for a multihop scenario.

In this paper, we are interested in proposing and studying the multi-link version of the PF algorithms for multihop wireless ad hoc networks, called Multi-link Proportional Fair (MPF). We are particularly interested in their modified versions that accommodate QoS constraints required by multiple traffic sessions. MPF is modified to satisfy minimum rate constraints using a token counter mechanism inspired by the scheme developed for cellular systems [12], thus it is named Multi-link Proportional Fair with Minimum Rate (MPFMR).

MPFMR: *In a time slot k, select the active links*

$$\arg\max_{i \in \mathcal{S}} \sum_i e^{a_i T_i(k)} \frac{R_i(k)}{\bar{R}_i(k)} \ , \tag{7}$$

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 Proportional Fair algorithm [17], [18]:

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

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:

$$T_i(k+1) = \max\{0, T_i(k) + \bar{R}_i^{\,min} - R_i(k)\} \ . \tag{8}$$

The proof follows our previous work in [12], and is given in [23]. 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 (8)) 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.

In this study, we also considered PF scheduling without minimum rate constraint (**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

$$\arg\max_{i \in \mathcal{S}} \sum_i \frac{R_i(k)}{\bar{R}_i(k)} \ . \tag{9}$$

		Proportional Fair
Multi-Link Algorithms	without Min Rate	MPF
	with Min Rate	MPFMR
One-at-a-time Algorithms	without Min Rate	PF
	with Min Rate	PFMR
Implementation		Average rate needed
Comments		Take advantage of diversity and guarantee long-term fairness.

TABLE I

SCHEDULING ALGORITHMS FOR TD/CDMA WIRELESS AD HOC NETWORKS.

C. 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.

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 $\Phi = \sum_{i \le j} v_i$, 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.

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

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.

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;
$v_i = e^{a_i T_i} \frac{R_i^0}{\bar{R}_i}$, for PFMR.
The various scheduling algorithms considered in this paper are summarized in Table I.

IV. PERFORMANCE EVALUATION

One benchmark algorithm is the optimal (centralized) MPFMR 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

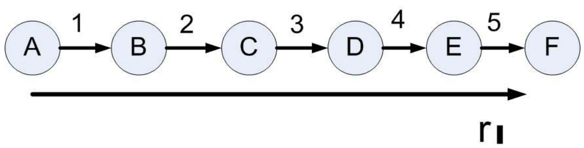

Fig. 2. A Linear TD/CDMA wireless Ad-hoc network

Algorithms	$\bar{R}_{r_I}^{eff}$	$\bar{\mathbf{R}}$	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

TABLE II

EFFECTIVE RATE AND TOTAL AVERAGE RATE (BOTH IN KBPS) IN THE LINEAR NETWORK. (G):GREEDY ALGORITHM

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.

A. 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. A network of chain topology and the corresponding intra-cluster routing configuration is given, see Fig. 2. It is assumed that routes are given for fixed destinations and marked with arrows in the Figure. There is one route (r_I) for destination node F in the linear network. 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 simpliest case of relaying traffic sequentially and represents intra-cluster traffic to a fixed destination (cluster head).

In order to quantify the performance of different algorithms, all the nodes generate traffic such that the network is fully loaded, i.e., each node will have enough data to transmit at any time slot. It is also assumed that the traffic sources are Poisson with different 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* ($\bar{R}_r^{eff}$) as the minimum average rate among all the links in the path r, i.e.,

$$\bar{R}_r^{eff} = \min_{i \in r} \bar{R}_i \tag{10}$$

Higher effective rate of a path implies higher QoS-support capability. The minimum rate requirement is $\bar{R}_I^{min} = 160$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 the cluster head (node F) in every time slot. We use 1.6667 msec time slot as defined in 3G1xEV-DO (HDR) [25].
2) It is assumed that the link gains have the following form
$$h_{ij}(k) = d_{ij}^{-4}(k) A_{ij}(k) B_{ij}(k) \tag{11}$$
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 meters.
4) It is assumed that the standard deviation of A_{ij} is 8 dB [24].
5) It is assumed that the Doppler frequency is 8 Hz, corresponding to pedestrian mobile users [24].
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.

B. Linear Network

The results of the linear network are summarized in Table II and Fig 3. We observe that the proportional fair family of algorithms maintain fairness among links by assigning each link similar amount of slots in the long-term. Thus they will not balance the average rate along the routes. However, they tend to achieve higher total average data rate ($\bar{\mathbf{R}}$) because they are channel-aware. In other words, they take advantage of the wireless channel fluctuations and assign slots to links with relatively better channel quality.

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 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 Fig 3.

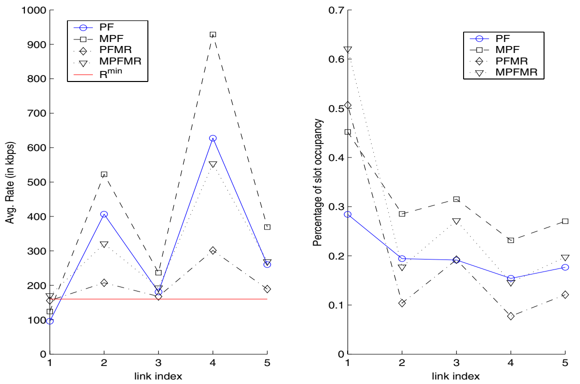

Fig. 3. Comparison of PF-family of algorithms in a linear TD/CDMA wireless ad-hoc network

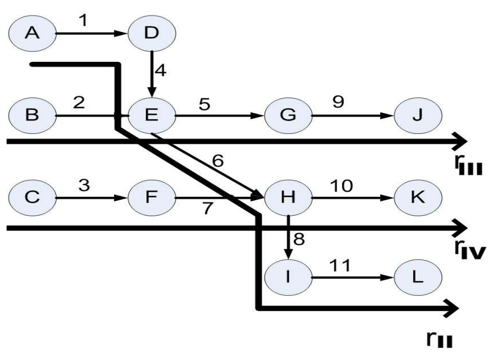

Fig. 4. A TD/CDMA wireless Ad-hoc network with Crossover Traffic

In Fig 3, 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.

C. Network with Unbalanced Crossover Traffic

In this part of the simulation, there are three routes traversing through the network in Fig. 4 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 $\bar{R}^{min}_{II} = 90$kbps, $\bar{R}^{min}_{III} = 190$kbps and $\bar{R}^{min}_{IV} = 100$kbps. 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 performance (especially fairness) of the proposed PF-family of algorithms will be tested against malicious node under multiple traffic sessions.

Algorithms	$\bar{R}^{eff}_{r_{II}}$	$\bar{R}^{eff}_{r_{III}}$	$\bar{R}^{eff}_{r_{IV}}$	$\bar{\mathbf{R}}$	satisfy min rates ?
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

TABLE III

EFFECTIVE RATES OF ROUTE II, III AND IV AND TOTAL AVERAGE RATE (ALL IN KBPS) IN THE NETWORK WITH UNBALANCED TRAFFIC. (G):GREEDY ALGORITHM.

Another family of scheduling algorithms, namely, the throughput-optimal family of algorithms [26], [27], are used for comparison purposes. These algorithms maximize a weighted sum of user rates and have provable stability properties shown in much previous work in various contexts involving data scheduling and resource allocation. Two versions of this type of algorithms that guarantees *queue stability* are used here. The QR algorithm is a one-at-a-time scheduling algorithm and the scheduling rule is

$$\arg\max_{i \in \mathcal{S}} Q_i R_i(k) \ . \qquad (12)$$

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

$$\arg\max_{i \in \mathcal{S}} \sum_i Q_i R_i(k) \ . \qquad (13)$$

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. The malicious node A (traffic session r_{II}) grab most of the slots. On the other hand, the PF-family of algorithms still provide required minimum rate for all the traffic sessions and surpress the disturbance caused by the malicious node. The multi-link gains are significant, 45.2% for MPF and 84.4% for MPFMR, respectively. All the multi-link PF-family of algorithms are able to support all the minimum rate requirements.

V. DISTRIBUTED IMPLEMENTATION

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.

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:

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.

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 [15] and [13].)
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 estimate 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 (for example, $v_i = R_i/\bar{R}_i$ for MPF) is maximized.
6) Update the token counter according to equation (8) for the algorithms using the token counter mechanism.

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

VI. 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, i.e., 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 Proportional Fair scheduling algorithm with Minimum Rate constraints (MPFMR) is proposed to solve the constrained optimization problem **(P.1)**. A generic token counter mechanism is employed to satisfy the minimum rate requirements. Note that by ensuring different minimum rate for different traffic sessions, service differentiation can also be achieved. Some preliminary simulation results of the distributed implementation are given in [23], more extensive experiments are on the way.

ACKNOWLEDGMENT

The authors would like to thank OPNET Technologies, Inc. for providing the OPNET software. This research work is supported in part by the U.S. Army Research Laboratory under Cooperative Agreement No. W911NF-04-2-0054. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.

REFERENCES

[1] H. Hassanein and A. Safwat, "Virtual base stations for wireless mobile ad hoc communications: an infrastructure for the infrastructure-less," *International Journal of Commun. Syst.*, vol.14, pp.763-782, 2001.

[2] C.R. Lin and M. Gerla, "Adaptive Clustering for Mobile Wireless Networks," *IEEE Journal on Selected Areas of Communications*, vol.15, no.9, pp.1265-1275, Sep 1997.

[3] R. Ramanathan and M. Steenstrup, "Hierarchically-organized, Multihop Mobile Wireless Networks for Quality-of-Service Support," *Mobile Networks and Applications*, vol.3, no.1, pp.101-119, 1998.

[4] A. Muqattash and M. Krunz, "CDMA-Based MAC Protocol for Wireless Ad Hoc Networks," *Proc. of MobiHoc'03*, pp.153-164, Annapolis, MD, 2003.

[5] S. Xu and T. Sandawi. "Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?," *IEEE Communications Magazine*, pp.130-137, Jun 2001.

[6] V. Kawadia and P. R. Kumar, "Power Control and Clustering in Ad Hoc Networks," *Proc. of IEEE INFOCOM*, pp.459-469, 2003.

[7] R.L. Cruz and A. Santhanam, "Optimal Routing, Link Scheduling and Power Control in Multi-hop Wireless Networks," *Proc. of IEEE INFOCOM*, pp.702-711, 2003.

[8] T. ElBatt and A. Ephremides, "Joint Scheduling and Power Control for Wireless Ad-hoc Networks," *Proc. of IEEE INFOCOM*, pp.976-984, 2002.

[9] J. Fang and R. Rao, "An Integrated and Distributed Scheduling and Power Control Algorithm for Maximizing Network Utility for Wireless Multihop Networks," *Proc. of IEEE MILCOM*, 2003.

[10] U.C. Kozat, I. Koutsopoulos and L. Tassiulas, "A Framework for Cross-Layer Design of Energy-Efficient Communication with QoS Provisioning in multihop Wireless Networks," *Proc. of IEEE INFOCOM*, 2004.

[11] K. Kumaran and L. Qian, "Uplink Scheduling in CDMA Packet-Data Systems," *Proc. of IEEE INFOCOM*, Vol.1, pp.292-300, San Francisco, Apr 2003.

[12] M. Andrews, L. Qian and A. Stolyar, "Optimal Utility Based Multi-User Throughput Allocation subject to Throughput Constraints," *Proc. of IEEE INFOCOM*, Miami, March 2005.

[13] M. Neely, E. Modiano, and C. Rohrs, "Dynamic Power Allocation and Routing for Time Varying Wireless Networks," *Proc. of IEEE INFOCOM*, pp.745-755, 2003.

[14] R. Bhatia and M. Kodialam, "On Power Efficient Communication over multihop Wireless Networks: Joint Routing, Scheduling and Power Control," *Proc. of IEEE INFOCOM*, 2004.

[15] M. Grossglauser and D. Tse, "Mobility Increases the Capacity of Ad-hoc Wireless Networks," *Proc. of IEEE INFOCOM*, 2001.

[16] R. Berry and E. Yeh, "Cross-Layer Wireless Resource Allocation," *IEEE Signal Processing Magazine*, pp.59-68, Sep 2004.

[17] A.Jalali, R.Padovani, and R.Pankaj, "Data Throughput of CDMA-HDR, a High Efficiency - High Data Rate Personal Communication Wireless System," In *Proc. of the IEEE Semiannual Vehicular Technology Conference, VTC2000-Spring,* Tokyo, Japan, May 2000.

[18] P. Viswanath, D. Tse and R. Laroia, "Opportunistic Beamforming using Dumb Antennas," *IEEE Transactions on Information Theory*, 48(6), 2002.

[19] S. Borst, "User-level performance of channel-aware scheduling algorithms in wireless data networks," *Proc. of IEEE INFOCOM*, San Francisco, CA, April 2003.

[20] H. Kushner, P. Whiting, "Asymptotic Properties of Proportional Fair Sharing Algorithms," *Proc. of the 40th Annual Allerton Conference on Communication, Control, and Computing.* Monticello, Illinois, USA, October 2002.

[21] L. Jiang and S. Liew, "Proportional Fairness in Wireless LANs and Ad Hoc Networks," *Proc. of IEEE WCNC*, New Orleans, LA, 2005.

[22] R. Chakravorty, S. Katti, I. Pratt and J. Crowcroft, "Flow aggregation for enhanced TCP over wide area wireless," In *Proc. of IEEE INFOCOM*, 2003.

[23] L. Qian and D.R. Vaman, "Joint Power Control and Scheduling for TD/CDMA Multi-hop Wireless Ad Hoc Networks," *Technical Report*, CeBCom Research Center, Prairie View, TX, 2005.

[24] G. Stüber, *Principles of Mobile Communication*, Kluwer Academic Publishers, 2nd Ed. 2001.

[25] *3GPP2 Standard*, see http://www.3gpp2.org

[26] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, and P. Whiting, "Providing quality of service over a shared wireless link," *IEEE Comm. Magazine*, vol. 39, no. 2, pp.150154, 2001.

[27] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling for maximum throughput in multihop radio networks," *IEEE Transactions on Automatic Control*, vol.37, no.12, pp.1936-1949, Dec 1992.