Joint Scheduling and Power Control for Wireless Ad-hoc Networks

Tamer ElBatt
Network Analysis and Systems Dept.
HRL Laboratories, LLC
Malibu, CA 90265, USA
telbatt@wins.hrl.com

Anthony Ephremides
Electrical and Computer Engineering Dept.
University of Maryland
College Park, MD 20742, USA
tony@eng.umd.edu

Abstract— **In this paper we introduce power control as a solution to the multiple access problem in contention-based wireless ad-hoc networks. The motivation for this study is two fold, limiting multi-user interference to increase single-hop throughput, and reducing power consumption to increase battery life. We focus on next neighbor transmissions where nodes are required to send information packets to their respective receivers subject to a constraint on the signal-to-interference-and-noise ratio. The multiple access problem is solved via two alternating phases, namely scheduling and power control. The scheduling algorithm is essential to coordinate the transmissions of independent users in order to eliminate strong interference (*e.g. self-interference*) that can not be overcome by power control. On the other hand, power control is executed in a distributed fashion to determine the admissible power vector, if one exists, that can be used by the scheduled users to satisfy their single-hop transmission requirements. This is done for two types of networks, namely TDMA and TDMA/CDMA wireless ad-hoc networks.**

I. Introduction

It is well known that power is a precious resource in wireless networks due to the limited battery life. This is further aggravated in ad-hoc networks since all nodes are mobile terminals of limited weight and size. In addition, power control is of paramount importance to limit multi-user interference and, hence, maximize the number of simultaneous single-hop transmissions [1].

Power control has been studied extensively in the context of cellular radio systems, both channelized [2], [4] and CDMA-based [7], [8]. Distributed iterative power control algorithms have been introduced for cellular systems and convergence results have been established [2], [4], [7]. Our main objective in this paper is to develop a power control based multiple access algorithm for contention-based wireless ad-hoc networks. This is done via investigating the similarities and differences of this problem from the problem solved earlier for cellular networks. The concept of controlling the transmission radii in multi-hop packet radio networks was first introduced in [11]. They determined the optimal transmission radius (that maximizes the packet forward progress towards destination) under the constraint that the transmission powers for all nodes are the same. In [12], the authors developed a model for analyzing the throughput and forward progress where each mobile node may have a variable and different transmission range. Recently, the work in [13] employed transmission power as the link metric for shortest-path routing algorithms in an attempt to realize the minimum-power routing algorithm discussed in [9]. However, the congestion caused by multi-user interference was not represented in the link metric. In [14], the authors employed transmission power adjustment in order to control the topology of wireless ad-hoc networks. Unlike [14], our work employs power control as part of the multiple access algorithm. Although the authors in [15] introduced a power control based multiple access protocol, it was limited only to the class of "carrier sense multiple access with collision avoidance (CSMA/CA)" protocols. In this study, we introduce the notion of power control as part of a contention-based multiple access protocol that characterizes successful transmissions depending on a set of signal-to-interference-and-noise ratio (SINR) constraints. Moreover, there are no guarantees in [15] that the computed powers are minimum, while in our study we determine the minimum power vector subject to SINR constraints.

Our main contribution in this work is to solve the multiple access problem via two alternating phases that search for an admissible set of users along with their transmission powers. In the first phase, the *scheduling* algorithm is responsible for coordinating independent users' transmissions to eliminate strong levels of interference inherent to wireless ad-hoc networks (e.g. self-interference caused by a node simultaneously transmitting and receiving). Self-interference, along with other types of interference described later, can not be overcome by *computationally-expensive* power control algorithms and have to be eliminated first via scheduling. In the second phase, *power control* is executed, in a distributed fashion, to determine the *"admissible"* set of powers that could be used by the scheduled nodes, if one exists. If no set of positive powers can be found, control is transferred again to the scheduling phase to reduce interference via deferring the transmissions of one or more users participating in this scenario.

The paper is organized as follows: In section II, the assumptions and definitions necessary for formulating the problem are presented. This is followed by a detailed description of the joint scheduling-power control algorithm in section III. Section IV is devoted to introducing the distributed power control algorithm for wireless ad-hoc networks. The simulation results and discussion are given in section V. Finally, the conclusions are drawn in section VI.

II. Assumptions and Definitions

In this section, we provide the assumptions underlying this study and introduce appropriate notations:
1. Consider a wireless ad-hoc network consisting of n nodes.

There is no wireline infrastructure to interconnect the nodes, *i.e.* they can communicate only via the wireless medium.

2. Each node is supported by an omni-directional antenna.

3. Each node knows the geographical location of all other nodes via *location discovery* schemes [16], [17]. This information is necessary for the receivers to feedback their SINR measurements to their respective transmitters.

4. Routing is not considered in this study. We focus on *next neighbor transmissions* since the power control algorithm depends solely on the next neighbor transmission requirements. The main objective is to allow nodes to send information packets to their specified neighbors while, at the same time, satisfy a set of SINR constraints at their respective receivers.

5. The effect of users' mobility is not considered in this study. However, this assumption can be relaxed to the case of low users' mobility (typically pedestrians) where the link gain matrix is expected to change slowly compared to the dynamics of the iterative power control algorithm.

6. Assume that all nodes share the same frequency band, and time is divided into equal size slots that are grouped into frames. Furthermore, the proposed algorithm is investigated in the context of two multiple access schemes, namely TDMA and TDMA/CDMA.

7. The slot duration is assumed to be larger than packet duration by an interval called a "guard band". These bands are needed to compensate for arbitrary delays incurred by transmitted packets due to signal propagation delays or clock drifts.

8. In this study we assume that the frame length (or transmission schedule length) is fixed throughout system operation. It is chosen, heuristically, depending on the number of nodes, network load and quality-of-service constraints. However, there is an inherent trade-off between the choice of the frame length and the convergence of the power control algorithm as illustrated in the following extreme cases: short frame lengths lead to packing excessive number of transmissions in each slot and thus make it impossible for the power control algorithm to experience convergence in many slots. On the other hand, long frame lengths make it easier for the power control algorithm to converge at the expense of wasting system resources since most slots will be underutilized. Therefore, we envision room for balancing this trade-off at the expense of adapting the frame length dynamically depending on the number of required transmissions in each frame and their spatial separation. More precisely, the objective would be to find, on a frame-by-frame basis, the minimum frame length that guarantees convergence of the power control algorithm in all slots. This trade-off falls out of the scope of this paper and is a subject of future research. The complexity of this problem stems from its combinatorial nature which renders heuristic techniques unavoidable.

9. Each node generates information packets (*e.g.* data packets) of fixed length, destined to all other nodes, according to a Poisson distribution with aggregate rate λ packets/sec.

10. We assume that each generated packet is intended for a single neighbor only, *i.e.* the cases of broadcasting and multicasting are out of the scope of this paper.

11. We assume a maximum power level, denoted P_{max}, that a node can use for transmission. This is enforced by the limited weight and size of the wireless terminals.

12. The interference model adopted assumes that each node in the area causes interference at any receiving node, even if it is too far. We consider this model more realistic than the models introduced in the literature (*e.g.* IEEE 802.11) which assume that the transmission range of any node is circular and beyond that range no interference is caused [11], [12], [14]. The reason behind this is that a very large number of far interferers might cause negligible amounts of interference individually, but their aggregate effect could disrupt an on-going transmission.

13. The power decay law is assumed to be inversely proportional to the fourth order of the distance between the transmitter and the receiver. Accordingly, the link gain matrix is assumed to be constant throughout this study.

14. We assume the existence of a separate feedback channel that enables receivers to send their SINR measurements to their respective transmitters in a *contention-free* manner.

15. We assume the existence of a central controller responsible for executing the scheduling algorithms presented in section III. Introducing distributed scheduling algorithms is out of the scope of this paper and is a subject of future research. On the other hand, computationally-expensive power control is to be executed in a distributed fashion in order to reduce the communication overhead.

16. Define the *Average Slot Throughout* as the long run average of the percentage of packets successfully received by single-hop neighbors in each time slot.

III. ALGORITHM DESCRIPTION

In this section, we present the joint scheduling-power control algorithm. This algorithm is to be executed at the beginning of each time slot in order to cope with excessive interference levels that might be developed in some slots. The proposed algorithm determines the admissible set of users that can safely transmit in the current slot without disrupting each other's transmission. Accordingly, the objective of the algorithm is two fold: first, to determine the set of users who can attempt transmission simultaneously in a given slot. Second, to specify the set of powers needed in order to satisfy SINR constraints at their respective receivers. This is done via two alternating phases, namely scheduling and power control. The following two definitions are instrumental in illustrating the problem since they are related to the scheduling and power control phases respectively.

Definition 1 In TDMA wireless ad-hoc networks, a transmission scenario is **valid** iff it satisfies the following three conditions:

- A node is not allowed to transmit and receive simultaneously.
- A node can not receive from more than one neighbor at

the same time.

- A node receiving from a neighbor, should be spatially separated from any other transmitter by at least a distance D.

However, if nodes use unique signature sequences (*i.e.* joint TDMA/CDMA scheme), then the second and third conditions can be dropped, and the first condition only characterizes a valid transmission scenario. The purpose of the third condition above is to enforce *spatial separation* among simultaneous transmissions in order to reduce the amount of interference induced at non-intended receivers before executing computationally-intensive power control algorithms. The choice of the parameter D affects the amount of interference eliminated via scheduling. If D is too small, no spatial separation between simultaneous transmissions is guaranteed and most of the interference will be passed to the power control phase. On the other hand, if D is large, considerable amounts of interference are eliminated via the scheduling phase. For example, to limit multi-user interference to levels comparable to those in channelized cellular systems, the parameter D should be equal to the *"frequency reuse distance"* parameter [21]. The choice of the parameter D generally depends on the minimum acceptable SINR levels.

Definition 2 A transmission scenario involving m links is **admissible** iff there is a set of transmission powers, $P_{ij} \geq 0$, which solves the following minimization problem,

$$\min_{P_{ij}} \sum_{m\ links} P_{ij} \qquad (1)$$

s.t.

$$SINR_{ij} \geq \beta, \qquad \forall\ ij \text{ links}$$

The key observation that led to the development of the proposed two-phase solution is two fold: first, examining the *"validity"* constraints of a given transmission scenario is much easier and computationally more efficient than examining the *"admissibility"* conditions (which involves solving the optimization problem in (1)). Second, eliminating strong levels of interference (indicated in Definition 1) in the scheduling phase is essential since they can not be overcome by power control alone. In addition, employing a scheduling algorithm first makes the structure of the power control problem in wireless ad-hoc networks *exactly similar* to the structure of the power control problem in cellular networks. This interesting observation has led to the applicability of existing power control algorithms to emerging wireless ad-hoc networks as shown in the next section.

Figure 1 shows a flowchart that demonstrates the operation and interaction of the scheduling and power control phases of the algorithm. Given the transmission schedule specified at the beginning of each frame, the scheduling phase is responsible for checking whether the scenario in the current slot is valid or not. If valid, it proceeds to the power control phase. Otherwise, it searches for a valid subset of users via deferring the transmissions of some of the users causing high interference to the next slot in the frame. The power control phase is responsible for investigating the power admissibility of the valid scenario specified in the scheduling phase. If it turns out to be power admissible, the specified nodes start transmission in the current slot using the determined set of powers. Otherwise, control is transferred again to the scheduling phase where a search algorithm is activated to find the optimum subset of users who are admissible.

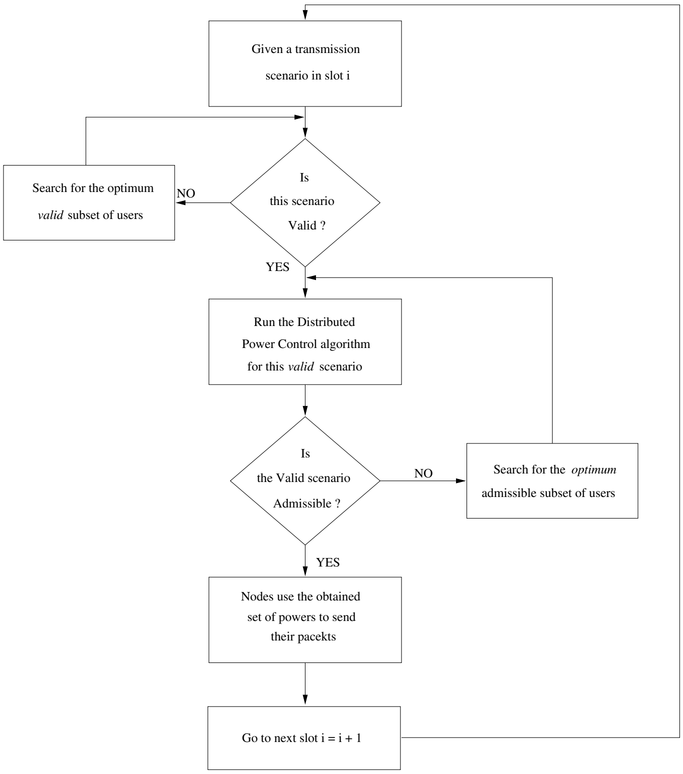


Fig. 1. Flowchart of the joint scheduling-power control algorithm

From the above discussion, we conclude that there are two combinatorial optimization problems. First, the *"Valid Scenario Optimization"* problem attempts to find the largest subset of users in an invalid set subject to the valid scenario constraints. Second, the *"Admissible Scenario Optimization"* problem searches for the largest subset of users in the valid inadmissible set subject to the admissibility (SINR) constraints. The complexity of both problems is *exponential* in the number of users participating in the transmission scenario. It is worth mentioning that the maximization operation is done in both problems on a slot-by-slot basis. Even though discrete exhaustive search would be practically infeasible, due to the real-time nature of the algorithm, it is quite insightful and serves as a benchmark for gauging the performance of heuristic policies. Therefore, we examine two simple heuristic algorithms and show their performance compared to the optimum. For the valid scenario search problem, a simple algorithm is to examine the set of valid scenario constraints sequentially and defer users' transmissions accordingly to resolve the conflicts. It is evident that this algorithm is sub-optimal in the sense that it could lead to deferring more transmissions than needed in order to reach a valid scenario. On the other hand, for the admissible scenario search problem, we examine a heuristic policy introduced earlier by Zander [2]. It suggests deferring the user with minimum SINR as an attempt to lower the level of multi-access interference. This might allow other users to converge to the optimum power vector quite fast. Moreover, this algorithm lends itself to distributed implementation if the SINR measurement at each receiver is fed back to all transmitters via flooding.

IV. Distributed Power Control

In this section, we formulate the power control problem and introduce possible distributed implementations. In the following two sections we consider TDMA and TDMA/CDMA wireless ad-hoc networks.

A. TDMA Wireless Ad-Hoc Networks

In this section, we assume that all nodes share the same frequency band and those scheduled will attempt transmission to their respective neighbors in the assigned time slot. Prior experience, from the context of *co-channel interference control* in channelized (FDMA or TDMA) cellular systems [2], [4], shows the existence of distributed power control algorithms which converge exponentially fast to the optimal (minimum) power vector, if one exists.

The main result of this section indicates that under some transmission constraints, the structure of the power control problem at hand is similar to the problem formulated and solved earlier for channelized cellular systems. This encouraged us to borrow the distributed power control algorithm developed in [4] as it turns out to be directly applicable to wireless ad-hoc networks. The uplink power control algorithm executed by node i follows the following iteration,

$$P_i(N+1) \;=\; \frac{\beta}{SINR_i(N)}\, P_i(N), \qquad \forall\, i \qquad (2)$$

where,
P_i = power transmitted by node i to its base station (BS),
$SINR_i$ = signal-to-interference-and-noise ratio at BS i,
N = iteration number.

Theorem 1 For valid transmission scenarios in TDMA wireless ad-hoc networks, the distributed power control algorithm in (2) converges exponentially fast to the minimum power vector, if one exists.

Proof: Our approach to prove the above assertion is to show the similarity of the problem structure at hand to the power control problem in channelized cellular systems. Once we achieve this, it is straightforward to establish the proof since convergence results are already available for the iterative algorithm in (2) in the context of channelized cellular systems[4]. Accordingly, we compare the mathematical structure of the two problems and show their similarity under the aforementioned set of valid scenario constraints.

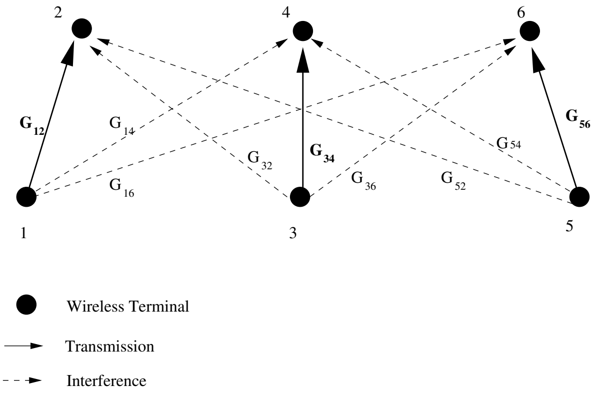


Fig. 2. Example of a valid transmission scenario ($m = 3$ links) $\{1 \to 2, 3 \to 4, 5 \to 6\}$ for a TDMA wireless ad-hoc network of $n = 6$ nodes

We compare the structure of the power control problem for a valid scenario that has m links (shown in Figure 2), where $m \le \frac{n}{2}$, to that of a channelized cellular system having m users in different cells reusing the same frequency channel as shown in Figure 3. The objective, in both problems, is to minimize the total power transmitted by participating nodes subject to a constraint on the SINR at their receivers. The formulation of the power control problem for a valid scenario in TDMA wireless ad-hoc networks is given by,

$$\min_{P_{ij}} \sum_{m\ links} P_{ij} \qquad (3)$$

s.t.

$$SINR_{ij} \ge \beta, \qquad \forall\ ij \text{ links}$$

where P_{ij} is the power transmitted from node i to node j and,

$$SINR_{ij} = \frac{P_{ij}\ G_{ij}}{I_j^i\ +\ \sigma^2}$$

where,
G_{ij} = link gain from node i to node j = $\frac{1}{d_{ij}^4}$, (d_{ij} is the distance between nodes i and j),
σ^2 = receiver thermal noise power and,
I_j^i = interference power at node j from transmitters other than node i. It is given by,

$$I_j^i = \sum_{k \ne i,j} P_{kx}\ G_{kj}, \qquad x \ne j \ \ and\ \ d_{kx} < d_{kj}$$

It is worth noting that the receiver x in the above expression depends on the specific scenario under investigation. Since we are focusing on *valid* transmission scenarios, the constraint $k \ne j$ in the above expression represents the first condition in Definition 1. On the other hand, the constraint $x \ne j$ is necessary to satisfy the second condition (no common receivers among the m links). Finally, the constraint $d_{kx} < d_{kj}$ guarantees the satisfaction of the third validity constraint. The parameter D introduced in Definition 1 is chosen to be equal to the distance between the interferer k and its intended receiver x (*i.e.* $D = d_{kx}$) as an example of spatially separating simultaneous transmissions. Accordingly, the constraints in (3) can be written in the form,

$$P_{ij} - \frac{\beta}{G_{ij}} \sum_{k \neq i,j} P_{kx} \, G_{kj} \geq \frac{\beta \, \sigma^2}{G_{ij}} \qquad (4)$$

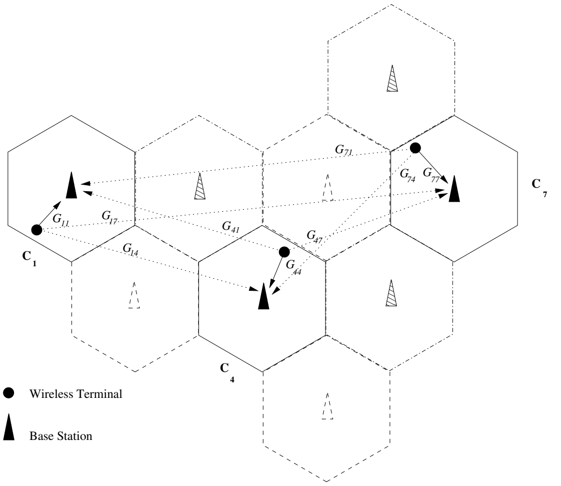


Fig. 3. A *channelized* cellular system of 9 cells and frequency reuse factor $K = 3$

On the other hand, it is shown in [4], [9] that the SINR constraints in the uplink power control problem formulated for channelized cellular systems can be reduced to:

$$P_i - \frac{\beta}{G_{ii}} \sum_{k \neq i} P_k \, G_{ki} \geq \frac{\beta \, \sigma^2}{G_{ii}} \qquad (5)$$

where P_i is the power transmitted from node i to BS i and G_{ii} = link gain from node i to BS i.

It is straightforward to notice that for channelized cellular systems, the first, second and third conditions of the valid scenario constraints are inherently satisfied by the different uplink and downlink frequencies, the system's cellular structure, and the frequency reuse constraints respectively. From (4) and (5), it is evident that the power control problem formulated for a specific valid scenario in TDMA wireless ad-hoc networks has exactly the same structure as the power control problem for channelized cellular systems. They are both characterized as eigenvalue problems for non-negative matrices [19]. Therefore, for a transmission scenario involving m links, whether in channelized cellular or TDMA wireless ad-hoc networks, there will be m^2 different link gains between all transmitters and receivers. The only difference between the two cases is that in cellular systems, wireless terminals are restricted to communicate only with their assigned BSs, whereas in ad-hoc networks a wireless terminal can potentially establish communication with any neighbor. Accordingly, the distributed power control algorithm in (2) and its convergence properties turn out to be directly applicable to TDMA wireless ad-hoc networks. ■

Based on Theorem 1, the results of power control with maximum power constraint for channelized cellular systems[5] are also directly extendable to TDMA wireless ad-hoc networks. In this case the iterative power control algorithm in (2) is modified to the following form,

$$P_i(N+1) = min[P_{max}, \frac{\beta}{SINR_i(N)} \, P_i(N)] \qquad (6)$$

B. TDMA/CDMA Wireless Ad-Hoc Networks

In this section, we assume that, on top of the TDMA scheme, each node has a unique pre-assigned signature sequence that it can use to encode the transmitted symbols. Again, our main objective is to develop a distributed power control algorithm for this type of ad-hoc networks. For cellular CDMA systems, a distributed power control algorithm, similar to the one in (2), has been introduced in the literature[7], [8].

First, we introduce the physical layer assumptions underlying the CDMA system. We adopt a simple signaling structure with BPSK modulation. The symbol stream is assumed to be i.i.d. and the ± 1 symbols are assumed to be equally probable. The noise is assumed to be independent of the symbols and has variance σ^2. Users are assumed to have pre-assigned, unique signature sequences which they use to modulate their information bits. The signature sequence of user i is denoted $s_i(t)$ which is non-zero only in the bit interval $[0, T_b]$ and is normalized to unit energy, *i.e.* $\int_0^{T_b} s_i^2(t) \, dt = 1$. The receiver is assumed to be a *conventional single-user* detector, namely a bank of filters matched to the signature waveforms of various users [22]. For each user i, we assume that all other users create interference *asynchronously.* The relative delays of the users, which can have any value not exceeding the bit duration T_b, do not change with time and are assumed to have a *uniform* distribution. For the *l*th bit of a given user i, an interfering user creates interference by either bits *(l-1)* and l or bits l and *(l+1)*, depending on whether the interfering user has a *positive* or *negative* delay relative to the user of interest. In Figure 4, two possible cases are depicted. The delay of user j relative to the matched filter of user i is denoted T_{ij}. In Figure 4, user j has a positive delay relative to user i and creates interference to the l-th bit of user i with bits *(l-1)* and l. On the other hand, user h has a negative relative delay with respect to user i and creates interference to the l-th bit of user i with bits l and *(l+1)*. Accordingly, three types of cross correlations between the signature sequences of any two users i and j can be defined. They are denoted as $\bar{\rho_{ij}}$, ρ_{ij} and $\tilde{\rho_{ij}}$, and represent the cross correlations between the symbol of interest in one hand and the previous symbol, current symbol and next symbol of an interferer respectively.

Theorem 2 For valid transmission scenarios in TDMA/CDMA wireless ad-hoc networks, the distributed power control algorithm in (2) converges exponentially fast to the minimum power vector, if one exists.

Proof: Again, our approach is to show the similarity of

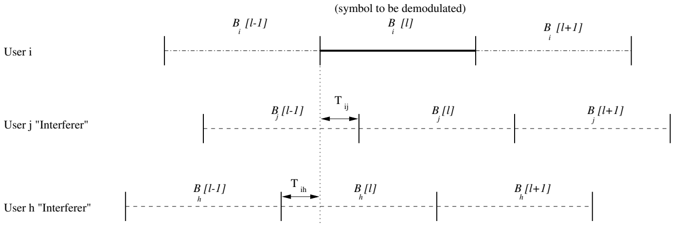


Fig. 4. Asynchronous CDMA System

the problem structure at hand to the power control problem in cellular CDMA systems. We compare the structure of the power control problem for a valid scenario that has m links, as shown in Figure 5, to that of a multi-cell CDMA system having m users, as shown in Figure 6. The power control problem for a valid transmission scenario in TDMA/CDMA wireless ad-hoc networks would have a formulation similar to (3). In this case, the interference power is given by,

$$I_j^i = \sum_{k \neq i,j} P_{kx} \; G_{kj} \; (\bar{\rho_{ki}}^2 + \rho_{ki}^2 + \tilde{\rho_{ki}}^2)$$

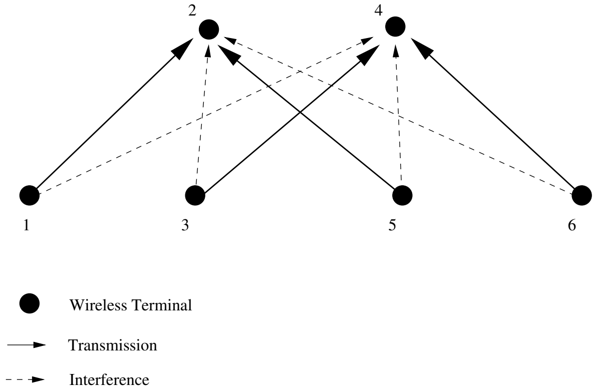


Fig. 5. Example of a valid transmission scenario ($m = 4$ links) $\{1 \rightarrow 2, 3 \rightarrow 4, 5 \rightarrow 2, 6 \rightarrow 4\}$ in a TDMA/CDMA wireless ad-hoc network of $n = 6$ nodes

Under the CDMA assumption, the constraint $k \neq j$ is sufficient to characterize a valid scenario. It represents that each node is not allowed to transmit and receive simultaneously. Accordingly, the SINR constraints can be written in the form,

$$P_{ij} - \frac{\beta}{G_{ij}} \sum_{k \neq i,j} P_{kx} \; G_{kj} \; (\bar{\rho_{ki}}^2 + \rho_{ki}^2 + \tilde{\rho_{ki}}^2) \;\geq\; \frac{\beta \, \sigma^2}{G_{ij}} \tag{7}$$

For cellular CDMA systems, it can be shown that the SINR constraints are given by (7), where BS x represents the closest BS to node k. In addition, the aforementioned valid scenario constraint is inherently satisfied by the different uplink and downlink frequency bands. Based on the above observation, we conclude that the power control problem formulated for a specific valid scenario in TDMA/CDMA wireless ad-hoc systems has exactly the same structure as the power control problem formulated in [7], [8] for minimizing multi-user interference in cellular CDMA systems. In this case, for a scenario consisting of m physical links, there will be m^2 *"effective"* link gains, due to the cross correlations between the spreading sequences of various transmitters, *irrespective of the number of receivers* involved. Accordingly, the distributed power control algorithm in (2) and its convergence properties turn out to be directly applicable to TDMA/CDMA wireless ad-hoc networks. ■

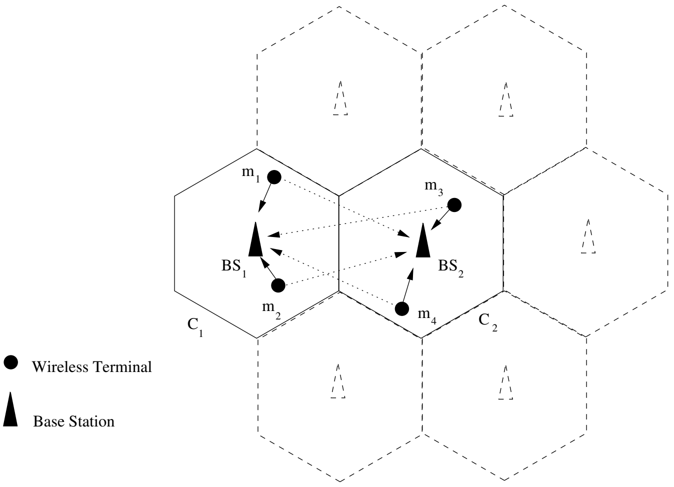


Fig. 6. A cellular CDMA system with 4 users located in 2 cells

Finally, it is straightforward to show that the constrained distributed power control algorithm in (6) is directly applicable to TDMA/CDMA wireless ad-hoc networks.

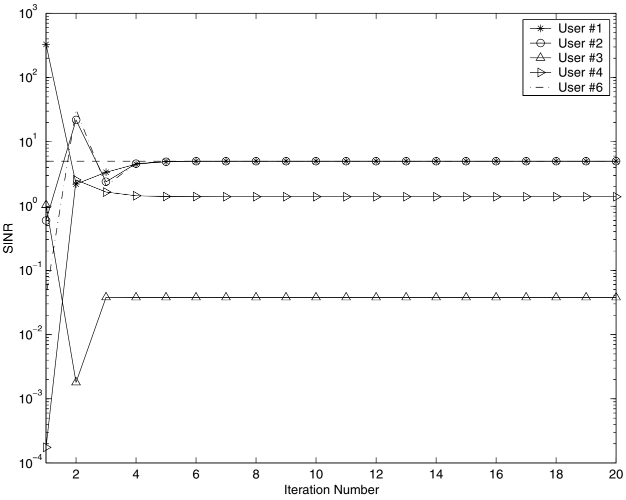
V. Results and Discussion

In this section, we show the behavior of the power control algorithm and its convergence properties for admissible transmission scenarios. In addition, we show the relative performance of the joint scheduling-power control algorithm for TDMA and TDMA/CDMA wireless ad-hoc networks. The simulations were carried using the numerical parameters given in Table I. We limit our attention to a small system consisting of $n = 7$ nodes since it adequately captures the trade-offs addressed in this paper, and provides valuable insights about the joint algorithm behavior under various interference conditions.

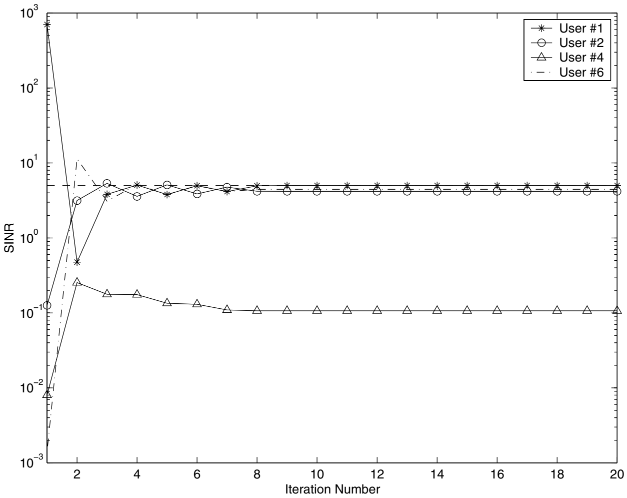
First, we verify, via simulations, the applicability of the distributed iterative power control algorithm in (6) to wireless ad-hoc networks. For TDMA/CDMA wireless ad-hoc networks, Figure 7 shows the behavior of the power control algorithm applied to a valid scenario that involves five links. In Figure 7(a), it can be noticed that the algorithm fails to converge due to the inadmissibility of this scenario. By deferring the user with minimum SINR, according to the heuristic policy described in section III, the power control algorithm fails, again, to converge as shown in Figure

TABLE I
System Parameters

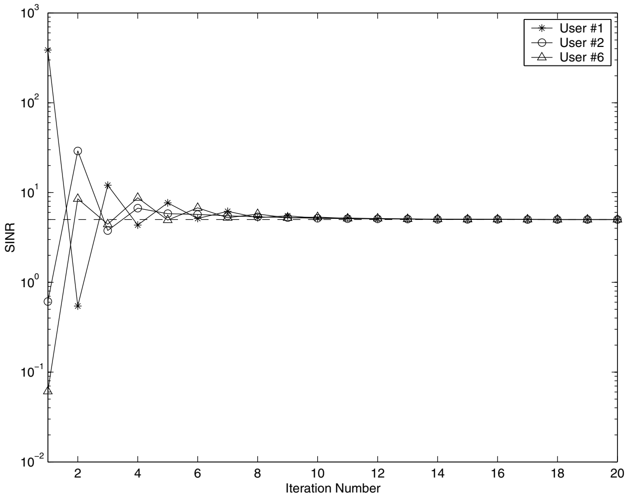
Number of nodes (n)	7
Slot Duration	2 msec
Frame Length	3 slots
Packet Inter-Arrival Time($\frac{1}{\lambda}$)	6, 7, ... 20 msec
SINR Threshold (β)	5
Noise Variance(σ^2)	3.5
Maximum Power (P_{max})	100
Maximum Number of Iterations	30



(a)



(b)



(c)

Fig. 7. (a) Example of an *Inadmissible* scenario with $m = 5$ links in a TDMA/CDMA wireless ad-hoc network (b) An *Inadmissible* sub-scenario with $m = 4$ links (c) *Admissible* sub-scenario with $m = 3$ links

7(b). Finally, by deferring another transmission according to the same heuristic policy, the transmission scenario having $m = 3$ links becomes admissible as demonstrated in Figure 7(c).

Next, we show the average slot throughput for the optimum valid and admissible scenarios under *light* and *heavy* load conditions. In Figure 8, we notice that the average slot throughput for a TDMA/CDMA wireless ad-hoc system outperforms that of a TDMA wireless ad-hoc system by a factor that varies from approximately twice the throughput at heavy loads to 17% higher at light loads. This, in turn, emphasizes the benefits of deploying CDMA at the expense of the computational complexity associated with determining the cross correlations at various receivers. In Figure 9, we compare the slot throughput performance of the optimum valid and admissible scenarios to their heuristic counterparts described earlier in section III. It can be easily noticed that the optimum policy significantly outperforms the heuristic policy by a factor of 57% at heavy loads. This performance gain gradually diminishes as load decreases. For larger systems, we expect the gap in performance to be even larger, specially at heavy loads. Therefore, we envision more room for developing computationally efficient heuristic scheduling policies that achieve performance levels close to the optimum and at the same time guarantee *fairness* among various users.

Finally, we demonstrate the behavior of the average power transmitted in a slot, normalized by the slot throughput, as the system load varies for both TDMA and TDMA/CDMA systems. As expected, Figure 10 demonstrates that the normalized transmitted power monotonically increases with the system load. Moreover, the average normalized power consumption per slot for a TDMA/CDMA system is almost half that of a TDMA system. This implies that the CDMA system saves transmission power, at the expense of the power consumed in the computations associated with determining the cross correlation coefficients at various receivers.

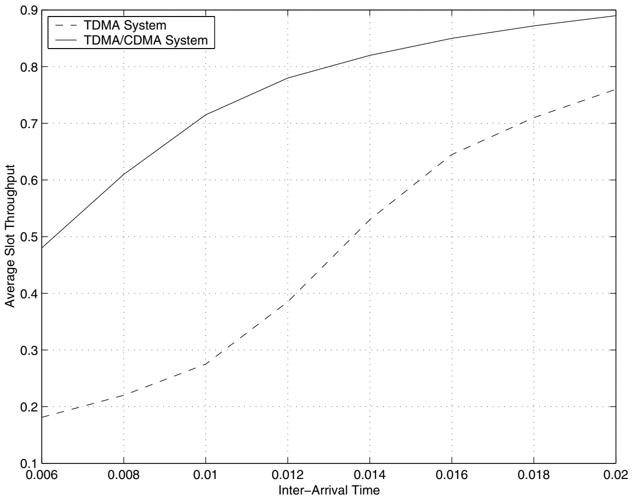


Fig. 8. Average Slot Throughput of the Optimum Valid and Admissible Scenario policies

Hence, there is a fundamental trade-off between transmission power and computation power that needs to be studied carefully during the design phase of power-controlled multiple access algorithms. In Figure 11, we compare the normalized power consumption of the optimum and heuristic scheduling policies for TDMA/CDMA wireless ad-hoc networks. We notice that the normalized power consumption of the optimum policy is noticeably less than the heuristic policy, specially at heavy loads.

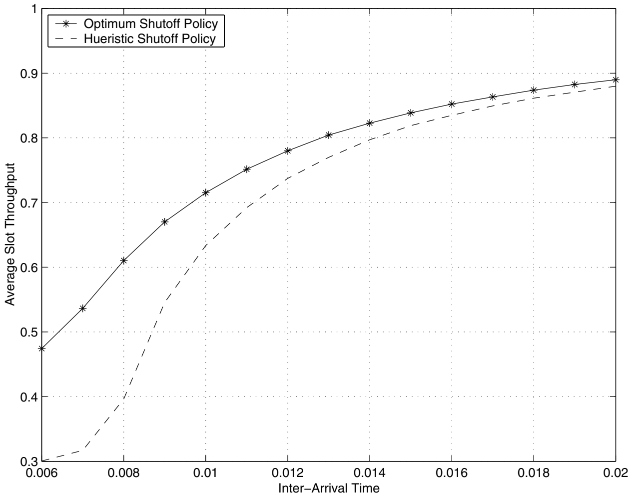


Fig. 9. Average Slot Throughput of the Optimum and Heuristic shut-off policies for TDMA/CDMA Wireless Ad-Hoc Networks

VI. Conclusions

In this paper we introduced a joint scheduling-power control solution to the multiple access problem in wireless ad-hoc networks. We focused on next neighbor transmissions where nodes are to send packets while, at the same time, satisfy a set of SINR constraints. Our main contribution in this paper is to solve the problem via two alternating phases until an admissible set of users, along with their transmission powers, are reached. In the first phase, a simple scheduling algorithm coordinates independent users' transmissions to eliminate strong levels of interference that can not be overcome by power control alone. In the second phase, a distributed power control algorithm determines the set of powers that could be used by the scheduled users to satisfy their transmissions, if one exists. We showed that distributed power control algorithms introduced earlier for cellular networks are directly applicable to emerging wireless ad-hoc networks. Furthermore, we conducted a simulation study that emphasizes the theoretical convergence results of the proposed algorithm. This was done, first, under the assumption of a TDMA scheme, and later for TDMA/CDMA ad-hoc networks. Finally, we showed the

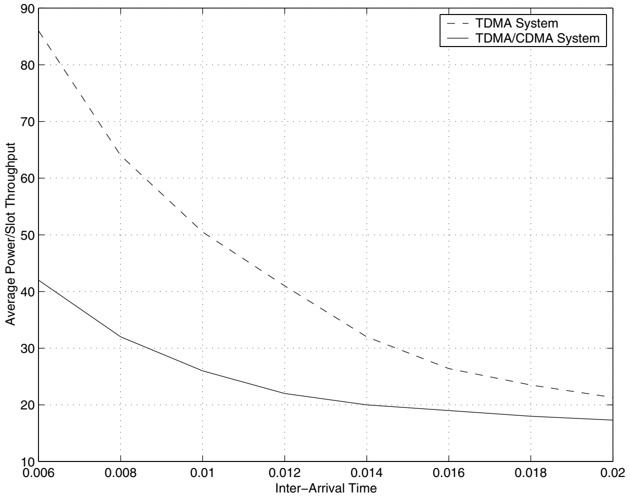


Fig. 10. Average Normalized Power of the Optimum shut-off policies

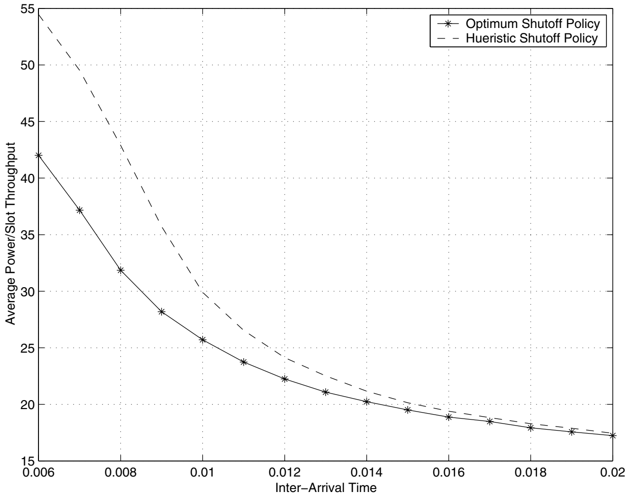


Fig. 11. Average Normalized Power of the Optimum and Heuristic shut-off policies for TDMA/CDMA Wireless Ad-Hoc Networks

performance of the optimum valid and admissible scenarios and compared it to simple heuristic policies under light and heavy load conditions.

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