Distributed Power Controlled Medium Access Control for Ad-hoc Wireless Networks

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Abstract—**In this paper, we develop and investigate a new medium access control (MAC) algorithm and protocol for ad-hoc wireless networks that employs power control spatial-reuse scheduling techniques. We introduce a novel interference graph (*the Power-based Interference Graph*), whose independence and chromatic numbers provide fundamental bounds for the integrated scheduling–power control problem. Based on the properties of the Power-based Interference Graph, we develop two distributed algorithms (the Distributed Power Controlled Scheduling Algorithms, DPCSs), which merely utilize the local information in the process of time slot allocation and power control. We show both algorithms to lead to significant increase in the network throughput level through spatial reuse of the communications resources while (Pareto) optimizing the power consumption.**

I. Introduction

One major common feature of wireless networks is the scarcity of spectrum. An important issue is therefore to design multiple access mechanisms to control channel utilization efficiently. This has motivated the need for channel spatial reuse, i.e. having users sufficiently apart use the same time slot, frequency band, or code.

[9] introduces some modifications in IEEE 802.11's handshaking protocol that allow for a greater number of simultaneous transmissions than 802.11 by adapting the transmission ranges to be the minimum value required to satisfy successful reception at the intended receivers. The COMPOW protocol introduced in [8] reduces the contention at the MAC layer and asymptotically maximizes capacity based on the assumptions of the Protocol Interference Model. This protocol suggests the reduction of the common power level to the lowest value at which the network remains connected. In [11], a power controlled multiple access protocol is introduced for supporting packetized data traffic in wireless networks. Under this protocol, the power level optimization for every transmitter is based on both its backlog level and the observed local interference, which captures the packet delay vs. transmission power trade-off.

A prevalent medium access scheme for channel spatial reuse is *spatial time division multiple access* (STDMA), in which time is divided into fixed length slots that are organized cyclically ([1],[4],[2],[3],[5],[6],[7]). In each cycle, or timeframe, every slot is allocated to different users such that all transmissions are received successfully at their intended receivers. In [18], a distributed joint scheduling and power control algorithm for multicasting in ad-hoc wireless networks is introduced. The algorithm, which is based in the previous results on flow control [20], eliminates the *strong interferers* (e.g. self-interference) and enables the entitled transmissions to solve the power control problem.

[12] introduces a simple interesting joint scheduling-power allocation algorithm, which operates via two alternating phases, namely scheduling and power control. In phase one, a subset of transmissions is selected in order to eliminate strong interferences. This phase is performed based on sequentially examining a set of constraints in a centralized fashion and is a function of *frequency reuse distance* D (i.e. the spatial separation between a node receiving from a neighbor and any other transmitter.) In the second phase of the algorithm, power control is executed to allocate power to each selected transmission in phase one. The authors show that the distributed algorithm, earlier introduced for power control in cellular architecture [16], can be utilized in the second phase of their algorithm. The choice of parameter D is not addressed in the paper, though, as the authors indicate, the value of D has a significant impact on the performance of their algorithm. Even in channelized cellular systems, estimation of D is not that straight forward and is affected by various parameters such as frequency reuse pattern, number of cochannel cells, geographic terrain contour, transmission power at each cell, and the minimum required signal-to-interference and noise ratio (SINR) [17].

In this paper, we develop and investigate a new medium access control (MAC) algorithm and protocol for ad-hoc wireless networks that employs power control spatial-reuse scheduling techniques. We introduce the notion of *Power-based Interference Graph*, whose independence and chromatic

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numbers provide fundamental bounds for the integrated scheduling–power control problem. Based on the properties of the Power-based Interference Graph, we develop two distributed algorithms (the Distributed Power Control Scheduling Algorithms, DPCSs) for this problem. DPCS algorithms, similar to the algorithm in [12], consist of two major phases, i.e. scheduling and power control. However, as opposed to the algorithm in [12], DPCS algorithms provide a high compatibility between the two phases, which results in higher throughput in the network. Moreover, both phases in DPCS algorithms are distributed and operate based on merely local information. Finally, DPCS algorithms have the advantage that they are not a function of the unknown (or at best, hard-to-estimate) parameter D**.** We show both DPCS algorithms to lead to significant increase in the network throughput level through spatial reuse of the communications resources while (Pareto) optimizing the power consumption.

The rest of the paper is organized as follows. In section II, we introduce the system assumptions. The notion of the Power-based Interference Graph is introduced in section III. We present the distributed joint power control and scheduling algorithms in section IV. Simulation results and conclusions are discussed in section V and section VI, respectively.

II. System Description

We consider an ad-hoc wireless network with *n* immobile nodes. All nodes operate in the same channel and are equipped with identical half-duplex radios and omni-directional antennas. The maximum transmission power is $P_{\max}$ and every transmission is performed under a fixed data rate R. We say node i and node j are neighbors if they can directly communicate with each other under $P_{\max}$ in the absence of interference.

Let G_{ij} denotes the link gain modeling the path loss for transmission from node i to node j. We assume G_{ij} 's are either constant or vary slowly with respect to the dynamism of our algorithm. Furthermore, links between nodes are assumed to be bi-directional. Every node measures the propagation attenuation for transmission of test packets in its neighborhood and notifies all its neighbors about the estimation. We assume the existence of a separate feedback channel with a strong error correction code that allows *successful* transmission of control information between neighbor nodes.

We denote the power for transmission from node i to node j and the thermal noise at every receiver by P_{ij} and N, respectively. A transmission from node i to node j is represented by $i \to j$. We refer to the set of all transmissions scheduled at the same time slot as a *transmission scenario*. Time slot duration is assumed to be slightly larger than the transmission time of a packet in order to accommodate for the signal propagation delay and possibly clock drift. Routing is not considered in this paper and it is assumed to be given.

Under our medium access model, we assume every transmission has exactly one intended receiver. We refer to this requirement as the *unicasting constraint*. Moreover, every node can either receive or transmit at every time slot. We refer to such a limitation as the *half-duplexing constraint*. In addition, a node cannot be the intended receiver of more than one transmission in a time slot. We call this constraint as the *receptivity constraint.* We note that the set of unicasting, half-duplexing, and receptivity constraints for a transmission scenario $X = \{i_1 \to j_1, ..., i_M \to j_M\}$ is equivalent to distinction of nodes $i_1, j_1, ..., i_M, j_M$.

For distinct nodes $i_1, j_1, ..., i_M, j_M$, we say a transmission scenario $X = \{i_1 \to j_1, ..., i_M \to j_M\}$ is *feasible* if and only if under appropriately selected power vector $P = (P_{i_1 j_1}, ..., P_{i_M j_M})$, $0 \le P_{i_k j_k} \le P_{\max}, k = 1,2,...,M$, the signal-to-interference and noise ratio (SINR) at each intended receiver is not less than the minimum required threshold γ, i.e.

$$\frac{G_{i_r j_r} P_{i_r j_r}}{N + \sum_{\substack{k=1 \\ k \ne r}}^{M} G_{i_k j_r} P_{i_k j_k}} \ge \gamma, \quad r = 1,2,...,M. \tag{1}$$

We refer to the set of unicasting, half-duplexing, receptivity, and SINR constraints as the *feasibility constraints*. Any transmission scenario satisfying all the feasibility constraints is referred to as a *feasible transmission scenario.*

The power vector $P = (P_{i_1 j_1}, P_{i_2 j_2}, ..., P_{i_M j_M})$ is said to be *Pareto optimal* with respect to a transmission scenario $X = \{i_1 \to j_1, i_2 \to j_2, ..., i_M \to j_M\}$ if

i. X is a feasible transmission scenario under P
and
ii. Any other power vector P' satisfying (i) would require at least as much power from every transmitter, i.e. $P' \ge P$ component-wise [13].

Similar to [12], we adopt the distributed power control algorithm that was originally introduced for cellular architecture ([19],[16]). In this algorithm, every transmitter i_k operates based on the following recursive equation:

$$P_{i_k j_k}{}^{(v+1)} = \min\{P_{\max}, (\frac{\gamma}{\Gamma_{j_k}{}^{(v)}}) P_{i_k j_k}{}^{(v)}\}, \quad P^{(0)} = P_0, P_0 > 0, v \ge 0 \tag{2}$$

where $P_{i_k j_k}{}^{(v)}$ is the power of transmission from i_k to j_k at the v-th iteration, and $\Gamma_{j_k}{}^{(v)}$ is the observed SINR in j_k at the v-th iteration. Since the measurement of SINR has to be made at j_k, the result has to be sent back to i_k. It has been proven that for a transmission scenario X the above distributed recursive relation converges exponentially fast to a Pareto optimal solution if one exists [19].

III. The Power-based Interference Graph

Let assume transmissions $i_1 \to j_1$ and $i_2 \to j_2$ are the only transmissions in the network and i_1, j_1, i_2, j_2 are distinct (Fig. 1). Based on (1) transmission $i_1 \to j_1$ is successfully received at j_1, if

$$\frac{G_{i_1 j_1} P_{i_1 j_1}}{N + G_{i_2 j_1} P_{i_2 j_2}} \geq \gamma, \tag{3}$$

or equivalently,

$$G_{i_1 j_1} P_{i_1 j_1} - \gamma G_{i_2 j_1} P_{i_2 j_2} \geq \gamma N, \tag{4}$$

where

$$(0,0) \leq (P_{i_1 j_1}, P_{i_2 j_2}) \leq (P_{\max}, P_{\max}). \tag{5}$$

Similarly, transmission $i_2 \to j_2$ is successfully received at j_2 if and only if

$$-\gamma G_{i_1 j_2} P_{i_1 j_1} + G_{i_2 j_2} P_{i_2 j_2} \geq \gamma N. \tag{6}$$

We define the set of all points $(P_{i_1 j_1}, P_{i_2 j_2})$ that simultaneously satisfies inequalities (4), (5), and (6) as the *Power Region* associated with transmissions $i_1 \to j_1$ and $i_2 \to j_2$. Clearly, simultaneous transmission of $i_1 \to j_1$ and $i_2 \to j_2$ under any power vector $(P_{i_1 j_1}, P_{i_2 j_2})$ inside the power region will be received successfully.

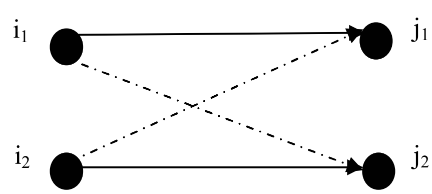

Figure. 1. Illustration of two simultaneous transmissions $i_1 \to j_1$ and $i_2 \to j_2$.

Lemma 1. For distinct nodes i_1, j_1, i_2, j_2, transmission scenario X={$i_1 \to j_1$,$i_2 \to j_2$} is a feasible transmission scenario if and only if

$$\begin{pmatrix}0\\0\end{pmatrix} \leq C \begin{pmatrix} G_{i_2 j_2} + \gamma G_{i_2 j_1} \\ G_{i_1 j_1} + \gamma G_{i_1 j_2} \end{pmatrix} \leq \begin{pmatrix} P_{\max} \\ P_{\max} \end{pmatrix}, \tag{7}$$

where C is a real scalar defined as

$$C = \gamma N / (G_{i_1 j_1} G_{i_2 j_2} - \gamma^2 G_{i_2 j_1} G_{i_1 j_2}). \tag{8}$$

Proof. The system of linear inequalities

$$\begin{aligned} G_{i_1 j_1} P_{i_1 j_1} - \gamma G_{i_2 j_1} P_{i_2 j_2} &\geq \gamma N \\ -\gamma G_{i_1 j_2} P_{i_1 j_1} + G_{i_2 j_2} P_{i_2 j_2} &\geq \gamma N \end{aligned} \tag{9}$$

can be written as

$$\left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & \gamma G_{i_2 j_1} / G_{i_1 j_1} \\ \gamma G_{i_1 j_2} / G_{i_2 j_2} & 0 \end{bmatrix} \right) \begin{pmatrix} P_{i_1 j_1} \\ P_{i_2 j_2} \end{pmatrix} \geq \begin{bmatrix} \gamma N / G_{i_1 j_1} \\ \gamma N / G_{i_2 j_2} \end{bmatrix}, \tag{10}$$

since, by definition, G_{ij}'s are positive. Based on the Perron-Frobenius theorem ([14]), (10) has a nonnegative solution if and only if the spectral radius of

$$A = \begin{bmatrix} 0 & \gamma G_{i_2 j_1} / G_{i_1 j_1} \\ \gamma G_{i_1 j_2} / G_{i_2 j_2} & 0 \end{bmatrix} \tag{11}$$

is strictly less than one. Furthermore,

$$\begin{aligned} \begin{pmatrix} P_{i_1 j_1} \\ P_{i_2 j_2} \end{pmatrix} &= \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & \gamma G_{i_2 j_1} / G_{i_1 j_1} \\ \gamma G_{i_1 j_2} / G_{i_2 j_2} & 0 \end{bmatrix} \right)^{-1} \begin{bmatrix} \gamma N / G_{i_1 j_1} \\ \gamma N / G_{i_2 j_2} \end{bmatrix} \\ &= \left(\frac{\gamma N}{G_{i_1 j_1} G_{i_2 j_2} - \gamma^2 G_{i_1 j_2} G_{i_2 j_1}} \right) \begin{pmatrix} G_{i_2 j_2} + \gamma G_{i_2 j_1} \\ G_{i_1 j_1} + \gamma G_{i_1 j_2} \end{pmatrix} \end{aligned} \tag{12}$$

is Pareto optimal solution with respect to transmission scenario X={$i_1 \to j_1$,$i_2 \to j_2$} if spectral radius of A is less than one and $P_{\max} = \infty$. Therefore, if $(P_{i_1 j_1}, P_{i_2 j_2})$, calculated based on (12), does not satisfy $(0,0) \leq (P_{i_1 j_1}, P_{i_2 j_2}) \leq (P_{\max}, P_{\max})$, X={$i_1 \to j_1$,$i_2 \to j_2$} is not a feasible transmission scenario.

On the other hand, based on the definition of a feasible transmission scenario the proof of the sufficiency of (7) is straightforward.■

Let define set V as the union of all available packets in the network. The *Power-based Interference Graph G(V,E)* is defined as an undirected graph, in which V and E are the set of vertices and the set of edges of graph G, respectively. Therefore, every vertex in graph G corresponds to an ordered pair of nodes in the network (which are the transmitter and the receiver of the underlying packet). Vertices (i_1,j_1) and (i_2,j_2) are connected to each other by an edge in G if and only if one of the following conditions are satisfied:

i. Nodes i_1,j_1,i_2, and j_2 are not distinct.
ii. Transmissions $i_1 \to j_1$ and $i_2 \to j_2$ do not satisfy (7).

As a result, every two adjacent vertices in the Power-based Interference Graph has the property that successful simultaneous transmission of them under any power allocation is impossible.

Theorem 2. The associated transmission scenario of every maximal independent set of the Power-based Interference Graph is maximal with respect to the property that it is not a proper subset of any feasible transmission scenario.

Proof. Assume there exists a maximal independent set IS, whose associated transmission scenario is a proper subset of the feasible transmission scenario $X = \{i_1 \to j_1, ..., i_M \to j_M\}, |IS| < M$. By definition of a feasible transmission scenario, there exists a power vector $P = (P_{i_1 j_1}, ..., P_{i_M j_M})$, $0 \le P_{i_k j_k} \le P_{\max}, k = 1,2,...,M$, under which simultaneous transmission of all transmissions in X result in $SINR \ge \gamma$ at all intended receivers. Therefore, under the same transmission power vector *P,* simultaneous transmission of every two transmissions in X can be successfully received at their intended receivers. But, this contradicts the maximality of the maximal independent set and the proof is complete. ■

Corollary 2.1. In any wireless network, the maximum number of simultaneous successful transmissions, under any transmission power allocation, is always bounded by the independence number of the Power-based Interference Graph.

Corollary 2.2. The minimum number of time slots required for transmission of all packets in set V is equal to the chromatic number of the Power-based Interference Graph G(V,E).

IV. Distributed Power Controlled Scheduling Algorithms

Let N_{i_1} be the set of all nodes located in the two-hop neighborhood of node i_1. We say slot *s* is an *accessible time slot* for transmission $i_1 \to j_1$ if $X = \{i_1 \to j_1, i_k \to j_k\}, i_k \in N_{i_1}, k \ne 1$, is a feasible transmission scenario, where $i_k \to j_k, k \ne 1$, is any other transmission that has been already allocated to slot *s*.

A succinct description of DPCS_I is presented in Fig. 2 by a flowchart. The more detailed description of the algorithm is as follows:

[DPCS_I)]

1. Every node transmits a *test packet* under $P_{\max}$.

2. Each node that receives a test packet estimates the associated channel attenuation and sends back this information to all its neighbors (including the initial transmitter) under $P_{\max}$. Therefore, assuming bi-directionality, every node obtains the information regarding the channel attenuation in all the links of its one-hop neighbors and a subset of links in its two-hop neighbors. All these information is ordered in a *local gain matrix.*

3. Each node transmits its local gain matrix to its neighbors.

4. As node i receives/generates a (data) packet for transmission to node j, it *temporarily* allocates $i \to j$ to its first accessible time slot and informs all its neighbors regarding this temporary allocation by sending a *reservation packet* under $P_{\max}$.

5. As node i receives a reservation packet for a transmission whose transmitter is its neighbor, it sends the reservation to all its neighbors under $P_{\max}$. As a result, every node in the network obtains the information regarding the allocation of time slots in its two-hop neighborhood.

6. If node i has a temporary allocation in the current time slot for transmission to node j, it uses the recursive equation (2) for the power control operation.

(i) If after q iterations the algorithm converges, $q \le L$, transmission $i \to j$ is transmitted under power $P_{ij}^{(q)}$.
(ii) Otherwise, transmission $i_k \to j_k$ is removed randomly or based on the minimum $\Gamma_{j_k}^{(0)}$ [16].
- If $i = i_k$, node i performs step 4 for reallocating the transmission $i \to j$ to the next accessible time slot.
- Otherwise, node i performs Step 6.

We note that the temporary allocation in step 4 is (almost) equivalent to coloring of the Power-based Interference Graph, which provides an apposite initialization point for the start of the power control algorithm and final allocation of time slots (see section V for simulation results).

Let $\{i_2 \to j_2, \cdots, i_M \to j_M\}$ be the set of all transmissions that have been already allocated to time slot s, which $i_k \in N_{i_1}, k = 2, \cdots, M$. DPCS_II is similar to DPCS_I with the difference that prior to the temporary allocation of $i = i_M \to j_M$ to the first accessible time slot *s* (i.e. step 4 of DPCS_I), it solves the following system of linear equations

$$AP = B, \tag{13}$$

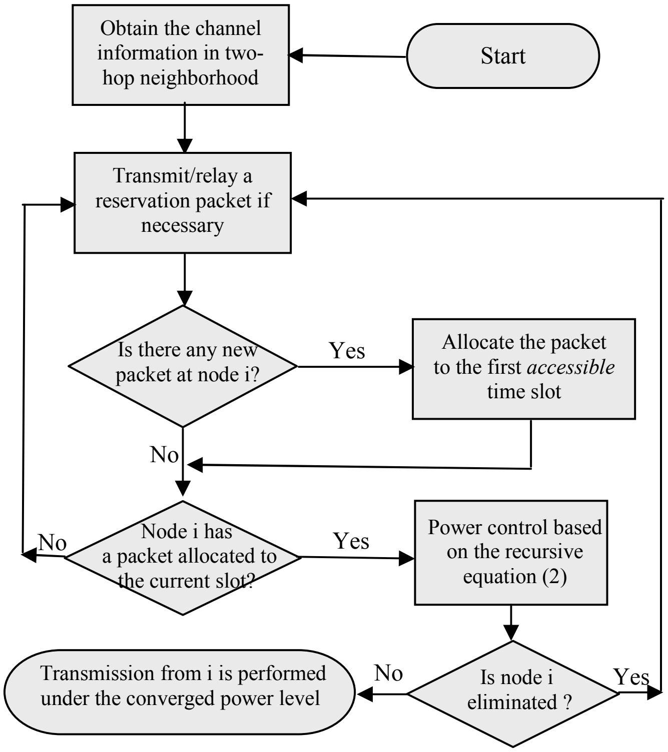

Figure. 2. The flowchart of the DPCS_I algorithm.

where I is the MxM identity matrix, $P=(P_{i_1j_1}, P_{i_2j_2},\ldots,P_{i_Mj_M})'$ is the column vector of transmission powers, $B=(N\gamma, N\gamma,\ldots,N\gamma)'$, and A is the matrix with entries

$$A_{rs} = \begin{cases} G_{rs}, & if\ r = s \\ -\gamma G_{sr}, & otherwise \end{cases}, r = 1,\cdots, M, s = 1,\cdots, M. \quad (14)$$

Based on the Perron-Frobenius theorem ([10],[14]), if $0 \le P_{i_kj_k} \le P_{\max}, k = 1,\ldots M$, transmission scenario $X = \{i_1 \to j_1,\ldots,i_M \to j_M\}$ is not feasible. Therefore, in DPSA_II node i disregards time slot *s* and checks the next accessible time slot for possible allocation of transmission $i = i_M \to j_M$.

We note that verifying the latter supplementary condition has the complexity of O(M^3) [15] and therefore ignorable, since the number of simultaneous transmissions in any two-hop neighborhood is typically very small. Moreover, this operation is merely based on the local information (similar to DPSC_I) and does not require the exchange of any additional control information.

V. Simulation Results

In our simulation, 30 nodes are distributed independently and uniformly in a disk of 1000 square meter. We assume power decays inversely proportional to the fourth order of the distance between every transmitter and receiver. Noise power and the minimum required SINR are -100 dBm and 10 dB, respectively. The maximum transmission power is set to be 100 mW. Every node generates packets based on a Poisson arrival process with intensity of λ=0.05 packets per slot for each of its neighbors.

We use the algorithm in [12] as the benchmark of our simulation analysis. For the sake of brevity, we refer to the algorithm as the Two-Phase Algorithm (TPA). In Fig. 3 we compare the throughput under DPCS_I, DPCS_II, and TPA algorithms as a function of the frequency reuse distance D. Clearly, DPCS_I, DPCS_II are independent of D. However, we observe that TPA is extremely sensitive to the choice of D. DPCS_II always results in the maximum throughput value. Even the throughput of TPA under the optimum value of D (i.e. 190m) is still less than that under DPCS_II. Also, it can be seen that except for one point, the throughput under DPCS_I is greater than that under TPA.

In DPCS and TPA algorithms the initial transmission scenario for the underlying time slot is trimmed in the power control phase, which results in elimination of one or more transmissions from the transmission scenario. Therefore, the number of transmissions scheduled at every time slot is equal to the cardinality of the associated initial transmission scenario minus number of eliminations during the power control operation. As a result, throughput (in terms of packets per slot) is equal to the average cardinality of the initial transmission scenario minus the average number of eliminations within the power control operation (see Fig. 3, Fig. 4, and Fig. 5).

In Fig. 4 we compare the cardinality of the initial transmission scenario in DPCS_I, DPCS_II, and TPA algorithms as a function of the frequency reuse distance D. As expected, the average cardinality of the initial transmission scenario in TPA is a monotonically decreasing function of D. Meanwhile, we note that the cardinality of the initial transmission scenario under DPCS_II is slightly smaller than that under DPCS_I. This can be justified due to fact that DPCS_II imposes more constraints on the process of generation of initial transmission scenario.

In Fig. 5 we illustrate the average number of eliminations in DPCS_I, DPCS_II, and TPA algorithms as a function of the frequency reuse distance D. As expected, DPCS_II has a lower number of eliminations in comparison with DPCS_I, since in DPCS_II there is more compatibility between the generation of the initial transmission scenario and the power control operation. Though the supplementary condition in DPCS_II reduces the size of the initial transmission scenarios

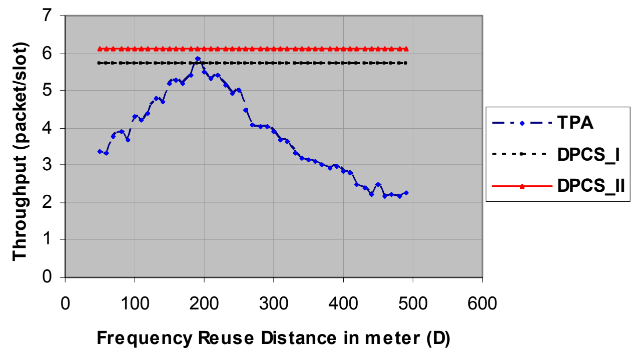

Figure 3. Comparison among the throughput of DPCS_I, DPCS_II, and TPA.

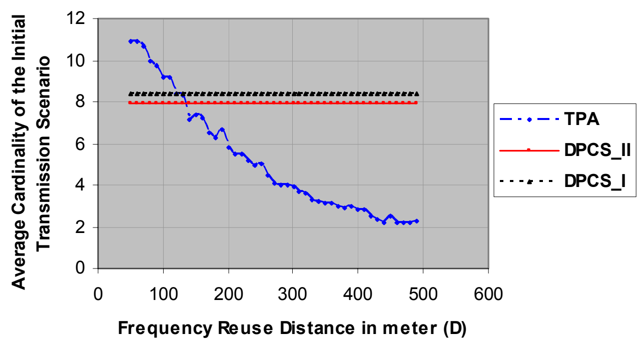

Figure 4. Illustration of the average cardinality of the initial transmission scenarios in DPCS_I, DPCS_II, and TPA.

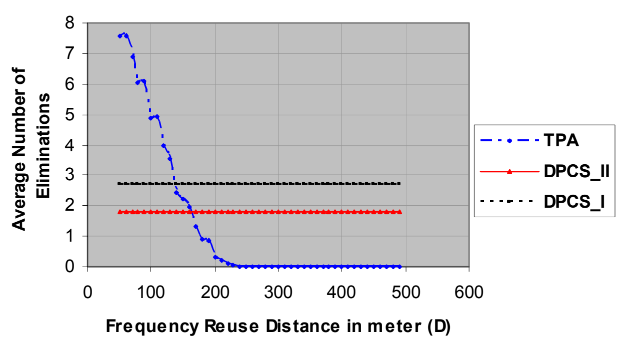

Figure 5. Comparison among the average number of eliminations in DPCS_I, DPCS_II, and TPA.

with respect to DPCS_I, it results in higher reduction in number of eliminations within the power control operation, which overall increases the throughput (see Fig. 3). Interestingly, by comparison of Fig. 3, Fig. 4, and Fig. 5, we observe that as D increases, both average cardinality of the initial transmission scenario and average number of eliminations in TPA decreases, while throughput (which is equal to the difference of the latter two values) is not necessarily a monotonically decreasing function of D (Fig. 3)

There are several reasons for having a better throughput performance under the DPCS algorithms: assuming that the cardinality of the initial transmission scenario is larger than one, under the worst scenario, a single transmission will be allocated to the underlying time slot in the TPA algorithm. In turn, assuming that the initial transmission scenarios in DPCS algorithms is larger than one, the number of allocated transmissions to the underlying time slot will not be less than two (based on the definition of the Interference Graph). The other reason for supremacy of the results under DPCS is Theorem 2: DPCS guarantees that the initial transmission scenario is not a proper subset of any feasible transmission scenario. In turn, as indicated in [12], TPA could start the power control operation from an initial transmission scenario, which is a proper subset of some feasible transmission scenarios. This is due to the fact that TPA could lead to deferring more transmissions than needed in providing an initial transmission scenario.

VI. Conclusions

In this paper we study the problem of integrated scheduling-power control in ad-hoc wireless networks. We introduce a novel interference graph (*the Power-based Interference Graph*), whose independence and chromatic numbers provide fundamental bounds for the integrated scheduling–power control problem. Based on the properties of the Power-based Interference Graph, we develop two distributed algorithms (DPCS_I and DPCS_II), which merely utilize the local information in the process of joint scheduling and power control, and satisfy the requirement that a minimum signal-to-interference and noise ratio (SINR) is met at all intended receivers. We compare the throughput performance of DPCS_I and DPCS_II versus the previous algorithms in the literature via simulation.

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