Optimizing Spatial Reuse by Dynamic Power Control

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***Abstract*—This paper first presents a geometric analysis of the convergence condition for the Foschini-Miljanic power control algorithm. Then, based on the analysis, the Dynamic Distributed Power Control MAC (D^2PC-MAC) scheme is proposed for wireless networks. D^2PC-MAC achieves high spatial reuse, since power control enables nesting of concurrent links, thereby achieving a high density of successful links. The MAC scheme starts by trying to accommodate all links and then eliminating transmitters causing too much interference in two stages, a local stage and a global stage. Both stages operate in a fully distributed manner. Simulation results confirm the expected gains relative to standard MAC schemes: the spatial density of successful links is increased by about a factor of 4 compared to CSMA and about a factor of 8 compared to ALOHA.**

I. Introduction

A. Motivation and Contribution

Since the wireless channel is shared, the maximum number of possible concurrently scheduled links is critical for the network capacity. Therefore, it is a crucial design issue in MAC layer to find the largest subset of links that can be used simultaneously and to assign optimal power levels. In this paper, Dynamic Distributed Power Control MAC (D^2PC-MAC) is proposed, which increases the spatial reuse significantly compared with ALOHA and CSMA protocols. D^2PC-MAC is a joint MAC and power control algorithm that operates in two stages. A subset of links is preselected in the local stage of D^2PC-MAC scheme. Instead of essentially creating a guard zone around the receivers as in CSMA, a novel method is proposed to obtain a valid subset of links. In the global stage of D^2PC-MAC, a modified distributed power control algorithm is used to guarantee that the remaining links can successfully transmit with optimal power levels.

B. Related Work

Transmission power control plays an important role in the design of wireless networks. Much of the study on cellular network power control started in 1990s and involved minimizing the total power while maintaining the fixed target signal-to-interference ratio (SIR) or signal-to-interference-and-noise ratio (SINR) at the desired receiver such as [1], [2], [3]. An efficient and distributed power control algorithm for cellular systems was provided in [1]. [4] has shown the applicability of the distributed power control algorithm in [1] to wireless ad hoc networks. A heuristic scheduling scheme is provided in [4] to determine a maximum subset of concurrently active links by shutting down the link with the minimum SINR until all the SINR requirements are satisfied. [5] proposed a joint power control and scheduling algorithm.

There has been intensive recent research on MAC protocols for wireless networks (see [6], [7] and the references therein). Some MAC protocols with power control are considered in [8], [9], [10]. Limited to CSMA, transmissions are scheduled in such a way that close nodes never transmit simultaneously to avoid collision. In contrast, D^2PC-MAC allows transmissions as long as the convergence conditions of the power control algorithm are satisfied. As a result, the spatial reuse is improved, which leads to better network performance.

II. Convergence Condition for Power Control

A. Review of Power Control Algorithm

Here we briefly review the power control algorithm proposed in [1]. The goal of power control is to adjust the transmit powers such that the SINR of each receiver meets a given threshold required for acceptable performance. The SINR for the ith receiver is given by

$$\rho_i = \frac{a_{ii}P_i}{\sum_{i\neq j} a_{ij}P_j + \eta}, \tag{1}$$

where a_{ij} is the channel gain from the jth transmitter to the ith receiver, P_i is the power of the ith transmitter, and η is the noise power. Each receiver has a minimal SINR requirement $\rho > 0$. This constraint can be represented in matrix form as

$$(I - F)P \geq u, \tag{2}$$

where $P = (P_1, \cdots, P_n)^T \in \mathbb{R}^n_+$ (denoted as $P > 0$) is the column vector of transmit powers, $u = (\frac{\rho\eta}{a_{11}}, \frac{\rho\eta}{a_{22}}, \cdots, \frac{\rho\eta}{a_{nn}})^T$, and F is a matrix with

$$F_{ij} = \begin{cases} 0, & \text{if } i = j \\ \frac{\rho a_{ij}}{a_{ii}}, & \text{if } i \neq j \end{cases} \tag{3}$$

where $i, j \in \{1, 2, \cdots, n\}$.

The Perron–Frobenius eigenvalue σ_F of the matrix F is defined as the maximum modulus of all eigenvalues of F. From [1], if $\sigma_F < 1$, there exists a vector $P^* > 0$ that satisfies (2). Also, when the eigenvalue condition holds, the iterative distributed power control algorithm

$$P_i(k+1) = \frac{\rho}{\rho_i(k)} P_i(k) \tag{4}$$

converges, where $\rho_i(k)$ is the current SINR for ith receiver at time k, and $P_i(k)$ is the power of the ith transmitter at time k.

B. The Two-Transmitter Case

Assume that the channel gain is $a_{ij} = (\frac{d_0}{d_{ij}})^\gamma$, where γ is path loss exponent, d_0 is the normalization distance, and d_{ij} is the distance between transmitter j and receiver i. For the two-transmitter case, the eigenvalue condition of matrix F is:

$$\frac{d_{12}d_{21}}{d_{11}d_{22}} > \rho^{\frac{2}{\gamma}}. \tag{5}$$

Now, assume that the distance between the two receivers is $2a$ and receiver 1 (Rx1) is at $(-a, 0)$ and receiver 2 (Rx2) at $(a, 0)$. Our goal is to find out what constraint these two transmitters (Tx1, Tx2) have to satisfy in order to guarantee that the distributed power control algorithm converges.

First, fix the location of Tx1 and define a parameter b:

$$b \triangleq \rho^{\frac{2}{\gamma}} \frac{d_{11}}{d_{21}}. \tag{6}$$

The convergence condition (5) can then be written as

$$\frac{d_{12}}{d_{22}} > b. \tag{7}$$

Given b, (6) and the following equation

$$\frac{d_{12}}{d_{22}} = b, \tag{8}$$

describe two circles. It is apparent that the condition (5) for the power control convergence only depends on the ratios d_{12}/d_{22}, d_{11}/d_{21}.

Define two critical circles $\mathcal{C}_1$ and $\mathcal{C}_2$ corresponding to (6), (8) respectively:

$$\mathcal{C}_1 = \{x \in \mathbb{R}, y \in \mathbb{R} : (x - x_1)^2 + y^2 = R_1^2\}, \tag{9}$$
$$\mathcal{C}_2 = \{x \in \mathbb{R}, y \in \mathbb{R} : (x - x_2)^2 + y^2 = R_2^2\}, \tag{10}$$

where

$$x_1 = a\frac{b^2 + \rho^{4/\gamma}}{b^2 - \rho^{4/\gamma}}, \;\; R_1 = \frac{2ab\rho^{2/\gamma}}{|\rho^{4/\gamma} - b^2|},$$
$$x_2 = a\frac{b^2 + 1}{b^2 - 1}, \;\; R_2 = 2a\frac{b}{|b^2 - 1|}.$$

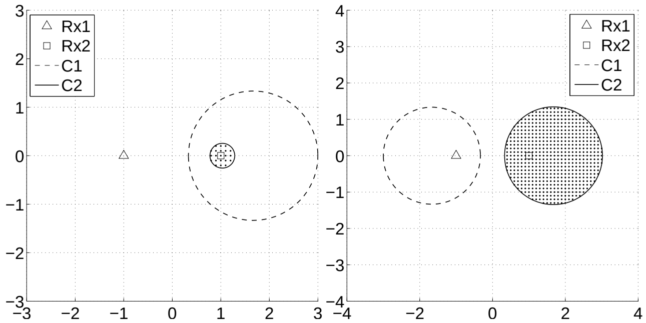
The points that satisfy $b = 1$ form a circle (denoted by $\mathcal{C}$) centered at $(x_0, 0)$ with radius R_0, where

$$x_0 = -a\frac{\rho^{4/\gamma} + 1}{\rho^{4/\gamma} - 1}, \quad R_0 = 2a\frac{\rho^{2/\gamma}}{|\rho^{4/\gamma} - 1|}.$$

In the following, we distinguish two cases, the *Far Case* for which $b > 1$ and the *Near Case* for which $b \leq 1$. Therefore, the circle $\mathcal{C}$ is a boundary for the two cases.

1) Far Case ($b > 1$): In this case when Tx1 is fixed on circle $\mathcal{C}_1$, Tx1 is in the area outside the boundary circle $\mathcal{C}$. Eq (7) means that Tx2 has to be located inside the circle $\mathcal{C}_2$ when Tx1 is on $\mathcal{C}_1$. As the parameter b increases from 1 to ∞, the locations for Tx1 will cover all the area outside the boundary circle $\mathcal{C}$, and for every location of Tx1 there is a corresponding area inside circle $\mathcal{C}_2$ for Tx2's location.

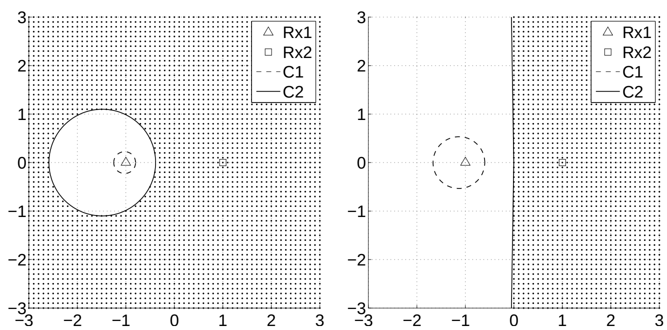
Fig. 1 illustrates the Tx2's location constraint for different ratios d_{11}/d_{21}. For Fig. 1(a), when Tx1 is on the dashed circle ($d_{11}/d_{21} = 2$), the dotted area shows the region of convergence for the power control algorithm. Here, the region of convergence (ROC) is defined as the area of Tx2's location that can guarantee the convergence of the power control algorithm when Tx1 is fixed. The case is especially interesting because Rx2 is sometimes closer to Tx1 than Rx1 and it can still receive from Tx2 as long as Tx2 is inside the circle $\mathcal{C}_2$. Clearly, CSMA would not allow such two links to be concurrently scheduled.



(a) $\frac{d_{11}}{d_{21}} = 2$ (b) $\frac{d_{11}}{d_{21}} = \frac{1}{2}$

Figure 1: Tx2's ROC for different locations of Tx1 in the Far Case: $a = 1, \gamma = 4, \rho = 12$ dB

2) Near Case ($b \leq 1$): For $b = \rho^{\frac{2}{\gamma}} d_{11}/d_{21} \leq 1$, Tx1 is inside or on the circle $\mathcal{C}$, and (7) describes the area outside the circle $\mathcal{C}_2$. Fig. 3 shows Tx2's ROC for different locations of Tx1 inside $\mathcal{C}$. In particular, for Fig.3(b), the circle $\mathcal{C}_2$ turns into the y axis ($b = 1$ and $d_{12}/d_{22} = 1$) and therefore the "interior" of $\mathcal{C}_2$ is just the right half plane.



(a) $\frac{d_{11}}{d_{21}} = \frac{1}{9}$ (b) $\frac{d_{11}}{d_{21}} = \frac{1}{4}$

Figure 2: Tx2's ROC for different locations of Tx1 in the Near Case: $a = 1, \gamma = 4, \rho = 12$ dB

Generally speaking, if Tx1 is located on the circle $\mathcal{C}_1$, Tx2 can be located either inside or outside the circle $\mathcal{C}_2$ depending on the value of b. If Tx1 is inside the circle $\mathcal{C}$ ($b \leq 1$), Tx2 can only be located outside the circle $\mathcal{C}_2$; on the other hand, Tx2 is always inside the circle $\mathcal{C}_2$ if Tx1 is outside the circle $\mathcal{C}$ ($b > 1$).

C. Relation of 2-Transmitter Case and n-Transmitter Case

Assume that there are a total of $n > 2$ transmitter-receiver pairs (links) in the system. For any two of them, if their pairwise SINR conditions cannot be satisfied, the overall SINR conditions cannot, either. This result is intuitive: if the concurrent transmission of two links cannot be guaranteed, that of more than two links cannot, either.

On the other hand, it is possible that the overall SINR conditions cannot be satisfied although every link pair among the $\binom{n}{2}$ pairs satisfies the pairwise SINR conditions. However, it is highly likely that there is at least one link pair that violates the pairwise SINR conditions when the n-link system cannot satisfy the SINR conditions. In this case, those link pairs are the cause of the overall SINR violation. If at least one link of a pair that violates the pairwise SINR conditions is eliminated, the system likely satisfies the overall SINR conditions. Recall that for the Perron–Frobenius eigenvalue (σ_F) of matrix F in (3), $\sigma_F < 1$ is the convergence condition for the power control algorithm. If any subsystem consisting of two links (say link j and k) is chosen out of n, its power control convergence condition is $\sigma_{F[j,k]} < 1$, where $F[j,k]$ is defined as

$$F[j,k] = \begin{bmatrix} 0 & \frac{\rho a_{jk}}{a_{kk}} \\ \frac{\rho a_{kj}}{a_{jj}} & 0 \end{bmatrix}. \tag{11}$$

Conversely, if $\sigma_F \geq 1$, the power control algorithm for the n-link system will diverge and therefore the n links cannot coexist. Similarly if $\sigma_{F[j,k]} \geq 1$, the power control algorithm for the 2-link subsystem will also diverge. Therefore, the relation between the n-link divergence condition and 2-link divergence condition is equivalent to that between $\sigma_F \geq 1$ and $\sigma_{F[j,k]} \geq 1$. For the n-link system ($n \geqslant 2$), define the conditional likelihood of 2-link divergence given n-link divergence as the probability of 2-link divergence given that the n-link system diverges.

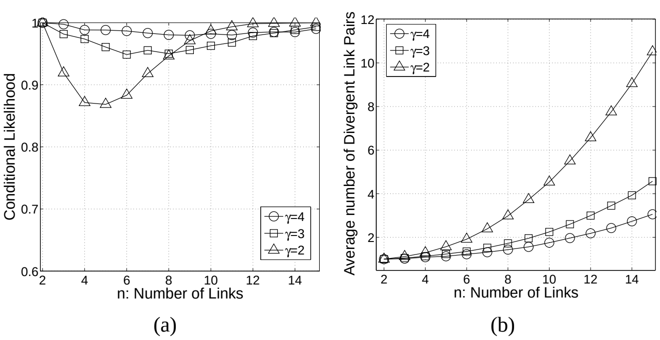


Figure 3: Relation between n-link divergence and 2-link divergence with different path loss exponent γ: $\sigma = \sqrt{2/\pi}$, $\rho = 12$dB

Fig. 3(a) shows the conditional likelihood of 2-link divergence given n-link divergence. In the simulation, transmitters are uniformly distributed in a 20×20 square and their associated receivers are uniformly located in the circle centered at these transmitters with radius R Rayleigh distributed with expectation $\mathbb{E}[R] = \sigma\sqrt{\pi/2}$. The same setup is used for the following simulations in this paper unless specified otherwise. It clearly illustrates that if the n-link system cannot satisfy the power control convergence conditions, there exists some link pair whose power control algorithm will diverge with high probability (≥ 0.98 for $\gamma = 4$). Therefore, the n-link system divergence is purely caused by the divergence of some link pair(s) in most cases. Fig. 3(b) shows the average number of link pairs failing to guarantee the convergence of the power control algorithm when the overall system diverges. As is shown, this number of such link pairs increases about quadratically with the total number of links. While the relation of the pairwise SINR violation and global SINR violation has been confirmed by simulation, a theoretical analysis may not be possible.

Next, define the Power Control Convergence Ratio (PCCR) as the ratio between the number of the experiments in which the power control algorithm converges ($\sigma_F < 1$) and the number of the experiments conducted.

Lemma 1. *A lower bound of the PCCR (denoted as PCCR$_\ell$) as a function of the distance ($2a$) between two receivers is*

$$\left[1 - \exp\left(-\frac{(2ab)^2}{2\sigma^2(b+4)^2}\right)\right] \cdot \left[1 - \exp\left(-\frac{(2a)^2}{2\sigma^2(b+1)^2}\right)\right]. \tag{12}$$

Proof: First fix the parameter b in (6) and the circle $\mathcal{C}_1$ can be obtained. Its corresponding circle $\mathcal{C}_2$ is also known by (10). Next, find the tangent circle (denoted as C_1') to $\mathcal{C}_1$ at point $(d_1, 0)$ and centered at $(-a, 0)$ and also that (denoted as C_2') to $\mathcal{C}_2$ at point $(d_2, 0)$ and centered at $(a, 0)$, where

$$d_1 = a\frac{b - \rho^{2/\gamma}}{b + \rho^{2/\gamma}}, \quad d_2 = a\frac{b-1}{b+1}.$$

By the conclusion in Section II-B, it is clear that if Tx1 is located inside C_1' and Tx2 inside C_2', their pairwise SINR condition can be satisfied. Note that the radii of C_1' and C_2' are R_1' and R_2', where

$$R_1' = \frac{2ab}{b + \rho^{2/\gamma}}, \quad R_2' = \frac{2a}{b+1}.$$

Two receivers (Rx1 and Rx2) are at $(-a, 0)$ and $(a, 0)$. The distance R_1' between Tx1 and Rx1 is Rayleigh distributed, and the angle between the segment Tx1-Rx1 and x axis is randomly chosen between 0 and 2π; Tx2 is chosen in the same way. As a result, the probabilities that Tx1 is inside C_1' and Tx2 inside C_2' are, respectively,

$$p_1 = 1 - \exp\left(-\frac{(2ab)^2}{2\sigma^2(b+4)^2}\right), \quad p_2 = 1 - \exp\left(-\frac{(2a)^2}{2\sigma^2(b+1)^2}\right).$$

Since the locations of Tx1 and Tx2 are independent, PCCR$_\ell$ = $p_1 \cdot p_2$. Therefore, (12) holds. ∎

Note that the pairwise SINR conditions can be easily satisfied if two links are well separated. Fig. 4 illustrates the PCCR as a function of the distance between two receivers ($2a$) in simulation and also its lower bounds given by Lemma 1. Fig. 4 indicates that when verifying the pairwise SINR condition, we might only need to calculate the pairwise SINR with its nearby links (*i.e.*, $2a < 3$) in order to further reduce the computational complexity.

III. Dynamic Distributed Power Control MAC

Our D^{2}PC-MAC scheme operates in two stages. First, link scheduling is responsible for preselecting a subset of links by removing the culprit links that cause strong levels of interference. Since the 2-link divergence and n-link divergence are well related, those culprits can be identified as the ones that violate the pairwise SINR conditions and therefore cause a violation of the overall SINR conditions. After all the culprit link pairs are identified, one link of each pair is eliminated either randomly or deterministically.

In the local stage above, a subset of links is obtained that has no pairwise SINR violations. As a result, most links that potentially cause strong interference to others have been eliminated. Yet, the power control algorithm for remaining links may still

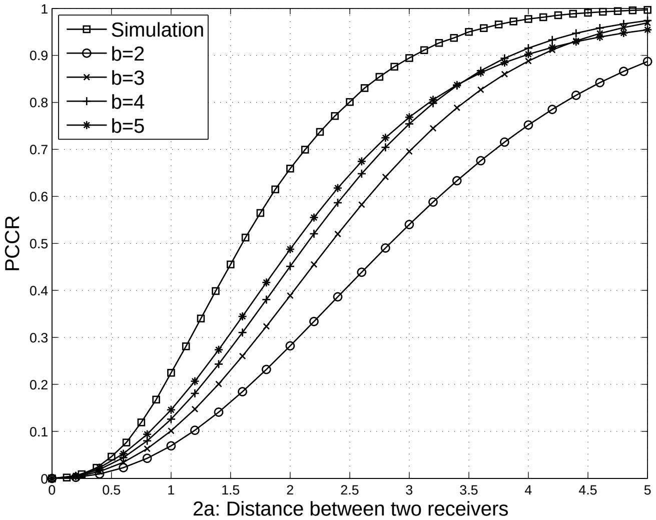


Figure 4: PCCR and its lower bounds with different b as a function of the distance between two receivers: $\sigma = \sqrt{2/\pi}, \gamma = 4, \rho = 12$ dB

diverge. In global stage of our MAC scheme, we will continue scheduling the subset of links while obtaining the optimal power levels and satisfying a peak power constraint $P_{\max}$ for each link at the same time. If the optimal power vector $P < P_{\max}$, the SINR conditions are satisfied. Otherwise, if some transmitter's power reaches $P_{\max}$, its SINR condition will be violated [5]. In the global stage, implement the power control algorithm in (4) and eliminate the links as soon as their transmit powers reach $P_{\max}$. Thus, the remaining links can satisfy their SINR conditions, and their power will converge to some $P < P_{\max}$. Consequently, the remaining links constitute the subset of links that can transmit concurrently with optimal power levels. The details are given in the following algorithms:

Algorithm 1 ($\mathrm{D^2}$PC-MAC version 1)

1: (**Local stage**) Given a set S of n links, calculate $\sigma_{F[j,k]}$ for all $j \neq k$, $j, k \in \{1, 2, \cdots, n\}$; **if** $\sigma_{F[j,k]} \geq 1$, label them as pairwise SINR violation pairs from 1 to n';
2: For link j_i and link k_i in labeled pair i, randomly remove one of them (say link j_i) from set S and get rid of the labels of the pairs that involve link j_i
3: Repeat *2* until all labels are removed and the updated set S has no pairwise SINR violations
4: (**Global stage**) Run the power control algorithm for the remaining links in set S;
if any link's power $P \geq P_{\max}$, shut down the link(s) immediately;
Run the algorithm until the iteration number reaches predefined N or the SINR for each link converges within the range of desired threshold ρ.

Remarks:

- Given a finite number of iterations, it is possible that the SINR requirement for some link cannot be satisfied even though its power assignment does not reach $P_{\max}$. However, the convergence rate of the power control algorithm is high. Moreover, the desired SINR can be chosen as $(1 + \epsilon)\rho$ ($\epsilon = 0.05$ in simulation) instead of ρ in (4) to speed up the convergence. Simulation also shows that our power control algorithm converges almost 100% within a number of N ($N = 30$ in simulation) iterations. The worst case is 98.1%, and the average is above 99%. Fig. 5 shows how the power levels are updated using **Algorithm 1**.
- The local stage is distributed if each node has the location information of the other nodes in its neighborhood, since the eigenvalue condition only depends on the distance between the nodes. Furthermore, Lemma 1 indicates that pairwise SINR violation is less likely if the two receivers are far from each other. Therefore, each link only need to calculate its pairwise SINR with the links nearby.
- The scheduling algorithm in [4] requires that each transmitter has the knowledge of the SINR measurements from all the receivers in order to make scheduling. However, the global stage of our MAC scheme only needs the SINR from its own receiver and decide if it can transmit based on its own power level.

Algorithm 2 ($\mathrm{D^2}$PC-MAC version 2)

1: **Algorithm 2** is the same as **Algorithm 1** except for step 2.
2: Let each link in the labeled pairs count in how many pairwise SINR violations it is involved. Denote the link with maximum number of pairwise SINR violations as T and eliminate it. For all the other links involved in a pairwise violation with T, remove their labels and reduce their number of violations by 1. For a draw where there is more than one transmitter that has the maximum number of pairwise violations, choose T randomly among all candidate links.

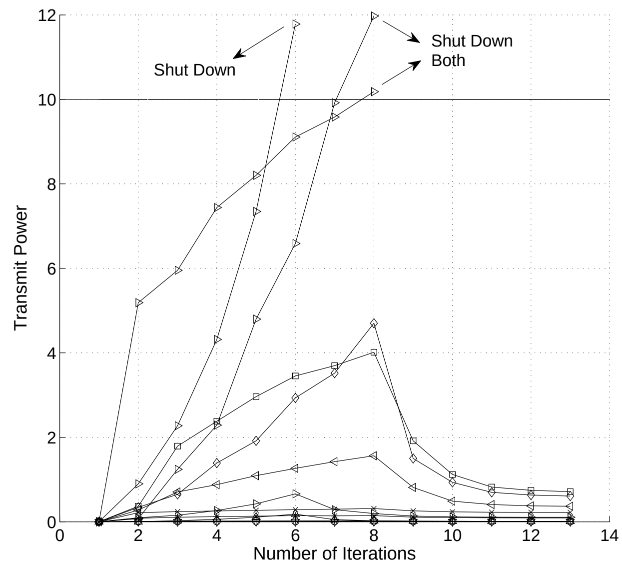


Figure 5: Power Trajectories: $\sigma = \sqrt{2/\pi}$, $\rho = 12$dB, $\gamma = 4$, $\beta = 1.5$, $P_{\max} = 10$

For the purpose of comparison, we use the CSMA scheme implemented as follows: if a receiver's interference power level is smaller than a threshold (P_0), the receiver sends a feedback signal to its transmitter to set it transmit using power level given by

$$P_i = \frac{\beta \rho_i \eta}{a_{ii}}, \tag{13}$$

where β serves as a marginal protection to tolerate interference from other links, and the other parameters are given in Section

II-A. The CSMA scheme is described in detail in **Algorithm** 3:

Algorithm 3 (CSMA)

1: Assign a random timer for each link among a total of n links; $k = 0$
2: **If** transmitter i's timer expires, receiver i calculates its received power $P_{r,i}$. If the power level $P_{r,i} < P_0$, link i can transmit with power given by (13). Admit link i into the subset of links scheduled. Set $k = k + 1$.
3: Wait for next timer expiration and **if** $k < n$ **go to** 2
4: **if** $k = n$ **end**

Denote this CSMA scheme above as Rx-CSMA since it uses the receiver to "sense" the channel. Similarly, Tx-CSMA lets the transmitter detect the power level and compares it to its predefined threshold to decide if it can transmit. Also, define ALOHA as scheduling each link independently with probability p. ALOHA can be optimized by choosing p as a function of total number of links n. For simplicity, p is fixed here. The power it uses is also given in (13).

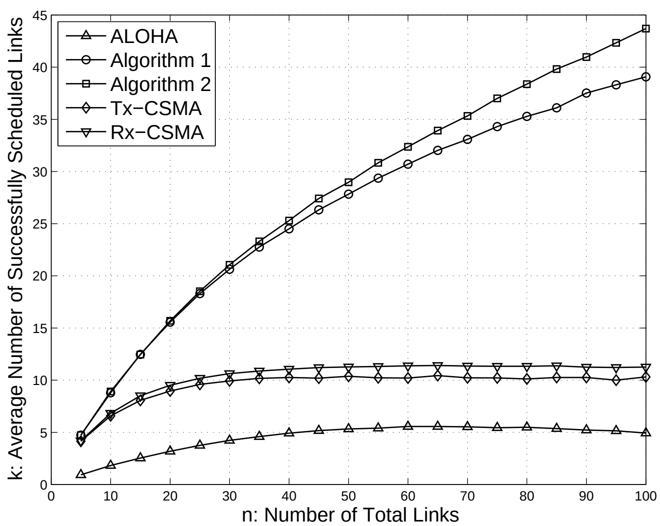


Figure 6: Average number of successfully scheduled links: $p = 0.2$, $\sigma = \sqrt{2/\pi}$, $\rho = 12$dB, $\gamma = 4$, $\beta = 1.5$, $P_{\max} = 10$

Fig. 6 shows the average number of successfully scheduled links (those that satisfy the SINR requirement). ALOHA embraces the least successfully scheduled links due to its randomness. Rx-CSMA and Tx-CSMA tend to converge to a maximum asymptotically since it essentially creates a guard zone around the receivers or transmitters. The figure verifies the statement in [11] that CSMA can increase the spatial reuse by about a factor of 2 compared to ALOHA. **Algorithm 1** and **Algorithm 2** can schedule much more links than ALOHA, Rx-CSMA and Tx-CSMA especially for larger number of total links (n). The spatial reuse is increased by about a factor of 4 compared to CSMA and about a factor of 8 compared to ALOHA. Moreover, D^2PC-MAC can make full use of the energy since it can schedule the links 100% successfully. For all successfully scheduled links, the total power using D^2PC-MAC is only about twice the power using CSMA when $n = 100$. It means that the D^2PC-MAC scheme schedules four times more links while using only about twice more power than CSMA. Therefore, the D^2PC-MAC scheme is very power-efficient.

IV. Conclusions

In this paper, we presented a geometric analysis of the power control convergence condition for the 2-transmitter case. A MAC scheme with power control was also proposed to schedule more links that can concurrently transmit and therefore increase the spatial reuse. In the local stage of the MAC scheme, a subset of links was selected based on the relation between 2-link divergence and n-link divergence. In the global stage, a distributed power control algorithm with peak power constraint determines the optimal power vector of the scheduled links with their SINR conditions satisfied while eliminating the links whose SINR conditions from transmitting cannot be guaranteed by deterring the links whose powers reach the power limit. The D^2PC-MAC scheme and ALOHA and CSMA schemes are compared in terms of number of successfully scheduled links. Simulations showed that D^2PC-MAC could increase the spatial reuse by about a factor of 4 compared to CSMA and about a factor of 8 compared to ALOHA. Also, the D^2PC-MAC scheme is very power-efficient.

Acknowledgment

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