Multiple Access Mechanisms with Performance Guarantees for Ad-Hoc Networks

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***Abstract*—This paper bears on the design and the quantitative evaluation of MAC mechanisms for wireless ad-hoc networks with performance guarantees. By this, we mean mechanisms where each accepted connection obtains a minimum rate or equivalently a minimum SINR level — which is not guaranteed by CSMA/CA — and which are adapted to the wireless ad-hoc network framework, namely are decentralized, power efficient and provide a good spatial reuse. Two such access control algorithms are defined and compared. Both take the interference level into account to decide on the set of connections which can access the shared channel at any given time. The main difference between the two is the possibility or not of adjusting the transmission power of the nodes. A thorough comparison of the performance of these two mechanisms and CSMA/CA is presented, based on a mix of analytical models and simulation and on a comprehensive set of performance metrics which include spatial reuse and power efficiency. Different network topologies, propagation environments and traffic scenarios are considered. The main aim of our study is to identify which of the proposed mechanisms outperforms CSMA/CA best depending on the scenario.**

***Index Terms*—Multiple Access, Ad-hoc Wireless Networks, Power Control, Performance Evaluation**

I. INTRODUCTION

Carrier Sensing Multiple Access (CSMA) is perhaps the medium access control (MAC) mechanism which is the most widely used in wireless ad-hoc networks. For example, in IEEE 802.11, a non slotted CSMA/CA is used, whereas a slotted one is used in the beacon-enabled IEEE 802.15.4. The popularity of CSMA/CA is mainly due to its simplicity. Its main feature is to avoid collisions by means of medium sensing: a node intending to transmit first senses the medium; if the latter is idle, the node transmits; else it backs off and tries again after a random time. An RTS/CTS handshake is generally used in addition to CSMA/CA to avoid the well known "hidden terminal" problem.

CSMA/CA suffers of many well known weaknesses. For instance, the problem of the "exposed terminal" is not solved by this handshake, and this unnecessarily reduces the number of simultaneous transmissions [1]. Also, the use of a fixed transmission power, independent of the distance between the transmitter and the receiver, prevents certain transmissions that could be accommodated with power adaptation. Moreover, there are no guarantees in terms of transmission success nor in terms of performance (e.g. rate); this makes CSMA/CA inappropriate for real time traffic. This lack of guarantees is mainly due to the fact that the *additive* character of the interference is not taken into account in the protocol as we show below. More precisely, we show in Sec. II that when shadowing/fading effects are taken into account, one may have a large collection of transmitters such that (i) each transmitter is outside the set of contenders of some tagged transmitter; (ii) none of these transmitters contend with each other and hence all are allowed to transmit simultaneously; (iii) the interference level at the tagged node tends to infinity with the size of the collection.

Much effort has been put into remedying this situation. Most of the papers on the matter are devoted to modifying particular parameters defined in the original CSMA/CA protocol (see for example [2]–[4]). The present paper focuses on a *clean slate approach*, aiming at revisiting or defining multiple access mechanisms which (i) are decentralized and hence adapted to the ad-hoc context (ii) guarantee a certain level of performance for all accepted transmissions in the presence of variable channel condition due to fading/shadowing effects.

For this, we argue that there is a need for mechanisms which explicitly take the SINR at the receivers into account for deciding which transmissions to accept/schedule from a given set of candidates. Two such mechanisms are discussed in the present paper. The first one, which will be referred to SBAC (SINR Based Access Control), roughly consists of admitting a new connection if its own SINR as well as that of each already active transmission are all larger than the required minimum (when taking the interference created by the new connection into account). The scheduling problem, which consists in determining a *maximal* set of simultaneous transmissions in such a way that the SINR at the receiver of each transmission is above a given threshold, is NP-complete for networks consisting of a set of transmitter-receiver pairs arbitrarily distributed in the Euclidean space [5]. Heuristics were proposed for this problem in [5] and [6] but these proposals have no known decentralized incarnations and they do not take shadowing/fading into account. SBAC can be seen as a greedy heuristic for solving this question, where transmissions are scanned in a random order and accepted as long as the above described condition is satisfied.

The second, which will be referred to as PCBA (Power Control Based Access) is based on power control: given a set of transmissions intending to access the channel, a subset is selected for which there exist feasible transmission powers such that the SINR for all of them is larger than a given threshold (for instance, all connections obtain the same SINR). It should be noted that power control is used as a way to increase the number of simultaneous transmissions and not as a mechanism for energy saving (as we shall see, PCBA is not always the best in terms of power efficiency). Power control is classical in cellular networks [7], [8]. It is also used for scheduling in such networks (see e.g. [9]–[13]). The papers which are the closest to PCBA are [12] and [13]. In [12], a two step scheduling mechanism is proposed. The first, centralized, step consists in finding a set of "valid" simultaneous transmissions. The main difference with our work is that we do not consider the first step and directly apply a distributed power control algorithm in order to determine the set of transmissions to be scheduled. In [13], the authors propose PCMA (Power Controlled Multiple Access), a wireless MAC protocol where each receiver sends busy-tone pulses to communicate its interference margin. The signal strength of the pulses is used to bound the transmission power of the interfering nodes. It is not clear however how to determine the interference margin in this context. In addition, an independent channel is required to the transmission of the busy-tones and contention between them is not addressed.

Both SBAC and PCBA guarantee a minimum prescribed rate but they differ in several aspects: SBAC assumes constant transmission power and actually provides rates larger than the required minimum, whereas PCBA adjusts power transmissions to provide exactly the prescribed rate for all the active transmissions.

The aim of the paper is twofold: (i) to discuss the usefulness and the implementability of these two mechanisms and (ii) to compare the performance of these mechanisms, in the context of wireless ad-hoc networks, specially with respect to classic CSMA/CA.

In order to compare SBAC, PCBA and CSMA/CA within this context, we consider different topologies: a line and a two-dimensional grid and different traffic scenarios: elastic (data) and non elastic (e.g. voice) traffic. For each case, several metrics, typical of ad-hoc networks, are studied; these metrics leverage rate, fairness, spatial reuse and power efficiency. The use of these metrics of course depends on the traffic scenario. For example, for data traffic, high rates are valuable, whereas for voice traffic a minimum rate level is required and anything larger is not really useful. We show that no mechanism outperforms the others in all cases. We also determine which one is best depending on the considered traffic type, the propagation model, the required SINR level, and of course the performance metric.

The paper is organized as follows. A model for CSMA/CA is presented in Sec. II, where we also discuss the lack of performance guarantees alluded to above. The proposed mechanisms are described in Sec. III. Sec. IV contains the performance comparison results. Implementation issues are discussed in Sec. V, where we analyze the complexity of each one of the proposed algorithms and discuss the question whether they can be implemented in a decentralized way. Finally, conclusions and future work are presented in Sec. VI.

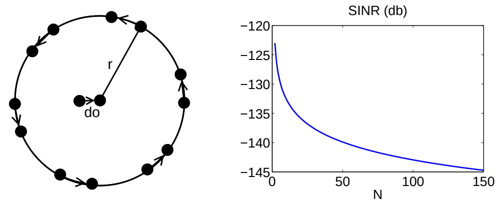
II. A Shadowing/Fading Aware Model for CSMA/CA

A. The Model

In [14], [15], the authors propose a packing approach to analyze the slotted version of CSMA/CA with its RTS/CTS handshake. Their analysis is based on the so-called Exclusion Domain (ED). The ED of a link is the set of nodes silenced (refrained from transmitting or receiving) by this link when active. In their model, the ED of a tagged link is defined as the union of two sets: (i) the set of nodes within the RXRange (receiving range) of the sender or the receiver of the tagged link, and (ii) the set of nodes within the CSRange (carrier sensing range) of the tagged sender. This definition of the ED is meant to represent the CSMA/CA RTS/CTS handshake: a node, different from the tagged receiver, which can decode a RTS (i.e. a node within the RXRange of the tagged transmitter) is silenced. Similarly, nodes that can decode a CTS (i.e. within the RXRange of the tagged receiver) are also silenced. In addition, CSMA/CA silences all nodes within the CSRange of the tagged sender (physical carrier sense).

We now describe the packing model of [14], [15] in more detail. This will be referred to as the CED (Constant Exclusion Domain) model below. The propagation model uses an attenuation function which is a deterministic and monotonic function of Euclidean distance. For a line topology, assuming that RXRange is equal to CSRange, the ED is the union of two (usually intersecting) discs, one centered at the transmitter and the other at the receiver of the tagged link. This means that the contenders of an active link (the nodes in its ED) are its nearest neighbors. This defines a minimum distance l between two active transmissions. For a given time slot, defining a transmission schedule (set of active links) is equivalent to finding a packing of the line with as many non-overlapping intervals of length l as possible. Once this packing is found, the throughput and the fairness can be deduced [16]. For more on this class of models, see for example [9], [17], [18].

The model which we introduce below can be seen as an extension of the CED model. The main new feature is the inclusion of variability of the channel conditions and in particular of the fading/shadowing effects. In our model, given two nodes, h and k, the power receiver from h by k is $P(h,k) = P_h F_k^h L(h,k)$, where P_h is the transmission power of node h, F_k^h is the fading/shadowing from node h to node k (which is a random variable), and $L(h,k) = A \max(r_0, d(h,k))^{-\alpha}$ is the path loss from h to k. As before, the RTS/CTS handshake defines the set of nodes that must be silenced by a tagged link. In this case, these nodes, which we shall call the Random Exclusion Domain (RED), are those whose reception power, from the tagged transmitter or from the tagged receiver, is larger than a certain threshold P_0. Given the random nature of the fading/shadowing, the RED of a link is not necessarily made of the nearest neighbors of the link as in the CED model. More precisely, let T_i and R_i denote the



(a) (b)

Fig. 1. (a) Example topology and (b) Mean SINR for the receiver located at the center of the circle.

transmitter and receiver of link i respectively; then the RED of link i is:

$$C(i) = \{j : P(h,k) > P_0 \text{ for } \; h \in \{T_i, R_i\}, k \in \{T_j, R_j\}\} .$$

Note that if the fading/shadowing is symmetric, i.e. $F_k^h = F_h^k$ for all nodes h, k, then the RED is also symmetric in the sense that if $j \in C(i)$, then $i \in C(j)$. This means that two contender links cannot access the channel at the same time.

In Sec. IV, we analyze this RED model, calculate the mean number of links silenced by an active transmission and we show that it actually differs from CED. We will use this model as a reference for comparison purposes throughout the paper. Finally, note that both ED models include the *Clear Channel Assessment* (CCA) in carrier sense mode, where the channel is considered busy if at least one signal is detected [19]. However, the analysis of CCA in energy detection mode is very complex and will be left for future work.

B. Motivating Example

Consider a network with several short links over a circle as in Fig. 1(a) and a propagation environment such that these links do not detect (contend with) each other (e.g. there are obstacles between them and the shadowing isolates them). Suppose that the network also has a link whose receiver is located at the center of the circle and that this link does not contend with the other links (e.g. because of distance). Suppose also that the timers are such that the central link is the smallest, then it senses the channel clear. All links are hence allowed to transmit simultaneously. We show below that the total interference created by the links located on the circle at the central receiver is possibly high.

Let N be the number of links, P be the transmission power of each transmitter, and r be the radius of the circle. Assuming Rayleigh fading, i.e. F_i^j is exponentially distributed with parameter 1. Then, the interference I seen by the central receiver is the sum of N independent exponential random variables, i.e. has a Gamma distribution with parameters N and $\lambda = 1/PAr^{-\alpha}$. The mean interference is then $N\lambda$, which grows linearly with N. Analogously, if we neglect the thermal noise (i.e. take $W = 0$ in (1)), the mean SINR is:

$$\overline{\text{SINR}} = PAd_0^{-\alpha}\mathbf{E}\left(\frac{1}{I}\right) = PAd_0^{-\alpha}\int_0^{\infty}\frac{1}{x}\frac{x^{N-1}e^{-x/\lambda}}{\Gamma(N)\lambda^N}dx$$
$$= \frac{PAd_0^{-\alpha}}{(N-1)\lambda}\int_0^{\infty}\frac{x^{N-2}e^{-x/\lambda}}{\Gamma(N-1)\lambda^{N-1}}dx = \frac{1}{N-1}\left(\frac{d_0}{r}\right)^{-\alpha},$$

where d_0 is the distance between the central transmitter and receiver. For the parameter setting of Sec. IV with $r = 100$ and $d_0 = 1$, Fig. 1(b) shows $\overline{\text{SINR}}$ as a function of N. As we can observe, a few links on the circle are enough to lead to a very poor SINR for the central link.

This toy example shows clearly why CSMA/CA, even when augmented by the RTS/CTS handshake, cannot guarantee any performance because it is based on pairwise exclusions only. Hence the need for protocols that take the interference created by all nodes in the network into account to decide which transmissions can access the channel.

III. Proposed Mechanisms

Motivated by the example in the previous section, we now consider admission mechanisms based on the total interference resulting from the active transmissions. More precisely, we define two mechanisms guaranteeing a *minimum rate* (equivalently SINR) for all accepted connections. Before describing the proposed mechanisms, let us introduce some notation. Let P_i be the power transmission of transmitter T_i to its receiver R_i. The SINR of an active link i is then:

$$\text{SINR}_i = \frac{P_i F_{R_i}^{T_i} L(T_i, R_i)}{W + \sum_{j \neq i} P_j F_{R_i}^{T_j} L(T_j, R_i)}, \tag{1}$$

where W is the thermal noise, which is considered constant and equal for all nodes. Let $A \in \mathcal{M}_{L \times L}$ be the *gain matrix*:

$$A_{ij} = \begin{cases} 0 & \text{if } i = j \\ \frac{\tau a_{ij}}{a_{ii}} & \text{if } i \neq j \end{cases}, \tag{2}$$

where τ is the target SINR and $a_{ij} = F_{R_i}^{T_j} L(T_j, R_i)$.

As a first step, we assume that time is divided in slots where all transmissions start and finish at the same time. The selection of the set of active transmissions is random and is the same, in law, at each time slot, but independent from time slot to time slot. At the beginning of the slot, the order at which each node tries to access the channel is decided randomly (for example, by using a timer). At its due turn, each transmitter/receiver pair decides whether or not to become active based on the multiple access mechanism selected. It must be noted that the assumed slotted division of time prevents all algorithms from creating unfairness (i.e. the well known "starvation phenomenon" [15]).

The mechanisms that we will introduce are still valid if specific performance levels are required for each transmission; it is enough to replace τ by τ_i. This can be useful, since different values of τ_i can be associated with different service levels.

A. SINR Based Access Control (SBAC)

In SBAC, power is constant and equal to P at each transmitter. A new connection is accepted if and only if the SINR it obtains (which depends on the connections already accepted) is larger than the target threshold and, at the same time, the new SINR that the already active transmissions obtain, when taking this new connection into account, is also larger than the threshold. More precisely we want that for all active connections, $\text{SINR}_i \geq \tau$. In terms of the gain matrix, the condition is:

$$\frac{\tau W}{P a_{ii}} + \tau \sum_{j \neq i} \frac{a_{ij}}{a_{ii}} \leq 1. \quad (3)$$

If $W = 0$ or negligible with respect to Pa_{ii}, then the previous condition is that the sum of all rows of matrix A are less than 1, i.e. the matrix A is sub-stochastic. If $W \neq 0$, the exact condition is that the sum of all rows must be less than 1 minus a term that depends on each link:

$$\tau \sum_{j \neq i} \frac{a_{ij}}{a_{ii}} \leq 1 - \frac{\tau W}{P a_{ii}}.$$

The algorithm is as follows. The first connection i attempting to access the channel is accepted if $\tau W / P a_{ii} \leq 1$ (the second term of the left part of (3) is zero). For the second one, if the matrix $A \in \mathbb{R}^2$ associated with the pair is sub-stochastic in the sense given above, then the connection is accepted, and it is rejected otherwise. For each new connection attempting to access the channel, its admission depends on the sum of the rows of the matrix A associated with the already accepted connections and this new one. Clearly the set of accepted connections depends on the order in which the nodes attempt to access the channel. This order is assumed random. We are aware that distributed implementations of this algorithm are not trivial due to the necessary exchange of information (possible ways to implement it in the slotted case are discussed in Sec. V). However, we believe that the comparison with this algorithm is still relevant since it can be considered as the "best" solution in the analyzed context.

B. Power Control Based Access (PCBA)

Our second mechanism is based on the power control algorithm introduced by Foschini *et al.* in [7]. In this case a new connection is accepted if and only if there exist feasible powers guaranteeing that the SINR obtained for all accepted transmission is larger than the minimum. In fact, Foschini's algorithm ensures that the SINR obtained by all accepted connections is equal to the target SINR. This algorithm can be applied in a distributed way (see Sec. V).

Foschini's algorithm: Let $\eta \in \mathbb{R}^L$ be the vector with entries $\eta_i = \tau W / a_{ii}$. There exists a power vector P such that $\text{SINR}_i \geq \tau \ \forall i$ if and only if $P \geq AP + \eta$. This inequality has a positive and finite solution if the spectral radius (maximal eigenvalue) of A is smaller than 1. A solution of the above inequality can be found iteratively as follows:

$$P_i(k+1) = (1-\beta) P_i(k) \left[1 + \left(\frac{\beta}{1-\beta} \right) \left(\frac{\tau}{S_i(k)} \right) \right], \quad (4)$$

where $S_i(k)$ is the SINR obtained by node i at iteration k. We see that $P_i(k+1)$ only depends on the local measurements of the actual power $P_i(k)$ and on the SINR $S_i(k)$, which is the basis of a very efficient distributed scheme. In [7], it is proved that, if the spectral radius of A is less than 1 and $\beta \leq 1$, then $P(k)$ converges to P^* starting from any initial vector $P(0)$, where P^* is the smallest solution of $P \geq AP + \eta$.

This algorithm can be used to decide whether a new link can access the channel. For each new connection attempting to access the channel, admission depends on the spectral radius of A, the matrix A associated with the already accepted connections and the new one. If this spectral radius is less than 1, then the new connection can be accepted. If it is larger than 1, then it should be rejected. A natural incarnation of the algorithm is that where a set of active connections is first built (using a random scanning of the connections and admitting/rejecting them based on this spectral radius criterion) and (4) is then performed to obtain the power vector P. A more efficient incarnation is discussed in Sec. V. For this power vector, the SINR obtained by all actives nodes is τ.

IV. Comparison Results

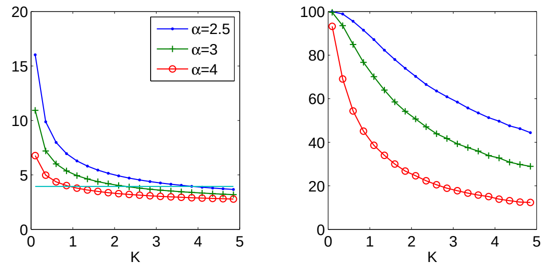
Assuming saturated traffic (each link always has data to send), a very important performance metric in the wireless ad-hoc setting is the number of simultaneous transmission that can be scheduled by the protocol. For this, we evaluate spatial reuse, which is defined as the mean proportion of links which are active at a typical time slot. However, as already explained, the accepted connections may obtain a very poor quality. We hence also measure the rate obtained by each of them. Since there is a clear tradeoff between spatial reuse and rate, we also define several different utilities to assess the overall performance of each algorithm. We also compare how fair is the rate distribution. A special emphasis is put on the comparison of the two mechanisms with CSMA/CA.

Network Topology: Two different topologies are considered: regular lattices in $\mathbb{R}$ (line) and in $\mathbb{R}^2$ (grid), with a distance d between two neighbor nodes. Each node can transmit or receive and that it communicates with its nearest neighbors.

Network Parameters: We assume $L = 100$ nodes for both topologies, distributed in a lattice of 10×10 for the grid. We also fix, $A = -53$dB, $r_0 = 0.01$ and $\alpha \in \{2.5, 3, 4\}$, which corresponds to different propagation scenarios (e.g. for a typical urban environment α is about 3). Finally we fix $P = 2.3$dBm and $W = -96$dBm for all nodes. Concerning the channel model, we analyze two different models: Rayleigh fading suitable when many obstacles are present and there is no line of sight between transmitter and receiver, and Log-normal distribution, more suitable to represent the shadowing effect. The random variables $\{F_i^j\}_{i,j}$ are independent and exponentially distributed with parameter $\mu = 1$ in the first case, and Lognormally distributed with standard deviation $\sigma = 4$dB in the second one.

The results of this section are obtained by a mix of simulation and analytical results. In the simulations, each algorithm is performed $N = 1000$ times, each time representing a slot. At each time slot, a symmetric matrix of random numbers is constructed representing the symmetric random fading/shadowing.

Due to space limitations, we have chosen default options — the line topology and Lognormal shadowing — and we only report on results for the other cases if they are illustrative (e.g.



(a) (b)

Fig. 2. (a) Mean number of contenders and (b) percentage of distant competitors for CSMA, as a function of $K = P_0/PAd^{-\alpha}$.

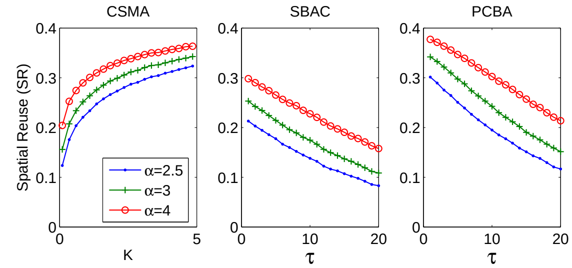


Fig. 3. Spatial Reuse (SR) comparison.

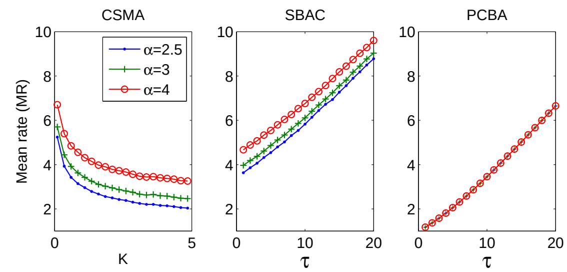


Fig. 4. Mean Rate (MR) comparison ($\rho = \log_2(1 + \text{SINR})$).

grid versus line topology) or if the differences are significant. For example, for a given channel model the comparison results obtained for both topologies are quite similar. However, for a given topology, the channel model may have a significant impact (see for instance Fig. 5 and 6).

A. RED Model Analysis

We first analyze the typical RED defined in Sec. II-A. Note that this set has the same law for all links on the infinite line or grid provided all transmitter receiver segments have the same length and orientation, which we assume; the law of the typical RED is then defined as the law of the RED of any such link. To the best of our knowledge, the analytical results on this random set are new. All performance metrics clearly depend on it: a large typical RED results into small access probability and so in poor spatial reuse. On the contrary a small RED results in high access probability and so in high spatial reuse. Let $N_i = \sum_{j \neq i} \mathbf{1}_{\{j \in C(i)\}}$ be the number of links in $C(i)$; then:

$$\mathbf{E}(N_i) = \sum_{j \neq i} P(j \in C(i)) = \sum_{j \neq i} p_{ij}.$$

Consider the (independent) events $A_{hk} = \{P(h,k) > P_0\} = \{F_k^h > \frac{P_0}{PL(h,k)}\}$ with $h \in \{T_i, R_i\}$ and $k \in \{T_j, R_j\}$; then:

$$p_{ij} = P\left(\bigcup_{h,k} A_{hk}\right) = 1 - P\left(\bigcap_{h,k} A_{hk}^c\right) = 1 - \prod_{h,k} P(A_{hk}^c),$$

where:

$$P(A_{hk}^c) = \begin{cases} e^{-\frac{P_0}{PL(h,k)}} & \text{for Rayleigh fading,} \\ \Phi(\frac{\log(P_0/PL(h,k))}{\sigma}) & \text{for Lognormal shadowing,} \end{cases}$$

and Φ is the Gaussian cumulative distribution function.

For the line topology and assuming $d(h,k) \neq 0$, we have $\frac{P_0}{PL(h,k)} = \frac{K}{|h-k|^{-\alpha}}$, where $K = P_0/PAd^{-\alpha}$. Figure 2(a) gives results on the line topology with Lognormal shadowing for different values of α as a function of the constant K. Note that for the same value of K, when α increases, the mean number of contenders decreases: for high values of α it is less likely that distant links interfere.

We now show that RED differs from CED or equivalently that fading/shadowing plays a role. Firstly, note that as K increases, for all values of α, the mean number of contenders converges to a value approximately equal to 4. This same value for CED would mean that the contenders of each link are its two left/right nearest neighbors. Although this mean number is the same, the actual contenders are not the same. In each sample, we counted the number of times there was at least one contender link outside this region. In Fig. 2(b), we show these results in percentage. For example, if $\alpha = 3$ and $K = 2.1$ (value of K for which the number of contenders is exactly 4), we obtain that in 51% of the cases, there is a contender which is not a two left/right neighbor.

This difference also translates into different performance results. It should be clear that for CED all performance metrics (e.g. spatial reuse or mean rate) are step functions of K. As we shall show in the following sections, this is not the case when fading is taken into consideration. Furthermore, numerical values change significantly. Just to mention an example, the spatial density of rate (cf. Sec. IV-C) decreases by roughly 30% from RED to CED.

B. Spatial Reuse and Mean Rate

In this section, we compare the spatial reuse (SR) and the mean rate (MR) obtained by each mechanism (see Fig. 3 and 4). The SR is calcuted as the mean link access probability and the rate is calculated as $\rho = \log_2(1 + \text{SINR})$. The minimum required SINR for the SINR-based algorithms is $\tau \in \{1, \ldots, 20\}$dB. It should be clear that for the same value of α, the spatial reuse increases (decreases) with K (τ). Small values of K correspond to large values of τ: in both cases, less connections are accepted. Note that for PCBA, the mean rate does not depend on α since it is equal to $\log_2(1 + \tau)$.

For each value of τ, PCBA has higher SR than SBAC. However, its MR is smaller since the rate obtained by all

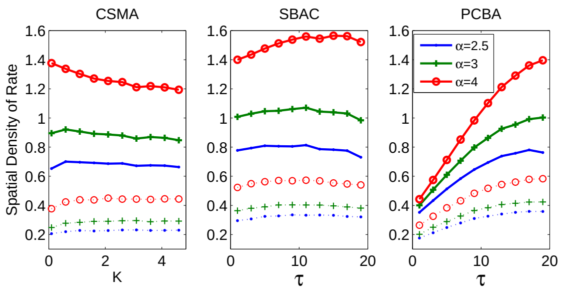


Fig. 5. Spatial Density of Rate (U_0) for the line topology (solid lines) and grid topology (dotted lines) with Lognormal shadowing.

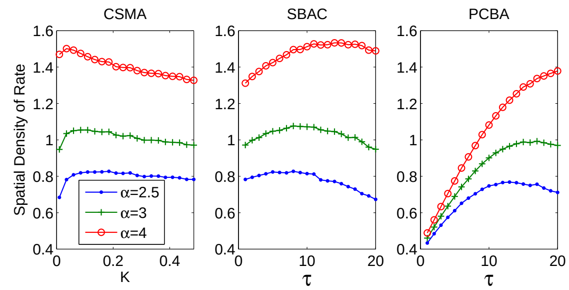


Fig. 6. Spatial Density of Rate (U_0) for the line topology with Rayleigh fading.

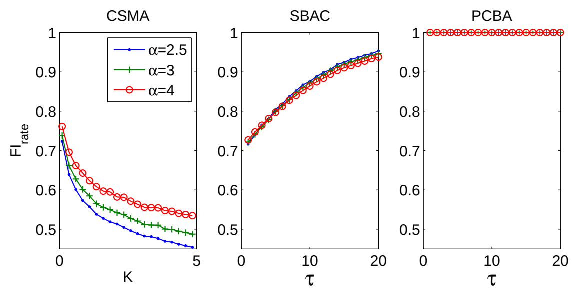


Fig. 7. Mean Rate Jain's index (FI_{rate}).

connections in SBAC is larger than the target minimum. On the other hand, CSMA achieves similar levels of SR and MR as PCBA. However, PCBA guarantees a minimum rate for all accepted transmissions. Consider for example $\alpha = 3$, where the maximum SR obtained by CSMA is 0.34. For the value of τ where PCBA obtains the same SR ($\tau = 1$), 44% of the connections accepted by CSMA obtain a SINR smaller than τ. The comparison with SBAC is slightly different since, in this case, CSMA can achieve values of SR that SBAC does not. Hence, if only the rate is considered, SBAC is the best solution. For the same SR level, a large number of CSMA connections obtain smaller SINR than the one guaranteed by SBAC. Then, for the same number of active links, better conditions will be obtained with PCBA or SBAC as expected.

Since SR and MR cannot be maximized at the same time, it is not clear which is the best combination. To evaluate more accurately this tradeoff, we consider several utility functions, depending of the type of traffic present on the network. In particular we concentrate in three types of traffic: Elastic Traffic (e.g. data), Elastic Traffic with minimum required SINR (what one would very much appreciate for data traffic in heavily loaded wireless LANs) and Constant Bit Rate (CBR) (e.g. voice traffic).

C. Elastic Traffic

For a given algorithm, connection i has an access probability p_i and obtains a rate ρ_i. Consider that each connection has a "revenue" represented by the product $p_i\rho_i$. For elastic traffic, there are no restrictions on the obtained rate; however one may want to have some kind of fairness between the accepted connections. Thus, the utility functions considered here are:

$$U_0 = \sum_{i=1}^{L} p_i\rho_i, \quad U_1 = \sum_{i=1}^{L} \log(p_i\rho_i), \quad U_2 = \sum_{i=1}^{L} -\frac{1}{p_i\rho_i}.$$

U_0 may be interpreted as the spatial density of rate; U_1 is a measure of fairness in the proportional sense and U_2 may be seen as a negative delay. Since conclusions for all the utilities are similar we will limit ourselves to considering only U_0.

Fig. 5 shows the obtained results for the line (solid lines) and the grid (dotted lines) topologies. For both topologies, if we concentrate in the maximum value obtained by each algorithm, we find that, for all values of α, SBAC and PCBA obtain better results than CSMA. Moreover, SBAC outperforms PCBA for almost all values of τ; obtaining also the maximum for the line topology. For the grid topology the maximum achieved by PCBA (obtained for a high value of τ) is slightly larger than the one obtained by SBAC; however as we may see in the figure, the difference is almost negligible.

As mentioned before, in general, our results do not change significantly with the fading/shadowing distribution. However, this is not entirely the case for this metric. Results for Rayleigh (instead of Lognormal) are reported in Fig. 6. We may see that results obtained by CSMA have improved with respect to the other mechanisms; obtaining similar results than SBAC specially for small values of α.

More in detail, looking at Fig. 5, we observe that the results obtained by CSMA and SBAC are almost constant in τ (for a given value of α), whereas those obtained by PCBA strongly depend on τ. This effect is a direct consequence of the fact that for each value of τ, all connections accepted under PCBA obtain exactly the same SINR and no more (which is not the case for SBAC), thus limiting its performance when this metric is considered; specially for small values of τ. The comparison between SBAC and CSMA is favourable to the former for all values of τ and K.

A very important aspect to be considered is fairness in the obtained rates, which we now analyze. Even if U_1 already takes this into account, we also study Jain's Index, i.e. $FI_{\text{rate}} = \left(\sum_{i=1}^{L}\rho_i\right)^2 / L\sum_{i=1}^{L}\rho_i^2$. Since with PCBA, all transmissions obtain the same SINR, this mechanism obtains the maximum fairness index independently of the value of α and τ (i.e. $FI_{\text{rate}} = 1$). In Fig. 7 we report on the results obtained

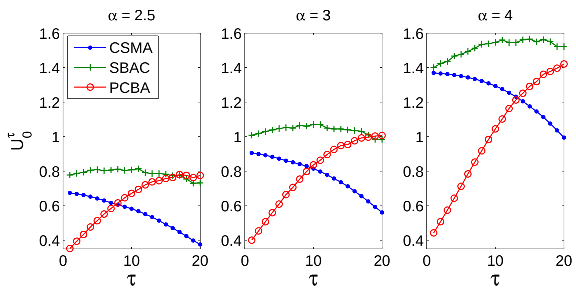


Fig. 8. Spatial Density of Rate when SINR $\geq \tau$ (U_0^τ).

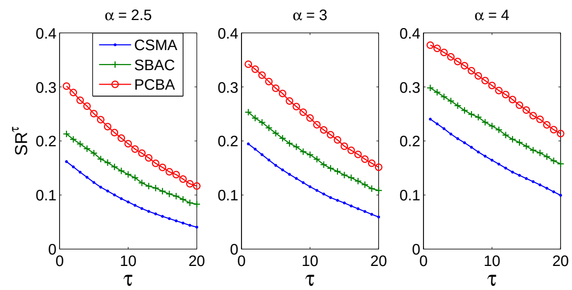


Fig. 10. Spatial Reuse when SINR $\geq \tau$.

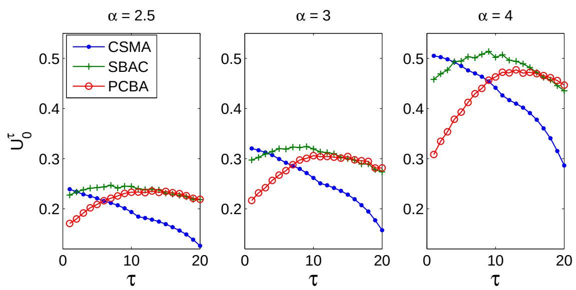


Fig. 9. Spatial Density of Rate when SINR $\geq \tau$ (U_0^τ) for the grid topology with Rayleigh fading.

by calculating the fairness index for each slot and averaging these values. As we observe, the results for the SINR-based algorithms largely outperform CSMA. This means that the rate distribution is more fair for each of the proposed mechanisms. Moreover, if we weight the utility U_0 by this index, we obtain that, due to its perfect index, PCBA now outperforms SBAC for $\alpha = 2.5$ and 3, however it is not enough to do it for $\alpha = 4$ (these results are not shown due to space limitations).

D. Elastic Traffic with Minimum Required SINR

The main difference between the considered algorithms is the guarantee or not of a minimum SINR. In this section we want to quantify this difference; for this, we define metrics that penalize situations where an active connection obtains a SINR smaller than the target minimum. Let $\mathbf{1}_r(i)$ be an indicator function that takes the value 1 when link i is active during the time slot r and 0 otherwise; and N_i the number of time slots that link i accessed the channel. We define:

$$p_i^\tau = \frac{1}{N}\sum_{r=1}^{N} \mathbf{1}_r(i)\mathbf{1}_{\{\text{SINR}_i \geq \tau\}},$$

$$\rho_i^\tau = \frac{1}{N_i}\sum_{r=1}^{N} \mathbf{1}_r(i)\mathbf{1}_{\{\text{SINR}_i \geq \tau\}} \log_2(1+\text{SINR}_i).$$

The first definition represents the probability to access the channel with a SINR larger than τ. Analogously, ρ_i^τ is the mean rate of these connections. The comparison metrics are (i) $U_0^\tau(x) = \frac{1}{L}\sum_{i=1}^{L} p_i^\tau \rho_i^\tau$ a modified spatial density of rate, and (ii) $SR^\tau = \frac{1}{L}\sum_{i=1}^{L} p_i^\tau$, the SR but considering only those connections whose SINR is larger than τ . Clearly, for SBAC and PCBA, these metrics coincide with that previously calculated. Yet, results for all mechanisms are reported to ease the comparison.

The results for the modified spatial density of rate are shown in Fig. 8, for different values of τ. For CSMA, we report on the maximum value since it depends on K. Note that for every value of τ, the best result is obtained by one of the SINR-based mechanisms. More precisely, SBAC essentially provides the best results, although it is in some cases slightly worse than PCBA (e.g. for $\alpha = 2.5$ and 3 and large values of τ). In fact, the difference between SBAC and PCBA decreases with τ and increases with α. This is mainly due to the SBAC property of guaranteeing a minimum SINR by actually providing more than the required minimum, from which this metric takes advantage. Regarding the comparison between CSMA and PCBA, we see that, for the former, U_0^τ decreases with τ, whereas, for the latter, it increases. Actually, for small values of τ, CSMA outperforms PCBA, whereas it is exactly the contrary for large values of τ. This situation can be explained by the fact that for small values of τ, most of the connections accepted by CSMA obtain a MR that exceed these values (see Fig. 4). But, as we will see in what follows, the transmission power required for both mechanism can be very different.

On the grid topology with Rayleigh fading, the results are slightly different. In Fig. 9, we see that the performance obtained by the three mechanisms is now more similar. In particular, for some small values of τ, CSMA obtains the best results, although the difference is not significant.

If the considered metric is the spatial reuse (see Fig. 10), PCBA outperforms the rest of the mechanisms for all values of τ and α. More precisely, and as expected, SBAC and PCBA outperforms CSMA since they guarantee a minimum SINR for all active connections. This means that, if the target is to guarantee a certain minimum SINR (independently of the particular level), SBAC and PCBA can accommodate more connections. PCBA is the one that obtains the best results since for the same given set of links it can adjust the transmission powers to accept more connections.

E. Constant Bit Rate (CBR)

This type of traffic needs a certain rate level and obtaining more than the required level is without value (e.g. voice traffic). To evaluate the performance of the algorithms in the presence of such a traffic, we consider the same metrics as before but imposing that the SINR is "equal" to a certain

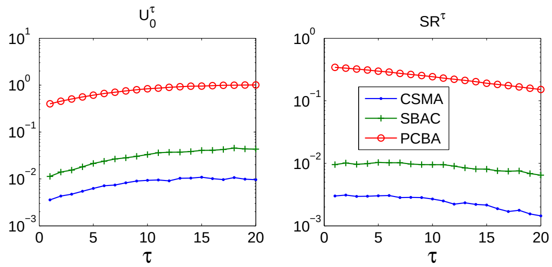


Fig. 11. Spatial Density of Rate and Spatial Reuse with SINR $= \tau$ for $\alpha = 3$.

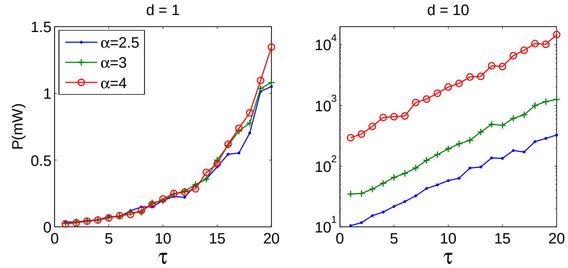


Fig. 12. Transmission power obtained by PCBA (mW).

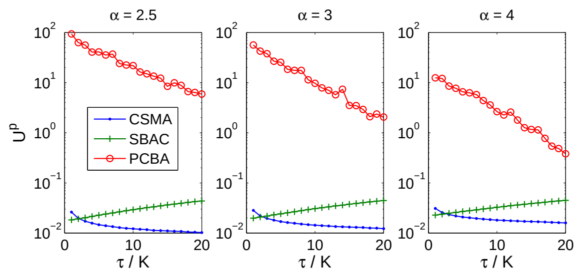


Fig. 13. Comparison of U^p for all mechanisms with $d = 10$.

threshold τ. In fact we consider an interval of values near τ, since if we consider values exactly equal to τ, no algorithm will make it. So, we define the interval $I = [0.99{*}\tau, 1.05{*}\tau]$.

We evaluate the same metrics as in the previous section, but replacing $\mathbf{1}_{\{\text{SINR}_i \geq \tau\}}$ by $\mathbf{1}_{\{\text{SINR}_i \in I\}}$. In this case, the results coincide for both metrics and without surprise, PCBA provides (by far) the best results for all values of α and τ. We report on results for $\alpha = 3$ in Fig. 11, where the y-axis is in log-scale to highlight the differences. It must be noted that CSMA obtains a very poor performance when this metric is evaluated (we have already seen that the rate fairness index can be very low, see Fig. 7). SBAC obtains intermediate results; they are largely better than CSMA's but still far off the very good results obtained by PCBA. It is not surprising that for this metric, the difference between SBAC and PCBA increases, since this metric prioritizes more equally distributed rates.

F. Rate vs Transmission Power

A very important aspect in ad-hoc networks is power consumption. In this section, we analyze the ratio between the mean rate and the required transmission power, i.e. how many bits per second can be transmitted with one power unit. We define the following metric that takes into account the relation between rate and power each time a transmission takes place:

$$U^p = \frac{1}{L}\sum_{i=1}^{L}\frac{1}{N_i}\left(\sum_{r=1}^{N}\frac{\rho_i(r)}{P_i(r)}\mathbf{1}_r(i)\right) = \frac{1}{L}\sum_{i=1}^{L}\overline{\left(\frac{\rho_i}{P_i}\right)},$$

where $P_i(r)$ is the power of link i in slot r. Since for PCBA, the rate is constant and equal to $R = \log_2(1+\tau)$ and since for the rest of the algorithms, the transmission power is always constant and equal to P, the metric becomes respectively:

$$U^p = R\frac{1}{L}\sum_{i=1}^{L}\overline{\left(\frac{1}{P_i}\right)} \quad \text{and} \quad U^p = \frac{1}{LP}\sum_{i=1}^{L}\overline{\rho_i}.$$

Note that the comparison between CSMA and SBAC is the same as presented in Sec. IV-B. The transmission power required to obtain the target level of SINR with PCBA depends on the value of d (distance between nodes). Results are shown in Fig. 12 for $d = 1$ and $d = 10$ and for different values of α. Clearly the required power increases with τ and α. From Fig. 12, we may conclude that for $d = 1$, PCBA obtains the best results in terms of the previously defined metric (the mean power is orders of magnitude smaller than the constant power assumed for the rest of the mechanisms). Fig. 13 reports on the results for $d = 10$. To ease the comparison, we plot all the algorithms together although they depend on different parameters: for CSMA (SBAC/PCBA) the x-axis must be understood as K (τ). As expected, the mechanism which obtains the best results is PCBA. However, the difference decreases with τ and α since the transmission power increases.

The distance d diversely affects the performance of the considered mechanisms. When d increases, for CSMA, there is no difference in SR but MR decreases. SBAC experiences a decrease in SR (less connections can be accepted). PCBA maintains its SR and MR rate but at the expense of an extreme increase of the power transmission: if P is the minimum power required to achieve the target SINR with $d = 1$, the corresponding value when $d \neq 1$ is $P' = Pd^\alpha$ (see Fig. 12). Then, for large values of d (e.g. $d = 100$), the performance of PCBA decreases, specially for high values of α.

V. Implementation Issues

In this section we discuss possible solutions to the main implementation issues of the proposed mechanisms.

1) SBAC: A transmission intending to access the channel must evaluate its SINR, and at the same time the already active transmissions must verify that the new SINR they will experience (if the new transmission is accepted) will still be larger than the target minimum. A possible solution is that the intending node sends a probing signal to the rest of the nodes, to give them the information necessary to evaluate their new SINR. In case a connection sees that its new SINR is not acceptable, this information must be sent back to the original node to cancel its transmission. A work in this direction is [20], which presents a mechanism to insert information of received power and interference level into MAC control packets.

Alternatively, we may think the problem in the following reverse sense: all nodes intending to send data are active (in particular sending "HELLO" messages to their destinations) and they are *inactivated* in random order. When its turn comes, the tagged node stops transmitting and starts "listening". If it receives an ACK from its receiver, it means that the SINR is enough to successfully receive the data and the connection is activated. If this ACK is not received after a certain time, the node will start to listen for the HELLO probes, i.e. it verifies if it is not the intending destination of another node. If it receives such packets, it answers with an ACK when they stop. Note that after all nodes have stopped sending HELLO messages the resulting active transmissions will obtain a minimum SINR level, enough to correctly decode data. In order to obtain an arbitrary minimum SINR level, each receiving node must estimate its SINR and answer with an ACK only if the estimation is larger than the required minimum.

2) PCBA: As mentioned before, PCBA can be implemented in a totally distributed way (see (4)). For real implementations, the two step decision described before (first decide which transmission are feasible and then calculate the corresponding power) is not realistic. In place, a useful property of this algorithm can be used: if the feasibility condition is not satisfied, it diverges at an exponential rate ([21]). Then, some iterations of (4) are calculated and if there is divergence, the connection is rejected; in other case it is accepted with the power obtained after these iterations.

VI. Conclusions

In this work, we analyzed some weaknesses of CSMA/CA and we proposed two decentralized multiple access mechanisms for wireless ad-hoc networks: SBAC and PCBA. The main advantage of these mechanisms is to guarantee a minimum rate for all the accepted transmissions. We compared their performance assuming different topologies, traffic scenarios and propagation models, for a slotted division of time and we devoted special attention to the comparison with CSMA.

We found that in all cases, irrespectively of the topology, traffic type and/or propagation model, one of the proposed mechanisms significantly outperforms CSMA, apart from a few cases where the differences are not significant. The rate distribution is also more fair for each of the proposed mechanisms than for CSMA. If elastic traffic is considered, SBAC is the algorithm which provides the best results. When a minimum rate is to be guaranteed, the best one depends on the considered metric, the minimum rate level and α. If the comparison is made in terms of spatial reuse, PCBA largely outperforms the rest of the mechanisms. This is due to its capacity of controlling the transmission power, thus accommodating more simultaneous connections. At the same time, since it gives exactly the same rate to all the connections, its performance decreases when other metrics (which include explicitly the rate) are considered. For example, SBAC is the mechanism which provides the best spatial density of rate.

Finally, PCBA also brings the best results when constant bit rate traffic is considered, irrespectively of the metrics and the propagation model. When the ratio between rate and transmission power is considered, again PCBA obtains very good results as long as links length is limited.

These results encourage us to continue with the search of an algorithm that guarantees minimal performance for the accepted transmissions. However, much work needs to be done, specially in the practical implementation of the decentralized algorithms. Among the most important open questions let us quote the impact of a maximum transmission power on PCBA and the extension of the proposed mechanisms to more dynamic scenarios. The analysis of the non slotted version of these algorithms is undoubtedly challenging and necessary. It would be interesting for instance to check whether the starvation phenomena experienced by CSMA are still present or not for the mechanisms proposed in this work.

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