Radio Link Admission Algorithms for Wireless Networks with Power Control and Active Link Quality Protection

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Abstract

In this paper we present a distributed power control scheme, which maintains the SIRs of operational (active) links above their required thresholds at all time (link quality protection), while new users are being admitted; furthermore, when new users cannot be successfully admitted, existing ones do not suffer fluctuations of their SIRs below their required thresholds values. We also present two admission/rejection control algorithms, which exercise voluntary drop-out of links inadmissible to the network, so as to reduce interference and possibly facilitate the admission of other links.

1 Introduction

Power control increases capacity in wireless networks by managing co-channel interference, resulting in efficient channel reuse. Early works on power control by Aein [1] and Nettleton [2] are based on the idea of balancing (equalizing) the SIRs on all radio links. Zander [3] and Gradhi, Vijayan & Goodman [4] have recently developed distributed versions of the SIR balancing algorithm. The SIR balancing approach has the nice property of quick, geometric convergence. However, several problems exist: (1) The final SIR achieved by SIR balancing may be unsatisfactory for every link. (2) Since SIR balancing equalizes SIR on all links, links with different SIR requirements (speech vs. data) cannot be accommodated. (3) Centralized control is needed to renormalize transmitter powers, which compromises the distributed property of the algorithm. We have proposed a global and a localized power control schemes [5, 6] free of the above problems, and guarantee that each user meets its SIR requirement. However, these two schemes are not fully distributed and require coordination between users.

Foschini & Miljanic [8] and Mitra [10] have proposed a fully distributed and asynchronous power control scheme that solves problem (2) and (3), by using transmitter power updates which incorporate SIR requirements and minimize the transmitter powers. However, when new links try to get admitted to the network, already established (active) ones may see their SIRs drop below their required thresholds, leading to inadvertent dropping of ongoing calls, because links are rendered unreliable. Moreover, if the SIR requirements cannot be simultaneously satisfied, the transmitter powers diverge to infinity.

We present a power control scheme that provably suppresses (rejects) the links which are below their SIR requirements, if links above the SIR requirements cannot tolerate additional interference. This scheme provably protects the operational links and prevents the dropping of on-going calls. We also present two call rejection schemes, which are based on voluntary drop-out of links that cannot become operational, due to network saturation. This work

*Corresponding author. Work supported in part by contracts NSF-NCR-9116268, ARPA-CSTO-93-112, and a National Young Investigator Award NSF-NCR-9258507.

†Work supported in part by contract ARPA-DAAB07-93-C-C501.

extends in several directions that of [7]. Due to restricted space, only key ideas and theorems are provided without any detailed proofs or extensive simulation results. A complete presentation of the issues is given in [14, 15].

2 The System Model

We assume that interference between different channels is negligible and consider only radio links operating in the *same channel* and the related *co-channel interference*. The bit-error-rate on each link in the channel is a function of the signal to interference ratio (SIR), which is

$$R_i = \frac{G_{ii}P_i}{\sum_{j\neq i} G_{ij}P_j + \eta_i}, \quad i = 1, 2 \dots N \quad , \qquad (1)$$

given that there are N transmitter-receiver pairs (links) communicating in the channel under consideration. $G_{ij} > 0$ is the power gain (actually, propagation loss) from the j-th transmitter to the i-th receiver and P_i is the power of the i-th transmitter. The thermal noise power at the i-th receiver is $\eta_i > 0$. For each link, there is a SIR threshold requirement γ_i, reflecting a certain *quality of service* that the link requires in order to operate properly. Therefore, we need to have

$$R_i \geq \gamma_i, \quad i = 1, 2 \dots N \quad . \qquad (2)$$

In matrix form, the SIR requirements in (2) can be written as

$$(\mathbf{I} - \mathbf{F})\mathbf{P} \geq \mathbf{u} \text{ and } \mathbf{P} \geq 0, \qquad (3)$$

where $\mathbf{P} = (P_1, P_2, ...P_i, ...P_N)'$ is the column vector of transmitter powers,

$$\mathbf{u} = (\frac{\gamma_1\eta_1}{G_{11}}, \frac{\gamma_2\eta_2}{G_{22}}, \frac{\gamma_3\eta_3}{G_{33}}, \dots \frac{\gamma_i\eta_i}{G_{ii}}, \dots \frac{\gamma_N\eta_N}{G_{NN}})' \qquad (4)$$

is the column vector of thermal noise powers rescaled by SIR targets and link power gains, and finally $\mathbf{F}$ is the matrix with entries

$$F_{ij} = \begin{cases} 0 & \text{if } i = j \\ \frac{\gamma_i G_{ij}}{G_{ii}} & \text{if } i \neq j \end{cases} \quad . \qquad (5)$$

Following the discussion in [10], we point out the following properties. The matrix $\mathbf{F}$ has non-negative elements and it is reasonable to assume that it is *irreducible*, since we are not considering totally isolated groups of links that do not interact with each other; therefore, by the Perron-Frobenious theorem [12], [13], [10], [8] we have that maximum modulus eigenvalue of $\mathbf{F}$ is real, positive and simple, while the corresponding eigenvector is positive componentwise. Denote the *maximum modulus eigenvalue* of $\mathbf{F}$ by λ_F. We then have the following fact.

Fact 1: *The following statements are equivalent:*

1. *There exists a power vector* $\mathbf{P} > 0$ *such that* $(\mathbf{I} - \mathbf{F})\mathbf{P} \geq \mathbf{u}$.
2. $\lambda_F < 1$
3. $(\mathbf{I} - \mathbf{F})^{-1} = \sum_{k=0}^{\infty} \mathbf{F}^k$ *exists and is positive component-wise.*

Also, if (3) has a solution, then

$$\mathbf{P}^* = (\mathbf{I} - \mathbf{F})^{-1}\mathbf{u} \qquad (6)$$

is a Pareto optimal solution of (3), in the sense that any other $\mathbf{P}$ satisfying (3) would require as much power from every transmitter [10], i.e.

$$\mathbf{P} \geq \mathbf{P}^* \quad . \qquad (7)$$

Therefore, if it is possible to satisfy the SIR requirements for all links simultaneously, a good power control strategy is to set the transmitter powers to $\mathbf{P}^*$.

Foschini & Miljanic [8] and Mitra [10] have investigated the following distributed iterative power updating algorithm, which has been shown to converge to $\mathbf{P}^*$ (*when that exists*):

$$\mathbf{P}(k+1) = \mathbf{F}\mathbf{P}(k) + \mathbf{u}, \qquad (8)$$

where $k = 1, 2, 3, ...$

The above algorithm can be simplified. Actually, only the signal to interference ratio at the receiver R_i is needed for the update. Observe that according to (8) the updates for the i-th link can be written as

$$P_i(k+1) = \frac{\gamma_i}{G_{ii}}(\sum_{j\neq i} G_{ij}P_j(k) + \eta_i). \qquad (9)$$

However, from (1) we have

$$\sum_{j\neq i} G_{ij}P_j(k) + \eta_i = \frac{G_{ii}P_i(k)}{R_i(k)}, \qquad (10)$$

and substituting in the previous expression, we get the following simplified form of the updating procedure in (8):

$$P_i(k+1) = \frac{\gamma_i}{R_i(k)} P_i(k) \quad . \qquad (11)$$

This updating rule specifies that the current transmitter power should be adjusted by a factor that is equal to the ratio of the target SIR γ_i over the measured SIR at the receiver. We note that this power updating rule looks similar to that proposed in [3, 4] for SIR balancing with the renormalization constant as γ_i.

3 An Algorithm for Distributed Power Control with Active Link Protection (DPC-ALP).

We want to develop a power control scheme which provides protection for links that are currently operational, in the sense that the SIRs of all operational links are maintained above their targets at all times, as new links try to enter the network; if the latter cannot be accommodated they are simply suppressed, without hurting the operational ones during the process. Below we develop such an algorithm which we call DPC-ALP algorithm (Distributed Power Control with Active Link Protection)

The DPC-ALP algorithm works by updating transmitter powers on the communication links (intended transmitter-receiver pairs) in steps indexed by $k = 1, 2, 3, ...$ Let $\mathcal{L}$ be the set of all links.

We define link $i \in \mathcal{L}$ to be *active* or *operational* during the k-th step if and only if

$$R_i(k) \geq \gamma_i. \qquad (12)$$

Let $\mathcal{A}_k$ be the set of all active links during the k-th step. We also define link $i \in \mathcal{L}$ to be *non-active* or *non-operational* or *new* (trying to get on the network with acceptable SIR, but currently not having achieved it) during the k-th step if and only if

$$R_i(k) < \gamma_i. \qquad (13)$$

Let $\mathcal{B}_k$ be the set of all non-operational links during the k-th step. Finally, let δ be a fixed parameter of the DPC-ALP algorithm, such that

$$\delta > 1, \qquad (14)$$

which is arbitrarily chosen at this point.

Algorithm 1: DPC-ALP (Distributed Power Control with Active Link Protection) *The DPC-ALP algorithm operates by updating transmitter powers $P_i(k+1)$ during the $(k+1)$-st step according to the following rule:*

$$P_i(k+1) = \begin{cases} \frac{\gamma_i \delta}{R_i(k)} P_i(k), & \text{if} \quad i \in \mathcal{A}_k \\ \delta P_i(k), & \text{if} \quad i \in \mathcal{B}_k \end{cases} \qquad (15)$$

The above DPC-ALP updating procedure makes two modifications to the original distributed power updating scheme (11):

1) It artificially raises the SIR target threshold for each active link in $\mathcal{A}_k$ to $\delta\gamma_i$ to provide a *protection margin* for SIRs of operational links,

2) It powers up each new link $i \in \mathcal{B}_k$ gradually, boosting its power by a factor of δ at every step. The objective is to induce a limited degradation on each already link at each step as new link is powering up.

The DPC-ALP algorithm has two potential drawbacks: First, the convergence rate could be slower than that of (11), because the new links can only power up at a constant factor-rate of δ. Secondly, in effect the SIR targets of all links are boosted by δ, the network capacity is reduced, due to the more stringent SIR requirements. However, both effects can be minimized by controlling the parameter δ, and the algorithm exhibits nice behavior. Its key beneficial properties are presented below:

Proposition 1: (Protection of Active Links) *For any fixed $\delta \in (1, \infty)$, we have that for every $k \in \{0, 1, 2, 3...\}$ and every $i \in \mathcal{A}_k$*

$$R_i(k) \geq \gamma_i \Rightarrow R_i(k+1) \geq \gamma_i, \qquad (16)$$

under the DPC-ALP power updating algorithm. Therefore,

$$i \in \mathcal{A}_k \Rightarrow i \in \mathcal{A}_{k+1} \tag{17}$$

Proof: The proof can be found in [7, 15]. □

REMARK 1: Proposition 1 shows that initially active links remain so throughout the evolution of the DPC-ALP algorithm, while non-active (new) ones may become active at some point, in which case they remain so forever after. This fits nicely with the notion of admitting new links into the network by rendering them active (when that is possible).

Proposition 2: (Increasingness of the SIRs of Non-Active Links) *For any fixed $\delta \in (1, \infty)$, we have that for every $k \in \{0, 1, 2, 3...\}$ and every $i \in \mathcal{B}_k$*

$$R_i(k) \leq R_i(k+1), \tag{18}$$

under the DPC-ALP power updating algorithm.

Proof: The proof can be found in [7, 15]. □

REMARK 2: Proposition 2 shows that the SIR of every currently non-active (new) link is non-decreasing during every step of the DPC-ALP algorithm, thus, continuously improving. By doing so, the link may reach at some time its intended target SIR requirement (if possible), in which case it becomes active and remains so forever after.

Proposition 3: (Bounded Power Overshoot) *For any fixed $\delta \in (1, \infty)$, we have that for every $k \in \{0, 1, 2, 3...\}$ and every $i \in \mathcal{A}_k$*

$$P_i(k+1) \leq \delta P_i(k), \tag{19}$$

under the DPC-APL power updating algorithm.

Proof: The proof can be found in [15]. □

REMARK 3: A major concern regarding the evolution of all power control algorithms is the magnitude of power fluctuations. This property shows that power overshoots under DPC-ALP are bounded by δ. Therefore the powers on each link change in a controlled smooth manner.

4 Admission of New Links into the Wireless Network under the DPC-ALP Algorithm.

We first prove a proposition which illustrates the behavior of the system when no non-active link ever becomes activated under DPC-ALP; in this case we call the new links *totally inadmissible*. This proposition is used later to prove that if there is a feasible power configuration under which all links (active and new) can satisfy their SIR requirements, then the DPC-ALP algorithm will eventually activate all the originally non-active links.

We consider a group of $N + M$ links, such that (originally) the ones in the set

$$\mathcal{A}_0 = \{1, 2, 3, ...N-1, N\} \tag{20}$$

are active, while the ones in the set

$$\mathcal{B}_0 = \{N+1, N+2, N+3, ...N+M-1, N+M\} \tag{21}$$

are non-active (new). In view of propositions 1 and 2, we are interested in studying whether the non-active links will eventually be activated by the DPC-ALP algorithm.

Proposition 4: (The Case of Totally Inadmissible New Links) *Given that the system operates under the DPC-ALP algorithm, if*

$$\mathcal{A}_k = \mathcal{A}_0 \neq \emptyset \quad \text{and} \quad \mathcal{B}_k = \mathcal{B}_0 \neq \emptyset, \tag{22}$$

for every $k \in \{1, 2, 3, ...\}$, then the following limits exist:

$$\lim_{k \to \infty} R_i(k) = R_i^* < \infty \tag{23}$$

and

$$\lim_{k \to \infty} \frac{P_i(k)}{\delta^k} = D_i^* < \infty \tag{24}$$

Moreover,

$$R_i^* = \gamma_i \quad \textit{for every initially active link} \quad i \in \mathcal{A}_0, \tag{25}$$

while

$$R_i^* \leq \gamma_i \quad \textit{for every initially non-active link} \quad i \in \mathcal{B}_0. \tag{26}$$

Proof: Due to space restriction, we will only give a sketch of the proof. A complete proof can be found in [14] and [15]. For initially non-active links, the results follow from increasingness in SIR (proposition 2) and that $\forall i \in \mathcal{B}_k,\ P_i(k) = \delta^k P_i(0)$. For each initially active link where $i \in \mathcal{A}_k$, we can express $P_i(k)/\delta^k$ as a weighted sum of three components: thermal noise powers, original powers of initially active links $P_j(0)$ ($j \in \mathcal{A}_0$) and original powers of initially inactive links $P_l(0)$ ($l \in \mathcal{B}_0$). Letting $k \to \infty$ and applying fact 1 for the link system involving only active links, we find that the limit of each component exists, and only the third component converges to a non-zero value and it can be computed. Substituting $\lim_{k \to infty} P_i(k)/\delta^k$ into our expression in (1) for R_i yields the desired result of $R_i^* = \gamma_i$. □

<u>*REMARK 4*</u>: Proposition 3 shows that if no initially non-active links in $\mathcal{B}_0$ ever becomes active, then the SIRs of the active ones in $\mathcal{A}_0$ converge to their lowest acceptable values γ_i, while the powers of all links blow up to infinity geometrically (proportionally to δ^k).

We can now study the situation where the $\mathcal{B}_0$ links are *fully admissible* to the network, in the sense that there exists a configuration of transmitter powers that satisfies the SIR requirements of all links in $\mathcal{A}_0 \bigcup \mathcal{B}_0$. That is, there is a positive power vector $\mathbf{P} > 0$ such that $(\mathbf{I} - \mathbf{F})\mathbf{P} \geq \mathbf{u}$, or equivalently (by Fact 1)

$$(\mathbf{I} - \mathbf{F})^{-1} \quad \text{exists and has positive entries,} \quad (27)$$

where $\mathbf{F}$ and $\mathbf{u}$ are defined as in section 2.

Proposition 5: (The Case of Fully Admissible Links) *If the initially non-active links in $\mathcal{B}_0$ are fully admissible, then there exists a finite time $k_o < \infty$ such that*

$$\mathcal{A}_k = \mathcal{A}_0 \bigcup \mathcal{B}_0, \quad \textit{for every} \ \ k \in \{k_o, k_o{+}1, k_o{+}2, \ldots\}. \quad (28)$$

Therefore, if the SIR requirements of all links are compatible, they will all eventually become active, and get admitted into the network.

Proof: Due to space restriction, only a sketch of the proof is given here. Please refer to [14, 15] for details. It is only necessary to show that there is a finite time when a link will move from the non-active to the active set, since each link in the active set will stay there forever. Arguing by contradiction, we assume on the contrary that all non-active links will stay in the non-active set indefinitely. Then letting $\mathbf{D}^* = \lim_{k \to \infty} \mathbf{P}/\delta^k$ and the fact from proposition 3 that $\forall i \in \mathcal{A}_0,\ R_i^* = \gamma_i$ and $\forall i \in \mathcal{B}_0,\ R_i^* \leq \gamma_i$, we obtain $(\mathbf{I} - \mathbf{F})^{-1} \leq 0$, which leads to a contradiction because $\mathbf{D}^* \neq 0$ and $(\mathbf{I} - \mathbf{F})^{-1} \geq 0$ from fact 1. □

<u>*REMARK 5*</u>: Proposition 4 shows that if the SIR requirements of all links are compatible, they will all eventually become active, and be admitted into the network. According to Proposition 1, they will remain active forever thereafter (or until they complete their intended communication).

The cases treated in propositions 1 and 2 provide fundamental insights into the dynamics of the DPC-ALP algorithm, and prove that the admission scheme behaves as it should in the extreme cases of totally inadmissible and fully admissible new links. However, in general, as the DPC-ALP algorithm evolves, some originally non-active mobiles will be admitted into the network (becoming active), and these will saturate the network to the point that some others will never achieve their target SIRs, remaining out of the network forever. We study this situation next.

5 The Case of Partially Admissible New Links — DPC-ALP with Voluntary Drop-Out.

5.1 SIR Saturation Based Drop-Out

We now propose an admission algorithm for activating new links in a wireless network. The admission process works as follows. Active links update their power according to the plain DPC-ALP algorithm (15). Each new (non-active) link i will keep trying to become active as long as it sees some minimum SIR improvement over a recent memory window of length M_i. If persistently (for more then M_i steps) no such improvement occurs, link i starts flipping a coin to decide whether to drop out in the following step or not. Coin flips are independent of each other and the drop-out probability is a decreasing function of the difference between the current SIR of the link and its target one.

As explained in the previous sections, because of Proposition 2, if the channel is congested and link

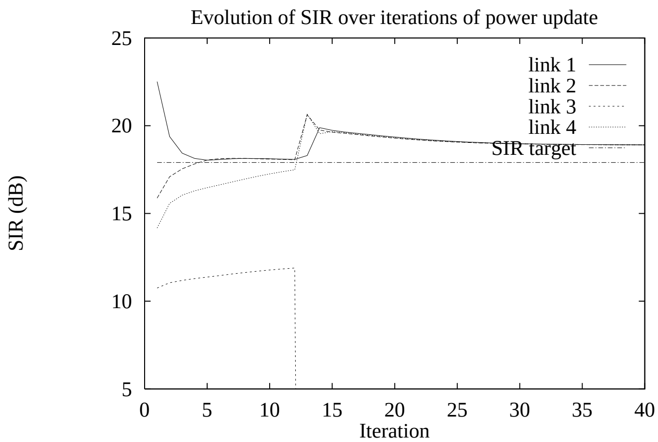

Figure 1: Evolution of the SIRs of the four mobile-to-base links under the DPC-ALP power control algorithm with SIR targets γ set 2dB above the SIR threshold achievable by all links.

i is not admissible, the latter will see its SIR become saturated below its target value. Repeated increases in power will not bring about significant SIR improvement indicating congestion in network. The link will therefore sense congestion and initiate the randomized drop-out process. If some other link drops out sooner, the one under consideration may experience some significant improvement of its SIR, which will restart the overall admission process giving a stronger chance to end successfully.

We have simulated the above algorithm for a cellular wireless network of four base stations located at the corners of a square. A mobile is generated around each base station. All target SIR requirements are taken to be equal to γ. We observe the evolutions of the SIRs on the uplinks (mobiles sending to base stations) under the DPC-ALP power update algorithm with δ set to 1 dB (SIR scales are logarithmic and units are dBs in this study). If an inactive link fails to improve its SIR by 0.1 dB for each dB increase in power after two consecutive power updates, it voluntarily drops out of the network.

Figures 1 show the evolution of each link's SIR over each iteration of the DPC-ALP algorithm for the same mobile-to-base configuration, when the SIR target γ is set at a level that is not achievable (Figure 1). The DPC-ALP algorithm exhibits the following behavior, as expected: (1) It maintains the SIR of every initially active link above its target threshold. (2) It suppresses the SIR of every link that fails to rise above its SIR target to become active; in this case these are links 3 and 4. (3) After two consecutive iterations where link 3 sees its SIR failing to improve by 0.1 dB for each dB increase in power, it concludes that the channel is congested and drops out of the channel voluntarily. (4) The drop-out of link 3 reduces interference in the channel and allows link 4 to become active.

The previous simulated example indicates that by allowing new links in a congested channel to drop out, we would alleviate congestion and make it easier for other new links to become active and get on the network. A link that drops out of some channel may try to get on another channel or even the same after a while. Next we present another strategy for link activation based on time out.

5.2 Time-Out Based Drop-Out

Another approach is to use the idea of a *time-out* period during which a new link tries to gain admission. All active links update their power according to the plain DPC-ALP algorithm (15). Each new (non-active) link i initially sets a target time span T_i for achieving admission, and tries to become active (until time T_i), updating its power according to the plain DPC-ALP algorithm. If it is not successful by time T_i, the link then computes a drop-out horizon D_i, as a (decreasing) function of the distance of its current SIR from its target one γ_i; the larger the distance the smaller the D_i. We choose $D_i = f_i(\gamma_i - R_i(T_i)) = \lfloor A_i e^{-\alpha_i(\gamma_i - R_i(T_i))} \rfloor$ where A_i and α_i are constants used to control the drop out horizon, $\lfloor\ \rfloor$ denotes the integer part of the argument. The link then continues to try to become active until time $(T_i + D_i)$ only, using plain DPC-ALP power updates.

If the link has not gained admission by time $(T_i + D_i)$, it drops out voluntarily, self-terminating its current admission process (it may reinitiate it later in the same or another channel after a back-off time B_i) The dropping out of this link reduces the interference on other links competing for admission in this channel and gives them a better chance of succeeding.

Let $l.u.$ be the length unit and $t.u.$ the time unit, that is the duration of a time slot. We have performed simulations [15] using the time-out based drop out for a wireless network spanning a $500 l.u. \times 500 l.u.$ region. Calls are generated according to a Bernoulli (geometric) process of arrival rate density λ_d $arrivals/(t.u. \times l.u.^2)$. We assume a single communication channel. When a link gains admission, the link communicates for a geometrically distributed time S with mean $1000 t.u.$ If a link drops out voluntarily, it reinitiates the admission process after a back off time B geometrically distributed with mean $100 t.u.$ The link transmitter is placed in the square region with uniform distribution and the receiver is placed isotropically around the transmitter at a mean length of $10 l.u.$ The power attenuation is assumed to follow the inverse fourth power law and the SIR requirement on each link is set to 7 dB. We set $\alpha_i = 0.23$ for every link. We set $\delta = 1.1$ for the DPC-ALP power update.

In figure 3, we observe that when inactive links never drop out, the network capacity is approximately $0.5 \times 10^{-7} arrivals/(t.u \times l.u.^2)$. However when the voluntary drop out (VDO) is implemented with $T = 20 t.u.$ and $A = 100 t.u.$, the network capacity increases to $6.8 \times 10^{-7} arrivals/(t.u. \times l.u.^2)$, a 14-fold increase over the no drop-out case. The reason for this is that the temporary backing off of some inactive links reduces interference and gives other links a better chance of gaining admission. Otherwise no additional links can gain admission and the channel clogs up quickly as more links arrive.

We next look at the effect of the length of time out. In figure 4, we note that as T decreases below 10 $t.u.$, the admission delay rises sharply. The reason is that most inactive links drop out prematurely. They would have gained admission had they persisted for a few more steps. The repeated retries by the links to gain admission build up interference and clog up the channel. On the other hand, as T increases beyond $20 t.u.$, the links tend to stay in the network more than necessary before dropping out, making it more difficult for other links to gain admission and increasing admission delays.

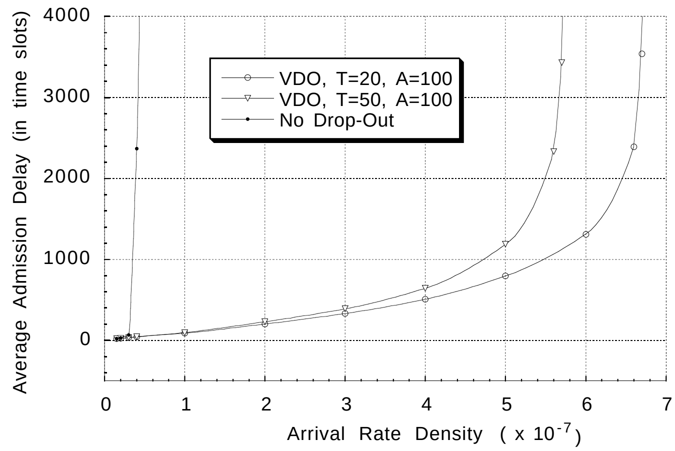

Figure 2: Average admission delay of a call (link) as a function of the arrival rate density λ_d for the cases of 1) voluntary drop-out (VDO) with $T = 20\ t.u.$ and $A = 100\ t.u.$, 2) voluntary drop-out with $T = 50\ t.u.$ and $A = 100\ t.u.$, and 3) no drop-out.

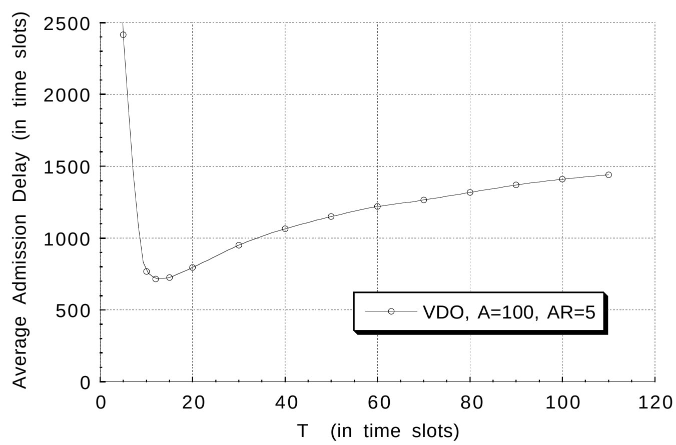

Figure 3: Average admission delay as a function of T for the case of voluntary drop-out (VDO) with $A = 100\ t.u.$ at fixed arrival rate (AR) density $\lambda_d = 5 \times 10^{-7}$ $arrivals/(t.u. \times l.u.^2)$.

6 Conclusions

We have presented a fully distributed, power control based, call admission-rejection scheme for wireless communication networks, which provably maintains the quality of (protects) operational transmission links while new links are trying to enter the network. Two distributed drop-out algorithms have also been provided, based on which inadmissible links drop-out voluntarily to reduce the channel congestion. We have observed that voluntary drop-out of congesting link increases the network throughput.

Extensive simulations of the power update scheme and drop out algorithms have been performed to study the behavior of the algorithm under different parameters, power range, etc. These results are reported in the paper [15].

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