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A Channel Probing Scheme for Wireless Networks

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Abstract — **A channel probing scheme for wireless networks is presented. By transmitting a probing signal in a channel and measuring the signal-to-interference ratio (SIR), a link can estimate the channel condition and predict the required transmission power without fully powering up. The channel probing scheme can be used as part of a distributed channel allocation algorithm, and simulations have shown that it outperforms some other comparable schemes.**

I. Introduction

Power control and dynamic channel allocation are two effective means to improve the capacity of a wireless network [1, 2, 3]. When trying to combine the two together, one is faced with the problem of how to characterize the channel congestion and how each individual link can use such information to make its channel selection. The current work introduces a channel probing scheme which allows a link to probe a channel and estimate the channel condition, and to further predict the required transmission power to meet its SIR. It is a fully distributed scheme which requires no communication between different links. By probing the channels, a link can make the best channel selection. The blocking probability for new arrivals, and the relocation and dropping probability for on-going transmissions are evaluated with simulations.

II. The system model

The power control algorithm used is the same as that in [3]. Suppose that there are M active links, labeled 1 through M, in a given channel. Each link consists of a transmitter and a receiver, and has a target signal-to-interference ratio γ^t. Let $g_{i,j}$ be the propagation gain between the jth transmitter and the ith receiver, and $G = [g_{i,j}]$ be the transmission gain matrix of the system. The SIR of a link is determined by the transmission powers of the active links, the transmission gain, the target SIR and the noise n_i at the receivers. When inter-channel interference is neglected, the SIR of link i is given by:

$$\gamma_i = \frac{g_{i,i}p_i}{n_i + \sum_{j=1,j\neq i}^{M} g_{i,j}p_j} = \frac{p_i}{v_i + \sum_{j=1}^{M} z_{i,j}p_j}, \qquad (1)$$

where $p_j > 0$ is the transmission power of link j. The quantities $z_{i,j}$ and v_i are the normalized transmission gain and receiver noise, defined as

$$v_i = \frac{n_i}{g_{i,i}}, \quad z_{i,j} = \begin{cases} \frac{g_{i,j}}{g_{i,i}} & \text{if } i \neq j \\ 0 & \text{if } i = j \end{cases}.$$

Transmission power control is applied is to make sure that the SIR γ_i of every link $\gamma_i \geq \gamma^t$, for $i = 1, 2, ...M$. Based on its SIR, each link updates its transmission power as,

$$p_i(k+1) = \min(\frac{\gamma^t}{\gamma_i}p_i(k), p_{max}), \quad i = 1, 2, ...M, \qquad (2)$$

where p_{max} is the maximal transmission power of the transmitter. When the maximal power p_{max} is not a constraint, the power control algorithm will converges to a unique solution

$$P^* = (I - \gamma^t Z)^{-1}\gamma^t V, \qquad (3)$$

in which $V = [v_1, v_2, ..., v_M]'$ and I is the identity matrix, if and only if the Perron eigenvalue (the largest eigenvalue) of matrix $Z = [z_{i,j}]$, $\rho_P(Z)$, satisfies $\rho_P(Z) < \frac{1}{\gamma^t}$ [4]. The M links are called admissible if they can all achieve their target SIRs, and inadmissible otherwise. In the latter case the system is called interference-limited, because the interference cannot be overcome simply by increasing the transmission power. When the maximal transmission power is taken into consideration, it is also necessary that

$$P^* \leq p_{max}. \qquad (4)$$

If $\rho_P(Z) < \frac{1}{\gamma^t}$ but the transmitters do not have enough power, the system is called power limited. Such a system can be made admissible by increasing the maximal transmission power constraint.

III. The channel probing algorithm

The channel probing mechanism is based on the fact that the set of active links update their transmission power constantly, and will react to increased interference in the channel by increasing their own power levels. When a set of new links join the channel and start to transmit, these active links experience additional interference, and as a consequence, will raise their powers accordingly. Their power increase is proportional to the power of the new links. If the new links transmit their signals at predefined power level and measure the corresponding SIR, it can estimate the channel condition. This is called channel probing. These new links, by probing a channel, can predict whether the channel is admissible, and if the answer is yes, what is the required transmission power. To simplify the analysis, we ignore the maximal power constraint in the next two sections, and assume the transmitters always have enough power. The effect of limited p_{max} will be discussed in Section V. The detail of the channel probing algorithm is given below:

Suppose a set of M links, 1 to M, are already transmitting in a channel, and they apply power control and have achieved their SIR balance with target SIR γ^t. Their transmission power vector is given by

$$P^M = (I - \gamma^t Z^M)^{-1}\gamma^t(V^M + E^M), \qquad (5)$$

where $P^M = [p_1, p_2, ..., p_M]'$ is their transmission power vector, $Z^M = [z_{i,j}]_{\{1,...,M\}\times\{1,...,M\}}$ is the interference matrix associated with the M links, $V^M = [v_1, v_2, ..., v_M]'$ is their receiver noise vector, and E^M is an extraneous noise vector. When a set of new links ($M+1$ to $M+N$) start to transmit in the same channel with transmission power vector $P^N = [p_{M+1}, ..., p_{N+N}]'$, they cause additional interference to the M existing links

$$E^M = E^M(P^N) = Z_N^c P^N, \tag{6}$$

where $Z_N^c = [z_{M+1}^c, z_{M+2}^c, ..., z_{M+N}^c]$, $z_j^c = [z_{1,i}, z_{2,j}, ..., z_{M,j}]'$. After re-balancing their SIRs, the powers of the M existing links become

$$\begin{aligned} P^M(P^N) &= (I - \gamma^t Z^M)^{-1}\gamma^t(V^M + Z_N^c P^N) \\ &= P^M(0) + (I - \gamma^t Z^M)^{-1}\gamma^t Z_N^c P^N. \end{aligned} \tag{7}$$

Note that the power increase is proportional to the transmission power P^N of the new links. The SIR of a new link k, $M+1 \le k \le M+N$, is given by

$$\begin{aligned} \gamma_k(P^N) &= \frac{p_k}{v_k + \sum_{i=1}^{M} z_{k,i} p_i(P^N) + \sum_{j=M+1}^{M+N} z_{k,j} p_j} \\ &= \frac{p_k}{\alpha_k + \sum_{j=M+1}^{M} \beta_{k,j} p_j}. \end{aligned} \tag{8}$$

where

$$\alpha_k = v_k + z_k^s P^M(0) \tag{9}$$

is the (normalized) noise and interference power at receiver k before the new links emit any power, and $\beta_{k,j}$ is given by

$$\begin{aligned} B^N &= [\beta_{k,j}]_{\{M+1,...,M+N\}\times\{M+1,...,M+N\}} \\ &= Z^N + Z_N^s(I - \gamma^t Z^M)^{-1}\gamma^t Z_N^c, \end{aligned} \tag{10}$$

and $Z^N = [z_{i,j}]_{\{M+1,...,M+N\}\times\{M+1,...,M+N\}}$, $Z_N^s = [{z_{M+1}^s}', {z_{M+2}^s}', ..., {z_{M+N}^s}']'$, $z_j^s = [z_{j,1}, z_{j,2}, ..., z_{j,M}]$. Note that each component of B^N is positive, and B^N is an all positive matrix. The positivity of B^N will play a major role later. Matrix B^N represents the interference among the N new links, and consists of two parts: the direct interference through propagation gain matrix (Z^N) and the indirect interference through the M active links. If these N new links update their transmission powers and achieve target SIR γ^t, their transmission powers are given by

$$P^N = (I - \gamma^t B^N)^{-1}\gamma^t A, \tag{11}$$

where $A = [\alpha_{M+1}, \alpha_{M+2}, ..., \alpha_{M+N}]'$, and the transmission powers of the M active links become

$$\begin{aligned} P^M &= (I - \gamma^t Z^M)^{-1}(V^M + Z_N^c P^N) \\ &= (I - \gamma^t Z^M)^{-1}(V^N + Z_N^c(I - \gamma^t B^N)^{-1}\gamma^t A). \end{aligned} \tag{12}$$

The N new links and the M existing links can achieve their target SIRs if and only if $(I - \gamma^t B^N)^{-1} > 0$ element wise, or equivalently, $\rho_P(B^N) < \frac{1}{\gamma^t}$. This is proved as follows:

Proposition 1: The channel is feasible for all the M active links as well as the N new links if and only if $\rho_P(B) < \frac{1}{\gamma^t}$, where $\rho_P(B)$ is the Perron eigenvalue of the B matrix.

Proof: The channel is feasible for the $M+N$ links iff $(I - \gamma^t Z^{M+N})^{-1} > 0$, where Z^{M+N} is the propagation matrix associated with the $M+N$ links. Rewrite Z^{M+N} as

$$Z^{M+N} = (z_{i,j})_{(M+N)\times(M+N)} = \begin{pmatrix} Z^M & Z_N^c \\ Z_N^s & Z^N \end{pmatrix},$$

and

$$\begin{aligned} (I - \gamma^t Z^{M+N})^{-1} &= \begin{pmatrix} I - \gamma^t Z^M, & -\gamma^t Z_N^c \\ -\gamma^t Z_N^s, & I - \gamma^t Z^N \end{pmatrix}^{-1} \\ &= \begin{pmatrix} C_{11}, & C_{12} \\ C_{21}, & C_{22} \end{pmatrix}, \end{aligned} \tag{13}$$

where

$$\begin{aligned} C_{11} &= (I - \gamma^t Z^M)^{-1} + {\gamma^t}^2 (I - \gamma^t Z^M)^{-1} Z_N^c * \\ &\quad (I - \gamma^t Z^N - {\gamma^t}^2 Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c)^{-1} * \\ &\quad Z_N^s (I - \gamma^t Z^M)^{-1}, \\ C_{12} &= \gamma^t (I - \gamma^t Z^M)^{-1} Z_N^c * \\ &\quad (I - \gamma^t Z^N - {\gamma^t}^2 Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c)^{-1}, \\ C_{21} &= \gamma^t (I - \gamma^t Z^M - {\gamma^t}^2 Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c)^{-1} * \\ &\quad Z_N^s (I - \gamma^t Z^M)^{-1}, \\ C_{22} &= (I - \gamma^t Z^N - {\gamma^t}^2 Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c)^{-1}. \end{aligned}$$

The fact that the M active links transmit in the same channel implies $(I - \gamma^t Z^M)^{-1} > 0$. Therefore the inequality holds iff

$$(I - \gamma^t Z^N - {\gamma^t}^2 Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c)^{-1} > 0, \tag{14}$$

and this is true iff

$$\rho_P(\gamma^t Z^N + {\gamma^t}^2 Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c) < 1, \tag{15}$$

or equivalently

$$\rho_P(Z^N + \gamma^t Z_N^s (I - \gamma^t Z^M)^{-1} Z_N^c) = \rho_P(B^N) < \frac{1}{\gamma^t}. \tag{16}$$

Q.E.D.

If the B^N matrix is known, we can check the feasibility condition ($\rho_P(B^N) < \frac{1}{\gamma^t}$) and calculate the required transmission power, and the problem is solved. However, it is very difficult, if not impossible, for the links to calculate (or estimate) the individual $\beta i, j$ in a distributed fashion. The following channel probing scheme is proposed as a way for the individual links to estimate the feasibility of the channel:

Each new link probes the channel by transmitting a probing signal, or "probing tone", with transmission power p^{ps}, and measure the corresponding SIR. The probing signal can simply be a predefined training sequence, or carry some basic information. All the probing nodes transmit with the same p^{ps}, and $P^N = p^{ps}\mathbf{1}$, where $\mathbf{1}$ is the all 1 column vector of length N. The SIR of link k during probing, γ_k^p, is given by

$$\begin{aligned} \gamma_k^p &= \gamma_k(p^{ps}\mathbf{1}) = \frac{p^{ps}}{\alpha_k + p^{ps}\sum_{j=M+1}^{M+N} \beta_{k,j}} \\ &= \frac{p^{ps}}{\alpha_k + p^{ps}\beta_k}, \end{aligned} \tag{17}$$

where $\beta_k = \sum_{j=M+1}^{M+N} \beta_{k,j}$. A link also measures the noise and interference at its receiver *before* transmitting the probing signal. By definition, this is α_k. With these information link k calculates β_k:

$$\beta_k = \frac{p^{ps} - \alpha_k \gamma_k^p}{p^{ps}\gamma_k^p}, \tag{18}$$

or, without measuring the SIR,

$$\beta_k = \frac{P_k^r(p^{ps}\mathbf{1}) - P_k^r(0) - p^{ps}}{p^{ps}} = \frac{P_k^r(p^{ps}\mathbf{1}) - \alpha_k}{p^{ps}} - 1, \tag{19}$$

where $P_k^r(p^{ps}\mathbf{1})$ is the received power when the links are probing the channel, and $P_k^r(0) = \alpha_k$ is the received power before they do so. Much information is carried in α_k and β_k. Link k checks the local admissibility condition:

$$\beta_k < \frac{1}{\gamma^t}. \tag{20}$$

If this condition is satisfied, the channel is called locally admissible to link k, and the link estimates its transmission power as

$$ep_k = \frac{\gamma^t \alpha_k}{1 - \gamma^t \beta_k}, \tag{21}$$

or, in vector form,

$$EP^N = (I - \gamma^t W^N)^{-1}\gamma^t A^N, \tag{22}$$

where $W^N = diag(\beta_{M+1}, \beta_{M+2}, ..., \beta_{M+N})$. Although the N links probe the channel simultaneously, they each make their individual decisions based on their probing results (α_k and β_k), and the whole scheme is distributed. The relationship between the local and the global admissibility is discussed in the next section.

IV. Some properties of the channel probing algorithm

We now prove some important properties of the channel probing algorithm. In particular, we show the equivalence between the local admissibility condition of each link and the global feasibility condition of the entire network.

The relationship between the Perron eigenvalue $\rho_P(B^N)$ of the positive matrix B^N and the individual β_k is given by the following lemma [5]:

Lemma 2: $\min(\beta_i) \le \rho_P(B^N) \le \max(\beta_i)$, where $\beta_i = \sum_{j=M+1}^{M+N} \beta_{i,j}$, $i = M+1, M+2, ..., M+N$. The equality holds only if $\min(\beta_i) = \rho_P(B^N) = \max(\beta_i)$.

We are now ready to prove the main result.

Theorem 3:

1. Suppose a set of M links already transmit in a channel and have achieved their target SIRs. If a set of N new links probe the channel simultaneously, and the channel is globally feasible for all the $M+N$ links, then, by probing the channel, at least one of the N new links will find the channel admissible and will be able to join. If the remaining new links continue to probe, all of them will eventually be admitted into the channel after at most N iterations. The convergence is guaranteed and upper bounded by N. Thus global feasibility leads to local admissibility.
2. If the channel is not globally feasible for the $M+N$ links, then it is impossible for all the new links to locally find the channel admissible from probing. For the subset of new links which do find the channel admissible (could be an empty or non-empty set), the channel is globally feasible for these links as well as for the set of active links. A globally infeasible link is never admitted and, out of a set of globally infeasible new links, the channel probing scheme produces a subset which is indeed feasible.

Proof: If the channel is feasible for all the $M+N$ links, $\rho_P(B^N) < \frac{1}{\gamma^t}$. There are two possible cases. In the first case, $\min(\beta_i) \le \rho_P \le \max(\beta_i) < \frac{1}{\gamma^t}$, all the N new links find the channel admissible by probing the channel, and they can all join the channel immediately. In the second case, $\min(\beta_i) < \rho_P < \frac{1}{\gamma^t} < \max(\beta_i)$. Not all N new links find the channel admissible, but the channel appears admissible to at least one of them (link k, where $\beta_k = \min(\beta_i)$), and at least one link joins. If the remaining links continue to probe, after each iteration at least one link will join, and eventually all the N links are admitted into the channel after at most N iteration.

If the channel is not feasible for all the $M+N$ links, $\frac{1}{\gamma^t} \le \rho_P$. There are two possible cases. In the first case, $\frac{1}{\gamma^t} < \min(\beta_i) \le \rho_P \le \max(\beta_i)$, all of the N new links find the channel inadmissible and none joins. In the second case, $\min(\beta_i) < \frac{1}{\gamma^t} < \rho_P < \max(\beta_i)$, the channel appears admissible to some, but not all of the links. Without lose of generality, assume $\beta_i < \frac{1}{\gamma^t}$ for $i = M+1, M+2, ..., M+L$, and $\beta_i \ge \frac{1}{\gamma^t}$ for $i = M+L+1, M+L+2, ..., M+N$. Because links $M+L+1$ to $M+N$ find the channel inadmissible and will not join the channel, the feasibility of the L new links (from $M+1$ to $M+L$) as well as the M active links are determined by a new interference matrix $D = [d_{i,j}]_{\{L\times L\}}$, where

$$d_{i,j} = b_{i,j}, i, j = M+1, M+2, ..., M+N.$$

Define $d_i = \sum_{j=M+1}^{M+L} d_{i,j} = \sum_{j=M+1}^{M+L} b_{i,j} < \sum_{j=M+1}^{M+N} b_{i,j} = b_i$, and $d_i < b_i < \frac{1}{\gamma^t}$, for $i = M+1, ..., M+L$. Therefore $\rho_P(D) \le \max_{i=M+1}^{M+L} d_i < \max_{i=M+1}^{M+L} b_i < \frac{1}{\gamma^t}$, and the channel is feasible for the L new links and the M active links. In this case, out of N new links which are not all admissible, the channel probing algorithm produces a subset of L links which are indeed feasible.

If $N = 1$, $B^1 = \beta_{M+1,M+1} = \beta_{M+1} = W^1$, and the link can determine the channel status accurately. The estimated transmission power is also accurate, $ep_{M+1} = p_{M+1}$. When $N > 1$, in general $EP^N = (I - \gamma^t W^N)^{-1}\gamma^t A^N \ne (I - \gamma^t B^N)^{-1}\gamma^t A^N = P^N$. When we assume all the N new links find the channel admissible ($\beta_k < \frac{1}{\gamma^t}$ for all $M+1 \le k \le M+N$, or $W^N < \frac{1}{\gamma^t}I$), we can define estimation error as $dP = EP^N - P^N$ and prove the following theorem:

Theorem 4: When $N > 1$, a link may overestimate or underestimate its transmission power, but it is impossible for all the N new links to overestimate ($dP > 0$) or underestimate ($dP < 0$) their transmission powers simultaneously.

Proof: The matrix $(I - \gamma^t W^N)^{-1}$ is diagonal and all the diagonal elements are positive, and $(I - \gamma^t B^N)^{-1} > 0$. Hence all the off-diagonal elements of the matrix $(I - \gamma^t W^N)^{-1} - (I - \gamma^t B^N)^{-1}$ are negative. If there exists $A^N > 0$ such that the estimation error $dP = EP^N - P^N = ((I - \gamma^t W^N)^{-1} - (I - \gamma^t B^N)^{-1})\gamma^t A^N > 0$ (or < 0), a necessary and sufficient condition is that the matrix $U = ((I - \gamma^t W^N)^{-1} - (I - \gamma^t B^N)^{-1})^{-1}$ exists and is all positive (negative) [5, 6]. If U exists, it is given by

$$
\begin{aligned}
U &= ((I-\gamma^t W^N)^{-1} - (I-\gamma^t B^N))^{-1} \\
&= (\gamma^t (I-\gamma^t W^N)(W^N - B^N)^{-1}(I-\gamma^t W^N) + \\
&\quad (I-\gamma^t W^N) \qquad (23)
\end{aligned}
$$

However $\det(W^N - B^N) = 0$, and $(W^N - B^N)^{-1}$ does not exists. Because $(I - \gamma^t W^N)$ is a diagonal matrix with full rank, U does not exist, and, as a consequence, there does not exist $A^N > 0$ such that $dP > 0$ (or $dP < 0$). Q.E.D.

V. Effect of limited transmission power

In the discussions above, we assume that the links always have enough power to meet their target SIRs. When the maximal transmission power is limited, it is possible that a transmitter k cannot produce enough power, or $p_{max} < p_k$, where p_k is the required transmission power. This limits the feasibility region of the system, which becomes

$$
\rho_P(B^N) < \frac{1}{\gamma^t}, \quad P^N \le p_{max}. \qquad (24)
$$

As shown before, for $N > 1$, the links cannot accurately predict their transmission powers. The situation for large N is difficult to analyze. In a wireless network of moderate size, when the arrival rate is low (the expected number of simultaneous arrivals is less than 1), the most probable case of multiple arrivals is $N = 2$. It can be proven that for $N = 2$, the predicted power levels for the two links are repelled from each other. This means if $p_{M+1} > p_{M+2}$, the estimated power levels $ep_{M+1} > p_{M+1}$ and $ep_{M+2} < p_{M+2}$. If all the transmitters have the same p_{max}, it can be concluded that every link, once determining it is admissible by probing the channel, always has enough power to meet its target SIR. This is proven as follows:

Theorem 5: For $N = 2$, no link will be mistakenly admitted into the channel. Every admitted link will have enough transmission power to meet its target SIR.

Proof: Without loss of generality, let $p_{M+1} > p_{M+2}$. Link $M+1$ will overestimate its transmission power and link $M+2$ will underestimate, and $ep_{M+1} > p_{M+1} > p_{M+2} > ep_{M+2}$. Suppose every link only knows its estimated power ep, and will make decision based on this local information. If $p_{max} \ge ep_{M+1} \ge ep_{M+2}$, both decide the channel is admissible. Because $p_{max} > p_{M+1} > p_{M+2}$, both have enough powers, and their SIRs can be achieved. If $ep_{M+1} > p_{max} \ge ep_{M+2}$, link $M+1$ is blocked and only link $M+2$ is admitted. Being the only new link joining the channel, the required transmission power for link $M+1$ becomes

$$
\begin{aligned}
p'_{M+2} &= \frac{\gamma^t \alpha_{M+2}}{1-\gamma^t \beta_{M+2,M+2}} \\
&< \frac{\gamma^t \alpha_{M+2}}{1-\gamma^t (\beta_{M+2,M+1} + \beta_{M+2,M+2})} \\
&= ep_{M+2} \le p_{max}. \qquad (25)
\end{aligned}
$$

Link $M+2$ will have enough transmission power to meet its SIR. If $p_{M+1} > p_{M+2} > ep_{M+2} > P_{max}$, both links are blocked and the statement is trivially true. Q.E.D.

So far only the power limit of the new links are taken into account. However, the existing links are also limited by their maximal transmission power. Simply by probing a channel, a new link cannot predict the increase of the transmission power of the other links. It may cause excessive interference to the existing links and drive their transmission powers too high. Some links can be forcefully dropped. This is a very undesirable situation because it is more important not to drop an on-going transmission than to admit a new one. Solutions have been proposed in [7, 2], but none of them is truly satisfactory. The problem is not likely to be solved completely without resorting to extensive message exchange among the nodes, which is not our intention here. Limited p_{max} also forces one to choose the power of the probing signal (p^{ps}) carefully. The degree to which the active links are disturbed depends on p_{max} as well as the offered traffic, and is assessed through simulations in this work.

VI. Probing based channel allocation

For a given set of links and a number of channels in a TDMA/FDMA system, finding a good channel assignment is a difficult problem. The channel probing scheme provides a simple, yet effective means to do so.

When a node needs to find a channel and transmit to another node, the two nodes can pair up as a link and perform channel probing. The link can probe all (or some) of the channels, and determine which channels are available and predict the transmission powers. It can choose the channel requiring the lowest power, thus thus saving battery as well as reducing the interference in the channel. This way more links can be admitted into the system, thus increasing the network capacity, or the transmission power of the links can be reduced, thus enhancing the battery life. Although the channel probing scheme cannot always predict the transmission power accurately, single arrival ($N = 1$) is the most likely case in a system of modest size, and the probing scheme works well.

We study the following channel allocation schemes and compare their performances. The first scheme is random channel selection (RCS). When a link looks for a channel, it chooses a channel randomly and starts to power up. The second scheme is called sensing based channel selection (SCS). It differs from RCS in that when a link looks for a channel, its receiver measures the interference and noise power in all the channels, and chooses the channel with the lowest interference level. SCS is similar to the scheme in [2]. In the probing based channel selection scheme (PCS), a link probes all the channels, and picks the one with the lowest predicted transmission power. If all the channels are inadmissible, the link is blocked without trying to power up in any of the channels. This way the interference caused to other links is reduced significantly (In RCS and SCS, a link learns its inadmissibility to a channel "the hard way", and can cause excessive interference to on-going transmissions and force some transmissions to be dropped).

The difference between the three channel allocation schemes stops here. Once admitted into a channel, a link applies power control and tries to maintain its target SIR, until it transmission ends and it releases the channel, or its SIR is consistently lower than the target and it deems the current channel becomes unavailable. In the second case, if the link is new to the channel, it stops its transmission and is blocked from the system. If the link is an old link and has been active in the channel for sometime, before it is dropped from the system, it tries to find another feasible channel, using the same scheme as a newly arrived link. It is dropped when it fails to

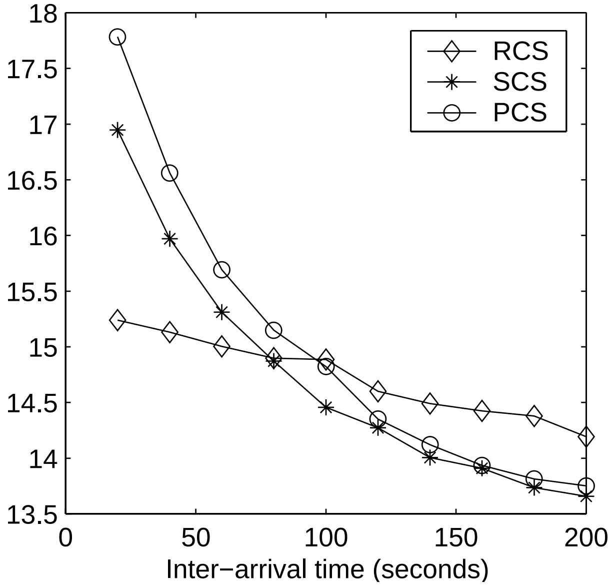

Figure 1: Average transmission power (mW) per link.

find an admissible channel after a number of trials. The performance of the channel allocation schemes are measured in terms of the blocking probability of newly arrived transmission requests (P_b), the forced dropping (termination) probability of on-going transmissions (P_d), the probability that an on-going transmission is forcefully relocated to another channel (P_r), and the average transmission power of the links. The channel allocation schemes are evaluated with simulation in the next section.

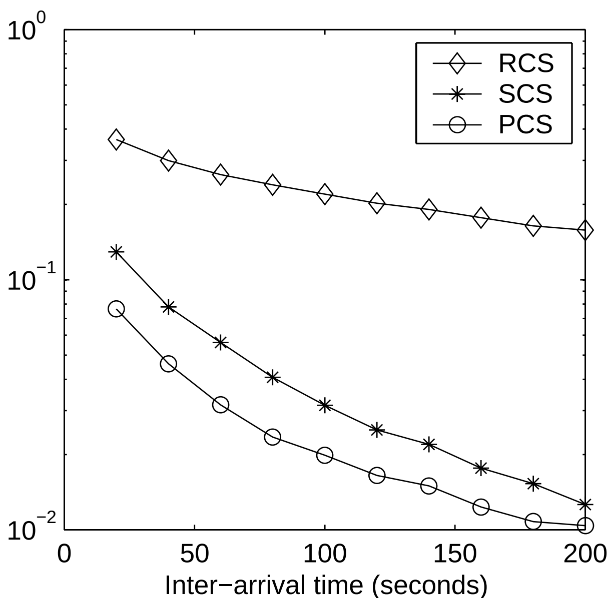

Figure 2: Blocking probability for arrivals.

VII. Simulations

The simulations are carried out in a TDMA-based ad hoc network with 6 channels in an area of 10 km by 10 km. There

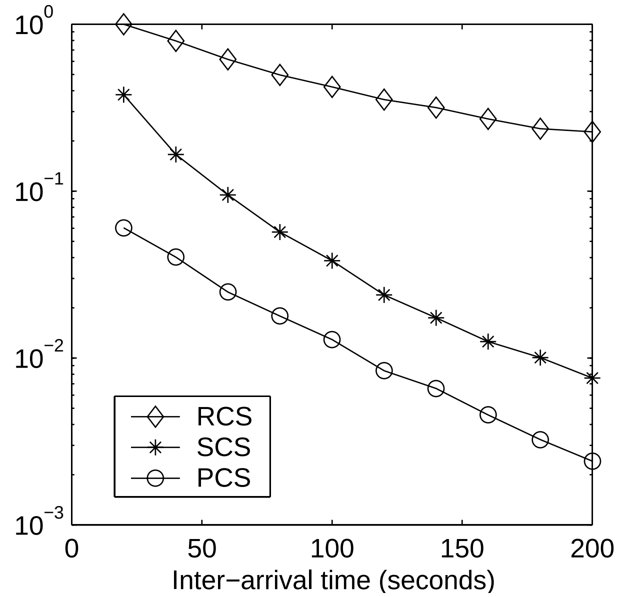

Figure 3: Relocation probability for on-going calls.

are 40 pairs of links in the network, each consisting of a transmitter and a receiver. The position of a transmitter is generated following an uniform distribution in the area. The corresponding receiver is placed randomly in a circle with diameter $1km$ centered at the receiver. The propagation gain from transmitter i to receiver j is given by $z_{i,j} = \frac{1}{d_{i,j}^4}$, where $d_{i,j}$ is the Euclidean distance between them. The receiver noise n is $10^{-15}W$ and the maximal transmitter power $p_{max} = 1W$. A power update interval (PUI) is defined as the time required for a link to measure its SIR and update its transmission power accordingly. We take a PUI to be $200ms$. All the active links update their transmission power every PUI. For simplicity, we assume all the active links update their transmission powers synchronously, although the asynchronous power control algorithm converges as well [4]. We assume a receiver transmits its SIR measurement to its transmitter through a separate channel, and no delay or error is incurred. Network traffic, arriving at the individual links, consists voice calls and has Poisson arrival rate and exponential service time with a means of 120 seconds. The offered load is controlled by varying the expected inter-arrival time of new call requests to each link. The target SIR is $\gamma^t = 16dB$. If an active link finds its SIR below the target for 2 consecutive seconds, it is forced to withdraw from its current channel and starts to look for a new one, using the same scheme as a newly arrived link. It is dropped from the system when it fails to find a valid channel after 2 trials. A new link is blocked immediately if it fails to reach its SIR in the channel it selects after 2 seconds. It is not given a second chance. There is no communication between different links. Different links only interact through the interference they cause to each other.

In the channel probing scheme, the probing power $p^{ps} = 0.1mW$. The average SIR of the probing signal is approximately $4dB$. When a new link probes the channel, it uses $\gamma^n = \gamma^t$. No SIR penalty for the new links is used. When a channel is being probed by some new links, the transmission power in the channel increases by about 15%. A probing sig-

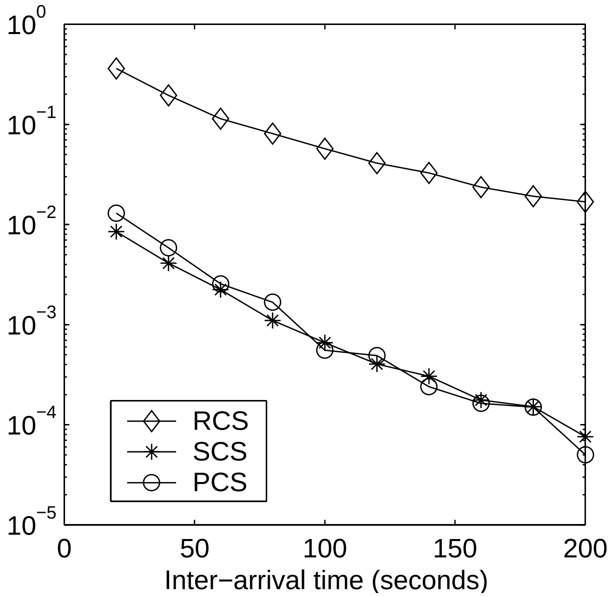

Figure 4: Dropping probability for on-going calls.

nal must last long enough to allow other links to react fully. In the simulation a probing signal has a duration of 5 PUI (1 second). Because it is shorter than the time for an active link to withdraw from a channel due to link degradation (2 seconds), it is not likely that an active link is forced out of its channel by probing signals.

In the experiments, 100,000 calls are simulated for each case and the results are shown in Figures 1 to 4. As expected, the RCS algorithm works the worst in almost all the performance measures. Because no attempt is used to select a good channel, a newly arrived call has a high blocking probability. Choosing the wrong channel not only causes new call requests to be blocked, but also causes significant disturbance to on-going transmissions and results in a high relocation probability and dropping probability. Under heavy load the average transmission power is lower in RCS than SCS and PCS, because the blocking and dropping probabilities are much higher. Between the other two schemes, overall the PCS algorithm outperforms the SCS algorithm. It has a lower blocking probability as well as a lower relocation probability. The ability to take into consideration the response of the active links (β), in addition to the current interference (α), provides a better method for channel selection. What is more important is the ability to determine the inadmissibility of a link before it actually powers up and causes significant damage to other links. In the SCS algorithm, active links often have to switch to other channels, when new links force their way into the system. Link relocation is much less frequent in the PCS algorithm, which means on-going transmissions are less disturbed. However, link relocation provides a means of load-balancing. As the links are re-shuffled more frequently in the SCS algorithm, channel congestion is reduced. This leads to a lower average transmission power in the SCS algorithm than in the PCS algorithm. The dropping probability for active links are roughly the same for these two algorithms. The relative performance of the two algorithms does not change significantly as the traffic varies from light to heavy.

VIII. Discussions and Conclusions

The channel probing scheme presented here differs from [7] in a number of ways. In [7], channel probing is performed as part of the controlled power update, while in the current work, channel probing is carried out by an explicit probing signal with predefined power. This makes it possible for multiple new links to probe a channel at the same time. A newly admitted link powers up just like any other links, so it can achieve its target SIR within a few PUIs. Also the distress signal in [7] is not used here. Channel probing is more applicable in a voice network than in a data network, because the network traffic changes slowly with voice calls than with bursty data transmissions. If the traffic fluctuates too much, it may be impossible to measure the SIR and to apply power control. Currently the channel probing scheme is limited by the time required to measure the SIR (in the order of a fraction of a second). It will become more adaptive if this time can be reduced. In the simulations, it is assumed that there is a separate channel to transfer the SIR information from the receiver to the transmitter. This is necessary because the simulated traffic is one-way. In a real network, most of the traffic will be two-way traffic, and the SIR information can be piggy-backed to the user traffic, or as part of a control message exchanged between the nodes. To conclude, a channel probing scheme for wireless networks has been developed. By transmitting a low powered probing signal, a link can estimate the channel condition and predict the required power. Some important properties of the scheme have been proven, most noticeable the equivalence between the local and the global admissibility. Effect of maximal transmission power has also been discussed. The channel scheme can be used as a means of distributed channel allocation, and simulations have shown that it outperforms some other comparable channel allocation schemes.

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