A Distributed Channel Probing Scheme for Wireless Networks

Chenxi Zhu and M. Scott Corson
Institute for Systems Research
University of Maryland
College Park, Maryland 20742
email: czhu, corson@isr.umd.edu

Abstract—This paper presents a distributed channel probing scheme for wireless networks. By transmitting a probing signal in a channel and measuring the signal-to-interference ratio (SIR), a wireless node can estimate channel admissibility and predict its 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 other schemes.

Keywords—Wireless networks, power control, channel probing, dynamic channel allocation, admission control.

I. INTRODUCTION

Power control and dynamic channel allocation are two effective means to improve the capacity of a wireless network [1], [2], [3], [4], [5]. When trying to combine the two together, one is faced with the problem of how to characterize channel utilization and how an algorithm, running from the perspective of an individual node independently, can use such information to facilitate its channel selection. Most DCA schemes use interference power as a criterion for channel selection [6], [7], [8]. This paper introduces a channel probing scheme which allows a transmitter, in cooperation with its corresponding receiver, to probe a channel, to estimate the channel’s condition and to further predict the required transmission power to meet its desired SIR. It is a fully distributed scheme which requires no communication between different links (a link is a transmitter/receiver pair), yet the local admissibility of each link and the global feasibility of the entire system are shown to be equivalent. By probing channels, the algorithm executing for a given link can choose the best channel. Hence it can be used as part of a dynamic channel allocation scheme, which uses transmission power as the criterion for channel selection. This scheme is compared with other channel allocation schemes via simulation. The simulation results show that with the new scheme, newly-arrived transmissions experience less blocking and the on-going transmissions suffer less disruptions.

II. THE SYSTEM MODEL

We consider a TDMA (or FDMA)-based wireless network where the transmitters can adjust their transmission power continuously within a given range. Each time slot in a TDMA time frame (or a carrier frequency in a FDMA system) is referred to as a channel. Nodes perform a closed loop power control algorithm described as follows. The power control algorithm used is the same as that in [5]. 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 $\gamma_i$. We assume this transmitter/receiver pair is determined by some other schemes, and it is considered fixed in this case. The terms link and transmitter/receiver pair are used interchangeably, and transmission power and SIR of a link respectively means the output power of the transmitter and the SIR at the receiver. Let $g_{i,j}$ be the propagation gain between the $j$th transmitter and the $ith$ receiver, and let $G = [g_{i,j}]$ 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:

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

(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 as to make sure that the SIR $\gamma_i$ of every link $\gamma_i \geq \gamma_i^t$, for $i = 1, 2, \ldots, M$. Based on its SIR, each link updates its transmission power as,

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

(2)

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

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

(3)

if and only if the Perron eigenvalue (the largest eigenvalue) of matrix $Z = [z_{i,j}], \rho_p(Z)$, satisfies $\rho_p(Z) < \frac{1}{\gamma_i}$ [9]. 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

$$P^* \leq p_{\text{max}} 1,$$

(4)

where 1 is the all 1 vector with appropriate length. If $\rho_p(Z) < \frac{1}{\gamma_i}$ but 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 proposed 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 $p_{\text{max}}$ will be discussed in Section V. The details of the channel probing algorithm is given as follows.

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 $\gamma^t$. Their transmission power vector is given by

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

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

$$E^M = E^M(P^N) = Z_N^t P^N,$$

where $Z_N^t = [z_{M+1}^{N}, z_{M+2}^{N}, \ldots, z_{M+N}^{N}]'$.

After re-balancing their SIR, the powers of the $M$ existing links become

$$P^M(P^N) = (I - \gamma^t Z^M)^{-1}(V^M + Z_N^t P^N) = P^M(0) + (I - \gamma^t Z^M)^{-1}Z_N^t P^N.$$  \hspace{1cm} (7)

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

$$\gamma_k(P^N) = \frac{p_k}{v_k + \sum_{j=M+1}^{M+N} z_{k,j} p_j} \hspace{1cm} \text{(8)}$$

where $v_k = [\beta + \alpha^t Z_N^t Y^t Z_N]^t$ is the (normalized) noise and interference power at receiver $k$ before the new links emit any power, and $\beta_{k,j}$ is given by

$$\beta_{k,j} = \frac{1}{\alpha_k + \alpha p^s \sum_{j=M+1}^{M+N} \beta_{k,j}}.$$  \hspace{1cm} \text{(9)}

where $\alpha_k = [\beta + \alpha^t Z_N^t Y^t Z_N]^t$ is the normalized version of $p_k^e(0)$, where the normal-
The parameter \( g_{k,k} \) can be obtained as
\[
g_{k,k} = \frac{p_p^k (p_p^p + 1)}{p_p^k (1 + \gamma_k^p)^2}, \tag{14}
\]
and
\[
\alpha_k = \frac{p_p^k (0)}{g_{k,k}}. \tag{15}
\]
The parameter \( \beta_k \) is given by
\[
\beta_k = \frac{p_p^p - \alpha_k \gamma_k^p}{p_p^p + \gamma_k^p}. \tag{16}
\]

Significant information is carried in \( \alpha_k \) and \( \beta_k \). Link \( k \) checks its local admissibility condition:
\[
\beta_k < \frac{1}{\gamma_k^p}. \tag{17}
\]

If this condition is satisfied, the channel is called 'locally admissible' to link \( k \), and the link estimates its transmission power as
\[
e_p^k = \frac{\gamma_k^p \alpha_k}{1 - \gamma_k^p \beta_k}, \tag{18}
\]
or, in vector form,
\[
E_P^N = (I - \gamma W^N)^{-1} \gamma A^N, \tag{19}
\]
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 \( (\alpha_k \) and \( \beta_k \)), 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 \( \beta_k \) is given by the following lemma:

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

**Proof:** see Appendix.

We are now ready to prove the main result.

**Theorem 3:**

1. Suppose a set of \( M \) links are already transmitting 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 \( N \) new links to 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, \( \rho_P(B^N) < \frac{1}{\gamma} \). There are two possible cases. In the first case, \( \min(\beta_i) \leq \rho_P(B^N) \leq \max(\beta_i) < \frac{1}{\gamma} \), 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, \( \min(\beta_i) < \rho_P(B^N) < \frac{1}{\gamma} \) 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, \( \frac{1}{\gamma} \leq \rho_P(B^N) \). There are two possible cases. In the first case, \( \frac{1}{\gamma} < \min(\beta_i) \leq \rho_P(B^N) \) max(\( \beta_i \)), all of the \( N \) new links find the channel inadmissible and none join. In the second case, \( \min(\beta_i) < \frac{1}{\gamma} < \rho_P(B^N) < \max(\beta_i) \), the channel appears admissible to some, but not all of the links. Without lose of generality, assume \( \beta_i < \frac{1}{\gamma} \) for \( i = M + 1, M + 2, ..., M + L(L < N) \), and \( \beta_1 \geq \frac{1}{\gamma} \) for \( i = M + L + 1, M + L + 2, ..., M + N. \) Because links \( M + L + 1 \) \( M + N \) 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 \( C_L = \{c_{i,j}\}_{i=M+1, M+L+1}^{M+1, M+1} \times \{M+1, M+1\} \) where

\[
c_{i,j} = b_{i,j}, i,j = M + 1, M + 2, ..., M + L.
\]

The matrix \( C_L \) is a submatrix of \( B^N \). Because \( B^N \) is non-negative, the Perron eigenvalue of \( C_L \), \( \rho_P(C_L) \), is not larger than \( \rho_P(B^N) \) [10]. It can further be proven that \( \rho_P(C_L) < \frac{1}{\gamma} \) \( \rho_P(B^N) \). Define \( c_i = \sum_{j=M+1}^{M+L} c_{i,j} = \sum_{j=M+1}^{M+N} b_{i,j}, \) and \( b_i < \frac{1}{\gamma} \), for \( i = M + 1, ..., M + L. \) Therefore \( \rho_P(C_L) < \max_{i=M+1}^{M+L} c_i < \max_{i=M+1}^{M+L} b_i < \frac{1}{\gamma} \), 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. Q.E.D.

If \( N = 1, B^1 = \beta_{M+1,M+1} = \beta_{M+1} = W^1, \) the new link can determine the channel status accurately. The estimated transmission power is also accurate, \( e_p^{M+1} = p_{M+1}. \) When \( N > 1, \) in general \( E_P^N = (I - \gamma W)^{-1} \gamma A^N \neq (I - \gamma B^N)^{-1} \gamma A^N = C^N. \) If we assume all the \( N \) new links find the channel admissible \( \beta_k < \frac{1}{\gamma} \) for all \( M + 1 \leq k \leq M + N \), or \( W < \frac{1}{\gamma} I \), we can define estimation error \( dP^N = E_P^N - C^N \) and have 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 \( (dP^N > 0 \) element-wise) or underestimate \( (dP^N < 0 \) element wise) their transmission powers simultaneously.
Although in the above proves we use the same target SIR $\gamma^t$ for all the links, it can be proven that the same properties hold even if different links have different target SIRs. With little modification, the scheme can be extended to a DS/CDMA system which uses random spreading waveform and conventional matched filter receiver. In such a system, the signal of user $i$ is spread with a randomly chosen waveform $s_i$, and it is demodulated at the receiver by a matched filtering with the same waveform $s_i$. The SIR of link $i$ is given by [11]

$$\gamma_i = \frac{(s_i \cdot s_i^t)^2 p_i}{(s_i \cdot s_i) v_i + \sum_{j=1}^{M} (s_i \cdot s_j)^2 z_{i,j} p_j} \approx \frac{p_i}{v_i + \frac{1}{PG} \sum_{j=1}^{M} z_{i,j} p_j},$$

(20)

where $PG$ is the processing gain. After we replace $z_{i,j}$ with $\frac{s_i \cdot s_j}{PG}$, all the equations apply. The global feasibility condition becomes $\rho P (\frac{1}{PG} Z) < \frac{1}{\gamma^t}$. In particular, from the view point of an individual link, the channel probing scheme (Equations 13-19) does not change at all. This makes the same scheme applicable to a CDMA system as well as a TDMA or FDMA system.

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 $p_{\text{max}} < p_k$, where $p_k$ is the required transmission power. This limits the feasibility region of the system, which becomes

$$\rho P (B^N) < \frac{1}{\gamma^t}, \quad P^N \leq p_{\text{max}} 1.$$  

(21)

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 shown 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 will be $e p_{M+1} > p_{M+1}$ and $e p_{M+2} < p_{M+2}$. This proof is omitted here. If all the transmitters have the same $p_{\text{max}}$, it can be shown 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:** see Appendix.

In the discussions so far, only the power limits of the new links are taken into account. Doing so implies that the active links are always below their transmission power limit. This is not true in general. 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 may drive their transmission powers too high. As a consequence, some links may reach $p_{\text{max}}$ and are forcefully dropped. When multiple channels are available, an active link forced out of its current channel can try in other channels, and it is dropped out of the system when it cannot find a feasible channel within a certain time. Forceful dropping of active links is a very undesirable situation, because it is more important not to drop an on-going transmission than to admit a new one. Various solutions to this problem has been proposed, but none of them solves the problem satisfactorily. In [12], [5] it is assumed that when an existing link finds it power being driven towards the upper limit, it transmits a distress signal, and any newly-admitted link will back off on receiving such a signal. This requires a separate channel, and because a newly-admitted link can cause power outage of an existing link anywhere in the network (the two links are not necessarily in close vicinity), the delay for the distress signal to reach the new link can be too long to shut it down before the existing link is dropped. Another way to reduce (but not to eliminate) this negative effect is to introduce a protective margin ($\gamma^p > 0$), and use higher SIR $\gamma^n = (\gamma^n + \gamma^p) > \gamma^t$ for the newly admitted links [8]. When probing the channel, a new link uses $\gamma^n$ to determine the channel admissibility and to predict its transmission power. This way it predicts a higher transmission power and adjusts itself higher (to the disadvantage of the existing links) thus reducing the probability of a forced drop out. Once admitted, the new link uses the same $\gamma^t$ as other existing links and powers up with the same power control algorithm. The dropping probability is reduced at the cost of increased blocking probability. But in this method, it is still possible for a new link to knock out an on-going link, and it is difficult to find the optimal protection margin ($\gamma^p$). Neither way is a perfect solution to this problem. It is difficult to solve the problem completely without resorting to extensive message exchange among the nodes, which is not our intention here. The approach we take here is not to take any special precautions and to examine the dropping probability of these naive algorithms. The probability of forced drop out depends on the maximal transmission power as well as offered traffic, and can be assessed through simulations.

Limited transmission power requires careful selection of the power of the probing signal ($p^{PS}$). If $p^{PS}$ is chosen too low, the perturbation experienced by the active links is insignificant, and their transmission powers hardly increase. This makes it difficult to estimate the parameter $\beta$ accurately. If $p^{PS}$ is too high, it disturbs the active links too much. Because it takes time (a few power update intervals) for the links to adjust their powers and to regain the SIR, these active links may suffer temporary SIR degradation. It is also possible that the transmission powers of some links are driven towards $p_{\text{max}}$. Should this occur, not only will these links suffer from link quality degradation, but the link probing the channel may underestimate the $\beta$ parameter. This causes the new link to underestimate its transmission power (thus underestimating the channel congestion). When it admits itself into the channel and powers up, it almost certainly forces those links whose powers are already at $p_{\text{max}}$ during the probing phase to be dropped. This 'over-aggressiveness' benefits the new link and makes it possible to be admitted into a channel otherwise inadmissible. To conclude, the power of the probing signal must be high enough to allow accurate channel.
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 nodes (for the link) can probe all (or some) of the channels, and determine which channels are available and thus predict their transmission powers. It can choose the channel requiring the lowest power, thus saving energy as well as reducing the interference in the channel. This way more links can be admitted into the system, thereby increasing the network capacity, and 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, the case of a single arrival ($N = 1$) is the most common case in a system of modest size and low arrival rate, and the predicted transmission power is accurate.

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 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. It is similar to the scheme for channel selection used in [6], [7], [8] and is most common in the DCA literature. With the notation in Section III, the channel with the lowest $\alpha$ is selected. In 'probing-based channel selection' (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 its transmission ends and it releases the channel, or its SIR is consistently lower than the target and it deems the current channel 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 in the channel (has been active 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 lost when it fails to find an admissible channel after a number of trials.

For the special case when the number of channels is one, the channel allocation schemes degenerate into rules of admission control. The PCS scheme becomes 'probing-based admission control' (PAC), where admissibility is determined first by channel probing. The RCS and SCS become the same scheme, since there is only one channel. Without probing, a new link is only blocked from the channel after it tries to power up and fails, and there is indeed no admission control. For this reason RCS and SCS can be called 'null admission control' (NAC) in a single-channel system.

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. Although forced termination of an on-going transmission is the most unfavorable case, a transmission forcefully relocated to a different channel suffers temporary link quality degradation, and $P_r$ reflects the disturbance experienced by on-going transmissions. The channel allocation schemes are evaluated via simulation in the next section.

VII. SIMULATION STUDIES

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 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 radius 1 km centered at the receiver. The propagation gain from transmitter $i$ to receiver $j$ is given by $g_{i,j} = \frac{1}{d_{i,j}^2}$, where $d_{i,j}$ is the Euclidean distance between them. The receiver noise $n$ is $10^{-15}W$. The maximal transmission 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. Following [13], the length of a PUI is taken to be 200ms. All active links update their transmission power every PUI. For simplicity, we assume all the active links update their transmission pow-
ers synchronously, although the asynchronous version of the power control algorithm converges as well. 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 (single hop), consists of voice calls and has Poisson arrival and exponential service times 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 reach its SIR in the channel it selects. It is not given a second chance. There is no communication between different links (hence no 'distress signal'). Different links only interact through the interference they cause to each other.

In the channel probing scheme, the probing power $p^{p^s} = 0.1mW$. The average SIR of the probing signal is approximately $4dB$. When a new link probes the channel, it uses $\gamma^n = \gamma^p$. No SIR penalty for the new links is applied. When a channel is being probed by some new links, the transmission power in the channel increases by about 15%. A probing signal 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 worst in all the performance measures. Because no attempt is made 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 of much higher blocking and dropping probability. 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 link ($\beta$), in addition to the current interference ($\alpha$), provides a better way for channel selection. What is more important is the ability to detect the inadmissibility of a link before it fully powers up and causes excessive 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, frequent link relocation provides a means of load-balancing. As the links are re-shuffled more frequently in the SCS algorithm, traffic hot spots are eliminated. This leads to a lower average transmission power in the SCS algorithm than in the PCS algorithm. The dropping probability for active links is roughly the same for these two algorithms. The relative performance of the two algorithms does not change much as the traffic varies from light to heavy, so it can be advantageous to use PCS even in a lightly-loaded system.

We also simulated the channel probing scheme in a CDMA network with random spreading sequence and conventional matched filter receiver. Because the spreading sequence is random, a transmitter has little control of its spreading sequence, and can only control its transmission power, and whether to transmit at all. This can be viewed as a single channel system, where the PCS scheme becomes PAC (probing-based admission control), and the RCS and SCS schemes become NAC (null admission control). The topology of the simulated network is the same as before, with a processing gain of 128 (PG = 128) and a target SIR of 9dB. Due to the wider bandwidth, the receiver noise increases to $10^{-15}$W. The maximal transmission power is 1.5W. Figure 5 compares the blocking probability of newly-arrived calls and dropping probability of on-going calls for the PAC and the NAC schemes. Because of the admission control imposed by channel probing, newly-arrived calls experience a higher blocking probability with the PAC scheme than with the NAC scheme. However, with the NAC scheme, no protection is provided for on-going transmissions, therefore on-going transmissions suffer a high dropping probability. On the other hand, no on-going transmission was dropped with the PAC scheme in the simulation, hence the PAC scheme exhibits a dropping probability of virtually zero. This demonstrates better protection for on-going transmissions by the channel probing scheme. This is important because the system should not drop on-going calls just to admit a newly-arrived call. Therefore the channel probing scheme is also suitable for a CDMA system as an admission control scheme.

VIII. DISCUSSION

The idea of channel probing was first introduced in [12], as part of the DCA-ALP controlled power update algorithm for protection of active links. In DCA-ALP, the transmission power of a new link is updated in a controlled manner, in order to protect the active links. A new link can estimate the channel admissibility from its SIR measurements in the first two power-up steps. The channel probing scheme of [14] measures the change of interference power while a probing signal is transmitted, but does not relate the measurement directly to the channel feasibility condition. We note the similarity between our scheme and the scheme in [12]. Compared with [12], our scheme allows multiple links to probe the channel simultaneously. In its current form, the channel probing scheme is more applicable in a voice network than in a data network, because the network traffic changes slowly with voice streams than with bursty data transmissions. If the traffic fluctuates too much in a short time scale, it may be impossible to accurately measure the SIR and apply power control, and the channel probing scheme breaks down. In a system where bursty data transmission takes place, its more appropriate to take a probabilistic approach than the deterministic approach for power control [15]. The channel probing scheme can be used in an outdoor environment as well as indoors, as long as the propagation gain remains relatively static to allow the power control to converge. For this reason it might be difficult to use the scheme in a mobile environment where the users are moving quickly. Here we are concerned with the long-term feasibility of a channel rather than with temporary SIR fluctuation of an individual link. An active transmission will suffer temporary SIR degradation when a new link probes and joins the same channel. If it is necessary to maintain the SIR of an active link at all time, the frame structure of [14], which separates the probing segment from the data segment, can be used to protect the actual data transmission. Because the channel probing scheme, as well as the dynamic channel allocation scheme utilizing channel probing, is distributed and requires little communication between different nodes (except that between a transmitter and its corresponding receiver), it is attractive to wireless networks lacking fixed infrastructure, such as ad hoc networks, where it is difficult for nodes to communicate and coordinate with each other. Of course, it can also be applied to a more traditional cellular network. An interesting feature of the current scheme is that not all nodes are required to support channel probing before channel probing can be used in a system. All that is required is that every node can execute the power control algorithm described earlier. For a node which cannot perform channel probing itself, it simply experiences SIR degradation when the channel is probed by another link. When this link adjusts its power to re-achieve its target SIR, it cooperates in the channel probing process of other links without realizing it. This makes
it possible to gradually introduce the channel probing scheme as an add-on feature to some systems which are already deployed.

Currently the channel probing scheme, as well as the power control algorithm, 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. Compared with the time scale for SIR measurement, the transmission delay for these messages is very short, and such an approach can be justified.

IX. CONCLUSION

A distributed channel probing scheme for wireless networks has been developed. It allows a new link to estimate the channel condition by transmitting a low powered probing signal. Some important properties have been proven, most noticeably the equivalence between the local and the global admissibility. The effect of maximal transmission power has also been discussed. The channel scheme can also be used as a means of distributed channel allocation, and simulations have shown that it outperforms other channel allocation schemes.

X. APPENDIX

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

\[
Z^{M+N} = (z_{i,j})_{(M+N) \times (M+N)} = \begin{pmatrix} Z_M & Z_N \\ Z_M & Z_N \end{pmatrix},
\]

and

\[
(I - \gamma Z^{M+N})^{-1} = \begin{pmatrix} I - \gamma Z_M & -\gamma Z_N \\ -\gamma Z_N & I - \gamma Z_N \end{pmatrix}^{-1} = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix},
\]

where

\[
C_{11} = (I - \gamma Z_M)^{-1} + \gamma^2 (I - \gamma Z^M)^{-1} Z_N, \\
C_{12} = \gamma (I - \gamma Z_M)^{-1} Z_N, \\
C_{21} = \gamma (I - \gamma Z_M)^{-1} Z_N, \\
C_{22} = (I - \gamma Z_N)^{-1} + \gamma^2 (I - \gamma Z^N)^{-1} Z_M.
\]

Feasibility for the \( M+N \) links requires each of the \( C_{11}, C_{12}, C_{21}, C_{22} \) \( > 0 \). The fact that the \( M \) active links transmit in the same channel implies \((I - \gamma Z^M)^{-1} > 0\). Inspecting one of the four \( C \) terms shows the inequality \((I - \gamma Z^{M+N})^{-1} > 0\) holds iff

\[
(I - \gamma Z^N - \gamma^2 Z_N (I - \gamma Z^M)^{-1} Z_N)^{-1} > 0,
\]

and this is true iff

\[
\rho (\gamma Z^N, \gamma Z^N (I - \gamma Z^M)^{-1} Z_N < 1,
\]

or equivalently

\[
\rho (Z^N + \gamma Z^N (I - \gamma Z^M)^{-1} Z_N) = \rho (B^N) < \frac{1}{\gamma^4}.
\]

Q.E.D.

Proof of Lemma 2: From Perron-Frobenius theorem, \( B > 0 \Rightarrow \rho (B) > 0 \), and the corresponding eigenvector \( Y = [y_{M+1}, y_{M+2}, \ldots, y_{M+N}]^T > 0 \). \( BY = \rho (Y) \Rightarrow \sum_{j=M+1}^{M+N} \beta_{i,j} y_j = \rho (Y) \Rightarrow \rho = \sum_{j=M+1}^{M+N} \beta_{i,j} y_j \). The proof is by contradiction. If \( \rho < \min (\beta_{i,j}) \), then for all \( M+N \leq i \leq M+N \rho \rho = \sum_{j=M+1}^{M+N} \beta_{i,j} y_j < \sum_{j=M+1}^{M+N} \beta_{i,j} \Rightarrow \sum_{j=M+1}^{M+N} \beta_{i,j} (y_j - y_i) < 0 \), but for \( y_k = \min (y_j) \), \( y_j - y_k \geq 0 \) for all \( j \), hence \( \sum_{j=M+1}^{M+N} \beta_{i,j} (y_j - y_k) > 0 \), a contradiction. Therefore \( \min (\beta_{i,j}) \leq \rho \).

If \( \rho = \min (\beta_{i,j}) \), \( \sum_{j=M+1}^{M+N} \beta_{i,j} (y_j - y_i) = 0 \Rightarrow y_j = y_k = \min (y_j) \) for all \( j \), hence \( \rho = \sum_{j=M+1}^{M+N} \beta_{i,j} (y_j - y_k) = (i) \) for all \( i \).

Similarly, we can show \( \rho = \max (\beta_{i,j}) \) by replacing \( y_k = \max (y_j) \) in the above proof and find a similar contradiction. The second part is also a corollary of the Gersgorin's theorem. Q.E.D.

Proof of Theorem 4: The matrix \((I - \gamma W^N)^{-1} \) is diagonal and all the diagonal elements are positive, and \((I - \gamma B^N)^{-1} > 0 \). Hence all the off-diagonal elements of the matrix \((I - \gamma W^N)^{-1} - (I - \gamma B^N)^{-1} \) are negative. If there exists \( A^N > 0 \) such that the estimation error \( dP^N = E P^N - P^N = ((I - \gamma W^N)^{-1} - (I - \gamma B^N)^{-1}) \gamma A^N > 0 \) (or \( < 0 \)), a necessary and sufficient condition is that the matrix

\[
U = ((I - \gamma W^N)^{-1} - (I - \gamma B^N)^{-1} \) exists and is all positive (or negative) [10], [16]. If \( U \) exists, it is given by

\[
U = ((I - \gamma W^N)^{-1} - (I - \gamma B^N)^{-1}) = \gamma^4 (I - \gamma W^N)(W^N - B^N)^{-1}(I - \gamma W^N) + (I - \gamma W^N)
\]

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

Proof of Theorem 5: 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 \( e p_{M+1} > p_{M+1} > p_{M+2} > e p_{M+2} \). Suppose every link only knows its estimated power \( e p \), and will make decision based on this local information. If \( p_{max} \geq e p_{M+1} \geq e p_{M+2} \), 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 \( e p_{M+1} > p_{max} \geq e p_{M+2} \), link \( M+1 \) is blocked and only link
$M + 2$ is admitted. The required transmission power for link $M + 2$ becomes

$$\begin{align*}
p_{M+2} &= \frac{\gamma^t \alpha_{M+2}}{1 - \gamma^t \beta_{M+2,M+2}} \\
&< \frac{\gamma^t \alpha_{M+2}}{1 - \gamma^t (\beta_{M+2,M+1} + \beta_{M+2,M+2})} \\
&= \epsilon p_{M+2} \leq p_{\text{max}}. \quad (27)
\end{align*}$$

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

REFERENCES