Distributed Power Control and Removal Algorithms for Multimedia CDMA Wireless Networks

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Abstract: **We study in this paper both distributed power control and removal algorithms for multimedia CDMA wireless networks. In our study, users can have different data rates as well as different quality of service (QoS) requirements. We derive a necessary and sufficient condition for the fully distributed power control (FDPC) algorithm to find a feasible power set. We also prove that, if the maximal power level is used at the start, then the distributed constrained power control (DCPC) algorithm is equivalent to the FDPC algorithm. For the connection removal algorithm, we prove that the non-reinitialized removal algorithm finds a feasible power set faster and employs smaller power levels than the reinitialized one does. Performances of some connection removal criteria are also studied. Our simulation results reveal that the smallest normalized CIR (SNC) and largest CIR requirement (LCR) criteria result in smaller outage probability than the smallest CIR (SC) criterion in a multimedia environment.**

Index Terms: **Distributed, power control, removal, multimedia, CDMA.**

I. INTRODUCTION

In CDMA wireless networks, all users share the same frequency band and thus the interference sets a limit on system capacity. Therefore, it is important to use power control technique to reduce the interference and allow as many receivers as possible to obtain satisfactory reception. Several centralized and distributed power control algorithms had been proposed [1]– [8] to achieve the goal. In centralized power control, a network center can compute the optimum power levels for all users simultaneously. However, it requires measurements of all the link gains and communication overhead between network center and base stations and thus is difficult to realize in a large system. Distributed power control, on the other hand, uses only local information to iteratively adjust the transmitting power of each individual user. It is much more scalable than centralized power control. However, the speed for finding a feasible power set, i.e., a power set which can meet the QoS requirements, may be a major concern. In recent years, two distributed power control algorithms were proposed in the literature, one is the distributed constrained power control (DCPC) algorithm [6], and the other is the fully distributed power control (FDPC) algorithm [4]. In the DCPC algorithm, the power levels are always constrained to the maximal power level, while in the FDPC algorithm, the power levels are adjusted only when the QoS requirements are satisfied.

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In this paper, we study the distributed power control algorithms for multimedia CDMA wireless networks. In our discussions, users can have different data rates and different QoS requirements in terms of bit energy-to-interference ratios. Since it is important to choose the initial power levels for the distributed power control algorithm, we provide some guidelines for this choice in this paper. For the initial power assignment of the FDPC algorithm, we derive a necessary and sufficient condition to find a feasible power set. We also prove that, if the maximal power level is used at the start, then the DCPC algorithm is equivalent to the FDPC algorithm.

For distributed power control, one connection is removed if, after a pre-specified number of iterations of power control, the QoS requirements are not all satisfied. Two types of connection removal algorithms are proposed in the literature, one is the reinitialized removal (RR) algorithm which resets the transmitter power levels after removal [1], [4], [5] and the other is the non-reinitialized removal (NRR) algorithm which makes the transmitter power levels unchanged after removal [7]. In [7], the NRR algorithm is applied to single type of service. In this paper, we apply the NRR algorithm to multiple types of services and prove that the NRR algorithm finds a feasible power set faster and employs smaller power levels than the RR algorithm does.

For real applications, it is important to adopt an efficient removal criterion to determine the priority of removal. Therefore, we study and compare the performance of some connection removal criteria for the distributed power control algorithm. The smallest CIR (SC) removal criterion removes the connection with the smallest CIR and was employed in [1], [4], [5] for single type of service. To provide better services for multimedia users, we propose in this paper two removal criteria: the smallest normalized CIR (SNC) criterion and the largest CIR requirement (LCR) criterion. Our simulation results reveal that the SNC and LCR criteria result in smaller outage probability than the SC criterion in a multimedia environment.

The rest of this paper is organized as follows. Section II describes the investigated system model. Distributed power control and removal algorithms are studied in Sections III and IV, respectively. Numerical examples are presented in Section V. Finally, we draw conclusion in Section VI.

II. SYSTEM MODEL

We consider the reverse link of a CDMA wireless network. As mentioned previously, users are allowed to have different data rates and QoS requirements in terms of bit energy-to-interference ratios. We treat the link gains as constant during the operation of power control. It is possible in the wireless local loop (WLL) system, wireless local area networks (WLAN) and other personal communication systems, where the users are

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still or move slowly relative to the speed of power control algorithm.

We assume that there are N active base stations in the network with K_i users connected to base station i, $1 \leq i \leq N$. Notice that K_i is constant during the process of power control. The pair (i,k) is used to denote the kth user connected to the ith base station. Consider user (i,k). Let P_{ik}, r_{ik} and G_{ik} represent its transmitting power, data rate and processing gain, respectively. Also, let η_i denote the thermal noise for the receiver of the ith base station and W denote the spread bandwidth. As a result, since , $G_{ik} = W/r_{ik}$, the received bit energy-to-interference ratio for user (i,k) is given by

$$\begin{aligned} E_{ik} &\equiv (\frac{E_b}{I_0})_{ik} \\ &= \frac{P_{ik}L_{(n,k)i}/r_{ik}}{(\sum_{n=1}^{N}\sum_{l=1}^{K_n} P_{nl}L_{(i,l)i} - P_{ik}L_{(i,k)i} + \eta_i)/W} \\ &= \frac{P_{ik}L_{(n,k)i}G_{ik}}{\sum_{n=1}^{N}\sum_{l=1}^{K_n} P_{nl}L_{(i,l)i} - P_{ik}L_{(i,k)i} + \eta_i}, \end{aligned} \quad (1)$$

where $L_{(i,l)i}$ represents the link gain between user (n,l) and base station i. To minimize transmitting power, a user is connected to base station i if the link gain between the user and base station i is greater than that between the user and base station j for all $j \neq i$.

After some manipulations, (1) can be rewritten as

$$\sum_{n=1}^{N}\sum_{l=1}^{K_n} P_{nl}L_{(n,l)i} + \eta_i = P_{ik}L_{(i,k)i}(1 + G_{ik}/E_{ik}),$$
$$1 \leq i \leq N \text{ and } 1 \leq k \leq K_i. \quad (2)$$

Let Q_{ik}denote the QoS requirement, i.e., the minimum bit energy-to-interference ratio requirement, of user (i,k). For all the users to meet their QoS requirements, we must find a power set $\mathbf{P} = \{P_{ik}\}$ $(1 \leq i \leq N,\ 1 \leq k \leq K_i)$ such that $P_{ik} > 0$ and

$$E_{ik} = \frac{P_{ik}L_{(n,k)i}G_{ik}}{\sum_{n=1}^{N}\sum_{l=1}^{K_n} P_{nl}L_{(i,l)i} - P_{ik}L_{(i,k)i} + \eta_i} \geq Q_{ik}$$
$$\text{for } 1 \leq i \leq N \text{ and } 1 \leq k \leq K_i. \quad (3)$$

As in [3], such a power set is called a feasible power set. Given a configuration specified by $\mathbf{K}=\{K_i\}$ $(1 \leq i \leq N)$ and $\mathbf{L}=\{L_{(n,l)i}\}$ $(1 \leq i \leq N,\ 1 \leq k \leq K_n)$, if there exists a feasible power set $\mathbf{P} = \{P_{ik}\}$, then this configuration is said to be feasible. Otherwise, it is said to be infeasible. Furthermore, for two power sets $\mathbf{P}' = \{P'_{ik}\}$ and $\mathbf{P} = \{P_{ik}\}$, we say that $\mathbf{P}' \leq \mathbf{P}$ if and only if $P'_{ik} \leq P_{ik}$ for all i and k.

III. DISTRIBUTED POWER CONTROL ALGORITHMS

For power control, it is important to devise an efficient algorithm to find a feasible power set. As proved in [8], for any feasible configuration specified by $\mathbf{K} = \{K_i\}$ and $\mathbf{L} = \{L_{(n,l)i}\}$, there exists a feasible power set $\mathbf{P}^* = \{P^*_{ik}\}$ such that

$$E^*_{ik} = \frac{P^*_{ik}L_{(n,k)i}G_{ik}}{\sum_{n=1}^{N}\sum_{l=1}^{K_n} P^*_{nl}L_{(i,l)i} - P^*_{ik}L_{(i,k)i} + \eta_i} = Q_{ik}, \quad (4)$$

and

$$\mathbf{P}^* \leq \mathbf{P} \text{ for any feasible power set } \mathbf{P}. \quad (5)$$

According to (5), we call $\mathbf{P}^*$ the optimal feasible power set because it employs the smallest power levels for all users. Moreover, if the link gains for all users are known, then the optimal feasible power set can be obtained by solving a set of linear equations. However, measuring all the link gains and sending all the measurements to a network center obviously become impractical for a large system. In this section, we study the distributed power control algorithms which use only local information to iteratively adjust the transmitting power of each individual user. Throughout this section, $\mathbf{P^0}=\{P^0_{ik}\}$ denotes the initial transmitter power set. Also, $\mathbf{P^m}=\{P^m_{ik}\}$and $\mathbf{E^m} = \{E^m_{ik}\}$ denote the transmitter power set and the set of received bit energy-to-interference ratio in the mth discrete time, respectively. Two distributed power control algorithms are considered here, one is the distributed constrained power control (DCPC) algorithm, and the other is the fully distributed power control (FDPC) algorithm. Both are modified for our system model and described below.

DCPC Algorithm

$\mathbf{P}^*=\{P^*_{ik}\}$

and

$P^{m+1}_{ik} = \min\{P_{\max}, Q_{ik}\frac{P^m_{ik}}{E^m_{ik}}\}$,

where $P_{\max}$ is the maximum power level for all users.

Obviously, we have the following property:

Property 1: For the DCPC algorithm, $P^m_{ik} \leq P_{\max}$ for all i, k, and m.

FDPC Algorithm

$\mathbf{P}^*=\{P^*_{ik}\}$

and

$P^{m+1}_{ik} = a^m_{ik} * P^m_{ik}$,

where

$a^m_{ik} = \frac{\min(E^m_{ik}, Q_{ik})}{E^m_{ik}}$.

Because $a^m_{ik} \leq 1$, we have the following property.

Property 2: For the FDPC algorithm, $P^{m+1}_{ik} \leq P^m_{ik}$ for all i, k, and m.

Furthermore, it can be easily seen that the following two properties also hold.

Property 3: For the FDPC algorithm, when $E^m_{ik} < Q_{ik}$, $P^{m+1}_{ik}=P^0_{ik}$ for all i, k, and m.

Property 4: For the FDPC algorithm, when $E^m_{ik} \geq Q_{ik}$, $P^{m+1}_{ik}=\frac{Q_{ik}}{E^m_{ik}}P^m_{ik} \leq P^0_{ik}$, for all i, k, and m.

One important issue for the distributed power control algorithm is to choose the initial power levels. Given a feasible configuration, the initial power assignment for the FDPC algorithm can be guided through the following facts. First, as proved in [4] and [8], if $\mathbf{P^0} \geq \mathbf{P}^*$, then the FDPC algorithm can always find a feasible power set with probability one. Second, according to (5), one cannot find a feasible power set $\mathbf{P} = \{P_{ik}\}$ which satisfies $P_{ik} < P^*_{ik}$ for some i and k. Finally, from Property 2, the power set for the FDPC algorithm is monotone decreasing. Therefore, we cannot find a feasible power set when $P_{ik}^0 < P_{ik}^*$ for some i and k. On the basis of the above discussions, we have the following proposition.

Proposition 1: Given a feasible configuration, the FDPC algorithm can find a feasible power set, if and only if $\mathbf{P}^0 \geq \mathbf{P}^*$.

The above proposition provides a necessary and sufficient condition for the FDPC algorithm to find a feasible power set. However, in real applications, we cannot know the optimal feasible power set in advance. So, the reasonable choice for the initial power level should be $P_{\max}$.

The initial power assignment $P_{ik}^0 = P_{\max}$ for all i and k also makes the DCPC algorithm equivalent to the FDPC algorithm. We assert this relationship in the following theorem. For convenience, we let $P_{ik,D}^m$ and $E_{ik,D}^m$ denote the transmitter power level and received bit energy-to-interference ratio for the DCPC algorithm, respectively, and $P_{ik,F}^m$ and $E_{ik,F}^m$ denote the transmitter power level and received bit energy-to-interference ratio for the FDPC algorithm, respectively.

Theorem 1: If $P_{ik,D}^0 = P_{ik,F}^0 = P_{max}$ for all i and k, then $P_{ik,D}^m = P_{ik,F}^m$ and $E_{ik,D}^m = E_{ik,F}^m$ for all i, k, and m.

Proof: We prove Theorem 1 by mathematical induction. For $m=0$, since $P_{ik,D}^0 = P_{ik,F}^0$ for all i and k, we have $E_{ik,D}^0 = E_{ik,F}^0$ for all i and k. Assume that for $m = M$, $P_{ik,D}^M = P_{ik,F}^M$ and $E_{ik,D}^M = E_{ik,F}^M$ for all i and k. Consider the case $m = M+1$. If $E_{ik,F}^M < Q_{ik}$, then according to Property 3, we have $P_{ik,F}^{M+1} = P_{ik,F}^M = P_{ik,D}^M = P_{max}$. Since $E_{ik,D}^M = E_{ik,F}^M < Q_{ik}$, we get $P_{ik,D}^{M+1} = \min\{P_{\max}, \frac{Q_{ik}}{E_{ik,D}^M} P_{\max}\} = P_{\max}$. As $P_{ik,D}^{M+1} = P_{ik,F}^{M+1}$, it is clear that $E_{ik,D}^{M+1} = E_{ik,F}^{M+1}$.

On the other hand, if $E_{ik,F}^M \geq Q_{ik}$, then we have $P_{ik,D}^M = P_{ik,F}^M \leq P_{\max}$. This leads to $P_{ik,D}^{M+1} = \min\{P_{\max}, \frac{Q_{ik}}{E_{ik,D}^M} P_{ik,D}^M\} = \frac{Q_{ik}}{E_{ik,D}^M} P_{ik,D}^M$ and $P_{ik,F}^{M+1} = \frac{\min\{E_{ik,F}^M, Q_{ik}\}}{E_{ik,F}^M} P_{ik,F}^M = \frac{Q_{ik}}{E_{ik,F}^M} P_{ik,F}^M$. It is obvious that $P_{ik,D}^{M+1} = P_{ik,F}^{M+1}$, so we can get $P_{ik,D}^{M+1} = P_{ik,F}^{M+1}$. This completes the proof of Theorem 1. □

IV. REMOVAL ALGORITHMS

After a pre-specified number (say L) of iterations of power control, if no feasible power set is found, one user is removed. In the following, we study the removal algorithm for the FDPC algorithm. For convenience, every L iterations are counted as a round and the round number is denoted by n. Moreover, for the simplicity of notations, we let Ω represent the set of all connections and renumber the users so that user (i, k) is mapped to connection j, where $1 \leq i \leq N$, $1 \leq k \leq K_i$ and $1 \leq j \leq \sum_{i=1}^{N} K_i$. Hence, we have $P_j^m = P_{i,k}^m$ for all i, k, j and m. The removal algorithm can be described as follows.

Step 1: Let $n = 1$, $\Omega = \{1, 2, \cdots, \sum_{i=1}^{N} K_i\}$ and $P_j^0 = P_{\max}$ for all connections j.
Step 2: Execute at most L iterations with the FDPC algorithm.
Step 3: Stop if a feasible power set is found. Else, remove connection u from Ω according to some connection removal criterion.
Step 4: Let $n = n + 1$, $\Omega = \Omega - \{u\}$ and $P_j^0 = P_j^L$ for all connection $j \in \Omega$. Go to Step 2.

In Step 4, the power levels remain unchanged after removal, so the above algorithm is called the non-reinitialized removal (NRR) algorithm. On the contrary, the removal algorithms in [1], [4], [5] reset the power levels to the initial values after removal, thus we call them the reinitialized removal (RR) algorithms. In the following, we compare the performance of the NRR algorithm with that of the RR algorithm. We assume that the connection removed by both NRR and RR algorithms are the same in every round. Under such assumption, we prove that the NRR algorithm performs better than the RR algorithm.

Let $\mathbf{P}_r^{n,m} = \{P_{r,j}^{n,m}\}$ and $\mathbf{E}_r^{n,m} = \{E_{r,j}^{n,m}\}$ denote respectively the transmitter power set and the set of bit energy-to-interference ratio in the mth iteration of round n for the RR algorithm. Similarly, let $\mathbf{P}_{nr}^{n,m} = \{P_{nr,j}^{n,m}\}$ and $\mathbf{E}_{nr}^{n,m} = \{E_{nr,j}^{n,m}\}$ represent those sets for the NRR algorithm.

Lemma 1: Assume that a connection has to be removed at the end of round n. If $E_{nr,j}^{n,L} \geq Q_j$, then $E_{nr,j}^{n+1,0} \geq Q_j$ for all j and n.

Lemma 2: Assume that, at the beginning of round n, the following two conditions hold

(i) $P_{nr,j}^{n,0} \leq P_{r,j}^{n,0}$ for all connections j, and

(ii) $E_{nr,j}^{n,0} \geq Q_j$ if $E_{n,j}^{n,0} \geq Q_j$ for any connection j.

We have, for all iterations $m \leq L$ of round n,

(iii) $P_{nr,j}^{n,m} \leq P_{r,j}^{n,m}$ for all connections j, and

(iv) $E_{nr,j}^{n,m} \geq Q_j$ if $E_{n,j}^{n,m} \geq Q_j$ for any connection j.

The above lemmas can be easily derived from Lemma 1 and Lemma 2 of [7], so their proofs are omitted here. The meaning of Lemma 2 is that if, at the beginning of a round, the power levels employed in the NRR algorithm are smaller than or equal to those employed in the RR algorithm and, moreover, connection j satisfies its QoS requirement in the NRR algorithm if it is so in the RR algorithm, then the same conditions hold after every iteration of the round. On the basis of Lemmas 1 and 2, we obtain the following theorem.

Theorem 2: It holds for all n that,

(i) $P_{nr,j}^{n,m} \leq P_{r,j}^{n,m}$ for all j and m, and

(ii) $E_{r,j}^{n,m} \geq Q_j$, then $E_{nr,j}^{n,m} \geq Q_j$ for all j and m.

Proof: We prove Theorem 2 by mathematical induction. For $n = 0$, $P_{nr,j}^{0,0} = P_{r,j}^{0,0}$ and $E_{nr,j}^{0,0} = E_{r,j}^{0,0}$ for all j, thus according to Lemma 2, (i) and (ii) are true. Assume that the theorem is true for $n = N$. Consider the case $n = N+1$, since $P_{r,j}^{N+1,0} = P_{\max}$ and $P_{nr,j}^{N+1,0} = P_{nr,j}^{N,L}$ for all j, by Property 2, it is clear that $P_{nr,j}^{N+1,0} \leq P_{r,j}^{N+1,0}$ for all j.

If $E_{nr,u}^{N,L} < Q_u$ for some connection u, then from Property 3, we conclude that $P_{nr,u}^{N,L} = P_{\max}$. Since $P_{nr,u}^{N+1,0} = P_{r,u}^{N+1,0} = P_{max}$ and $P_{nr,j}^{N+1,0} \leq P_{r,j}^{N+1,0}$ for all j, if $E_{r,u}^{N+1,0} \geq Q_u$, we also have $E_{nr,u}^{N+1,0} \geq Q_u$.

On the other hand, if $E_{nr,u}^{N,L} \geq Q_u$, then according to Lemma 1, it holds that $E_{nr,u}^{N+1,0} \geq Q_u$. So, if $E_{r,u}^{N+1,0} \geq Q_u$, we also have $E_{nr,u}^{N+1,0} \geq Q_u$.

On the basis of the above discussions and Lemma 2, we conclude that (i) and (ii) are true for $n = N + 1$. This completes the proof of Theorem 2. □

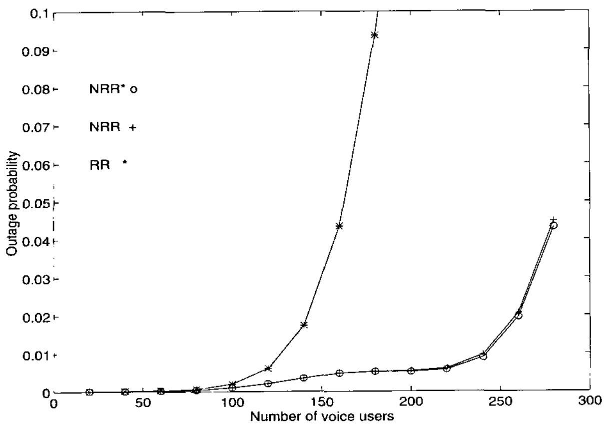

Fig. 1. The outage probability against the number of voice users for the NRR and RR algorithms.

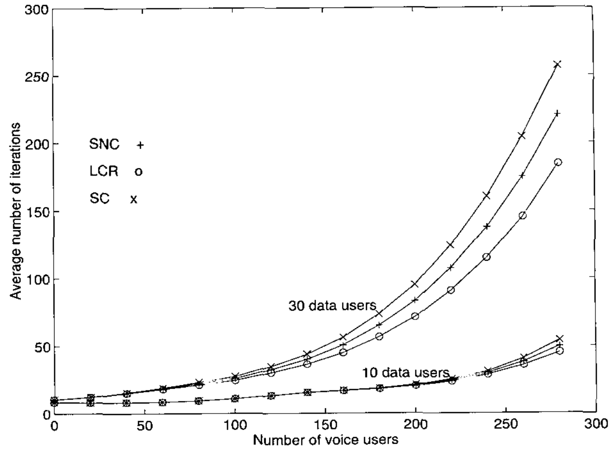

Fig. 2. Average number of iterations to find a feasible power set against number of users for different number of data users.

A consequence of Theorem 2 is that the NRR algorithm employs smaller power levels and finds a feasible power set faster than the RR algorithm. Numerical results presented in the following section show that the NRR algorithm may result in a much smaller outage probability than the RR algorithm.

Another important issue for the removal algorithm is to choose the connection removal criterion to determine the priority of removal. Listed below are three possible connection removal criteria. Let CIR_j, Γ_j, E_j, Q_j and G_j represent the carrier-to-interference ratio, the CIR requirement, the bit energy-to-interference ratio, the QoS requirement and the processing gain for the jth connection, respectively, we have $CIR_j = E_j/G_j$ and $\Gamma_j = Q_j/G_j$.

(1) Smallest CIR (SC) criterion.
Remove connection $u \in \Omega$ which has the smallest CIR among all connections in Ω (i.e., $CIR_u \leq CIR_j$ for all $j \in \Omega, j \neq u$).

(2) Smallest normalized CIR (SNC) criterion.
Remove connection $u \in \Omega$ which has the smallest normalized CIR among all connections in Ω (i.e.,$(CIR_u/\Gamma_u) \leq CIR_j/\Gamma_j$ for all $j \in \Omega, j \neq u$).

(3) Largest CIR requirement (LCR) criterion.
Remove connection $u \in \Omega$ which has the largest CIR requirement among all connections in Ω . If there exist multiple such connections, the one with the smallest CIR is removed.

The idea of the above three criteria is to remove a connection which is unlikely to meet its CIR requirement. For the SNC criterion, the connection which has the largest difference (in dB) between its CIR requirement and current CIR is removed.

V. NUMERICAL RESULTS

In this section, we study an integrated voice/data CDMA wireless network which is composed of 19 hexagonal cells. The radius of the cell is 1 Km and a base station is located in the middle of each cell. We adopt the FDPC algorithm in the considered network and assume that the locations of the users are uniformly distributed over the cell area. The initial power level is set to 1 W and the thermal noise is 10^{-15} W. A user is connected to the base station with the largest link gain to minimize its transmitting power level and the number of iterations L for removal algorithms is chosen to be eight. The spread bandwidth W is set to 1.25 MHz. The data rate and QoS requirement of voice users are 9.6 Kbps and 7 dB, respectively. Data users send data at 38.4 Kbps with 9dB QoS requirement. The same characteristics were used in [12], [13]. Numerical results are obtained by means of computer simulation for 10000 independent configurations.

The link gain $L_{(n,l)i}$is modeled as $L_{(n,l)i} = A_{(n,l)i}/d^{\alpha}_{(n,l)i}$, where $A_{(n,l)i}$ is the attenuation factor, $d_{(n,l)i}$is the distance between user (n, l) and base station i, and α is a constant that models the large scale propagation loss. The attenuation factor models power variation due to shadowing. $A_{(n,l)i}, 1 \leq i, n \leq N$ and $1 \leq l \leq K_n$, are assumed to be independent, log-normal random variables with 0 dB expectation and σ variance. The parameter value of in the range of 4–10 dB and the propagation constant in the range of 3–5 usually provide good models for urban propagation [11]. In our simulations, we choose $\alpha = 4$ and σ = 8dB as in [9], [10].

In Fig. 1, we plot the outage probability against the number of voice users (no data user present) for the NRR and RR algorithms. The outage probability is defined as the ratio of the number of removed connections to the number of total connections. In the NRR and RR algorithms, the connection with the smallest received initial CIR is first removed. It can be seen that the NRR algorithm results in a much smaller outage probability than the RR algorithm. In this figure, the curve for NRR* represents the outage probability for the NRR algorithm in which the connection removed in round n is the one which has the smallest CIR after one iteration of the round. It can be seen that outage probabilities for NRR and NRR* algorithms are close to each other. In Fig. 2, we plot the average number of iterations needed to find a feasible power set for different removal criteria. Finding a feasible power set faster also means that the removal algorithm has smaller outage probability. It can be seen that the LCR criterion finds a feasible power set faster than the SNC criterion, which in turn finds a feasible power set faster than the SC criterion. The reason is that the connection with a larger CIR requirement needs more iterations to reduce its received interference so that its CIR requirement can be satisfied. Therefore, by removing the connection with a larger CIR requirement, one can usually decrease the number of iterations needed in finding a feasible power set. We also perform simulations for data applications with various other bit rates and CIR requirements. The results are consistent, i.e., the LCR criterion performs better than the SNC criterion, which in turn has a better performance than the SC criterion. However, the difference becomes smaller as the CIR requirement of data applications gets closer to that of the voice applications.

VI. CONCLUSION

We have studied in this paper both distributed power control and removal algorithms for multimedia CDMA wireless networks. We provide a necessary and sufficient condition for the FDPC algorithm to find a feasible power set. We also prove that, if the maximal power level is used at the start, then the DCPC algorithm is equivalent to the FDPC algorithm. For real applications, if no feasible power set is found after a pre-specified number of iterations of power control, the removal algorithm is invoked. We prove in this paper that the non-reinitialized removal algorithm finds a feasible power set faster and employs smaller power levels than the reinitialized one does. The proposed removal criteria aim to speed up the process in finding a feasible power set and reduce the outage probability. From our numerical results, the LCR criterion results in better performance than the other removal criteria. Since different types of connections are likely to have different bandwidth requirements, it is worth while to study other removal criteria which can maximize bandwidth utilization or minimize some cost function.

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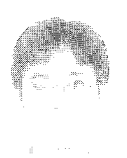

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