CENTRALIZED POWER CONTROL IN CDMA CELLULAR MOBILE SYSTEMS

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This work is supported by BUPT-Nortel Telecom R&D Center

Abstract — Efficient power control is of great importance in the design of high capacity cellular radio systems. Optimum power control scheme, in the sense that it minimizes the outage probability, has been fully investigated for FDMA/TDMA cellular systems. In this paper, the optimum power control and several centralized power control algorithms are proposed for CDMA cellular systems. Simulation results indicate that the optimum power control scheme outperforms the perfect average power control algorithm by approximately 1.9dB under IS-95 defined radio condition.

I. Introduction

Early in the 1980s, Nettleton and Alavi apply the idea of SIR balancing to CDMA cellular radio systems and show that SIR balancing substantially improves the capacity of such systems. But unlike the conditions in FDMA/TDMA cellular radio systems where in any cochannel set only one mobile exists in each cell, in CDMA cellular systems all the mobiles in each cell use the same frequency, which results in three dimensional link gain matrices. SIR balancing is not an eigenvalue problem any more unless intra-cell SIR balancing is assumed and the link gain matrices are simplified to two dimensions[1]. The optimum transmitter power control theory for narrowband cellular systems[2] seem not to be available for CDMA cellular systems directly.

The aim of this paper is to find the optimum transmitter power control scheme for CDMA cellular systems. Before that, the authors succeed in translating the SIR balancing problem for CDMA cellular systems to an eigenvalue problem. The optimum transmitter power control scheme is used to derive the upper performance bound for any type of transmitter power control algorithm. Several centralized algorithms which require substantially less computation effort are also discussed.

II. System Model

Throughout this paper we will study a large, but finite, CDMA cellular radio system consisting of N cells with Q active mobiles. We will in the sequel assume the transmission quality to be dependent only on the SIR ratio. The background noise is negligible in a high capacity, interference limited system.

Let us denote the link gain on the path from the m-th mobile in cell k to the base station in cell q at some given moment by G_{kmq}. Through some one to one corresponding relationship (see Fig 1), we can map (k,m) to i, where $1 \le i \le Q$. For simplicity, we let

$$i = \sum_{n=1}^{k} L_{n-1} + m \qquad 1 \le i \le Q \tag{1}$$

where $L_0 = 0, L_n (n = 1,2,\ldots\ldots N)$ is the number of active mobiles in cell n at the given moment. Using these notations, we may derive the uplink SIR for mobile i in cell k

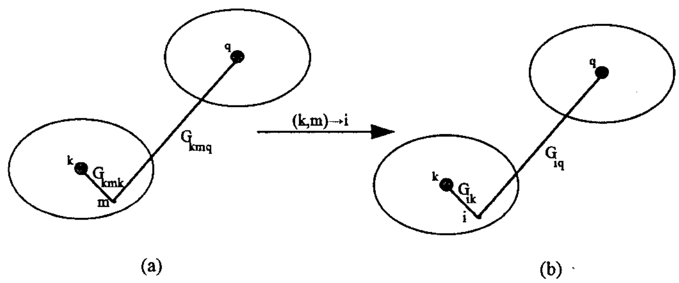

Fig 1 link gain model

$$\Gamma_i = \frac{G_{ik} P_i}{\sum_{j \ne i}^{Q} G_{jk} P_j} \tag{2}$$

where P_i is the uplink transmitter power of mobile i in cell k. Further dividing the right-hand side of (2) by G_{ik}, which is the link gain of the desired path, yields

$$\Gamma_i = \frac{P_i}{\sum_{j \ne i}^{Q} P_j \frac{G_{jk}}{G_{ik}}} = \frac{P_i}{\sum_{j=1}^{Q} P_j W_{ij}} \tag{3}$$

where W_{ij} is defined as

$$W_{ij} = \begin{cases} \dfrac{G_{jk}}{G_{ik}} & i \ne j \\ 0 & i = j \end{cases} \tag{4}$$

Note that k in the right-hand side of (4) is not an independent variable, but is determined by i according to the one to one

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mapping function of (1). W_{ij} is the link gain from mobile j to the base station which mobile i belongs to, normalized by the link gain on the desired path of mobile i. Thus we may introduce the normalized uplink gain matrix $\mathbf{W}=\left\{W_{ij}\right\}$, which has the following form.

$$\mathbf{W}=\begin{bmatrix} 0 & \frac{G_{21}}{G_{11}} & \cdots\cdots & \frac{G_{Q1}}{G_{11}} \\ \frac{G_{11}}{G_{21}} & 0 & \cdots\cdots & \frac{G_{Q1}}{G_{21}} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \frac{G_{11}}{G_{L_1,1}} & \frac{G_{21}}{G_{L_1,1}} & \cdots\cdots & \frac{G_{Q1}}{G_{L_1,1}} \\ \frac{G_{12}}{G_{L_1+1,2}} & \frac{G_{22}}{G_{L_1+1,2}} & \cdots\cdots & \frac{G_{Q2}}{G_{L_1+1,2}} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \frac{G_{12}}{G_{L_1+L_2,2}} & \frac{G_{22}}{G_{L_1+L_2,2}} & \cdots\cdots & \frac{G_{Q2}}{G_{L_1+L_2,2}} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \frac{G_{1N}}{G_{QN}} & \frac{G_{2N}}{G_{QN}} & \cdots\cdots & 0 \end{bmatrix}_{Q\times Q} \qquad (5)$$

Let us denote the link gain on the path from the base station in cell q to the m-th mobile in cell k at some given moment by g_{kmq}. Through one to one mapping of (1), we may in the same manner derive the downlink SIR of mobile i in cell k

$$\tau_i=\frac{g_{ik}P_i}{\sum_{j\neq i}^{Q} g_{il}p_j} \qquad (6)$$

where k, l denote the cells to which mobile i and j belong respectively, and p_i is the downlink transmitter power for mobile i by the base station in cell k. Then we can further derive

$$\tau_i=\frac{p_i}{\sum_{j\neq i}^{Q} p_j\frac{g_{il}}{g_{ik}}}=\frac{p_i}{\sum_{j=1}^{Q} p_j Z_{ij}} \qquad (7)$$

where Z_{ij} is defined as

$$Z_{ij}=\begin{cases}\frac{g_{il}}{g_{ik}} & i\neq j \\ 0 & i=j\end{cases} \qquad (8)$$

Z_{ij} represents the link gain from the base station including mobile j to mobile i, normalized by the link gain in the desired path of mobile i. Note that k and l in the right-hand side of (8) are not independent variables, but are determined by i and j respectively, according to the one to one mapping relationship of (1). In the same manner, we can introduce the normalized downlink gain matrix $\mathbf{Z}=\left\{Z_{ij}\right\}$, which has the following form

$$\mathbf{Z}=\begin{bmatrix} 0 & \frac{g_{11}}{g_{11}} & \cdots\cdots & \frac{g_{11}}{g_{11}} & \frac{g_{12}}{g_{11}} & \cdots\cdots & \frac{g_{12}}{g_{11}} & \cdots\cdots & \frac{g_{1N}}{g_{11}} \\ \frac{g_{21}}{g_{21}} & 0 & \cdots\cdots & \frac{g_{21}}{g_{21}} & \frac{g_{22}}{g_{21}} & \cdots\cdots & \frac{g_{22}}{g_{21}} & \cdots\cdots & \frac{g_{2N}}{g_{21}} \\ \vdots & \vdots & & \vdots & \vdots & & \vdots & & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots & \vdots & \cdots\cdots & \vdots & \cdots\cdots & \vdots \\ \frac{g_{L_1,1}}{g_{L_1,1}} & \frac{g_{L_1,1}}{g_{L_1,1}} & \cdots\cdots & 0 & \frac{g_{L_1,2}}{g_{L_1,1}} & \cdots\cdots & \frac{g_{L_1,2}}{g_{L_1,1}} & \cdots\cdots & \frac{g_{L_1,N}}{g_{L_1,1}} \\ \frac{g_{L_1+1,1}}{g_{L_1+1,2}} & \frac{g_{L_1+1,1}}{g_{L_1+1,2}} & \cdots\cdots & \frac{g_{L_1+1,1}}{g_{L_1+1,2}} & 0 & \cdots\cdots & \frac{g_{L_1+1,2}}{g_{L_1+1,2}} & \cdots\cdots & \frac{g_{L_1+1,N}}{g_{L_1+1,2}} \\ \vdots & \vdots & & \vdots & \vdots & & \vdots & & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots & \vdots & \cdots\cdots & \vdots & \cdots\cdots & \vdots \\ \frac{g_{L_1+L_2,1}}{g_{L_1+L_2,2}} & \frac{g_{L_1+L_2,1}}{g_{L_1+L_2,2}} & \cdots\cdots & \frac{g_{L_1+L_2,1}}{g_{L_1+L_2,2}} & \frac{g_{L_1+L_2,2}}{g_{L_1+L_2,2}} & \cdots\cdots & 0 & \cdots\cdots & \frac{g_{L_1+L_2,N}}{g_{L_1+L_2,2}} \\ \vdots & \vdots & & \vdots & \vdots & & \vdots & & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots & \vdots & \cdots\cdots & \vdots & \cdots\cdots & \vdots \\ \frac{g_{Q1}}{g_{QN}} & \frac{g_{Q1}}{g_{QN}} & \cdots\cdots & \frac{g_{Q1}}{g_{QN}} & \frac{g_{Q2}}{g_{QN}} & \cdots\cdots & \frac{g_{Q2}}{g_{QN}} & \cdots\cdots & 0 \end{bmatrix}_{Q\times Q}$$

(9)

In this paper , we only focus on the uplink performance which determines the CDMA system capacity.

Ⅲ. Optimum Power Control and Several Centralized Power Control Algorithms

Now, let us first consider a power control algorithm (PCA) of the uplink, which in every moment has access to the entire uplink gain matrix **W** and may instantaneously control the entire power vector **P**. Zander obtained the procedure to achieve optimum uplink power vectors in the sense that it minimizes the outage probability[2]:

Optimum PCA (BFA) [2][3]

(1) Step 1: Determine γ^* corresponding to **W**. If $\gamma^*\geq\gamma_0^U$, then use the eigenvector $\mathbf{P}^*$ and stop, else perform step 2.
(2) Step 2: Remove all combination of i mobiles and compute the eigenvalues of each reduced system, i is increased from 1 to at most Q-2. If for some i, $\gamma^*\geq\gamma_0^U$, then use corresponding eigenvector and stop, else remove Q-1 mobiles and stop.

γ^* is given by $\gamma^*=1/\lambda^*$, where λ^* is the largest real eigenvalue of **W**, and $\mathbf{P}^*$ is the corresponding eigenvector. γ_0^U is the minimum required SIR threshold of the uplink. Note that Q of a spread spectrum cellular system is much larger than that of a narrowband cellular system in which only the mobiles in one cochannel set is considered. Therefore, some algorithms with less computation complexity need to be discussed.

Stepwise Removal Algorithm (SRA) [2]

(1) Step 1: Determine γ^* corresponding to $\mathbf{W}$. If $\gamma^* \geq \gamma_0^U$, then use the eigenvector $\mathbf{P}^*$ and stop; else set $Q' = Q$ and perform step 2.

(2) Step 2: Remove mobile k for which the maximum of the row and column sums

$$r_k = \sum_{j=1}^{Q'} W'_{kj} \quad , \quad r_k^T = \sum_{j=1}^{Q'} W'_{jk}$$

is maximized and form the $(Q'-1)\times(Q'-1)$ matrix $\mathbf{W}'$. Determine γ^* corresponding to $\mathbf{W}'$. If $\gamma^* \geq \gamma_0^U$, then use the corresponding eigenvector and stop; otherwise set $Q' = Q' - 1$ and repeat step 2.

Stepwise Maximum-Interference Removal Algorithm (SMIRA) [3]

The SMIRA algorithm is the same as the SRA algorithm except that in step 2 mobile k is removed if the maximum of the two sums

$$r_k = \sum_{j=1}^{Q'} W'_{kj} P_j \quad , \quad r_k^T = \sum_{j=1}^{Q'} W'_{jk} P_k$$

is maximized.

Due to Lin's original mind, r_k represents the total interference for mobile k in the uplink and r_k^T represents the total interference to other mobiles caused by mobile k [3]. However, r_k and r_k^T do not represent these two concepts exactly due to the denominators in the normalized link gain matrices. We also introduce this algorithm because it is found to be better than SRA algorithm in narrowband cellular system, with only negligible additional computation complexity.

Constant Transmitter Power -Minimum SIR Stepwise Removal Algorithm (CTP-MSIR SRA)

(1) Step 1: Determine γ^* corresponding to $\mathbf{W}$. If $\gamma^* \geq \gamma_0^U$, then use the eigenvector $\mathbf{P}^*$ and stop; else set $Q' = Q$ and perform step 2.

(2) Step 2: Remove mobile k of which the SIR level is minimized when all the Q' mobiles transmits with the same power level and form the $(Q'-1)\times(Q'-1)$ matrix $\mathbf{W}'$. Determine γ^* corresponding to $\mathbf{W}'$. If $\gamma^* \geq \gamma_0^U$, then use the corresponding eigenvector and stop; otherwise set $Q' = Q' - 1$ and repeat step 2.

This algorithm is introduced because it is the upper bound of the distributed LI-SRA algorithm proposed by Zander [4].

Stepwise Optimal Removal Algorithm (SORA)

(1) Step 1: Determine γ^* corresponding to $\mathbf{W}$. If $\gamma^* \geq \gamma_0^U$, then use the eigenvector $\mathbf{P}^*$ and stop, otherwise set $Q' = Q$ and perform step 2.

(2) Step 2: Remove mobile k for which γ^* of the remaining system is maximized and form the $(Q'-1)\times(Q'-1)$ matrix $\mathbf{W}'$. If this maximized $\gamma^* \geq \gamma_0^U$, then use corresponding eigenvector $\mathbf{P}^*$ and stop, else set $Q' = Q' - 1$ and repeat step 2.

Ⅳ. Numerical Results

To derive some numerical results, more specific system model and additional assumptions for simulation are described in the following . The system includes a total 16 square-grid cells, at the center of which base stations are located with omnidirectional antennas. The mobiles are randomly located in the system with a uniform density and transmit at a constant information rate without the use of voice activity detection. For the reason of comparison, the perfect average power control algorithm[5] and the absolute SIR balancing algorithm[1] are also simulated in this paper. The link gain G_{ij} is modeled as $G_{ij} = A_{ij} / d_{ij}^{\alpha}$, where A_{ij} is the lognormal fading component with 0dB expectation and σ dB log-variance. d_{ij} is the propagation distance and α is the path loss exponent.

Fig 2, 3 show the system performance achieved by the SORA, SRA, SMIRA, CTP-MSIR SRA, absolute SIR balancing and perfect average power control algorithms for N=16, the spreading factor W/R=150, and $\left(\overline{E_b/I_0}\right)_{req}$ per diversity branch = 7dB. The capacities corresponding to the above algorithms are 20, 18, 18, 18, 15 and 13 mobiles/cell, respectively. The capacity of the SORA algorithm gains 1.9dB over the perfect average power control algorithm.

From Fig2-3, we note that:

(1) The absolute SIR balancing algorithm outperforms the perfect average power control algorithm at the region of low outage probability. As the mobile density increasing, the absolute SIR balancing algorithm will go bad rapidly.

(2) There is little difference between the SRA and SMIRA algorithms. The SMIRA algorithm cannot be considered as an approximation to the optimal performance, which is different from that of the narrowband cellular systems[3].

(3) The SORA algorithm performs much better than all the other algorithms, and can be considered as the approximation to the upper performance bound for all types of power control algorithms found up to now for CDMA cellular systems.

(4) CTP-MSIR SRA is efficient enough for distributed power control algorithms.

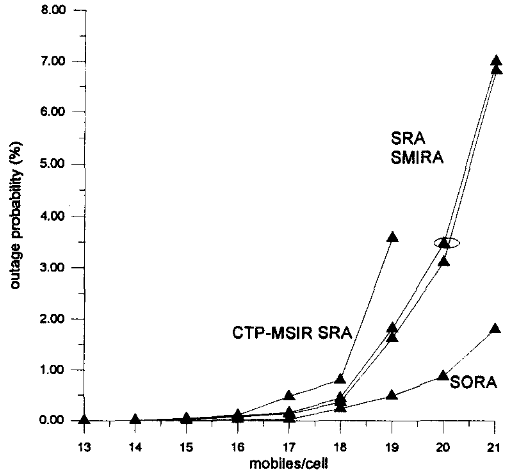

Fig 2. Outage probability comparison. The system investigated contains 16 cells. Lognormal fading $\sigma = 8dB$, $\alpha = 4$. W/R=150, $\left(\overline{E_b/I_0}\right)_{req}$ per diversity branch=7dB.

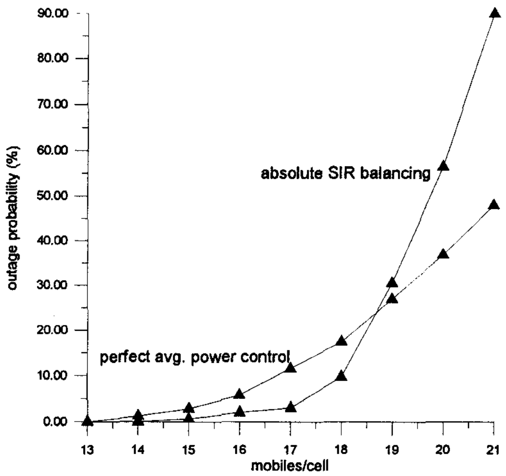

Fig 3. Outage probability comparison. The system investigated contains 16 cells. Lognormal fading $\sigma = 8dB$, $\alpha = 4$. W/R=150, $\left(\overline{E_b/I_0}\right)_{req}$ per diversity branch=7dB.

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