

CDMA Cellular Downlink Transmission with Transmit Arrays and Power Control: Circuit-Switched and Packet-Switched Systems*

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Abstract—Wireless CDMA cellular downlink communications with transmit antenna arrays in multipath fading channels is studied. Transmit diversity and various beamforming techniques are investigated and compared, in conjunction with power control. No instantaneous downlink channel information is assumed; however, the obtained results are also compared with results assuming ideal feedback. The study is carried out for both circuit-switched and packet-switched systems, for which different conclusions are drawn.

I. INTRODUCTION

Cellular base stations can make use of an antenna array to achieve diversity gains or antenna gains to improve system capacity [3]. In this study, we focus on array processing techniques to improve CDMA cellular downlink transmission, which is foreseen to be of crucial importance for third generation communication systems supporting wireless Internet, video on demand, and multimedia services.

Perhaps the simplest form of spatial processing is open loop transmit diversity, which will serve as the performance baseline in this study. Sectorization, which can be interpreted as fixed beam transmission, is well known to be an effective way to improve system capacity. Other array processing techniques belong to the beamforming category. A simple form of transmit beamforming is beam steering, which assumes knowledge of the mobile's position and forms a beam in the direction of line-of-sight. The performance of beam steering degrades in multipath channels with angle spread. A more sophisticated use of the array is to determine the antenna weighting vector that maximizes signal-to-noise ratio (SNR) at the mobiles. Alternatively, one can borrow the idea from uplink receive array processing and come up with a maximum signal-to-interference ratio (SIR) solution for weighting vector design, i.e., maximizing the ratio of the received power of the signal at the desired user and that leaked to the other users. Note that the downlink communication scenario is different from that of the uplink. While in the uplink the weighting vector designs for different users are de-coupled, optimal beamforming for the downlink will have to be considered jointly, because the weighting vector for one user will impact the interference received by other users as well as the useful signal power received by the desired user. A joint power control and downlink beamforming algorithm has been proposed in [7] and [8], and will also be used as the performance baseline.

Power control was conceived originally as a mechanism to deal with the near-far problem, but a more general emerging view is that it is a flexible mechanism to provide different quality-of-service to users with heterogeneous requirements [1]. For downlink transmission, power control is also important for energy conservation and interference mitigation. In circuit-switched systems, when we perform the above

downlink transmission array processing together with power control, we execute it in two steps: 1) an array weighting vector is determined (not needed for transmit diversity) and the signal-to-interference-and-noise ratio (SINR) is calculated (as functions of transmitted powers) for each mobile receiver; 2) transmitted power is allocated among users so as to minimize the total transmitted power from the base station while keeping the SINR of all links above a certain threshold. However, in packet-switched systems, where users are delay tolerant, we carry out rate control instead of power control, assuming the base station transmits at its maximum power. We mainly assume the powers are equally allocated; but an optimal power allocation scheme will also be studied. Throughout the paper, no instantaneous downlink channel state information (CSI) is assumed; however, the obtained results are also compared with results assuming ideal CSI.

This paper is organized as follows: in Section II the system model is introduced. Power control/allocation algorithms for circuit/packet switched systems are addressed in Section III under a common framework. In Section IV, various transmit array-processing techniques are presented. Section V provides numerical comparison results for these array processing techniques for both circuit-switched and packet-switched systems. Section VI concludes the paper.

II. SYSTEM MODEL

We assume a CDMA frequency division duplex (FDD) cellular system. In each cell K mobile users, each employing a single antenna, communicate with a base station having an M -element antenna array. The spreading codes employed within a cell by different users, or different antenna elements and different users (for code transmit diversity) are assumed to be mutually orthogonal with spreading gain N ; while any two codes with different delays are assumed to be independent. The physical channel between the mobile and the base station is assumed to be wide sense stationary with uncorrelated scattering (WSSUS) multipath frequency-selective fading. We assume for simplicity that there are L paths for each user.

For the transmit diversity technique, the discretized received signal at the i th mobile is given by

$$\mathbf{r}_i = \sqrt{\frac{G_i}{M}} \sum_{m=1}^M \sum_{k=1}^K \sqrt{P_k} b_k \mathbf{C}_{km} \mathbf{h}_m^i + \mathbf{n}_i, \quad (1)$$

where G_i is the path gain from the transmit array to the i th user which combines the effects of path loss and shadowing; P_k is the power assigned to the user k 's signal; b_k is the transmitted data for user k ; $\mathbf{C}_{km} = [\mathbf{c}_{km}^1, \dots, \mathbf{c}_{km}^L]$, whose columns are delayed versions of \mathbf{c}_{km} corresponding to different paths,

and \mathbf{c}_{km} is the spreading code for the k th user in the m th antenna¹; $\mathbf{h}_m^i = [\alpha_{m1}^i, \dots, \alpha_{mL}^i]^T$ collects the instantaneous small-scale fading coefficients of the L paths from the m th antenna to the i th user, which are independent for different paths and different antennas; and \mathbf{n}_i is the noise, which includes the interference from two tiers of surrounding cells. All the cells' settings are assumed to be identical. The total transmitted energy of one user is normalized with the antenna number M .

For beamforming techniques, the discretized received signal at the i th mobile is given by

$$\mathbf{r}_i = \sqrt{G_i} \sum_{k=1}^K \sqrt{P_k} b_k \mathbf{w}_k^H \sum_{l=1}^L \alpha_{il} \mathbf{a}_{il} \mathbf{c}_k^l + \mathbf{n}_i, \quad (2)$$

where \mathbf{w}_k is the transmit beamforming weight vector for user k ; \mathbf{c}_k^l is a delayed version of the k th user's spreading code corresponding to the l th path; and α_{il} and \mathbf{a}_{il} are the small-scale fading coefficient and the array response of the l th path from the antenna array to the i th user, respectively. Other elements of (2) are self-explanatory.

III. POWER CONTROL/ALLOCATION ALGORITHMS

For a circuit-switched system, a commonly used power control criterion is formulated as follows:

$$\min \sum_{k=1}^K P_k \quad s.t. \quad \text{SINR}_k \geq \gamma_k, \quad 1 \leq k \leq K, \quad (3)$$

i.e., minimize the total transmitted power with the constraints that each link obtains a SINR above a certain threshold. For a packet-switched system, we can simply allocate power equally among the active users, or we can allocate power in some optimal way. An optimal power assignment scheme proposed in [11] is formulated as follows:

$$\max \text{SINR}_{\min} \quad s.t. \quad \sum_{k=1}^K P_k \leq P_{\max}, \quad (4)$$

i.e., maximize the minimum link SINR with the total transmitted power constraint. This scheme tries to be fair to all users, which is not necessarily a good strategy for maximum throughput without taking into consideration the data link budget and network schedule. It turns out that these two power control/allocation schemes are related to the same algebraic theorem – the Perron-Frobenius Theorem and its applications, with respect to a square non-negative² irreducible matrix \mathbf{T} together with its maximum eigenvalue r [4].

Application 1: A necessary and sufficient condition for a non-negative solution \mathbf{x} to the equation $(s\mathbf{I} - \mathbf{T})\mathbf{x} = \mathbf{c}$ to exist for any nonnegative (non-trivial) vector \mathbf{c} is that $s > r^3$. In this case there is only one strictly positive solution given by $(s\mathbf{I} - \mathbf{T})^{-1}\mathbf{c}$.

The power control criterion of (3) is related to Application 1 of the theorem as follows. The general form of the power control problem can be reformulated as

¹ A total of KM Walsh codes are required. To conserve codes, techniques such as space-time spreading can be used, but the performance achieved is not different from that found here.

² Here the term nonnegative refers to a vector or matrix all of whose elements are nonnegative. The definition for strictly positive is similar.

³ \mathbf{I} is an identity matrix

$$\min \sum_{k=1}^K P_k \quad s.t. \quad (\mathbf{I} - \mathbf{DF})\mathbf{p} = \mathbf{u}, \quad (5)$$

where \mathbf{D} is a diagonal matrix with entries $\gamma_1, \dots, \gamma_K$, \mathbf{F} is a non-negative irreducible matrix (interference term), $\mathbf{p} = [P_1, P_2, \dots, P_K]^T$ collects the powers assigned to all users, and \mathbf{u} is a positive vector (noise term)⁴. So we have a feasible (positive) solution for power allocation vector if and only if the spectral radius of \mathbf{DF} is less than one, otherwise we will claim an outage occurs. We call this a type-I outage and call the case in which we do get a positive solution but the total transmitted power exceeds a threshold, i.e., $\mathbf{p}^T \mathbf{1} > P_{\max}$, a type-II outage. The solution to (5), if it exists, is given by $(\mathbf{I} - \mathbf{DF})^{-1}\mathbf{u}$ or alternatively by Jacobi iteration

$$\mathbf{p}^{(n+1)} = \mathbf{u} + \mathbf{DFp}^{(n)}, \quad (6)$$

which will converge for any initial value in this setting.

Application 2: If a non-negative (non-trivial) vector \mathbf{y} satisfies $\mathbf{T}\mathbf{y} \leq s\mathbf{y}$ ($s > 0$), then: $\mathbf{y} > 0$; $s \geq r$; and $s = r$ if and only if $\mathbf{T}\mathbf{y} = s\mathbf{y}$.

The power allocation criterion of (4) is related to Application 2 of the theorem as follows. It can easily be shown that this optimization scheme results in equal SINR = γ for all links. On writing $\mathbf{y} = [\mathbf{p}^T, 1]^T$, the objective functions then become

$$\mathbf{R}\mathbf{y} = \frac{1}{\gamma}\mathbf{y}, \quad (7)$$

with

$$\mathbf{R} = \begin{bmatrix} \mathbf{F} & \mathbf{h} \\ \mathbf{1}^T \mathbf{F} / P_{\max} & \mathbf{1}^T \mathbf{h} / P_{\max} \end{bmatrix}, \quad (8)$$

where $\mathbf{h} = \mathbf{u} / \gamma$, \mathbf{F} and \mathbf{u} is similarly defined as in (5), and $\mathbf{1}$ is an all-1 vector. As \mathbf{R} is a non-negative irreducible matrix, we always have a unique positive solution for \mathbf{p} and the SINR margin is the reciprocal of the largest eigenvalue of \mathbf{R} .

IV. ARRAY SIGNAL PROCESSING

In this section, various array signal processing techniques are discussed. We assume that the mobile receiver can learn the fading channel and perform RAKE combining. So the instantaneous SINR is obtained for each scheme, based on which the power control of Section III is then applied. Due to space limitations, only main the results are provided, the reader is referred to [1] for details of derivations.

A. Transmit Diversity

The SINR for user i is given by

$$\text{SINR}_i = \frac{\frac{G_i}{M} P_i (A^i)^2}{\sum_{k \neq i} \frac{G_i}{M} P_k C^i + \sigma_i^2 A^i}, \quad (9)$$

where σ_i^2 is the noise power at user i 's receiver,

$$C^i = \frac{1}{N} \sum_m \sum_{m'} \sum_l \sum_{l' \neq l} |\alpha_{ml}^i|^2 |\alpha_{m'l'}^i|^2 \quad \text{and} \quad A^i = \sum_{m=1}^M \sum_{l=1}^L |\alpha_{ml}^i|^2.$$

⁴ Exact SINR formulas will be given in the next section, together with the definitions for \mathbf{F} and \mathbf{u} .

The power control formula (5) is exemplified here by

$$F_{ij} = \begin{cases} 0 & i = j \\ \frac{C^i}{(A^i)^2} & i \neq j \end{cases}, \quad (10)$$

and

$$u_i = \frac{\gamma_i \sigma_i^2 M}{G_i A^i}. \quad (11)$$

B. Sectorization

The sectorizing antenna radiation pattern adopted here is formulated as follows [9]:

$$G_S(\theta) = \begin{cases} 1 - \frac{(1-b)}{(\pi/S)^2} \theta^2 & |\theta| \leq \sqrt{\frac{1-a}{1-b}} \frac{\pi}{S}, \\ a & \text{elsewhere} \end{cases}, \quad (12)$$

with $10 \log a = -15$ dB and $10 \log b = -3$ dB, and $S = 3$ or 6 .

C. Beamforming Techniques

Before we discuss the various beamforming options, let us first assume generally a set of unit-norm transmit weighting vectors $\{\mathbf{w}_i\}_{i=1}^K$ are adopted for the K users' signals at the base station.

The instantaneous SINR for user i is given by

$$\text{SINR}_i = \frac{P_i \mathbf{w}_i^H \mathbf{R}_i \mathbf{w}_i}{\sum_{k \neq i} P_k \mathbf{w}_k^H \mathbf{Q}_i \mathbf{w}_k + \sigma_i^2 \sum_l |\alpha_{il}|^2}, \quad (13)$$

where the spatial covariance matrices \mathbf{R}_i and \mathbf{Q}_i are given by

$$\mathbf{R}_i = G_i \sum_l \sum_{l'} |\alpha_{il}|^2 |\alpha_{il'}|^2 \mathbf{a}_{il} \mathbf{a}_{il'}^H \quad (14)$$

and

$$\mathbf{Q}_i = \frac{1}{N} G_i \sum_l \sum_{l' \neq l} |\alpha_{il}|^2 |\alpha_{il'}|^2 \mathbf{a}_{il} \mathbf{a}_{il'}^H. \quad (15)$$

The power control formula (5) is exemplified here by

$$F_{ij} = \begin{cases} 0 & i = j \\ \frac{\mathbf{w}_j^H \mathbf{Q}_i \mathbf{w}_j}{\mathbf{w}_i^H \mathbf{R}_i \mathbf{w}_i} & i \neq j \end{cases} \quad (16)$$

and

$$u_i = \frac{\gamma_i \sigma_i^2 \sum_{l=1}^L |\alpha_{il}|^2}{\mathbf{w}_i^H \mathbf{R}_i \mathbf{w}_i}. \quad (17)$$

In FDD systems, the separation between the uplink and downlink carrier frequencies is large enough to reject the reciprocity principle. However, if the frequency separation is not too large, the uplink and downlink will still share many common features, among which are the number of radio paths, their delays and angles, the large-scale path loss and shadowing, and the variance of small-scale fading. Although the instantaneous small-scale fading is uncorrelated between the uplink and downlink, their average strength is assumed to be insensitive to small changes in frequency, i.e.,

$$E\{|\alpha_{kl}^D|^2 |\alpha_{kl'}^D|^2\} = E\{|\alpha_{kl}^U|^2 |\alpha_{kl'}^U|^2\}, \quad (18)$$

which can be estimated via time average from uplink data. Further, as the array response is frequency-dependent, we es-

timate the downlink array response from the uplink data through high-resolution direction-of-arrival (DOA) estimation methods or training sequences, and ignore the estimation error. Therefore, the spatial covariance matrices are approximated as

$$\bar{\mathbf{R}}_i = G_i \sum_l \sum_{l'} E\{|\alpha_{il}|^2 |\alpha_{il'}|^2\} \mathbf{a}_{il} \mathbf{a}_{il'}^H \quad (19)$$

and

$$\bar{\mathbf{Q}}_i = \frac{1}{N} G_i \sum_l \sum_{l' \neq l} E\{|\alpha_{il}|^2 |\alpha_{il'}|^2\} \mathbf{a}_{il} \mathbf{a}_{il'}^H. \quad (20)$$

Based on these matrices, various beamforming schemes are illustrated below. Equations (13), (16) and (17) are adjusted accordingly.

1. Beam Steering

This scheme corresponds to the following antenna weights:

$$\mathbf{w}_i = \frac{\mathbf{a}^D(\theta_{i,\text{los}})}{\|\mathbf{a}^D(\theta_{i,\text{los}})\|}, \quad (21)$$

where $\theta_{i,\text{los}}$ denotes the azimuth angle of the line-of-sight of the i th user with the antenna array.

2. Maximum SNR

This scheme maximizes the SNR at the i th user. According to (13), it is equivalent to

$$\arg \max_{\mathbf{w}_i} \mathbf{w}_i^H \bar{\mathbf{R}}_i \mathbf{w}_i. \quad (22)$$

It is well known that the solution to (22) is given by the (normalized) principal eigenvector of the matrix $\bar{\mathbf{R}}_i$.

3. Maximum SIR/SINR

For circuit-switched systems, the powers of transmitted signals are not available at this stage (it is decided at the power control step), so we cannot conduct max SINR as uplink processing. The max SIR scheme is formulated as

$$\arg \max_{\mathbf{w}_i} \frac{\mathbf{w}_i^H \bar{\mathbf{R}}_i \mathbf{w}_i}{\mathbf{w}_i^H \bar{\mathbf{T}}_i \mathbf{w}_i} \quad \text{with} \quad \bar{\mathbf{T}}_i = \sum_{k \neq i} \bar{\mathbf{Q}}_k. \quad (23)$$

This \mathbf{w}_i is given by the (normalized) generalized principal eigenvector of $[\bar{\mathbf{R}}_i, \bar{\mathbf{T}}_i]$.

In packet-switched systems, our goal is to maximize the network throughputs with the maximum transmit power, so the power allocation is known in advance. In this case, Max SINR can be exploited as follows:

$$\arg \max_{\mathbf{w}_i} \frac{\mathbf{w}_i^H \bar{\mathbf{R}}_i \mathbf{w}_i}{\mathbf{w}_i^H \bar{\mathbf{T}}_i \mathbf{w}_i} \quad \text{with} \quad \bar{\mathbf{T}}_i = \sum_{k \neq i} \bar{\mathbf{Q}}_k + \frac{K \sigma^2}{P_i} \mathbf{I}, \quad (24)$$

which can be seen as a tradeoff between the Max SNR and Max SIR schemes.

4. Joint Power Control and Maximum SINR Beamforming

Due to space limitations, this scheme is omitted here. The reader is referred to [7] and [8] for details.

V. NUMERICAL RESULTS

In this section, we examine the performance of the various downlink transmission techniques discussed above through computer simulation. For circuit-switched systems, power control is carried out and we evaluate and compare the supportable user capacity with certain SINR requirement under some out-

age limit. For packet-switched systems, we allow each base station to transmit at the maximum power and equally divide the power among the active users. We examine the cumulative distribution function (CDF) of the SINR seen by a typical mobile user for performance comparison since the SINR is directly related to the achievable rate of the user. We also examine the effect of the optimal power assignment scheme of [11].

In our setting, the maximum transmitted power to ambient noise ratio is set to be 30 dB. The link SINR threshold is 5 dB for circuit-switched systems. The path loss parameter $\eta = 4$ and the standard deviation of the lognormal shadowing is 8 dB. The small-scale fading coefficients are generated through the typical urban (TUx) model used in W-CDMA 3G studies. The users are distributed uniformly within the sector of interest. We assume for each user there are three paths, the angles of which are Gaussian distributed around the direction of line-of-sight, with standard deviation of 10 degrees. The CDMA spreading gain is $N = 64$. The number of antennas M in our study is 2, 4, or 8 per sector. We assume each cell has three 120-degree sectors unless otherwise noted. When studying the transmit diversity scheme in the six sector case, the number of users and antennas per sector is reduced to one half of those in the three-sector scenario.

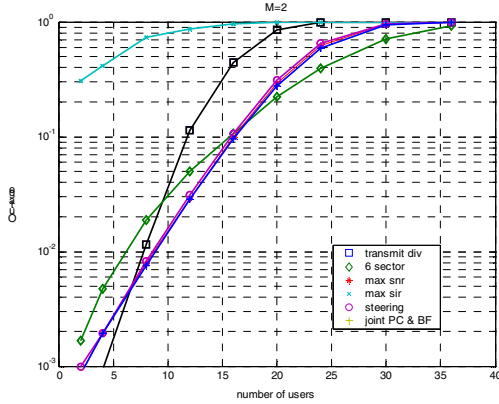


Fig. 1 Performance comparison of various transmission techniques with $M = 2$ antennas per sector (6 antennas per cell)

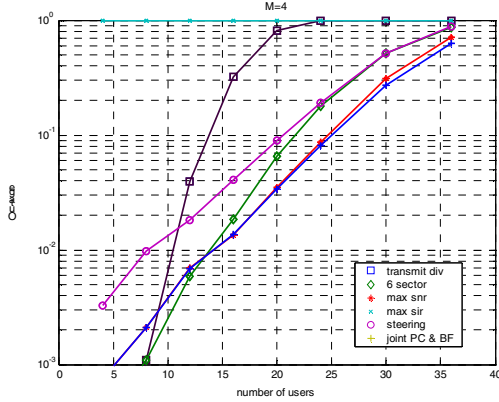


Fig. 2 Performance comparison of various transmission techniques with $M = 4$ antennas per sector (12 antennas per cell)

A. Circuit-Switched System

Figures 1 to 3 present the performance of the six transmission techniques combined with power control for circuit-switched systems, namely, transmit diversity, transmit diversity with

sectorization, Max SNR beamforming, Max SIR beamforming, beam steering, and joint power control and (Max SINR) beamforming. We assume no feedback from the mobile, while the loss due to this lack of feedback is also examined. For the sake of comparison, the number of users that can be supported in one cell with 5% outage is given in Table 1.

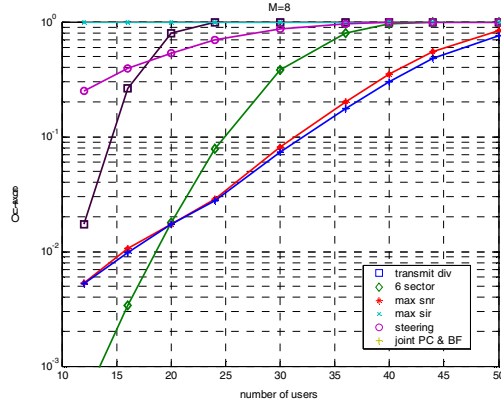


Fig. 3 Performance comparison of various transmission techniques with $M = 8$ antennas per sector (24 antennas per cell)

Table 1 Number of users supported in a cell with 5% outage

Transmit Diversity	Six Sector	Beam Steering	Max SNR	Max SNR with feedback	Joint	Joint with feedback	
	30	39	42	42	42	42	→ 6 antennas per cell
	36	57	66	72	66	72	→ 12 antennas per cell
	39	69	81	117	84	117	→ 24 antennas per cell

From these data, several conclusions can be made for CDMA downlink circuit-switched systems. First, we note that Max SNR beamforming approaches the optimal performance (that of joint power control and Max SINR beamforming) in the outage range of interest, while having much lower complexity. Second, Max SIR has totally unacceptable performance and thus is omitted in Table 1. Intuitively, putting too much emphasis on minimizing the interference to other users will hurt the desired user energy; so more power has to be assigned to achieve the SINR threshold, resulting in type-II outage. Another problem of Max SIR is due to the insufficient degrees of freedom the antenna array can offer compared to the number of users. Third, beam steering has good performance only when the number of antenna elements is small ($M = 2$); the gap between beam steering and Max SNR beamforming enlarges as M increases. Last, for transmit diversity, sectorization significantly improves the performance (6 to 30 users more as M goes from 2 to 8 at 5% outage); but the Max SNR beamforming technique still outperforms the six-sector transmit diversity scheme (6 to 12 users more as M goes from 2 to 8 at 5% outage).

We have also shown that, for transmit diversity, the gain from exploiting more antennas diminishes as the number of antennas increases. For Max SNR beamforming the gain through exploiting more antenna elements does not diminish but is restricted due to imperfect channel knowledge. On the other hand, if we assume ideal feedback, the gain achieved

through exploiting more antenna elements increases with the number of antennas. Also for Max SNR beamforming, the gap between that of no feedback and that with feedback increases as the number of antennas increases, but for small numbers of antennas ($M = 2, 4$), the loss due to approximation of channel parameters is insignificant. This means that for small numbers of antennas, Max SNR beamforming is the best choice even without feedback information.

B. Packet-Switched System

As a counterpart to the circuit-switched case, we also compare the performance of six transmission techniques for the packet-switched system. Because there is no power control in this case, we study the optimal power allocation combined with Max SNR instead. We perform equal power assignment unless otherwise noted. For the sake of comparison, the median (50% CDF) and peak (90% CDF) SINR values see by a typical user are given in Table 2 and 3, respectively. Note that for the $M = 8$ and $K = 4$ case, the number of simultaneously transmitted users is doubled. One should consider this when translating SINR to achievable rates and network throughput. “(f)” in the tables designates results with feedback channel parameter information.

Table 2 Median SINR (50% CDF) of a typical mobile user (dB)

Transmit Diversity	Six Sector	Beam Steering	Max SNR	Max SNR(f)	Max SINR	Max SINR(f)	Opt PA & Max SNR	Opt PA & Max SNR(f)	
8	11.8	10.8	11	11.1	10.6	10.8	10.6	10.7	$M=4 \text{ \& } K=2$
8	12	11.4	12.4	12.7	13.2	13.7	11.9	12.3	$M=8 \text{ \& } K=2$
4.2	7.2	7.6	8.5	8.8	6.4	7.2	7.7	8.2	$M=8 \text{ \& } K=4$

Table 3 Peak SINR (90% CDF) of a typical mobile user (dB)

Transmit Diversity	Six Sector	Beam Steering	Max SNR	Max SNR(f)	Max SINR	Max SINR(f)	Opt PA & Max SNR	Opt PA & Max SNR(f)	
11	17.5	15.5	15.7	15.7	21.6	21.6	13.8	13.8	$M=4 \text{ \& } K=2$
10.8	17.2	19.3	19.5	19.5	24.3	24.6	16.8	17.1	$M=8 \text{ \& } K=2$
6.8	10	12.7	13.3	13.4	18.8	19.3	10.3	10.6	$M=8 \text{ \& } K=4$

From these data, several conclusions can be drawn for CDMA downlink packet-switched systems. First, the optimal power allocation scheme has no benefit in packet-switched systems. A similar phenomenon can be observed for the Max SINR scheme and is omitted here. Second, contrary to the circuit-switched case, Max SINR beamforming has the best performance in terms of peak rate; it is also good at median rate with small numbers of users, while being comparable with others when there are more users. We have also noticed that Max SNR beamforming is almost the best in terms of median rate; it is also good in terms of peak rate performance. Beam steering is almost as good as max SNR in terms of peak rate performance, while a little worse (1 dB) in terms of median

rate performance. For transmit diversity, sectorization significantly improves the performance (4-7 dB). The Max SNR beamforming technique outperforms the six-sector transmit diversity scheme for $M = 8$ (1dB in median and 2-3 dB in peak); for $M = 4$, six-sector transmit diversity is better. We also find that feedback does not help much for beamforming in packet-switched systems.

VI. CONCLUSIONS

In this paper, we have seen that traffic type impacts the algorithm choice in downlink transmission. For circuit-switched downlink CDMA systems, the Max SNR beamforming scheme is the best choice (accommodating 12 to 42 more users than transmit diversity). For packet-switched systems, Max SINR beamforming has the best performance in terms of peak rate (10-14 dB more than transmit diversity); Max SNR beamforming is almost the best in terms of median rate (3-4 dB more than transmit diversity), but beam steering and transmit diversity with sectorization are also good choices. We also see that sectorization greatly improves the system performance, for both the circuit-switched and for the packet-switched case. For transmit diversity, the gain from exploiting more antennas diminishes, while this is not the case for beamforming, especially with feedback channel information. Optimum power control/allocation schemes have been shown to be either too complex or infeasible in practice.

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