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Data Throughput in a Multi-Rate CDMA Reverse Link: Comparing Optimal Spatial Combining vs. Maximal Ratio Combining

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I. Introduction

The total data carrying capacity or data throughput is a useful average metric when discussing the ability of a system to carry data communications. The total data throughput depends upon the type of data traffic and supporting communication system.

Previous commercial code-division multiple access (CDMA) systems, IS95A/B, employed low data rate (LDR) users only on the Reverse Link. Next generation CDMA systems, however, offer voice and high data rate (HDR) user traffic on the Reverse Link that can increase the total average Reverse Link data throughput.

Previous literature [1-3] has discussed the potential for Reverse Link capacity gains using OC vs. MRC. While in an isolated cell significant gains can be achieved, in an embedded CDMA multi-cell environment, other cell interference tends, on average, to limit gains.

In this paper, we use the standard CDMA power and interference equations of a multi-cell network, the results obtained in [4], and reference previous voice-data throughput literature to determine the total Reverse Link system data throughput using spatial OC vs. MRC.

Section II describes the general system model. The system capacity of a Reverse Link LDR system using MRC is discussed in Section III. Section IV develops the CDMA multi-cell interference relationships with regard to spatial combining gains. Increases in the number of LDR users using OC vs. MRC and total Reverse Link system throughput are developed in Section V. Section VI calculates the total increase in the ratio of Reverse Link throughput using OC vs. MRC and illustrates specific examples relevant in a typical cdma2000 system.

II. System Model

CDMA is an interference-limited system. A multi-rate (mixed voice-data) power and interference distribution model for the CDMA Reverse Link is described in this section.

A Rayleigh fading channel model, perfect average power control, other cell interference modeled as many LDR users, perfect estimates of all parameters, and uncorrelated fading on each antenna element making up the antenna array are assumed.

A. Interference Terms in the Reverse Link of a Multi-Cell CDMA System

CDMA capacity metrics depend upon on the interference in the system. The total received power, I_0W, at the receiver output of a Base Station Reverse Link antenna can be described as:

$$I_0 W = I_{in}W + I_{out}W + N_0 W = \sum_{i=1}^{K_u} v_i E_b R_i + I_{out}W + N_0 W \quad (1)$$

where I_n is an equivalent noise power density (dBm/Hz) and W is the equivalent noise power bandwidth (Hz).

The components of the total interference and related assumptions are described below:

1) $I_{in}W$ denotes the power of in-cell multiple access power from all K_u users, i.e. $I_{in}W = \sum_{i=1}^{K_u} v_i E_b R_i$ where v_i is the per user voice activity factor, E_b the bit energy (energy/bit), and R_i is the per user data rate (bit/sec).

2) $I_{out}W$ denotes the power of the multiple access interference, MAI, from all adjacent cells (multi-tier)

3) N_0W denotes the equivalent thermal noise power of the background noise and receive path signal conversion.

B. Ratio of Total Interference to Background Noise

The difference of the total interference, I_0W, to the background thermal noise, N_0W, can be described as [5]:

$$(I_0 - N_0)W = I_0W(1-\eta) \qquad (2)$$

where η represents the ratio of N_o/I_o (total interference to thermal noise ratio). Typical values for η = 0.5 to 0.1 which correspond to I_0/N_0 ratios of 3 dB to 10 dB.

C. Other Cell Interference and Relation to In-Cell Interference

The other cell interference parameter, f, can be described as the ratio of other-cell interference to the in-cell interference

$$f = I_{out}W / I_{in}W \qquad (3)$$

A typical value for f is f = 0.55. This value for f assumes an r^{-4} propagation exponent (r measured in distance), a log-normal shadowing standard deviation of σ = 8 dB, and equally loaded cells [6].

The in-cell MAI interference can be related to the total interference via:

$$I_{in}W = \frac{I_0W(1-\eta)}{(1+f)} = \sum_{i=1}^{K_u} v_i E_b R_i \qquad (4)$$

III. SYSTEM CAPACITY IN A LDR SYSTEM USING MRC

In this section we determine the equivalent data throughput in a LDR user scenario for a CDMA Reverse Link using MRC.

A. Calculation of Number of Equivalent 9.6kbps Data Users

The number of allowable LDR 9.6kbps calls that can be supported in a cdma2000 system can be calculated using:

$$\sum_{i=2}^{K_u} v_i \le \left(\frac{(1-\eta)}{(1+f)}\right)\left(\frac{W}{R}\right)\left(\frac{1}{E_b/I_0}\right) \qquad (5)$$

We define a typical CDMA Reverse Link System to understand the relative interference power ratios and to determine the number of LDR users via the following:

1) A voice activity factor v_i=1 (to illustrate equivalent number of full rate 9.6kbps calls), η = 0.25 (6 dB rise over thermal), W/R=128 (1.2288E6/9.6E3),and f=0.55..

2) $E_b/I_0 = 4.0\,dB$ for 2 antennae (assumes an implicit amount of mobility).

3) $E_b/I_0 = 0.5\,dB$ for 4 antennae (assumes an implicit amount of mobility). The decrease in Eb/Io relative to 2 antennae is assumed to come from: a) Aperture Gain with 2x antennae offers 3 dB improvement, and b) Diversity Gain offers 0.5 dB improvement due to increased fading margin. Total decrease in Eb/Io is 3.5 dB.

Using the above assumptions, Figure 1 illustrates the relative ratios of power and interference in a CDMA reverse link while also calculating the maximum number of LDR users (9.6 kbps) for 2 and 4 antennae.

Note that going from 2 to 4 antennae alone increases the Reverse Link system data throughput from 248 kbps to 542 kbps.

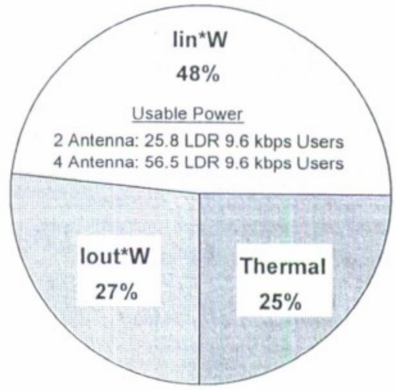

Figure 1. Relative Power and Interference for the CDMA Reverse Link with η=0.25 and f=0.55

IV. DATA USER POWER AND RELATION TO SPATIAL COLORING

This section develops a Reverse Link HDR user's power requirements and relationship to the standard CDMA interference equations discussed in Section II.

A. Data User Power Relative to Interference

We define κ to be the ratio of the data user's power to the total interference minus the data user's power:

$$\kappa = \frac{P_D}{I_0W - P_D} = \frac{P_D}{I_{TOT}^D W} = \frac{1}{\frac{I_{in}W\cdot(1+f)}{P_D\cdot(1-\eta)} - 1} \qquad (6)$$

with κ times the data user's processing gain ($G_D = W/R_D$) being equal to the data user's E_b^D / I_{TOT}^D :

$$\frac{E_b^D}{I_{TOT}^D} = \kappa \cdot \frac{W}{R_D} \qquad (7)$$

The ratio of the in-cell power to other-cell interference and background noise represents the maximum amount of spatial coloring (or maximum P_D) possible for a single HDR user:

$$\kappa_{\max} = \frac{I_{in}W}{I_{out}W + N_0\cdot W} = \frac{1}{\frac{(1+f)}{(1-\eta)} - 1} \qquad (8)$$

Table 1 illustrates $\kappa_{\max}$ for different rise over thermal values, η. Note that even at high rise over thermal ratios (η=0.1), the other-cell interference limits $\kappa_{\max}$.

TABLE I

Maximum Spatial Coloring, $\kappa_{\max}$ vs. η for f=0.55.

η (total interference to thermal noise ratio)	$\kappa_{\max} = \dfrac{1}{\dfrac{(1+f)}{(1-\eta)} - 1}$
0.50 (3 dB rise)	0.476
0.25 (6 dB rise)	0.935
0.10 (10 dB rise)	1.385

B. Single Dominant Data User on the Reverse Link Maximizes the Total Data Throughput

A data user having a data rate ε times that of an equivalent number of LDR users (9.6kbps)

$$\varepsilon = \frac{R_D}{R_v} \tag{9}$$

will encounter a lower total interference and will use a lower power, P_D, than ε low data rate users all having the same power, P_V (assuming same target Eb/Io).

The lower interference for the data user is due to the data users own power being coherent to itself, per multi-path, and thus the data user can subtract off its own power from the total system interference (often neglected in the case of low power LDR users).

A collection of ε independent low data users will therefore use more power than one high data rate user even though as a whole they have equivalent data throughput.

We can therefore state that in a multiple access scenario on the Reverse Link comparing OC vs. MRC, while employing mixed voice-data communications, one dominant high data rate user will allow for the highest total Reverse Link data throughput (given E_b^D/I_{TOT}^D, η, f, and R_D), and the lowest equivalent HDR user power, $P_{D\min}$:

$$P_{D\min} = \frac{E_b^D/I_{TOT}^D}{E_b^D/I_{TOT}^D + W/R_D} \cdot I_0 W \tag{10}$$

where I_0W can be normalized to one and the following assumptions are made:

1) The underlying modulation scheme can support the higher data rates.

2) Each mobile users transmit power, when adjusted for each user's channel loss, can meet the maximum P_D offered.

3) Flat fading channel (no multi-path)

These observations generally agree with previously derived results for maximum data throughput in a multi-rate CDMA Reverse Link [7].

In practice, finite mobile user transmit power and multi-path channels will limit the maximum data throughput from achieving the maximum theoretical value. Additionally, the minimum HDR user power, $P_{D\min}$, in (10) will only be obtained for a flat fading HDR user channel.

We choose to analyze the extreme case of a single path dominant HDR user, equivalently the case of maximum spatial coloring, to understand in the limit the gains achievable using OC vs. MRC (an upper bound).

V. Reverse Link Throughput For OC And MRC

The increase in the number of LDR users employing OC vs. MRC is proportional to the increased allowable in-cell interference from spatial filtering (OC) of the HDR user power.

In this section we use the concept of steady state in-cell interference to calculate Reverse Link system Throughput for OC and MRC.

A. Steady State In-Cell Interference

The Reverse Link will adapt up or allow an increased number of LDR users, when the HDR user is spatially filtered, to obtain a previously accepted steady state amount of in-cell interference, $I_{in}W$ (or equiv. total rise over thermal $I_0W(1-\eta)$ given parameter f in (3)).

We define the total number of users, K_U, to be equal to $K_U = K_V + K_D$ where K_V and K_D reflect the number of voice (LDR) and data (HDR) users.

We write the steady state in-cell interference, minus the HDR user's power, in a mixed voice-data system using OC vs. MRC as:

$$P_V^{MRC} \cdot K_V^{MRC} = P_V^{OC} \cdot K_V^{OC} = I_{in}W - P_D \cdot K_D \tag{11}$$

assuming all voice users have the same power, P_V, and all data users have the same power, P_D.

B. Spatial CINR Gains: $Z=CINR_{OC}/CINR_{MRC}$

Increases in the HDR user's power relative to the white spatial background noise offers a larger potential gain using OC vs. MRC.

The average value of Z, the gain using OC vs. MRC, was found in [4] by integrating over the vector angle difference, $\phi_{\vec{\alpha}-\vec{\beta}}$, between two users channel signatures, $\vec{\alpha}$ and $\vec{\beta}$, and the fading PDF of the high data user channel signature norm, $\|\beta\|$. Z was found to be dependent upon m, the number of antennae, and $c^2 = \frac{\sigma^2}{\sigma_v^2}$, the ratio of the background noise power to HDR user signal power.

Z for a single HDR user was defined as:

$$Z(m,c^2) = 1 + \frac{(m-1)}{c^2 \cdot (m+1)!} \cdot \left(\begin{array}{l} \sum_{r=0}^{m} (-1)^r (c^2)^r (m-r)! \\ + (-1)^{m+1} (c^2)^{m+1} \exp(c^2) \cdot Ei(1,c^2) \end{array} \right) \quad (12)$$

where $Ei(n,x) = \int_1^\infty \frac{\exp(-x \cdot t)}{t^n} dt$.

Note that κ in Section IV is inversely proportional to c^2, i.e. $\kappa = \frac{1}{c^2} = \frac{\sigma_v^2}{\sigma^2}$.

C. Per User Average Power Change Using OC vs. MRC

The vector angle difference, $\phi_{\vec{\alpha}_i - \vec{\beta}}$, between two users was shown to be independent of the users' underlying channel signature norm, $\|\alpha\|$ and $\|\beta\|$ [4,8]. We use the same assumptions to state that each LDR user's gain difference using OC vs. MRC is independent from all other LDR users.

It is noted, however, that all LDR user's gain Z_i are dependent on the PDF of the HDR users fading norm, $\|\beta\|$, and mean value of spatial coloring, κ.

Using the argument of independence between all LDR users, given $\|\beta\|$ and an already assumed η, we can write that the expected value of the sum of all LDR user's power using OC is equal to the sum of the expected value of each LDR user's power using OC. That is,

$$E\left[\sum_{i=1}^{K_V} Z_i \cdot P_{V,i}^{OC}\right] = \sum_{i=1}^{K_V} E\left[Z_i \cdot P_{V,i}^{OC}\right] = K_V \cdot Z \cdot P_V^{OC} \quad (13)$$

Equation (13) allows us, on average, to write each LDR user's power using OC in terms of a common Z (12) and a LDR user's power using MRC:

$$Z = \frac{P_V^{MRC}}{P_V^{OC}} \quad (14)$$

Combining (12) with (14) yields the increase in the number of low data users using OC in terms of the number of low data users using MRC and Z:

$$Z \cdot K_V{}^{MRC} = K_V{}^{OC} \quad (15)$$

We note that as the ratio of spatial coloring increases beyond $\kappa = 1$, the CDFs of the CINR using OC vs. MRC will vary and thus represent a difference in the final Eb/Io target of all LDR users to obtain the same FER. Hence, the validity of (15) is dependent upon the range that the CDF of the CINRs of OC and MRC are equivalent.

It is shown in [4] that the CDFs for the CINR using OC vs. MRC are nearly equivalent for $\kappa \leq 1$ which is suitable up to η=0.25 and f=0.55 as described in Table 1.

D. Increase in LDR Users Using OC vs MRC and Total Reverse Link Throughput

The total decrease in power from all the LDR users (decrease of in-cell interference) using OC vs. MRC is directly proportional to the increase in the number of LDR users that can be supported in the system.

The increase in the number of LDR users can be written, using (12, 15) as:

$$\begin{aligned} \text{Increase in LDR Users} &= Z \cdot K_V{}^{MRC} - K_V{}^{MRC} \\ &= (Z-1) \cdot K_V{}^{MRC} \end{aligned} \quad (16)$$

Using (9,12,15) we can write the total Reverse Link system Throughput, RLT, as:

$$RLT = \left(Z \cdot K_V{}^{MRC} + \varepsilon \cdot K_D\right) \cdot R_V \quad bps \quad (17)$$

where Z is equal to one for MRC, and greater or equal to one for OC (depending upon the amount of spatial coloring).

The maximum RLT attainable, RLT_{max}, in a multiple access environment, is with one LDR and one HDR user (single path) and can be calculated as:

$$RLT_{max} = Z(m, 1/\kappa_{max}) \cdot R_V + \frac{\kappa_{max} W}{E_b^D / I_{TOT}^D} \quad bps \quad (18)$$

Figure 2 illustrates (17), the RLT, vs. one HDR user's data rate, R_D, with η=0.25 and f=0.55 ($\kappa_{max} = 0.935$). As seen in Figure 2, the total RLT of a mixed voice-data system can increase beyond that of a LDR only Reverse Link system (Figure 1).

VI. Increases in Reverse Link Throughput Using OC vs. MRC

The increase in total RLT using OC vs. MRC, written as a ratio of RLT using OC combining versus the RLT using MRC, is of interest in understanding the gain possible in a mixed voice-data system employing OC.

The Reverse Link system Throughput ratio, RLT ratio, can be written as:

$$RLT\ ratio = \frac{RLT_{OC}}{RLT_{MRC}} = \frac{Z \cdot K_V{}^{MRC} + \varepsilon \cdot K_D}{K_V{}^{MRC} + \varepsilon \cdot K_D} \quad (19)$$

The RLT ratio between OC vs. MRC is illustrated in Figure 3 for $\kappa_{max} = 0.935$ and Eb/Io values discussed in Section III. Note that the gain using OC vs. MRC is most prevalent when both the HDR is highly colored (large κ) and there are a large number of LDR users present (mid-section of R_D range).

Practical examples using data rates supported in cdma2000 are illustrated in Table 2. Note that the overall system RLT ratio is at most a 5% increase even for 4 antennae.

VII. CONCLUSION

The OC vs. MRC gains determined were used to calculate the increase in the number of low data users and overall system data throughput for a CDMA multi-rate Reverse Link system.

A two antennae system having many low data users and one high data 153.6 kbps data user could expect an increase in total system data throughput of approximately 2.0% using OC vs. MRC in the most colored scenarios. A 4 antennae system having many low data users and one high data 307.2 kbps data user could expect an increase in total system data throughput near 5.0%.

While in general high degrees of spatial coloring offer significant gains for OC vs. MRC, typical CDMA Reverse Link systems are not that spatially colored dominantly due to adjacent cell interference and hence do not offer a case for large gains using OC vs. MRC.

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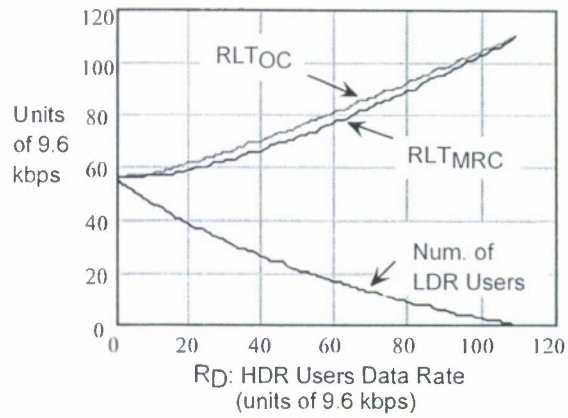

Figure 2. Reverse Link System Throughput, RLT, for a Four Antennae System and One HDR user: η=0.25 and *f*=0.55, Eb/Io=0.5 dB.

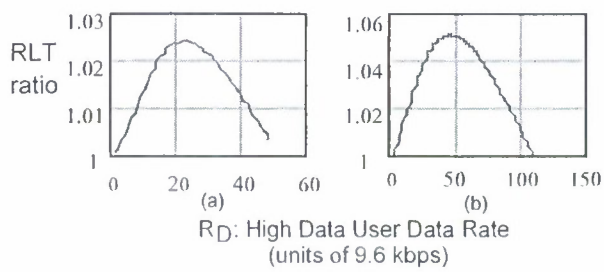

Figure 3. RLT ratio for OC vs. MRC with One HDR Users for System Parameters in Figure 3 and 4: a) Two Antennae Reverse Link, b) Four Antennae Reverse Link

TABLE 2

RLT ratio Increase for One HDR User: η=0.25 and *f*=0.55, Eb/Io=4 dB (2 antennae), Eb/Io=0.5 dB (4 antennae).

R_D for HDR User	Parameter	2 Antennae	4 Antennae
76.8 kbps (8x R_V)	Num. Kv	18.5	47.9
	Incr. Num. LDRs	0.29	0.5
	RLT ratio	1.01	1.01
153.6 kbps (16x R_V)	Num. Kv	13.28	41.5
	Incr. Num. LDRs	0.63	1.36
	RLT ratio	1.02	1.02
307.2 kbps (32x R_V)	Num. Kv	5.9	30.7
	Incr. Num. LDRs	0.76	2.84
	RLT ratio	1.02	1.05