A Simple Performance/Capacity Analysis of Multiclass Macrodiversity CDMA Cellular Systems

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***Abstract*—Multiclass CDMA systems, which support multiple services with various quality of service (QoS) requirements, are studied. The focus is on the reverse link capacity and application of macrodiversity with maximal ratio combining (MMRC), where the signals from each mobile station (MS) are received by multiple base stations (BSs) and coherently combined. A simple analytical solution is first derived for the multiclass reverse link carrier-to-interference ratio (CIR). Using this CIR solution, a simple capacity analysis is developed in terms of the QoS requirements. Finally, the analysis is fully supported by simulation results.**

***Index Terms*—Macrodiversity, maximal ratio combining, power control, call admission control.**

I. INTRODUCTION

FUTURE cellular systems must be able to support wireless services with different quality of service (QoS) requirements [1], [2]. CDMA is the major multiple access technology choice for the upcoming third generation wireless systems. Recently, macrodiversity with maximal ratio combining (MMRC) has been proven to be an effective way of improving the reverse link capacity in cellular CDMA systems [3]–[5]. In [3], the author proved the existence of a power control solution using MMRC, and showed that the capacity is unaffected by outside interference. In [4], by assuming equal reverse interference level at each BS, the authors constructed a simple proof indicating that MMRC reverse link capacity is close to an isolated cell capacity. The authors of [5] further generalized the results in [4] by considering nonuniform interference conditions, and showed MMRC's effectiveness on hierarchical system architectures. While [3] considers generalized multiclass systems, the results in [4] and [5] are limited to single class systems.

It is certain that employing MMRC will also benefit multiclass CDMA system capacity, and a detailed capacity/stability analysis is presented in [3]. However, the proof in [3] is mathematically complex. We construct a much simpler capacity analysis utilizing the solution for multiclass CIR. Our proof is expressed in terms of the QoS requirements and yields a result similar to [3]. Unlike [3], our analysis is fully verified by Monte Carlo simulation and the MMRC performance is compared with a system that uses macrodiversity with selective diversity (MSD). With the MSD scheme under consideration, each MS is allowed to connect to the BS which provides the best signal path. We show that our analysis is an excellent tool for predicting multiclass system capacity and useful for applications such as call admission control (CAC).

II. SYSTEM MODEL AND ANALYSIS

Our model consists of L cells and K classes of service with QoS requirements

$$\mathrm{CIR}_{\mathrm{target}\,1} < \mathrm{CIR}_{\mathrm{target}\,2} < \cdots < \mathrm{CIR}_{\mathrm{target}\,K}. \tag{1}$$

Assuming independent interference at each BS location, the MMRC reverse link CIR for the class-k MS p is

$$\begin{aligned}\mathrm{CIR}_k(p) &= \mathrm{CIR}_{1k}(p) + \cdots + \mathrm{CIR}_{Lk}(p)\\ &= \frac{C_{1k}(p)}{I_{1k}(p)} + \cdots + \frac{C_{Lk}(p)}{I_{Lk}(p)}\\ &= \left[\frac{G_1(p)}{I_{1k}(p)} + \cdots + \frac{G_L(p)}{I_{Lk}(p)}\right] T_k(p)\end{aligned} \tag{2}$$

where

$C_{ik}(p) \triangleq$ received signal power of class-k MS p at BS i
$I_{ik}(p) \triangleq$ interference power experienced by class-k MS p at BS i
$T_k(p) \triangleq$ reverse link transmit power of class-k MS p
$G_i(p) \triangleq$ link gain between class-k MS p and BS i. (3)

We neglect the background noise in our analysis. The MMRC reverse power control algorithm controls the transmit power level of each MS, $T_k(p)$, to satisfy the given system QoS requirement in (1). We are interested in finding the system capacity in relation to such QoS requirements. A standard iterative power control scheme controls the transmit power of MS p in the following way [6]:

$$T_k(p, n+1) = \frac{\mathrm{CIR}_{\mathrm{target}\,k}}{\mathrm{CIR}_k(p,n)} T_k(p,n) \tag{4}$$

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where $T_k(p, n)$ is the transmit power by MS p at epoch n. It has been proven by Yates [7] that such standard iterative power control algorithms, including MMRC, converge both synchronously and asynchronously, provided that the interference constraints derived from the QoS requirements are feasible. Yates also shows that the feasibility of the constraints is not a significant restriction for convergence. Since our emphasis is on finding the achievable system performance/capacity, we simply state that all $\mathrm{CIR}_k(p)$ converge to a uniform value CIR_k under the standard iterative power control algorithm. Later we will provide the solution for CIR_k in terms of given load and QoS requirements. Let us assume that each cell is loaded with a sufficiently large number of MSs such that the reverse link interference levels experienced by MSs of the same service class are nearly the same (e.g., $I_{ik}(p) \approx I_{ik} \forall p$). Let λ_{ik} be the ratio of I_{1k} and $I_{ik}, I_{1k}/I_{ik}$. Then $\mathrm{CIR}_k(p)$ can be expressed as

$$\begin{aligned}\mathrm{CIR}_k(p) &= \frac{[\lambda_{1k}G_1(p) + \lambda_{2k}G_2(p) + \cdots + \lambda_{Lk}G_L(p)]T_k(p)}{I_{1k}}\\ &= \frac{C_{\mathrm{reverse}\,k}}{I_{1k}}.\end{aligned} \tag{5}$$

Therefore, based on our model, all class-k MSs yield the same combined signal power $C_{\mathrm{reverse}\,k}$. Let M_{ik} be the number of class-k MSs in cell i. Given that class-k MS p is located in cell h, we can express I_{ik} as follows:

$$\begin{aligned}I_{ik} &\approx I_{ik}(p)\\ &= \sum_{r=1}^{M_{11}} C_{i1}(r)\Big|1 + \sum_{r=1}^{M_{12}} C_{i2}(r)\Big|1 + \cdots\\ &\quad + \sum_{r\neq p}^{M_{hk}} C_{ik}(r)\Big|h + \cdots + \sum_{r=1}^{M_{LK}} C_{iK}(r)\Big|L\\ &= \sum_{l=1}^{L}\sum_{n=1}^{K}\sum_{r=1}^{M_{ln}} C_{in}(r)|l - C_{ik}(p)|h, \quad 1 \le h \le L\end{aligned} \tag{6}$$

where $C_{in}\,|\,l$ is the received signal power by BS i given that the class-n MS is located in cell l. From (5), we can deduce that $C_{in}(p)\,|\,l = (C_{\mathrm{reverse}\,n} - \sum_{j\neq i}^{L} \lambda_{jn}C_{jn}(p)\,|\,l)/\lambda_{in}$. By substituting the above result into (6), we obtain

$$\begin{aligned}I_{ik} &\approx \sum_{l=1}^{L}\sum_{n=1}^{K}\sum_{r=1}^{M_{lk}} \frac{(C_{\mathrm{reverse}\,n} - \sum_{j\neq i}^{L}\lambda_{jn}C_{jn}(r)\,|\,l)}{\lambda_{in}}\\ &\quad - \frac{(C_{\mathrm{reverse}\,k} - \sum_{j\neq i}^{L}\lambda_{jk}C_{jk}(p)\,|\,h)}{\lambda_{ik}}\\ &= \sum_{l=1}^{L}\sum_{n=1}^{K} \frac{M_{ln}C_{\mathrm{reverse}\,n}}{\lambda_{in}} - \frac{C_{\mathrm{reverse}\,k}}{\lambda_{ik}}\\ &\quad - \left(\sum_{l=1}^{L}\sum_{n=1}^{K}\sum_{r=1}^{M_{ln}} \frac{\sum_{j\neq i}^{L}\lambda_{jn}C_{jn}(r)\,|\,l}{\lambda_{in}}\right.\\ &\quad \left. - \frac{\sum_{j\neq i}^{L}\lambda_{jk}C_{jk}(p)\,|\,h}{\lambda_{ik}}\right).\end{aligned} \tag{7}$$

With a large number of MSs, it can be approximated that the I_{ik} for different service classes are similar

$$\begin{aligned}&I_{i1} \approx I_{i2} \approx \cdots \approx I_{iK}\\ &\lambda_{i1} \approx \lambda_{i2} \approx \cdots \approx \lambda_{iK}.\end{aligned} \tag{8}$$

The interference power is the difference between the total received power and the desired signal power. Therefore, the above approximation is reasonable when the system load is large and the QoS requirements are not drastically different from one another, since the total received power does not change. The approximation is later justified in our simulation. Then, (7) becomes

$$\begin{aligned}I_{ik} &\approx \frac{1}{\lambda_{ik}}\left[\sum_{l=1}^{L}\sum_{n=1}^{K} M_{ln}C_{\mathrm{reverse}\,n} - C_{\mathrm{reverse}\,k}\right.\\ &\quad \left. - \sum_{j\neq i}^{L}\lambda_{jk}\left(\sum_{l=1}^{L}\sum_{n=1}^{K}\sum_{r=1}^{M_{ln}} C_{jn}(r)|l - C_{jk}(p)|h\right)\right]\\ &\approx \frac{1}{\lambda_{ik}}\left[\sum_{l=1}^{L}\sum_{n=1}^{K} M_{ln}C_{\mathrm{reverse}\,n}\right.\\ &\quad \left. - C_{\mathrm{reverse}\,k} - \sum_{j\neq i}^{L}\lambda_{jk}I_{jk}\right], \quad \lambda_{jk} = \frac{I_{1k}}{I_{jk}}\\ &\approx \frac{1}{\lambda_{ik}}\left[\sum_{l=1}^{L}\sum_{n=1}^{K} M_{ln}C_{\mathrm{reverse}\,n}\right.\\ &\quad \left. - C_{\mathrm{reverse}\,k} - (L-1)I_{1k}\right].\end{aligned} \tag{9}$$

Therefore,

$$\begin{aligned}\lambda_{ik} &= \frac{I_{1k}}{I_{ik}}\\ &\approx \frac{\lambda_{ik}I_{1k}}{\sum_{l=1}^{L}\sum_{n=1}^{K} M_{ln}C_{\mathrm{reverse}\,n} - C_{\mathrm{reverse}\,k} - (L-1)I_{1k}}.\end{aligned} \tag{10}$$

Solving the above equation for I_{1k} gives

$$I_{1k} \approx \frac{\sum_{l=1}^{L}\sum_{n=1}^{K} M_{ln}C_{\mathrm{reverse}\,n} - C_{\mathrm{reverse}\,k}}{L}. \tag{11}$$

Then the reverse link CIR of class-k MSs can be approximated as follows:

$$\begin{aligned}\mathrm{CIR}_k = \frac{C_{\mathrm{reverse}\,k}}{I_{1k}} &\approx \frac{L}{\sum_{l=1}^{L}\sum_{n=1}^{K} M_{ln}\frac{C_{\mathrm{reverse}\,n}}{C_{\mathrm{reverse}\,k}} - 1}\\ &\approx \frac{L}{\sum_{n=1}^{K} M_n\gamma_{nk} - 1}\\ &\approx \frac{L}{M_k - 1 + \sum_{n\neq k}^{K} M_n\gamma_{nk}}\end{aligned} \tag{12}$$

where $M_n = \sum_{l=1}^{L} M_{ln}$ is the total number of class-n MSs in the entire system and $\gamma_{nk} = C_{\mathrm{reverse}\,n}/C_{\mathrm{reverse}\,k}$. If we assume

TABLE I
MMRC ANALYTICAL AND SIMULATION PERFORMANCE COMPARISON

M_1	M_2	L	$\sum_{k=1}^{K}\mathrm{CIR}_{\mathrm{target}k}M_k - \frac{1}{K}\sum_{k=1}^{K}\mathrm{CIR}_{\mathrm{target}k}$	Analytical		Simulation, $T_{\max}=\infty$		Simulation, $T_{\max}=100$ mW	
				CIR_1	CIR_2	CIR_1	CIR_2	CIR_1	CIR_2
135	135	19.00	16.04	-13.27 dB	-10.26 dB	-13.06 dB	-10.06 dB	-13.07 dB	-10.07 dB
145	145	19.00	17.23	-13.58 dB	-10.57 dB	-13.39 dB	-10.39 dB	-13.39 dB	-10.39 dB
155	155	19.00	18.42	-13.87 dB	-10.86 dB	-13.69 dB	-10.69 dB	-13.69 dB	-10.69 dB
165	165	19.00	19.62	-14.14 dB	-11.13 dB	-13.97 dB	-10.97 dB	-13.93 dB	-10.93 dB
175	175	19.00	20.81	-14.40 dB	-11.39 dB	-14.24 dB	-11.24 dB	-13.99 dB	-11.03 dB
185	185	19.00	22.00	-14.64 dB	-11.63 dB	-14.49 dB	-11.49 dB	-14.03 dB	-11.17 dB
195	195	19.00	23.19	-14.87 dB	-11.86 dB	-14.73 dB	-11.73 dB	-14.09 dB	-11.38 dB

the system only supports single class-k service, then (12) becomes

$$\mathrm{CIR}_k \approx \frac{L}{M_k - 1} \tag{13}$$

which is the same result obtained in [5]. We now analyze the system capacity in the presence of multiclass MSs utilizing the derived solution for multiclass CIR. In order for a class-k MS to satisfy its QoS requirement,

$$\mathrm{CIR}_{\mathrm{target}\,k} \le \mathrm{CIR}_k \approx \frac{L}{M_k - 1 + \sum_{n\neq k}^{K} M_n \gamma_{nk}}. \tag{14}$$

Solving the above equation for $M_k - 1$ results in

$$\mathrm{CIR}_{\mathrm{target}\,k}(M_k - 1) \le L - \sum_{n\neq k}^{K} M_n \gamma_{nk} \mathrm{CIR}_{\mathrm{target}\,k}. \tag{15}$$

Here, $\mathrm{CIR}_{\mathrm{target}\,k}(M_k - 1)$ can be loosely interpreted as the amount of spectrum resource required to support M_k number of class-k MSs. Based on the assumption in (8), the combined received signal power, $C_{\mathrm{reverse}\,k}$, is the dominating factor in differentiating various CIR classes. We can then express γ_{nk} as $\mathrm{CIR}_{\mathrm{target}\,n}/\mathrm{CIR}_{\mathrm{target}\,k}$ when the system achieves the maximum capacity under a given set of QoS requirements. Now sum the $\mathrm{CIR}_{\mathrm{target}\,k}(M_k - 1)$ for all K classes:

$$\begin{aligned}
&\sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} M_k - \sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} \\
&\quad \le KL - \sum_{k=1}^{K}\sum_{n\neq k}^{K} M_n \mathrm{CIR}_{\mathrm{target}\,n} \\
&\sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} M_k - \sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} \\
&\quad \le KL - (K-1)\sum_{n=1}^{K} M_n \mathrm{CIR}_{\mathrm{target}\,n} \\
&K\sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} M_k - \sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} \le KL \\
&\sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} M_k - \frac{1}{K}\sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} \le L.
\end{aligned} \tag{16}$$

The above analysis shows that the achievable system capacity can be easily computed when the QoS requirements are available. The left-hand side of (16) represents the spectrum resource required to support the given system load, while the right hand side represents the total available system resource. Unlike in [3], the capacity of multiclass macrodiversity CDMA system is expressed in terms of exact CIR requirements. [3] uses a parameter defined as $\mathrm{CIDR}_k = L/(M_k + \sum_{n=0}^{K} M_n \gamma_{nk})$ rather than $\mathrm{CIR}_{\mathrm{target}\,k}$, which should yield a more conservative outcome. Also, our analysis provides the CIR solution which accurately predicts the convergence CIR value for each class of MS. Knowing the exact level of system performance for given system load is very useful for other important system analysis such as system planning and call scheduling. However, the basic interpretation of both results is the same, in that the system can support multiple QoS requirements as long as the required spectrum resource for the given system load does not exceed the total combined system resource L.

III. NUMERICAL RESULTS

A path loss exponent of 4 and a shadow standard deviation of 8 dB are used in our simulation. Rayleigh fading is also incorporated into our simulation. The simulation results are obtained by using the iterative power control algorithm outlined in [7], [8]:

$$T_k(p, n+1) = \min\left(\frac{\mathrm{CIR}_{\mathrm{target}\,k}}{I_k(p,n)}, T_{\max}\right) \tag{17}$$

where $I_k(p,n) = \sum_{i=1}^{L} G_i(p)/I_{ik}(p,n)$ and $T_{\max}$ is the maximum MS transmit power. The initial MS transmit power is set to 10 mW. On average, less than 10 iterations are required for the CIR values to converge. Table I shows the comparison between the analytical and simulation results of a 2-class MMRC system. The system consists of 19 equally sized cells with radius of 1500 m. $\mathrm{CIR}_{\mathrm{target}\,1}$ and $\mathrm{CIR}_{\mathrm{target}\,2}$ are set to -14 and -11 dB, respectively. The results are obtained from MSs located in and around the center cell to minimize border effects. The simulation is conducted for two distinct cases: ideal and nonideal. For the ideal case, each MS has unlimited transmit power and our analysis is based on this assumption. In reality, however, MSs will have finite power available to them and this is represented in the nonideal case where the MS transmit power is

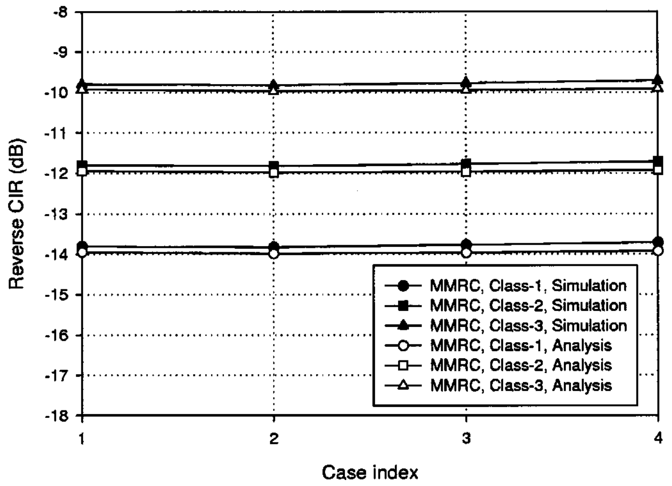

Fig. 1. MMRC Reverse CIR performances for load distributions in Table II.

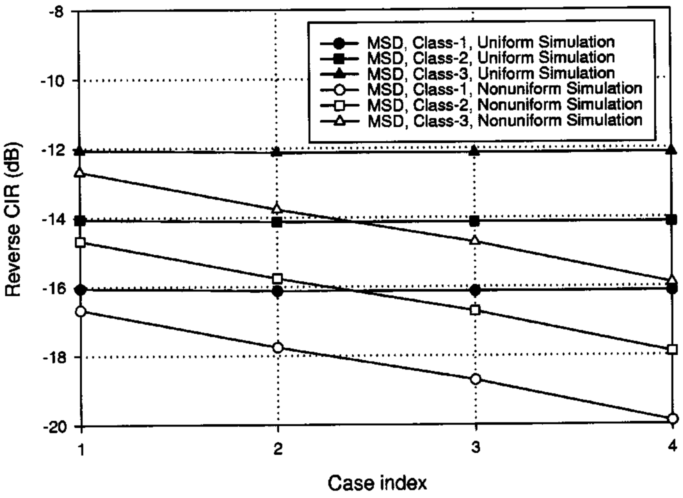

Fig. 2. MSD Reverse CIR performances for load distributions in Table II.

bounded by $T_{\max}$. Let us first examine the ideal case. Our analytical results closely match the ideal simulation results, while small deviations between the two results are due to our equal interference approximation in (8). This approximation becomes a better representation of the system behavior as the system load increases, since the differences in the desired signal power have less effect on resulting interference values. It is evidenced by the slow convergence of analytical and ideal simulation results as M_1 and M_2 increase. We also notice that the QoS requirements are satisfied as long as the required resource does not exceed the total system resource, L. We observe that our analysis still performs well in predicting the nonideal case performance. Some significant deviations between the ideal and nonideal results start appearing when the system fails to deliver the required CIR values $(175 \leq M_1, M_2)$. However, our primary interest is focused on the operation region where the CIR requirements are satisfied and our analysis does an excellent job of predicting the nonideal performance in the mentioned region.

Figs. 1 and 2 show the reverse link CIR performance comparison between MMRC and MSD schemes. The same 19-cell model is used in this part of the simulation also. Three classes of service are supported by the network with QoS requirements of -14 dB, -12 dB and -10 dB, respectively. Table II shows te different loading conditions among the three classes of MSs being analyzed. These loading conditions are selected so that $\sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} M_k - (1/K) \sum_{k=1}^{K} \mathrm{CIR}_{\mathrm{target}\,k} \approx L$, and the MSs are uniformly distributed throughout the system area. We immediately observe from the figures that MMRC performance is about 2 dB better than the MSD scheme with equal system load conditions. Obviously, MMRC benefits from combining the signals received at different BS locations. With uniform load distribution, the variation in MSD performance due to different loading conditions is minimal. However, the white marker lines in Fig. 2 represent the MSD performance when the half of the class-3 load is placed in the center cell. We see a major performance degradation for the MSD scheme as M_3 increases with nonuniform load distribution, while MMRC maintains near uniform performance. It has also been observed in [5] that the MSD performance is highly dependent on the load distribution when a hierarchical deployment is used. For MMRC, however, the performance is only limited by the overall system resource L and is neither affected by system architecture nor the load distribution.

TABLE II
SYSTEM LOAD DISTRIBUTIONS FOR CASES IN FIGS. 1 and 2.

Case Index	M_1	M_2	M_3	Total System Load
1	270	80	30	380
2	200	95	50	345
3	100	125	70	295
4	60	100	100	260

IV. CONCLUDING REMARKS

A simple MMRC capacity analysis for multiclass CDMA systems has been derived. By utilizing the solution for the multiclass CIR, the total available system resource is expressed in terms of the QoS requirements and the number of combined signals. It has been verified, both by analysis and simulation, that multiclass MMRC systems can satisfy the existing QoS requirements as long as the resource limit is not exceeded. Unlike the MSD scheme, multiclass MMRC performance is independent of the system load condition and distribution. Therefore, MMRC allows flexible and robust resource sharing among various services without penalizing the effective system performance. A possible application of our analysis lies in CAC, where the admission decision of multiclass calls is based on the capacity that is predicted by our method. One of the great challenges in CAC is accurately predicting the achievable system capacity and identifying the residual capacity which is used to serve newly arriving users. Employing MMRC greatly simplifies the CAC decisions since it removes any ambiguities associated with estimating the residual capacity by accurately predicting the system capacity for a given set of CIR requirements.

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