Capacity Analysis of Downlink CDMA Systems with Quasi-Orthogonal Sequences

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***Abstract*— We analyze the user capacity of downlink CDMA systems with quasi-orthogonal sequences(QOSs) considering various system parameters, such as user activity, spreading factor, the amount of transmission symbol energy allocated to common control channels, the amount of outer-cell interference, and sectorization factor. We also consider a power control mechanism with geometric factors such as propagation loss and shadowing effect. This user capacity analysis gives us the pole capacity of the system, which is the user capacity when all BSs transmit signals with unlimited power. Numerical examples show that the introduction of QOSs makes it possible to overcome the code limitation. We discuss how much the user capacity is increased according to various system parameters. For example, in an omni-cell environment with minimum outer-cell interference, if the mean channel activity and the required $\left(\frac{E_b}{I_0}\right)$ value are set to 0.2 and 2.0$[dB]$ respectively, the user capacity is 194 which is much higher than the code limitation.**

I. Introduction

Recently, data traffic has gradually increased in wireless communication systems. From this trend, data traffic is expected to be dominant in future wireless systems. Furthermore, there is more downlink traffic than uplink traffic. Several efficient downlink systems based on scheduling schemes have been proposed to accommodate this data traffic in wireless link [1], [2]. The basic idea of these systems is to share and schedule the wireless resources efficiently. However, data traffic is inherently bursty and generally exhibits low channel activities. These characteristics significantly increase the complexity of scheduling-based systems. In order to reduce the system complexity, we can accommodate this type of traffic using dedicated channels instead of shared channels. However, in this case, there is a limitation in wireless resources that can be used. In CDMA systems, this limitation occurs be due to a finite number of Walsh codes. Since the channel activity of data traffic is generally much lower than for voice traffic, the amount of interference becomes much lower. This characteristic causes a code limitation rather than a power limitation.

To overcome this code limitation situation, a concept of quasi-orthogonal sequences(QOSs) has been proposed [3]. It accommodates more MSs than the number of orthogonal codewords in downlink by using additionally generated non-orthogonal code sequences. WCDMA and cdma2000(IS-2000) systems also specify QOS schemes called a multi-scrambling code [4] and a quasi-orthogonal function [5], respectively, to enhance the system capacity. QOS sets are generated by multiplying a Walsh code set by different QOS masks. For example, the cdma2000 system specifies four different QOS sets each of which is generated by a distinct QOS mask. Each QOS mask corresponds to a row in a Walsh matrix of size 256. The masks selected by the cdma2000 standard are optimal in the sense that they minimize the cross-correlation between the generated QOSs and regular Walsh codes with the same length. Generally, QOS sets are found by exhaustive searches for this purpose [6]–[8].

As the number of QOSs increases, the inner-cell interference also increases. Thus, it is obvious that the number of QOSs should be bounded due to the corresponding inner-cell interference. It means that downlink CDMA systems with QOSs do experience a power limitation instead of a code limitation. Previous studies [7], [9] focused on how to enhance the performance of CDMA systems with QOSs. However, they did not provide a generalized form of capacity analysis. In this paper, we analyze the user capacity in the general form considering various system parameters, such as user activity, spreading factor, the amount of transmission symbol energy allocated to common control channels, the amount of outer-cell interference, and sectorization factor. We also consider a power control mechanism with geometric factors such as propagation loss and shadowing effect.

The remainder of this paper is organized as follows: In Section II, we define notations and explain the underlying assumptions for this analysis. In Section III, we analytically analyze the user capacity of downlink CDMA systems with QOSs. In Section IV, we take numerical examples for this analysis. Finally, we present conclusion and further work in Section V.

II. Notations and Assumptions for Analysis

A. Notations

b	Index of a home cell or a home BS
$\left(\frac{E_b}{I_0}\right)_t$	Required $\left(\frac{E_b}{I_0}\right)$ for a target BER or FER
$\left(\frac{E_s}{I_0}\right)_t$	Required $\left(\frac{E_s}{I_0}\right)$ for a target BER or FER
$E^{(t)}_{s,b\rightarrow(i,j,b)}$	Transmission symbol energy from BS b to MS(i,j,b)

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$E_{s,b}^{(t)}$	Total transmission symbol energy of BS b
$E_{s,max}^{(t)}$	Maximum of total transmission symbol energy of BS b
g	Index of adjacent cells or adjacent BSs
$I_{0,(i,j,b)}$	Total interference at MS(i,j,b)
M_b^p	Power capacity in cell b
M_b^{pole}	Pole capacity in cell b
M_{cs}	Total number of code sets allocated to both N_{cc} common control channels and M_b^p MSs $\left(=\lceil\frac{N_{cc}+M_b^p}{N_{oc}}\rceil\right)$
MS(i,j,b)	The MS allocated to the i-th code in the j-th code set in cell b
N_{adj}	Number of adjacent cells
N_{cc}	Number of common control channels
N_{oc}	Number of codes in a set
R_e	Radius of a circular cell
R^{FEC}	Channel(or forward error correction) code rate of downlink channel
$r_{b\rightarrow(i,j,b)}$	Distance from BS b to MS(i,j,b)
SF	Spreading factor
$U(x)$	Unit step function. (1 when $x \geq 0$, 0 otherwise)
$\lceil x\rceil$	The smallest integer which is larger than or equal to x
$\alpha_{(i,j,b)}$	Orthogonality factor affecting MS(i,j,b)
β_{PN}	Outer-cell interference suppression factor which is equal to the autocorrelation of a PN sequence at nonzero offset
β_{QOS}	Inner-cell interference suppression factor which is the square of the cross-correlation between two code sequences in distinct QOS sets
$\Gamma_{b\rightarrow(i,j,b)}$	Propagation loss from BS b to MS(i,j,b)
γ	Propagation loss exponent $(=4)$
λ	Sectorization gain
$\nu_{(i,j,b)}$	Channel activity factor of MS(i,j,b)
$\bar{\nu}$	Mean channel activity factor
μ	Modulation order (2 for QPSK, 4 for 16QAM)
ρ	Proportion of power allocated to common control channels
$\sigma_{\psi_{b\rightarrow(i,j,b)}}$	Standard deviation of shadow fading from BS b to MS(i,j,b)
$\Psi_{b\rightarrow(i,j,b)}$	Log-normal representation of shadow fading
$\psi_{b\rightarrow(i,j,b)}$	Shadow fading from BS b to MS(i,j,b)

B. Assumptions

A system model is considered in a multi-cell environment. Home cell is a hexagonal cell surrounded by six hexagonal ones. For the sake of simplicity, we approximate these hexagonal cells to equivalent circular ones. The radius of each circular cell is R_e. Common control channels are assumed to be allocated to the first N_{cc} Walsh code sequences. The remaining $(N_{oc}-N_{cc})$ Walsh code sequences are allocated to MSs and more than $(N_{oc}-N_{cc})$ MSs are supported by allocating QOSs one by one in the subsequent code set. Power control for forward links is perfectly performed by the BS. Here, the perfect power control means that the transmission power of the BS to each MS is adjusted so that the received $\left(\frac{E_b}{I_0}\right)$ value is always equal to the target value $\left(\frac{E_b}{I_0}\right)_t$ for a given bit error rate. Short-term fading is not considered in this paper. Shadow fading is considered as a log-normal distribution $\Psi_{b\rightarrow(i,j,b)} = 10^{-\psi_{b\rightarrow(i,j,b)}/10}$, and the propagation loss is modeled as $\Gamma_{b\rightarrow(i,j,b)} = r_{b\rightarrow(i,j,b)}^{-\gamma}$. Soft and softer handoffs are not considered.

III. Capacity Analysis of Downlink CDMA Systems with Quasi-Orthogonal Sequences

We now analyze the capacity of a downlink CDMA system with QOSs. Since there exists no code limitation due to utilization of QOSs, the user capacity is not limited by the number of codes in a cell. It is limited by only the maximum transmission power of a BS. Thus, the user capacity is equivalent to power capacity. The following analysis focuses on power capacity.

A. Power constraint at BS

Since the downlink transmission power of a BS causes interference to adjacent cells, the total downlink transmission power should be bounded by a specific value P_{max}. In other words, the total transmission symbol energy $E_{s,b}^{(t)}$ of a BS b is limited by the maximum total transmission symbol energy, $E_{s,max}^{(t)} = P_{max}\cdot T_s$. Dividing $E_{s,b}^{(t)}$ into two parts of downlink common control channels and downlink user traffic channels, the constraint for the total transmission symbol energy of BS b is written as:

$$E_{s,b}^{(t)} = \rho E_{s,max}^{(t)} + \sum_{(i,j,b)} \nu_{(i,j,b)} E_{s,b\rightarrow(i,j,b)}^{(t)} \leq E_{s,max}^{(t)} \quad (1)$$

Eq. (1) is a main requirement to determine the power capacity in CDMA systems. Thus, the user capacity is equal to the maximum number of downlink connections satisfying Eq. (1).

B. Interference at MS(i,j,b)

We assume that the total interference at MS(i,j,b) consists of inner-cell interference due to multipath signals, $I_{ic,(i,j,b)}^{MP}$, another inner-cell interference due to a loss in orthogonality among QOSs, $I_{ic,(i,j,b)}^{QOS}$, outer-cell interference due to interfering signals from adjacent cells, $I_{oc,(i,j,b)}$, and additive white Gaussian noise, N_0.

$$I_{0,(i,j,b)} = I_{ic,(i,j,b)}^{MP} + I_{ic,(i,j,b)}^{QOS} + I_{oc,(i,j,b)} + N_0 \quad (2)$$

1) Inner-cell interference at MS(i,j,b) due to multipaths: The partial loss in orthogonality due to multipath signals induces inner-cell interference at all MSs. The orthogonality factor α is defined with a range from 0(complete loss of orthogonality among the different signals) to 1(perfect orthogonality among the different signals). For example, profiles with almost perfect orthogonality($0.98 < \alpha < 1$) are assigned to LOS, profiles with good orthogonality($0.75 < \alpha < 0.98$) to Pedestrian A channels and all other profiles to Vehicular A [10]. Considering the factor α, the interference at MS(i,j,b) due to multipaths is expressed as Eq.(3).

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$$
\begin{aligned}
I^{MP}_{ic,(i,j,b)} &= \left(1-\alpha_{(i,j,b)}\right) E^{(t)}_{s,b}\cdot\Gamma_{b\to(i,j,b)}\Psi_{b\to(i,j,b)} \\
&= \left(1-\alpha_{(i,j,b)}\right)\left\{\rho E^{(t)}_{s,max}+\frac{1}{\lambda}\sum_{(x,y,b)}\nu_{(x,y,b)}E^{(t)}_{s,b\to(x,y,b)}\right\}\cdot\Gamma_{b\to(i,j,b)}\Psi_{b\to(i,j,b)}
\end{aligned}
\tag{3}
$$

2) Inner-cell interference at MS(i,j,b) due to QOSs: All code sequences within the same set are orthogonal one another, whereas the cross-correlation between two code sequences of distinct sets is nonzero. Here, it is meaningful to derive the lower bound for the maximum absolute cross-correlation. Let $\bar{c}=(c_1,c_2,\ldots,c_{N_{oc}})$ be any vector with symbols which are complex roots of unity. Then the lower bound for the maximum absolute cross-correlation $\left|R_{\bar{c},\bar{w_j}}\right|$ between $\bar{c}$ and any Walsh code $\bar{w_j}$ in the Walsh code set $W_{N_{oc}}$ is given by:

$$
max\left\{\left|R_{\bar{c},\bar{w_j}}\right|:\bar{c}\notin W_{N_{oc}},\bar{w_j}\in W_{N_{oc}}\right\}\geq\frac{1}{\sqrt{N_{oc}}} \tag{4}
$$

This bound also holds for the correlation between any two QOS sets. Thus, to minimize interference effect, it would be desirable to select proper masking functions such that the correlation between the QOS set and the Walsh code satisfies the above equality bound.

Let the square of this statistical cross-correlation be β_{QOS} and consider the relationship among code sequences. Then, we can classify the inner-cell interference due to nonzero cross-correlation among code sequences into three cases, as shown in Eqs. (5), (6) and (7). Here, we denote these three cases $j=1,\ 2\leq j\leq M_{cs}-1$ and $j=M_{cs}$ as the primary, middle and last code sets, respectively, where $M_{cs}=\lceil\frac{N_{cc}+M^p_b}{N_{oc}}\rceil$. The primary code set is equivalent to the conventional Walsh code set. As mentioned earlier, the first N_{cc} codes in the primary code set are allocated to common control channels. The middle code sets are additional $(M_{cs}-2)$ QOS code sets in which all the codes are fully allocated to MSs. Thus, the middle code sets are considered for $M_{cs}\geq 3$. The last code set indicates the last QOS code set in which one or more codes are allocated to MSs. The last code set is considered for $M_{cs}\geq 2$. Since the number of MSs allocated to each code set is different, the amount of inner-cell interference due to QOSs at MS(i,j,b) varies according to the code set to which the MS belongs, as shown in Eqs. (5), (6) and (7).

3) Outer-cell interference at MS(i,j,b): We can model outer-cell interference, as shown in Eq.(8). $I_{oc,(i,j,b)}$ has the maximum value when six adjacent BSs transmit signals with their maximum power, while $I_{oc,(i,j,b)}$ has the minimum value when those neighboring BSs transmit just common control channel signals. Here, β_{PN} is $\frac{1}{N_{oc}}$ [11].

C. Power Allocation for MS(i,j,b)

Let us construct the equations for the transmission symbol energy for MS(i,j,b). As mentioned in Section II, in this analysis, we assume that the transmission power is perfectly controlled. The BS adjusts the transmission power to enable all MSs to receive its signal with $\left(\frac{E_b}{I_0}\right)_t$. The required transmission symbol energy from BS b to MS(i,j,b) is expressed as:

$$
\begin{aligned}
E^{(t)}_{s,b\to(i,j,b)} &= I_{0,(i,j,b)}\left(\frac{E_s}{I_0}\right)_t\cdot\Gamma^{-1}_{b\to(i,j,b)}\Psi^{-1}_{b\to(i,j,b)} \\
&= \left\{I^{MP}_{ic,(i,j,b)}+I^{QOS}_{ic,(i,j,b)}+I_{oc,(i,j,b)}+N_0\right\} \\
&\quad\cdot\left(\frac{E_s}{I_0}\right)_t\Gamma^{-1}_{b\to(i,j,b)}\Psi^{-1}_{b\to(i,j,b)}
\end{aligned}
\tag{9}
$$

Applying Eqs.(3), (5), (6), (7) and (8) into Eq.(9), we can obtain M^p_b-dimensional simultaneous equations. Solving these simultaneous equations, we can find the exact M^p_b solutions of $E^{(t)}_{s,b\to(i,j,b)}$ which are the results of the perfect power control. However, in this analysis, we do not need to know the exact values of $E^{(t)}_{s,b\to(i,j,b)}$. As shown in Eq.(1), it is sufficient to know the total transmission symbol energy $E^{(t)}_{s,b}$ for analyzing the user capacity of the system.

Thus, we derive the general form of $E^{(t)}_{s,b}$ from these M^p_b-dimensional simultaneous equations using a matrix operation. First of all, we assume that the user activity $\nu_{(i,j,b)}$ of MS(i,j,b) is equal to its mean value $\bar{\nu}$ for all i and j. In addition, we let $\varepsilon=\frac{1}{\lambda}\cdot\beta_{QOS}\cdot\bar{\nu}\cdot\left(\frac{E_s}{I_0}\right)_t$, $\Omega=\beta_{QOS}\cdot\rho E^{(t)}_{s,max}\cdot\left(\frac{E_s}{I_0}\right)_t$ and $\Theta_{(i,j,b)}=\left\{I^{MP}_{ic,(i,j,b)}+I_{oc,(i,j,b)}+N_0\right\}\cdot\Gamma^{-1}_{(i,j,b)}\Psi^{-1}_{(i,j,b)}$. Then, we define a matrix Q, and two column vectors E and Z as follows:

Q is the QOS characteristic matrix which represents the relationship of cross-correlations among code sequences. It has an $(M^p_b\times M^p_b)$-dimension.

$$
Q=(q_{m,n}|1\leq m\leq M^p_b,1\leq n\leq M^p_b) \tag{10}
$$

where

$$
q_{m,n}=\begin{cases}1, & \text{if } m=n\\ 0, & \text{if } m\neq n \text{ and } \lceil\frac{m+N_{cc}}{N_{oc}}\rceil=\lceil\frac{n+N_{cc}}{N_{oc}}\rceil\\ -\varepsilon, & \text{otherwise.}\end{cases}
$$

E is a column vector of which elements are the transmission symbol energies $E^{(t)}_{s,b\to(i,j,b)}$ for MS(i,j,b) for all i and j.

$$
E=\begin{pmatrix}e_1 & e_2 & \cdots & e_{M^p_b}\end{pmatrix}^T, \tag{11}
$$

where

$$
e_m=E^{(t)}_{s,b\to\left(m+N_{cc}-\left(\lceil\frac{m+N_{cc}}{N_{oc}}\rceil-1\right)\cdot N_{oc},\ \lceil\frac{m+Ncc}{N_{oc}}\rceil,\ b\right)}
$$

Z is also a column vector of which elements represent the interference at MS(i,j,b) for all i and j excluding the interference due to nonzero cross-correlation from other user code sequences. It is expressed as

$$
Z=\begin{pmatrix}z_1 & z_2 & \cdots & z_{M^p_b}\end{pmatrix}^T, \tag{12}
$$

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- For MS(i,j,b), $j=1$

$$I^{QOS}_{ic,(i,j,b)} = \beta_{QOS}\cdot\left\{\frac{1}{\lambda}\sum_{l=2}^{M_{cs}-1}\sum_{k=1}^{N_{oc}}\nu_{(k,l,b)}E^{(t)}_{s,b\to(k,l,b)} + \frac{1}{\lambda}\sum_{k=1}^{M_b^p+N_{cc}-(M_{cs}-1)N_{oc}}\nu_{(k,M_{cs},b)}E^{(t)}_{s,b\to(k,M_{cs},b)}\right\}\cdot\Gamma_{b\to(i,j,b)}\Psi_{b\to(i,j,b)} \quad (5)$$

- For MS(i,j,b), $2\le j\le M_{cs}-1$

$$\begin{aligned} I^{QOS}_{ic,(i,j,b)} \;=\; \beta_{QOS}\cdot\Bigg\{&\rho E^{(t)}_{s,max} + \frac{1}{\lambda}\sum_{k=N_{cc}+1}^{N_{oc}}\nu_{(k,1,b)}E^{(t)}_{s,b\to(k,1,b)} + \frac{1}{\lambda}\sum_{l=2,l\ne j}^{M_{cs}-1}\sum_{k=1}^{N_{oc}}\nu_{(k,l,b)}E^{(t)}_{s,b\to(k,l,b)} \\ &+ \frac{1}{\lambda}\sum_{k=1}^{M_b^p+N_{cc}-(M_{cs}-1)N_{oc}}\nu_{(k,M_{cs},b)}E^{(t)}_{s,b\to(k,M_{cs},b)}\Bigg\}\cdot\Gamma_{b\to(i,j,b)}\Psi_{b\to(i,j,b)} \end{aligned} \quad (6)$$

- For MS(i,j,b), $j=M_{cs}$

$$I^{QOS}_{ic,(i,j,b)} = \beta_{QOS}\cdot\left\{\rho E^{(t)}_{s,max}+\frac{1}{\lambda}\sum_{k=N_{cc}+1}^{N_{oc}}\nu_{(k,1,b)}E^{(t)}_{s,b\to(k,1,b)}+\frac{1}{\lambda}\sum_{l=2}^{M_{cs}-1}\sum_{k=1}^{N_{oc}}\nu_{(k,l,b)}E^{(t)}_{s,b\to(k,l,b)}\right\}\cdot\Gamma_{b\to(i,j,b)}\Psi_{b\to(i,j,b)} \quad (7)$$

$$\begin{aligned} I_{oc,(i,j,b)} \;&=\; \beta_{PN}\cdot\sum_{g\ne b}E^{(t)}_{s,g}\cdot\Gamma_{g\to(i,j,b)}\Psi_{g\to(i,j,b)} \\ &=\; \beta_{PN}\cdot\sum_{g\ne b}\left\{\rho E^{(t)}_{s,max}+\frac{1}{\lambda}\sum_{(x,y,g)}\nu_{(x,y,g)}E^{(t)}_{s,g\to(x,y,g)}\right\}\cdot\Gamma_{g\to(i,j,b)}\Psi_{g\to(i,j,b)} \end{aligned} \quad (8)$$

where

$$z_m = \begin{cases} \Theta_{(m+N_{cc},\ 1,\ b)} & \text{if } 1\le m\le N_{oc}-N_{cc} \\ \Omega+\Theta_{\left(m+N_{cc}-\left(\lceil\frac{m+N_{cc}}{N_{oc}}\rceil-1\right)\cdot N_{oc},\ \lceil\frac{m+N_{cc}}{N_{oc}}\rceil,\ b\right)} & \text{if } N_{oc}-N_{cc}+1\le m\le M_b^p \end{cases}$$

Using Eqs. (10), (11), and (12), we can represent M_b^p-dimensional simultaneous equations obtained from Eq. (9) as follows:

$$Z = Q\cdot E \quad (13)$$

From Eq. (13), we can obtain

$$E = Q^{-1}\cdot Z \quad (14)$$

Here, we need to know the sum of all elements included in the matrix E. Using Eq.(14), the total transmission symbol energy of the BS b can be written as:

$$\begin{aligned} E^{(t)}_{s,b} &= \rho E^{(t)}_{s,max}+\sum_{x=1}^{M_b^p}\bar{\nu}\cdot E^{(t)}_{s,b\to\left(x+N_{cc}-\left(\lceil\frac{x+N_{cc}}{N_{oc}}\rceil-1\right)\cdot N_{oc},\lceil\frac{x+N_{cc}}{N_{oc}}\rceil,b\right)} \\ &= \rho E^{(t)}_{s,max}+\sum_{x=1}^{M_b^p}\bar{\nu}\cdot\left(\sum_{y=1}^{M_b^p}q^{inv}_{x,y}\cdot z_y\right) \\ &= \rho E^{(t)}_{s,max}+\sum_{y=1}^{M_b^p}\bar{\nu}\cdot\left(\sum_{x=1}^{M_b^p}q^{inv}_{x,y}\cdot z_y\right) \\ &= \rho E^{(t)}_{s,max}+\sum_{y=1}^{M_b^p}\bar{\nu}\cdot\left(S_y\cdot z_y\right), \end{aligned} \quad (15)$$

where $q^{inv}_{x,y}$ represents the element in x-th row and y-th column of Q^{-1} and S_y indicates the sum of the y-th column vector in Q^{-1}. It is derived as Eqs. (16), (17), and (18). Here, M_{PC}, M_{MC} and M_{LC} represent the numbers of MSs belonging to the primary, middle and last code sets, respectively.

Using Eqs. (16), (17), (18) and applying the constraint in Eq. (1), Eq. (15) can be rewritten as Eq. (20). Since we assume a perfect power control mechanism, Eq. (20) yields a complete estimation of the total transmission symbol energy at a given value of $\left(\frac{E_s}{I_0}\right)_t$. Thus, we can evaluate the user capacity of a CDMA system with QOSs. The user capacity is determined to be the maximum positive integer value of M_b^p satisfying the total transmission symbol energy constraint in Eq. (20). In addition, we can estimate the pole capacity of the system. In Eq. (20), as M_b^p increases by 1, $E^{(t)}_{s,b}$ increases more rapidly. It is because D approaches zero very rapidly as M_b^p increases. The pole capacity is the maximum value of M_b^p which makes D the smallest positive real number or zero. In Section IV, we show numerical examples under typical system parameters.

IV. Numerical Examples

We assume that the maximum transmission symbol energy of a BS is given by $\frac{15\times SF}{1.2288\times 10^6}\,[J]$ which is typically used for the cdma2000 system. In addition, we let the cross-correlation between two code sequences be $\frac{1}{\sqrt{N_{oc}}}$ which is the optimal cross-correlation bound, as explained in Section III-B.2. Thus, the interference factor due to the introduction of QOSs is $\beta_{QOS} = \left(\frac{1}{\sqrt{N_{oc}}}\right)^2 = \frac{1}{N_{oc}}$ which is the square value of the cross-correlation. Furthermore, we vary the data channel activity values from 0.1 to 0.5. The system parameters are listed in Table I. Under this environment, we analyze the system on the average point of view.

Fig. 1 illustrates how the power and pole capacities vary according to various channel activity values in an omni-cell

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- For $1 \le y \le N_{oc} - N_{cc}$

$$S_y = \frac{1 + \{U(M_{cs}-2)(M_{MC}+M_{LC}) - U(M_{cs}-3)(M_{MC}-N_{oc})\} \cdot \varepsilon + U(M_{cs}-3) M_{LC} N_{oc} \cdot \varepsilon^2}{D}, \tag{16}$$

- For $N_{oc} - N_{cc} + 1 \le y \le (M_{cs}-1) N_{oc} - N_{cc}$

$$S_y = \frac{U(M_{cs}-3) + U(M_{cs}-3)\left(M_{PC}+M_{LC}\right) \cdot \varepsilon + U(M_{cs}-3) M_{PC} M_{LC} \cdot \varepsilon^2}{D}, \tag{17}$$

- For $(M_{cs}-1) N_{oc} - N_{cc} + 1 \le y \le M_b^p$

$$S_y = \frac{U(M_{cs}-2) + \{U(M_{cs}-2) M_{PC} + U(M_{cs}-3) N_{oc}\} \cdot \varepsilon + U(M_{cs}-3) M_{PC} N_{oc} \cdot \varepsilon^2}{D}, \tag{18}$$

where

$$\begin{aligned} D \;=\; & 1 - U(M_{cs}-3)(M_{MC} - Noc) \cdot \varepsilon - U(M_{cs}-2)(M_{PC}M_{MC} + M_{MC}M_{LC} + M_{LC}M_{PC}) \cdot \varepsilon^2 \\ & - U(M_{cs}-3) M_{PC} M_{MC} M_{LC} \cdot \varepsilon^3 \end{aligned} \tag{19}$$

$$\begin{aligned} E_{s,b}^{(t)} \;=\; & \rho E_{s,max}^{(t)} + \sum_{y=1}^{M_b^p} \bar{\nu} \cdot S_y \cdot \left\{ U\left(y - (N_{oc} - N_{cc} + 1)\right) \cdot \Omega + \Theta_{\left(y + N_{cc} - \left(\lceil \frac{y+N_{cc}}{N_{oc}} \rceil - 1\right) \cdot N_{oc},\ \lceil \frac{y+N_{cc}}{N_{oc}} \rceil,\ b\right)} \right\} \\ \le\; & E_{s,max}^{(t)} \end{aligned} \tag{20}$$

TABLE I

SYSTEM PARAMETERS FOR NUMERICAL EXAMPLES.

Parameter	Value	Parameter	Value
ρ	0.2	$E_{s,max}^{(t)}$	$\frac{15 \times SF}{1.2288 \times 10^6}\,[J]$
N_{oc}	64	σ_ψ	$8\,[dB]$
N_{cc}	9	N_0	$-174\,[dBm]$
R_e	$1000[m]$	β_{PN}	$\frac{1}{N_{oc}}$
γ	4	β_{QOS}	$\frac{1}{N_{oc}}$
α	1	R_{FEC}	$\frac{1}{4}$
N_{adj}	6	μ	2 (QPSK)

with maximum outer-cell interference(OCI) environment. The maximum OCI indicates that all the traffic channels in adjacent cells are fully loaded. Three solid lines represent the total transmission symbol energy of the BS as a function of the number of users. We note that $E_{s,b}^{(t)}$ increases more rapidly as the number of MSs increases. It follows since the more inner-cell interference is induced by nonzero cross-correlation factors among code sequences. In addition, the power capacity is determined by the point where $E_{s,b}^{(t)}$ exceeds $E_{s,max}^{(t)}$. If we increase $E_{s,max}^{(t)}$, M_b^p increases, too. However, there is a limitation in the number of MSs even if we make $E_{s,max}^{(t)}$ infinitely large. This limitation of user capacity is called the pole capacity. Three vertical dotted lines indicate the pole capacities for the three different values of $\bar{\nu}, 0.1, 0.3$, and 0.5. If the channel activity is set to 0.1, the power capacity and pole capacity are 121 and 861, respectively.

Fig. 2 shows the power capacity versus $\left(\frac{E_b}{I_0}\right)_t$. The overall user capacity is determined for various mean channel activity values from 0.1 to 0.5 in an omni-cell with a maximum OCI environment. For example, in case of $\bar{\nu} = 0.2$ and $\left(\frac{E_b}{I_0}\right)_t < 2.8\,[dB]$, the system accommodates a larger number

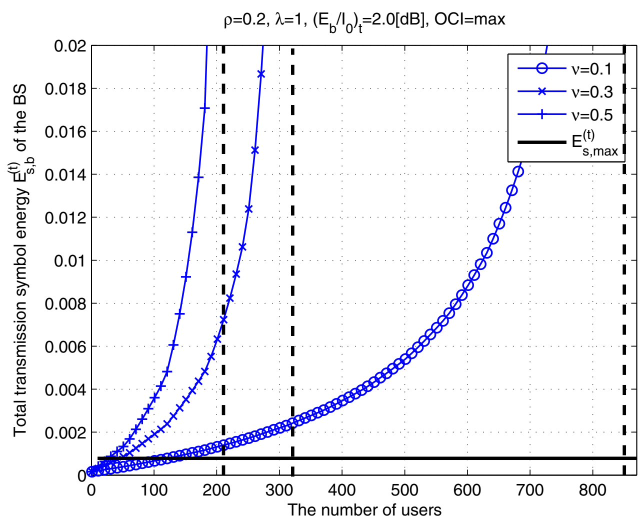

Fig. 1. Total transmission symbol energy $E_{s,b}^{(t)}$ versus the number of users

of MSs beyond the code limitation. In this situation, the conventional CDMA system cannot accommodate more MSs because of the code limitation despite of the availability of additional transmission power. On the contrary, in the case of $\bar{\nu} = 0.2$ and $\left(\frac{E_b}{I_0}\right)_t > 2.8\,[dB]$, the power capacity goes down below the code limitation. This implies that since the BS comsumes the maximum transmission symbol energy before the code limitation, there is even no chance to utilize more QOSs. Thus, in this case, we cannot obtain the capacity gain from QOSs. As the channel activity factor becomes higher, the power capacity goes down more rapidly due to an increase in inner-cell interference.

Fig. 3 shows the power capacity in a three-sector cell with a maximum OCI environment. Compared to the result shown in Fig. 2, the power capacity increases because the inner-

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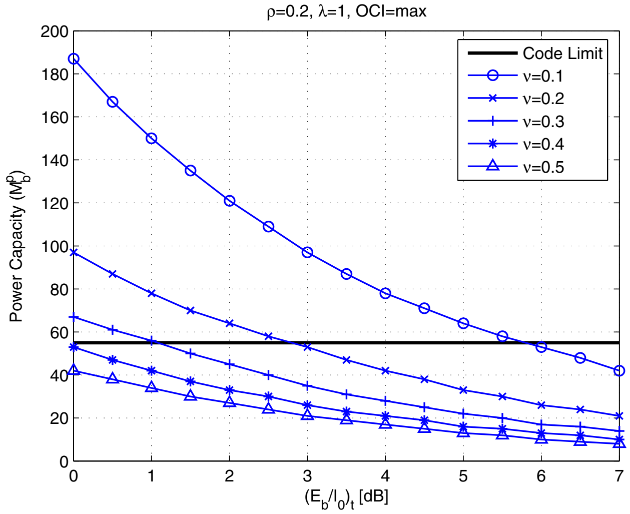

Fig. 2. Power capacity M_b^p versus $(E_b/I_0)_t$ in an omni-cell

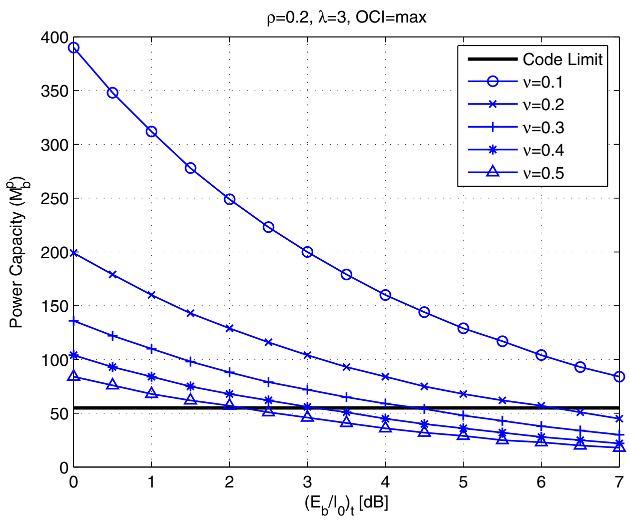

Fig. 3. Power capacity M_b^p versus $(E_b/I_0)_t$ in a three-sectorized cell

cell interference and outer-cell interference are reduced by using sector antennas. Thus, the sector antennas yield a further enhancement in user capacity. This is because a CDMA system with QOSs is not limited by codes but by power.

Fig. 4 shows the power capacity in an omni-cell environment. The OCI value in the x-axis is normalized by the maximum OCI value. The four lines represent the power capacities with $\left(\frac{E_b}{I_0}\right)_t$ values of $2.0\,[dB]$, $3.0\,[dB]$, $4.0\,[dB]$, and $5.0\,[dB]$. Here, we can observe that in an omni-cell with the minimum outer-cell interference environment, if $\bar{\nu}$ and $\left(\frac{E_b}{I_0}\right)_t$ are set to 0.2 and 2.0$[dB]$, respectively, the user capacity is 194 which is much higher than the code limitation 55.

V. Conclusions and Further Work

In this paper, we analyzed the power and pole capacities of CDMA systems with QOSs in a general form considering various system parameters. Since the QOSs are used to

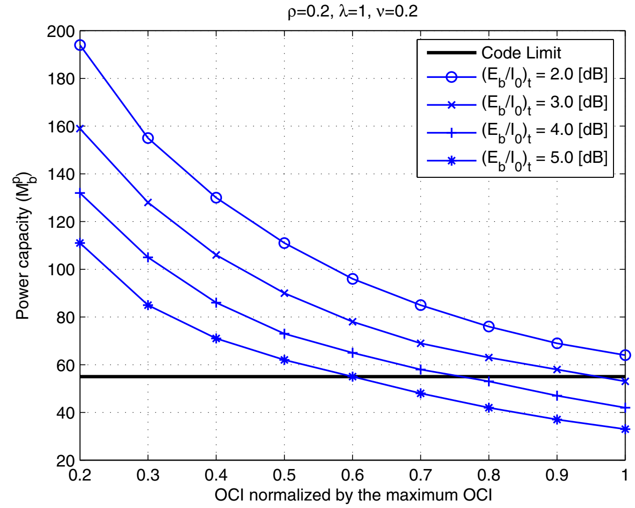

Fig. 4. Power Capacity M_b^p versus OCI normalized by the maximum OCI

overcome the code limitation, the user capacity is significantly improved as shown in numerical examples. The amount of this improvement is affected by system parameters. Especially, we noted that when the channel activity is low, the improvement becomes so large. For further work, we will compare the performance of QOSs with that of Orthogonal Code Hopping Multiplexing(OCHM) which is our proposed scheme to overcome the code limitation [12].

Acknowledgment

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