Cellular MIMO Channel Capacities of MC-CDMA and OFDM

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Abstract—**Multicarrier transmission techniques (i.e., orthogonal frequency division multiplexing (OFDM) and multi-carrier code division multiple access (MC-CDMA)) are the promising candidates for wireless access technique in future cellular communication systems because of their capability to eliminate the multipath interference. Multiple-input multiple-output (MIMO)-space division multiplexing (SDM) can increase the transmission rate without bandwidth expansion. A combination of multi-carrier technique and MIMO is a promising technique. However, the transmission performance of MC-CDMA severely degrades because of the inter-code interference (ICI) arising from the orthogonality distortion owing to the frequency-selective fading. In this paper, we derive the channel capacity formula for MC-CDMA MIMO taking into account the ICI and co-channel interference (CCI) in a cellular environment. Recently, many ICI cancellers have been proposed. The cellular channel capacity of MC-CDMA MIMO with perfect ICI cancellation is numerically evaluated and is compared to that of OFDM MIMO in a cellular environment. The impacts of the frequency-reuse factor and the number of propagation paths are also discussed. The numerical computation results show that the cellular channel capacity of MC-CDMA is larger than that of OFDM.**

Keywords-component; MIMO; multi-cell environment; link capacity

I. INTRODUCTION

Because of the rapid growth of multimedia services, high speed and high quality transmission is required for the future cellular communication systems. Orthogonal frequency division multiplexing (OFDM) is one of the transmission techniques which can improve the spectrum efficiency. Multi-carrier code division multiple access (MC-CDMA), which is a combination of OFDM and CDMA, has also been attracting much attention [1]. However, if the code-multiplexing is used, the transmission performance of MC-CDMA severely degrades because of inter-code interference (ICI) arising from the orthogonality distortion owing to the channel frequency-selectivity [2]. There have been tremendous works on ICI canceller and it has been shown by computer simulation that the bit error rate (BER) performance of MC-CDMA with ICI cancellation can approach the matched filter bound [3]-[5].

Multiple-input multiple-output (MIMO)-space division multiplexing (SDM) which utilizes multiple transmit and receive antennas can increase the transmission rate without expanding the signal bandwidth [6]. A combination of multi-carrier technique and MIMO is a promising technique for the future cellular communication system.

The capacity evaluation of MC-CDMA is presented in [7]-[9]. However, the channel capacity of MC-CDMA MIMO in a cellular environment has not been evaluated. Furthermore, application of ICI cancellation was not considered in any literature. In this paper, we derive the cellular channel capacity formula for MC-CDMA MIMO taking into account the ICI plus co-channel interference (CCI). The cellular channel capacity varies according to the path loss, shadowing loss and multipath fading. The cellular channel capacity of MC-CDMA MIMO with perfect ICI cancellation is compared to that of OFDM MIMO. The impacts of the frequency-reuse factor and the number of propagation paths are also discussed. The capacity comparison among MIMO, single-input multiple-output (SIMO), space-time block code-multiple-input single-output (STBC-MISO) [10][11] are also discussed. The comparison is made at the capacity value below which the cellular channel capacity drops at a probability of q=10%, 50%, and 90%, i.e., q%-outage probability [12][13].

The rest of the paper is organized as follows. In Sect. II, the system model is described and the cellular channel capacity formula is derived. Numerical results are presented in Sect. III. Section IV concludes the paper.

II. CELLULAR SYSTEM AND CHANNEL CAPACITY

In this paper, a hexagonal cell layout is considered. In a cellular system, the same frequency is re-used at the different cells with the frequency-reuse factor F (=p^2+pq+q^2 =1, 3, 4,…, where p and q are positive integers). Fig. 1 shows the case of F=3. The n-th data symbol ($n=0\sim\lfloor N_c/SF\rfloor-1$), $d_{i,u,n_t}(n)$, to be transmitted from the n_t-th transmit antenna ($n_t=0\sim N_t-1$) at the i-th BS ($i=0\sim I-1$) is spread by the u-th orthogonal spreading sequence $\left\{c_u^{oc}(k);k=0\sim N_c-1\right\}$, $u=0\sim U-1$, where SF and U are respectively the spreading factor and the code multiplexing order of the each BS (the same spreading factor is assumed for all BSs) and $\lfloor x\rfloor$ is the largest integer smaller than or equal to x. To maximize the data rate of MC-CDMA, full code-multiplexing (i.e., SF=U) is considered in this paper. Full code-multiplexed MC-CDMA gives the same data rate as OFDM. The signal to be transmitted from the n_t-th transmit antenna at the k-th sub-carrier ($k=0\sim N_c-1$) can be expressed as

$$S_{i,n_t}(k)=\sqrt{2P_t}\sum_{u=0}^{U-1}d_{i,u,n_t}(n)c_u^{oc}(k\bmod SF) \qquad (1)$$

with P_t being the BS transmit power per spreading code which is the same for all BSs. The frequency-domain signal

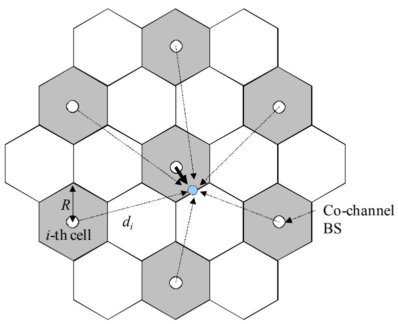


Figure 1. Co-channel interference model when F=3.

$\{S_{i,n_t}(k); k=0\sim N_c-1\}$ is multiplied by the common scramble sequence $\{c_i^{scr}(k); k=0\sim N_c-1\}$. N_c-point inverse fast Fourier transform (IFFT) is applied to transform the code multiplexed frequency-domain signal into the time-domain MC-CDMA signal as

$$s_{i,n_t}(t)=\sum_{k=0}^{N_c-1}\left\{S_{i,n_t}(k)c_i^{scr}(k)\right\}\exp\left(j2\pi(t/N_c)k\right). \qquad (2)$$

After inserting the N_g-point guard interval (GI) to avoid the inter-block interference (IBI), the MC-CDMA signal $\{s_{i,n_t}(t \bmod N_c); t=-N_g\sim N_c-1\}$ is transmitted from each transmit antenna.

The channel between the n_t-th transmit antenna and the n_r-th receive antenna ($n_r=0\sim N_t-1$) is assumed to be an L-path Rayleigh fading channel, where each propagation path is subjected to independent fading and can be expressed as

$$h_{i,n_r,n_t}(t)=\sum_{l=0}^{L-1}h_{i,n_r,n_t,l}\,\delta(t-\tau_l), \qquad (3)$$

where $h_{i,n_r,n_t,l}$ and τ_l are respectively the complex channel gain and the time delay of the l-th ($l=0\sim L-1$) path between the i-th BS and the desired MS ($E\left[\sum_{l=0}^{L-1}\left|h_{i,n_r,n_t,l}\right|^2\right]=1$ with $E[.]$ being the ensemble average operation and $\delta(.)$ is the delta function).

The received signal at the n_r-th receive antenna is given as

$$\begin{aligned} r_{n_r}(t)=&\sum_{n_t=0}^{N_t-1}\sum_{l=0}^{L-1}h_{0,n_r,n_t,l}\,s_{0,n_t}\left((t-\tau_l)\bmod N_c\right)\\ &+\sum_{i=1}^{I-1}\sum_{n_t=0}^{N_t-1}\sum_{l=0}^{L-1}h_{i,n_r,n_t,l}\,s_{i,n_t}\left((t-\tau_l)\bmod N_c\right)+n_{n_r}(t) \end{aligned}, \qquad (4)$$

where $n_{n_r}(t)$ is the zero-mean additive white Gaussian noise (AWGN) having the variance $2\sigma^2=2N_0/T_c$ with N_0 being the single-sided power spectrum density.

After the GI removal, the received signal $\{r_{n_r}(t); t=0\sim N_c-1\}$ is transformed by N_c-point fast Fourier transform (FFT) to frequency-domain signal, $\{\tilde{R}_{n_r}(k); k=0\sim N_c-1\}$. $\tilde{R}_{n_r}(k)$ is given by

$$\begin{aligned} \tilde{R}_{n_r}(k)&=(1/N_c)\sum_{t=0}^{N_c-1}r_{n_r}(t)\exp\left(-j2\pi\left(k/N_c\right)t\right)\\ &=H_{0,n_r,n_t}(k)\sum_{n_t=0}^{N_t-1}\left(S_{0,n_t}(k)c_0^{scr}(k)\right)\\ &\quad+\sum_{i=1}^{I-1}\left\{H_{i,n_r,n_t}(k)\sum_{n_t=0}^{N_t-1}\left(S_{i,n_t}(k)c_i^{scr}(k)\right)\right\}+\Pi_{n_r}(k) \end{aligned}, \qquad (5)$$

where $H_{i,n_r,n_t}(k)$ and $\Pi_{n_r}(k)$ are the Fourier transform of the channel impulse response between the i-th BS and MS and the noise component, respectively, and are given as

$$\begin{cases} H_{i,n_r,n_t}(k)=\sum_{l=0}^{L-1}h_{i,n_r,n_t,l}\exp\left(-j2\pi(k/N_c)\tau_l\right)\\ \Pi_{n_r}(k)=(1/N_c)\sum_{t=0}^{N_c-1}n_{n_r}(t)\exp\left(-j2\pi(k/N_c)t\right) \end{cases}. \qquad (6)$$

After removing the scramble code $c_0^{scr}(k)$ from $\tilde{R}_{n_r}(k)$, we have

$$\begin{aligned} R_{n_r}(k)&=\tilde{R}_{n_r}(k)c_0^{scr*}(k)\\ &=\sqrt{2P_0}\sum_{n_t=0}^{N_t-1}\begin{pmatrix} H_{0,n_r,n_t}(k)\\ \times c_u(k \bmod SF)\\ \times d_{0,u,n_t}(k \bmod SF)\end{pmatrix}+\mathrm{M}_{n_r}(k)+\Pi_{n_r}(k) \end{aligned} \qquad (7)$$

with the first term being the desired signal from the i=0[th]-BS and the second term being the ICI plus CCI, and the third term being the noise component. $\mathrm{M}_{n_r}(k)$ is given by

$$\begin{aligned} \mathrm{M}_{n_r}(k)=&\sqrt{2P_0}\sum_{n_t=0}^{N_t-1}\left\{\begin{matrix} H_{0,n_r,n_t}(k)\\ \times\sum_{\substack{u=0\\u'\neq u}}^{U-1}d_{0,u',n_t}(k)c_{u'}^{oc}(k \bmod SF)\end{matrix}\right\}\\ &+\sum_{i=1}^{I-1}\left\{\sqrt{2P_i}\sum_{n_t=0}^{N_t-1}\left\{\begin{matrix} H_{i,n_r,n_t}(k)c_i^{scr}(k)c_0^{scr*}(k)\\ \times\sum_{u'=0}^{U-1}d_{i,u',n_t}(k)c_{u'}^{oc}(k \bmod SF)\end{matrix}\right\}\right\} \end{aligned}, \qquad (8)$$

where the first term is the ICI and the second term is the CCI.

The k-th sub-carrier component can be expressed by using the matrix form as

$$\begin{aligned} \mathbf{R}(k)&=\left(R_0(k)\cdots R_{N_r-1}(k)\right)^T\\ &=\sqrt{2P_0}\,\mathbf{H}(k)\mathbf{d}_{i,u}(k)+\mathbf{M}(k)+\mathbf{\Pi}(k)\\ &=\sqrt{2P_0}\begin{pmatrix} H_{0,0,0}(k)c_u^{oc}(k) & & H_{0,0,N_t-1}(k)c_u^{oc}(k)\\ \vdots & \ddots & \vdots\\ H_{0,N_r-1,0}(k)c_u^{oc}(k) & & H_{0,N_r-1,N_t-1}(k)c_u^{oc}(k)\end{pmatrix}\begin{pmatrix} d_{0,u,0}(n)\\ \vdots\\ d_{0,u,N_t-1}(n)\end{pmatrix}\\ &\quad+\begin{pmatrix}\mathrm{M}_0(k)\\ \vdots\\ \mathrm{M}_{N_r-1}(k)\end{pmatrix}+\begin{pmatrix}\Pi_0(k)\\ \vdots\\ \Pi_{N_r-1}(k)\end{pmatrix} \end{aligned}. \qquad (9)$$

The channel matrix $\mathbf{H}(k)$ with the size of $N_r \times N_t$ is extended into the extended channel matrix $\widetilde{\mathbf{H}}(n)$ with the size of $(N_r \cdot SF) \times N_t$ as follows.

$$\begin{aligned}\mathbf{R}(n) &= \left(R_0(nSF) \ \cdots \ R_{N_r-1}((n+1)SF-1)\right)^T \\ &= \sqrt{2P_0}\begin{pmatrix} H_{0,0,0}(nSF)\times c_u^{oc}(0) & \cdots & H_{0,0,N_t-1}(nSF)\times c_u^{oc}(0) \\ \vdots & & \vdots \\ H_{0,0,0}((n+1)\times SF-1)\times c_u^{oc}(SF-1) & & H_{0,0,N_t-1}((n+1)\times SF-1)\times c_u^{oc}(SF-1) \\ \vdots & \ddots & \vdots \\ H_{0,N_r-1,0}(nSF)\times c_u^{oc}(0) & & H_{(0),N_r-1,N_t-1}(nSF)\times c_u^{oc}(0) \\ \vdots & & \vdots \\ H_{0,N_r-1,0}((n+1)\times SF-1)\times c_u^{oc}(SF-1) & \cdots & H_{0,N_r-1,N_t-1}((n+1)\times SF-1)\times c_u^{oc}(SF-1) \end{pmatrix}\begin{pmatrix} d_{0,u,0}(n) \\ \vdots \\ d_{0,u,N_t-1}(n)\end{pmatrix} \\ &\quad + \begin{pmatrix} \mathrm{M}_0(nSF) \\ \vdots \\ \mathrm{M}_0((n+1)SF-1) \\ \vdots \\ \mathrm{M}_{N_r-1}(nSF) \\ \vdots \\ \mathrm{M}_{N_r-1}((n+1)SF-1)\end{pmatrix} + \begin{pmatrix} \Pi_0(nSF) \\ \vdots \\ \Pi_0((n+1)SF-1) \\ \vdots \\ \Pi_{N_r-1}(nSF) \\ \vdots \\ \Pi_{N_r-1}((n+1)SF-1)\end{pmatrix}, \\ &= \mathbf{c}_u\widetilde{\mathbf{H}}(n)\left(\sqrt{2P_0}\mathbf{d}_{0,u}(n)\right) + \widetilde{\mathbf{M}}(n) + \widetilde{\mathbf{\Pi}}(n)\end{aligned} \tag{10}$$

where $\mathbf{c}_u = diag\left(c_u^{oc}(0), \cdots, c_u^{oc}(SF-1), \cdots, c_u^{oc}(0), \cdots c_u^{oc}(SF-1)\right)$ is the spreading code matrix with the size of $(N_r \cdot SF) \times (N_r \cdot SF)$.

The channel capacity is given as [6]

$$\eta = \frac{U}{N_c}\sum_{n=0}^{\lfloor N_c/SF \rfloor - 1}\eta(n) = \frac{U}{N_c}\sum_{n=0}^{\lfloor N_c/SF \rfloor - 1}\log_2\frac{\det A_s(n)\cdot \det A_r(n)}{\det A_u(n)}, \tag{11}$$

where

$$\begin{cases}\det A_s(n) = \det E\left[\left(\sqrt{2P_0}\mathbf{d}_{0,u}(n)\right)\left(\sqrt{2P_0}\mathbf{d}_{0,u}(n)\right)^H\right] \\ \det A_r(n) = \det E\left[\mathbf{R}(n)\mathbf{R}^H(n)\right] \\ \det A_u(n) = \det E\left[\mathbf{u}(n)\mathbf{u}^H(n)\right] \\ \mathbf{u}(n) = \left(\sqrt{2P_0}\mathbf{d}_{0,u}(n), \mathbf{R}(n)\right)^T\end{cases} \tag{12}$$

and

$$\begin{cases}E\left[\left(\sqrt{2P_0}\mathbf{d}_{0,u}(n)\right)\left(\sqrt{2P_0}\mathbf{d}_{0,u}(n)\right)^H\right] = 2P_0 \cdot \mathbf{I}_{N_t} \\ E\left[\mathbf{M}(n)\mathbf{M}^H(n)\right] \\ = \left(2N_t \cdot P_0 \cdot (U-1) + \sum_{i=1}^{I-1} 2N_t \cdot P_i \cdot U\right)\cdot \mathbf{I}_{(N_r \cdot SF)} \\ E\left[\mathbf{\Pi}(k)\mathbf{\Pi}^H(k)\right] = \frac{2N_0}{N_c \cdot T_c}\cdot \mathbf{I}_{(N_r \cdot SF)}\end{cases}, \tag{13}$$

where $\mathbf{I}_{N_t}$ is the identity matrix with the size of $N_t \times N_t$ and P_i is the received signal power per receive antenna associated with each transmit antenna of the i-th BS and is given as

$$P_i = \frac{S}{N_t}\cdot r_i^{-\alpha}\cdot 10^{-\xi_i/10} = \frac{E_c}{N_t \cdot SF \cdot T_c}\cdot r_i^{-\alpha}\cdot 10^{-\xi_i/10}, \tag{14}$$

where E_c is the signal energy per FFT sample and $r_i = d_i/R$ is the normalized distance with R being the cell radius, $S = A \cdot P_t \cdot R^{-\alpha}$ is the signal power received by an MS at the cell edge ($d_i = R$) with A being a constant value, α is the path loss exponent and ξ_i is the shadowing loss with the standard deviation σ dB for the i-th BS.

By substituting Eqs. (13) and (14) into Eq. (12), $\det A_s(n)$, $\det A_r(n)$, and $\det A_u(n)$ are given by

$$\begin{cases}\det A_s(n) \\ = \det\left(\frac{2E_c}{N_t \cdot SF \cdot T_c}\cdot r_0^{-\alpha}\cdot 10^{-\xi_0/10}\cdot \mathbf{I}_{N_t}\right) \\ \det A_r(n) \\ = \det\left(\begin{matrix}\frac{2E_c}{N_t \cdot SF \cdot T_c}\cdot \mathbf{c}_u\widetilde{\mathbf{H}}(n)\widetilde{\mathbf{H}}^H(n)\mathbf{c}_u^H \\ + \left(\begin{matrix}\frac{2E_c\cdot(U-1)}{SF\cdot T_c}\cdot r_0^{-\alpha}\cdot 10^{-\xi_0/10} \\ + \sum_{i=1}^{I-1}\frac{2E_c \cdot U}{SF \cdot T_c}\cdot r_i^{-\alpha}\cdot 10^{-\xi_i/10} + \frac{2N_0}{N_c \cdot T_c}\end{matrix}\right)\cdot \mathbf{I}_{(N_r \cdot SF)}\end{matrix}\right) \\ \det A_u(n) \\ = \det A_s \cdot \det\left(\left(\begin{matrix}\frac{2E_c\cdot(U-1)}{SF\cdot T_c}\cdot r_0^{-\alpha}\cdot 10^{-\xi_0/10} \\ + \sum_{i=1}^{I-1}\frac{2E_c \cdot U}{SF \cdot T_c}\cdot r_i^{-\alpha}\cdot 10^{-\xi_i/10} + \frac{2N_0}{N_c \cdot T_c}\end{matrix}\right)\cdot \mathbf{I}_{(N_r \cdot SF)}\right)\end{cases}. \tag{15}$$

We obtain a simple expression for the channel capacity expression by substituting Eq. (15) into Eq. (11) as

$$\eta = \frac{U}{N_c}\sum_{n=0}^{\left\lfloor \frac{N_c}{SF}\right\rfloor - 1}\log_2\det\left(\mathbf{I}_{N_t} + \frac{\Gamma_{MC}}{N_t}\cdot\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\mathbf{H}^H(k)\mathbf{H}(k)\right), \tag{16}$$

where Γ_{MC} is the signal power-to-interference plus noise power ratio (SINR) and is expressed as

$$\Gamma_{MC} = \frac{\frac{E_s}{N_0}\cdot r_0^{-\alpha}\cdot 10^{-\xi_0/10}}{\left(\left(\frac{U-1}{SF}\cdot\frac{E_s}{N_0}\right)\cdot r_0^{-\alpha}\cdot 10^{\frac{-\xi_0}{10}} + \frac{U}{SF}\cdot\frac{E_s}{N_0}\sum_{i=1}^{I-1}r_i^{-\alpha}\cdot 10^{\frac{-\xi_i}{10}} + 1\right)} \tag{17}$$

with $E_s = N_c \cdot E_c$ being the energy per symbol.

For perfect ICI cancellation, the received SINR is given by

$$\Gamma_{MC} = \frac{\frac{E_s}{N_0} \cdot r_0^{-\alpha} \cdot 10^{-\xi_0/10}}{\frac{U}{SF} \cdot \frac{E_s}{N_0} \sum_{i=1}^{I-1} r_i^{-\alpha} \cdot 10^{-\xi_i/10} + 1}. \tag{18}$$

In a cellular system with frequency-reuse factor F, the system bandwidth is divided into F sub-bands and a different sub-band is allocated to a different BS in a group of F cells. Accordingly, the cellular channel capacity of MC-CDMA with spreading factor SF and code multiplexing order U is given as

$$\eta_{MC} = \frac{1}{F} \cdot \frac{U}{N_c} \sum_{n=0}^{\left\lfloor \frac{N_c}{SF} \right\rfloor - 1} \log_2 \det \left(\mathbf{I}_{N_t} + \frac{\Gamma_{MC}}{N_t} \left(\frac{1}{SF} \sum_{k=nSF}^{(n+1)SF-1} \mathbf{H}^H(k) \mathbf{H}(k) \right) \right). \tag{19}$$

It can be understood from Eq. (19) that frequency diversity gain can be obtained.

Setting SF=U=1 in Eq. (19), the cellular channel capacity of OFDM is obtained as

$$\eta_{OFDM} = \frac{1}{F} \cdot \frac{1}{N_c} \cdot \sum_{n=0}^{N_c-1} \log_2 \det \left(\mathbf{I}_{N_r} + \frac{\Gamma_{OFDM}}{N_t} \cdot \mathbf{H}(n) \mathbf{H}^H(n) \right), \tag{20}$$

where Γ_{OFDM} is given as

$$\Gamma_{OFDM} = \frac{\frac{E_s}{N_0} \cdot r_0^{-\alpha} \cdot 10^{-\xi_0/10}}{\frac{E_s}{N_0} \sum_{i=1}^{I-1} r_i^{-\alpha} \cdot 10^{-\xi_i/10} + 1}. \tag{21}$$

Eq. (20) is identical to the result of [14].

III. NUMERICAL RESULTS

The cellular channel capacity is numerically evaluated using Eqs. (19) and (20). The numerical condition is summarized in Table 1. We consider 1×1 SISO, 1×4 SIMO, 4×1 STBC-MISO, and 4×4 MIMO for both OFDM and MC-CDMA. Note that when 4×1 STBC-MISO is used, the coding rate (i.e., transmission rate) is reduced to 3/4 [11]. The number of sub-carriers is set to N_c=256. The spreading factor SF is set to SF=256 and full code-multiplexing is assumed (i.e., U=SF). The channel is assumed to be a frequency selective block Rayleigh fading channel having an L-path uniform delay power profile. The path loss exponent and the standard deviation of the shadowing loss are assumed to be α=3.5 and σ=6.0 dB, respectively. The average E_s/N_0 at the cell edge is set to be 10.0 dB. The channel capacity loss owing to the GI insertion is not considered since both OFDM and MC-CDMA require the same GI length.

The cellular channel capacity is evaluated as follows. The location of an MS of interest is generated in the center cell. The path loss and shadowing loss between each co-channel cell and MS are generated and the received SINR is computed using Eq. (18) or (21) and then, the cellular channel capacity is computed using Eq. (19) or (20). By repeating the above process a sufficient number of times, the distribution of the cellular channel capacity is obtained for the given frequency-reuse factor F. In the simulation, the MS of interest is always connected to the i=0th BS.

TABLE I. NUMERICAL CONDITION

		MC-CDMA	OFDM
Number of sub-carriers		N_c=256	
Spreading factor		SF=256	
Code multiplexing		U=SF	
ICI cancellation		Perfect	
Cell structure		Hexagonal	
Frequency reuse factor		F=1, 3, 4, 7, 9, 12	
User distribution		Uniform	
Path loss exponent		α=3.5	
Shadowing standard deviation		σ=6.0 dB	
Channel model	Fading	Block Rayleigh fading	
	Number of multipath	L-path	
	Decay factor	0 dB	
Number of transmit antennas		N_t=1 or 4	
Number of receive antennas		N_r=1 or 4	

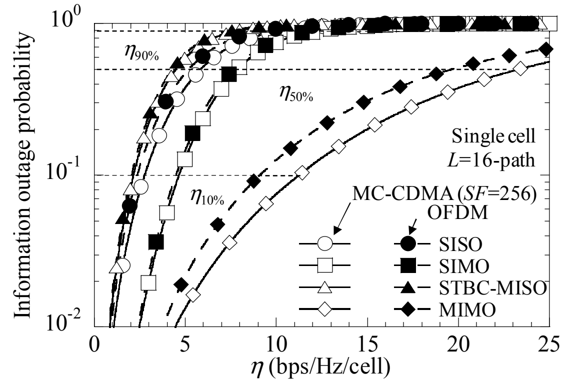


Figure 2. Information outage probability in a single-cell environemnt.

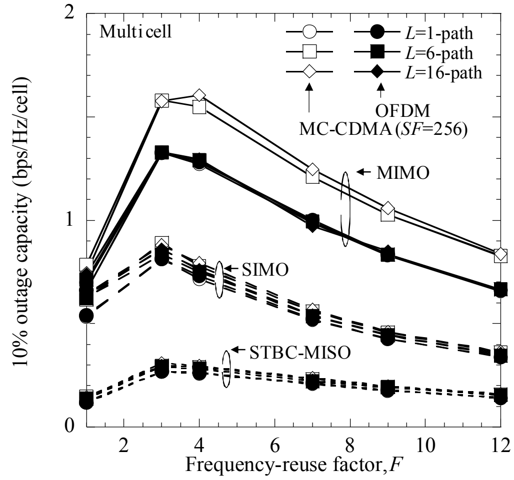
A. Single-cell environment

The information outage probability [13] for MC-CDMA and OFDM in a single-cell environment (i.e. noise-limited environment) is plotted in Fig. 2. From the figure, it can be seen that as anticipated, MIMO provides largest capacity, followed by SIMO and SISO, and STBC-MISO gives the lowest capacity. The cellular channel capacity of MC-CDMA is larger than that of OFDM because frequency diversity gain can be obtained as understood from Eq. (19). MC-CDMA and OFDM give almost the same information outage probability characteristics when SIMO and STBC-MISO are used. This can be explained as follows. The capacity improvement of MC-CDMA over OFDM is due to the frequency diversity gain owing to the frequency domain spreading. However, when transmit or receive diversity is used, the space diversity gain can be obtained both for MC-CDMA and OFDM. Because of this, the advantage of MC-CDMA diminishes.

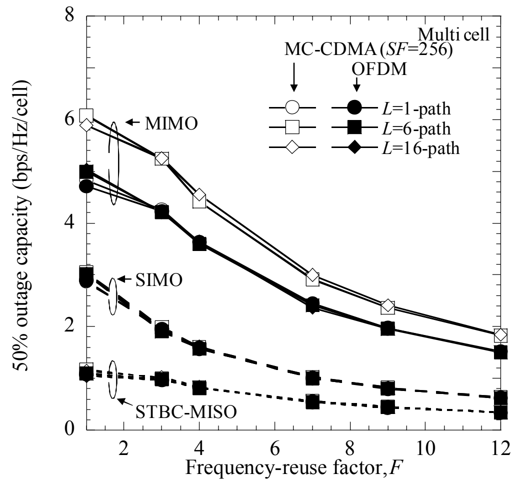
B. Multi-cell environment

The channel capacity varies because of not only noise but also CCI from the neighboring cells. The amount of CCI depends on the frequency-reuse factor F. The impact of F on the cellular channel capacity at a certain outage capacity is evaluated.

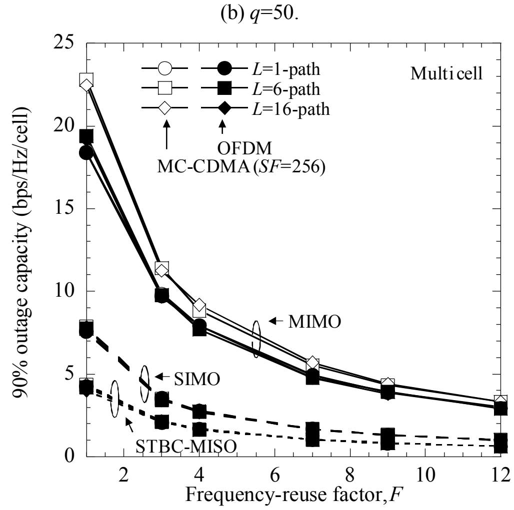
The q%-outage capacities of MC-CDMA and OFDM with q=10%, 50%, and 90% are plotted in Fig. 3 as a function of F with L as a parameter. The biggest contribution to determine



(a) q=10.



(b) q=50.



(c) q=90.

Figure 3. Impact of number of multipath, L on q%-outage capacity.

10%-outage capacity is made by the users near the cell edge, where the received signal is weak and the CCI is strong. 90%-outage capacity means that 10% users have the channel capacity larger than 90%-outage capacity and hence, 90%-outage capacity is affected by the users near the communicating BS, where the received desired signal is very strong and CCI is weak and hence the ICI is a dominant factor to determine the capacity. When L=1 (frequency-non selective fading), MC-CDMA and OFDM give the same capacity since the frequency diversity gain cannot be obtained. On the other hand, when L gets larger, MC-CDMA tends to achieve higher channel capacity compared to OFDM thanks to the increasing frequency diversity gain. The achievable channel capacity of MC-CDMA is about 1.2 times that of OFDM. Similar to the single-cell environment, the performance difference between MC-CDMA and OFDM is small for SIMO and STBC-MISO.

IV. Conclusion

In this paper, we derived the cellular channel capacity formula for MC-CDMA MIMO in a cellular environment taking into account the ICI and CCI. The cellular channel capacity of MC-CDMA was compared to that of OFDM MIMO. It was shown that MC-CDMA MIMO can achieve always larger cellular channel capacity compared to OFDM MIMO. In this paper, we assumed perfect ICI cancellation. The evaluation of the cellular channel capacity of MC-CDMA MIMO with the practical ICI cancellation technique is left as an interesting future study.

References

[1] S. Hara and R. Prasad, "Overview of multicarrier CDMA", IEEE Commun., Mag., vol.35, no.12, pp.126-133, Dec. 1997.

[2] F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," IEEE Wireless Commun., Mag., vol.12, no.2, pp.8-18, Apr. 2005.

[3] R. Dinis, P. Silva, and A. Gusmao, "An iterative frequency-domain decision-feedback receiver for MC-CDMA schemes," Proc. IEEE VTC'05-spring, vol.1, pp.271-275, May-June 2005.

[4] K. Takeda, K. Ishihara, and F. Adachi, "Frequency-domain ICI cancellation with MMSE equalization for DS-CDMA downlink," IEICE Trans. Commun., vol.E89-B, no.12, pp.3335-3343, Dec. 2006.

[5] K. Ishihara, K. Takeda, and F. Adachi, "Iterative frequency-domain soft interference cancellation for multicode DS- and MC-CDMA transmission and performance comparison," IEICE Trans. Commun., vol.E89-B, no.12, pp.3344-3355, Dec. 2006.

[6] G. J. Foschini and M. J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," Wireless Personal Commun., vol.6, no.3, pp. 311-335, Mar. 1998.

[7] Z. Kang and K. Yao, "On the capacity and asymptotic performance of MC-CDMA system over Nakagami-m fading channels," Proc. IEEE VTC'04-spring, vol.2, pp.1153-1157, May 2004.

[8] M. Ma, Y. Yang, H. Cheng, and B. Jiao, "A capacity comparison between MC-CDMA and CP-CDMA," Proc. IEEE VTC'06-fall, pp.1-4, Sept. 2006.

[9] M. Debbah, "Capacity of a downlink MC-CDMA multi-cell network," Proc. IEEE ICASSP'04, vol.4, pp.761-764, May 2004.

[10] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," IEEE J. Sel. Areas Commun., vol.16, no.8, pp.1451-1458, Oct. 1998.

[11] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," IEEE Trans. Inf. Theory, vol.45, no. 5, pp.1456-1467, July 1999.

[12] K. Adachi, F. Adachi, and M. Nakagawa, "On cellular MIMO channel capacity," Proc. IEEE VTC'07-fall, Oct. 2007.

[13] E. Biglieri, J. Proakis, and S. Shamai, "Fading channels: information-theoretic and communications aspects," IEEE Trans. Info. Theory, vol.44, no. 6, pp.2619-2692, Oct. 1998.

[14] H. Bölcskei, D. Gesbert, and A. J. Paulraj, "On the capacity of OFDM-based spatial multiplexing systems," IEEE Trans. Commun., vol.50, no.2, p.225-234, Feb. 2002.