A Study on Channel Capacities of MC-CDMA MIMO and OFDM MIMO

Koichi Adachi†, Fumiyuki Adachi‡, and Masao Nakagawa†

†Graduate School of Science and Technology, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
{kouichi, nakagawa}@nkgw.ics.keio.ac.jp

‡Graduate School of Engineering, Tohoku University
6-6-05 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579 Japan
adachi@ecei.tohoku.ac.jp

Abstract—**For the development of future wireless communication systems, an extremely spectrum-efficient transmission technology is required. Orthogonal frequency division multiplexing (OFDM) and multi-carrier code division multiple access (MC-CDMA) have been attracting much attention. The use of multiple-input multiple-output (MIMO) transmission is essential to achieve a very high speed data transmission with the limited bandwidth. In our previous paper, assuming perfect cancellation of inter-code interference (ICI), we have derived a channel capacity expression for MC-CDMA MIMO in a multi-cell environment and confirmed by numerical evaluation that MC-CDMA MIMO provides a slightly higher capacity than OFDM MIMO. In this paper, we theoretically show by using *Jensen's* inequality that the channel capacity of MC-CDMA MIMO assuming perfect ICI cancellation (ICIC) is always higher than or equal to that of OFDM MIMO. Furthermore, we compare the channel capacities of MIMO multiplexing and multiple single-input multiple output (SIMO) system.**

Keywords-component; MIMO; MC-CDMA; OFDM; channel capacity; theoretical study; Jensen's inequality

I. INTRODUCTION

In the future wireless communication system, much higher speed data services (up to 1 Gbps possibly with 100 MHz bandwidth) than in 3rd generation systems are demanded. Orthogonal frequency division multiplexing (OFDM) and multi-carrier code division multiple access (MC-CDMA), which is a combination of OFDM and CDMA, have been attracting much attention [1]. Using frequency domain equalization (FDE), MC-CDMA can take advantage of the channel frequency-selectivity and improve the transmission performance due to the frequency diversity gain obtainable by FDE. However, if code-multiplexing is used to increase the achievable transmission rate, the MC-CDMA transmission performance severely degrades due to the presence of inter-code interference (ICI) [2]. There have been many works on ICI cancellation (ICIC) techniques for MC-CDMA and direct sequence-CDMA (DS-CDMA). It was shown by computer simulation that the bit error rate (BER) performance of MC-CDMA with ICIC can approach the matched filter bound [3][4].

Multiple-input multiple-output (MIMO) space division multiplexing is a very promising technique to increase the transmission rate without expanding the signal bandwidth [5]. Recently, we investigated the channel capacity of MC-CDMA MIMO in a cellular system and showed that assuming perfect ICIC, the MC-CDMA can improve the information outage probability over OFDM [6].

In this paper, we first derive a channel capacity expression of MC-CDMA MIMO with perfect ICIC and show, by using *Jensen's* inequality [7], that the channel capacity of MC-CDMA MIMO with perfect ICIC can achieve always higher or equal to that of OFDM MIMO.

Recently, a lot of attention has been paid to iterative signal detection for OFDM MIMO, MC-CDMA MIMO, and DS-CDMA MIMO [8][9]. The transmission performance of MIMO-SDM is upper limited by multiple single-input multiple output (multiple SIMO) system. However, to the best of authors' knowledge, there has been no literature which discusses the channel capacity limit of MC-CDMA MIMO and OFDM MIMO. In this paper, we compare the channel capacities of MIMO system and multiple SIMO system and show that MC-CDMA MIMO can approach multiple SIMO system while OFDM MIMO cannot. The channel capacity of MIMO multiplexing is compared to those of SIMO receive diversity and multiple-input single-output space-time block code-multiple-input single-output (STBC-MISO).

The rest of the paper is organized as follows. In Sect. II, the system model is introduced and the channel capacity formula is derived. The channel capacity comparison between MC-CDMA MIMO and OFDM MIMO by using *Jensen's* inequality is presented in Sect. III. The capacity comparison between MIMO and multiple SIMO is discussed in Sect. IV. Numerical results are presented in Sect. V. Section VI concludes the paper.

II. TRANSMISSION SYSTEM MODEL

The transmitter/receiver structure with N_t transmit antennas and N_r receive antennas is illustrated in Fig. 1. In this paper, sample-spaced time representation of the signal is used. The u-th data symbol stream $\{d_{n_t,u}(n); n = 0 \sim \lfloor N_c/SF \rfloor - 1\}$ is spread by the u-th spreading code $\{c_{oc,u}(k); k = 0 \sim SF-1\}$, $u = 0 \sim U-1$, and then, transmitted from the n_t-th transmit antenna ($n_t = 0 \sim N_t - 1$), where N_c is the number of sub-carriers and $\lfloor x \rfloor$ is the largest integer smaller than or equal to x. The k-th subcarrier component ($k = 0 \sim N_c - 1$) can be expressed as

$$S_{n_t,u}(k) = \sqrt{2P} d_{n_t,u}(\lfloor k/SF \rfloor) c_{oc,u}(k \bmod SF), \quad (1)$$

where P is the transmit power per symbol stream and SF is the spreading factor. We assume that the same spreading code is used for all the transmit antennas.

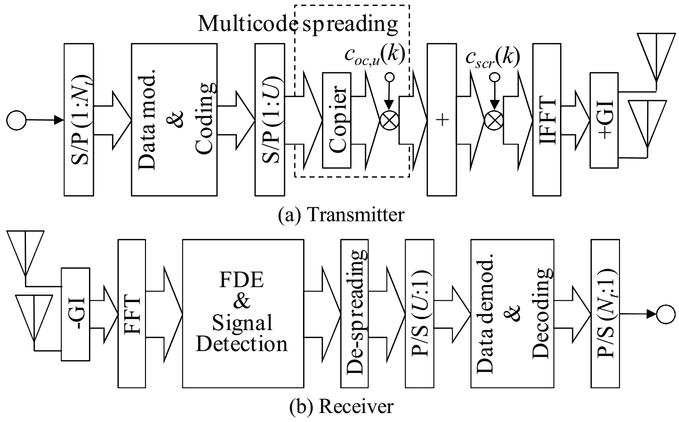

Figure 1. Transmission system model.

After code-multiplexing and multiplying the long scrambling code $\{c_{scr}(k); k=\cdots,-1,0,1,\cdots\}$, the time-domain MC-CDMA signal is generated by using the N_c-point inverse fast Fourier transform (IFFT) as

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

where

$$S_{n_t}(k)=\left(\sum_{u=0}^{U-1}S_{n_t,u}(k)\right)c_{scr}(k). \tag{3}$$

After inserting an N_g-point cyclic prefix (CP) into the guard interval (GI), the MC-CDMA signal $\{s_{n_t}(t \bmod N_c); t=-N_g \sim N_c-1\}$ is transmitted from the n_t-th transmit antenna.

The channel for each pair of the transmit and receive antennas is assumed to be an L-path channel, where each path is subjected to independent fading. The channel impulse response between the n_t-th transmit antenna and the n_r-th receive antenna can be expressed as

$$h_{n_r,n_t}(t)=\sum_{l=0}^{L-1}h_{n_r,n_t,l}\delta(t-\tau_l), \tag{4}$$

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

The received signal $\{r_{n_r}(t); t=-N_g \sim N_c-1\}$, after the GI removal, at the n_r-th receive antenna can be expressed as

$$r_{n_r}(t)=\sum_{n_t=0}^{N_t-1}\sum_{l=0}^{L-1}h_{n_r,n_t,l}s_{n_t}\left((t-\tau_l)\bmod N_c\right)+n_{n_r}(t), \tag{5}$$

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

The received signal $\{r_{n_r}(t); t=-N_g \sim N_c-1\}$ is transformed by using the N_c-point FFT to the frequency-domain signal $\{R_{n_r}(k); k=0 \sim N_c-1\}$. $R_{n_r}(k)$ is given by

$$\begin{aligned}R_{n_r}(k)&=(1/N_c)\sum_{t=0}^{N_c-1}r_{n_r}(t)\exp\left(-j2\pi(k/N_c)t\right)\\&=\sum_{n_t=0}^{N_t-1}H_{n_r,n_t}(k)S_{n_t}(k)+\Pi_{n_r}(k)\end{aligned}, \tag{6}$$

where $H_{n_r,n_t}(k)$ and $\Pi_{n_r}(k)$ are respectively the Fourier transforms of the channel impulse response and the noise and are given by

$$\begin{cases}H_{n_r,n_t}(k)=\sum_{l=0}^{L-1}h_{n_r,n_t,l}\exp\left(-j2\pi(k/N_c)\tau_l\right)\\ \Pi_{n_r}(k)=(1/N_c)\sum_{t=0}^{N_c-1}n_{n_r}(t)\exp\left(-j2\pi(k/N_c)t\right)\end{cases}. \tag{7}$$

Using $c_u(.)=c_{scr}(.)c_{oc,u}(.)$, $R_{n_r}(k)$ can be expressed as

$$R_{n_r}(k)=\sum_{n_t=0}^{N_t-1}H_{n_r,n_t}(k)\left(\sqrt{2P}\sum_{u=0}^{U-1}d_{n_t,u}\left(\left\lfloor\frac{k}{SF}\right\rfloor\right)c_u(k)\right)+\Pi_{n_r}(k). \tag{8}$$

Equation (8) can be rewritten as

$$R_{n_r}(k)=\sqrt{2P}\sum_{n_t=0}^{N_t-1}\begin{pmatrix}H_{n_r,n_t}(k)c_u(k)\\ \times d_{n_t,u}(\lfloor k/SF\rfloor)\end{pmatrix}+\mathrm{M}_{n_r}(k)+\Pi_{n_r}(k), \tag{9}$$

where $\mathrm{M}_{n_r}(k)$ is the ICI component and is given by

$$\mathrm{M}_{n_r}(k)=\sum_{n_t=0}^{N_t-1}H_{n_r,n_t}(k)\left(\sqrt{2P}\sum_{\substack{u'=0\\ \neq u}}^{U-1}d_{n_t,u'}(\lfloor k/SF\rfloor)c_{u'}(k)\right). \tag{10}$$

The k-th sub-carrier components received by N_r receive antennas can be expressed by using the matrix form as

$$\begin{aligned}\mathbf{R}(k)&=\left(R_0(k)\cdots R_{N_r-1}(k)\right)^T=c_u(k)\mathbf{H}(k)\mathbf{d}_u(k)+\mathbf{M}(k)+\mathbf{\Pi}(k)\\&=\sqrt{2P}c_u(k)\begin{pmatrix}H_{0,0}(k) & & H_{0,N_t-1}(k)\\ \vdots & \ddots & \vdots\\ H_{N_r-1,0}(k) & & H_{N_r-1,N_t-1}(k)\end{pmatrix}\begin{pmatrix}d_{0,u}(k)\\ \vdots\\ d_{N_t-1,u}(k)\end{pmatrix}\\&\quad+\begin{pmatrix}\mathrm{M}_0(k)\\ \vdots\\ \mathrm{M}_{N_r-1}(k)\end{pmatrix}+\begin{pmatrix}\Pi_0(k)\\ \vdots\\ \Pi_{N_r-1}(k)\end{pmatrix}\end{aligned}. \tag{11}$$

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

$$\begin{aligned}\mathbf{R}(n)&=\left(R_0(nSF)\ \cdots\ R_{N_r-1}((n+1)SF-1)\right)^T\\&=\sqrt{2P}\mathbf{c}_u\begin{pmatrix}H_{0,0}(nSF) & \cdots & H_{0,N_t-1}(nSF)\\ \vdots & \ddots & \vdots\\ H_{N_r-1,0}\begin{pmatrix}(n+1)\\ \times SF-1\end{pmatrix} & \cdots & H_{N_r-1,N_t-1}\begin{pmatrix}(n+1)\\ \times SF-1\end{pmatrix}\end{pmatrix}\begin{pmatrix}d_{0,u}(n)\\ \vdots\\ d_{N_t-1,u}(n)\end{pmatrix},\\&\quad+\begin{pmatrix}\mathrm{M}_0(nSF)\\ \vdots\\ \mathrm{M}_{N_r-1}((n+1)SF-1)\end{pmatrix}+\begin{pmatrix}\Pi_0(nSF)\\ \vdots\\ \Pi_{N_r-1}((n+1)SF-1)\end{pmatrix}\\&=\mathbf{c}_u\tilde{\mathbf{H}}(n)\left(\sqrt{2P}\mathbf{d}_u(n)\right)+\tilde{\mathbf{M}}(n)+\tilde{\mathbf{\Pi}}(n)\end{aligned} \tag{12}$$

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

The channel capacity is given as [5]

$$C_{MC}=\frac{U}{N_c}\sum_{n=0}^{\lfloor N_c/SF\rfloor-1}\log_2\frac{\det A_s(n)\cdot\det A_r(n)}{\det A_u(n)}. \quad (13)$$

In the case of perfect ICI cancellation, $\det A_s(n)$, $\det A_r(n)$, and $\det A_s(n)$ are given by (for the sake of brevity, their derivation is omitted)

$$\begin{cases}\det A_s=\det\left(2P\cdot\mathbf{I}_{N_t}\right)\\ \det A_r=\det\left(2P\cdot\mathbf{c}_u\widetilde{\mathbf{H}}(n)\widetilde{\mathbf{H}}^H(n)\mathbf{c}_u^H+\frac{2N_0}{N_c\cdot T_c}\cdot\mathbf{I}_{(N_r\cdot SF)}\right),\\ \det A_u=\det A_s\cdot\det\left(\frac{2N_0}{N_c\cdot T_c}\cdot\mathbf{I}_{(N_r\cdot SF)}\right)\end{cases} \quad (14)$$

where $\mathbf{I}_{N_t}$ is the identity matrix with the size of $N_t\times N_t$. By substituting (14) into (13), the channel capacity of MC-CDMA MIMO assuming perfect ICIC is given as

$$C_{MC}=\frac{U}{N_c}\sum_{n=0}^{\lfloor N_c/SF\rfloor-1}\log_2\det\left(\mathbf{I}_{N_t}+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\cdot\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\mathbf{H}^H(k)\mathbf{H}(k)\right)\right), \quad (15)$$

where E_s is the symbol energy.

III. Performance Comparison Between MC-CDMA MIMO and OFDM MIMO

The channel capacity of OFDM MIMO is given by [10]

$$C_{OFDM}=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\log_2\det\left(\mathbf{I}_{N_t}+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\mathbf{H}^H(k)\mathbf{H}(k)\right). \quad (16)$$

By applying the eigenvalue decomposition to $\mathbf{H}^H(k)\mathbf{H}(k)$, (16) can be rewritten as

$$C_{OFDM}=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left(\log_2\prod_{i=0}^{N_{\min}-1}\left(1+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\lambda_i(k)\right)\right), \quad (17)$$

where $\lambda_i(k)$ is the i-th eigenvalue ($i=0\sim N_{\min}-1; N_{\min}=\min(N_t,N_r)$).

On the other hand, the channel capacity of full code-multiplexed (i.e., $SF=U=N_c$) MC-CDMA MIMO assuming perfect ICIC is given from (15) as

$$C_{fullMC}=\frac{N_c}{N_c}\log_2\det\left(\mathbf{I}_{N_t}+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\mathbf{H}^H(k)\mathbf{H}(k)\right)\right), \quad (18)$$

which can be rewritten using eigenvalues as

$$C_{fullMC}=\frac{1}{N_c}\sum_{i=0}^{N_{\min}-1}\log_2\left(1+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\lambda_i(k)\right)\right)^{N_c}. \quad (19)$$

The *Jensen's* inequality states the mathematical relationship between the arithmetic mean and geometric mean as [7]

$$\left(\prod_{n=0}^{N-1}x_n\right)^{1/N}\le(1/N)\sum_{n=0}^{N-1}x_n, \quad (20)$$

where equality holds if and only if $x_n=x$, n=0~N–1. Using the *Jensen's* inequality, we have the following relationship between OFDM MIMO and MC-CDMA MIMO.

$$\begin{aligned}C_{OFDM}&=\frac{1}{N_c}\sum_{i=0}^{N_{\min}-1}\log_2\left(\prod_{k=0}^{N_c-1}\left(1+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\cdot\lambda_i(k)\right)\right)\\ &\le\frac{1}{N_c}\sum_{i=0}^{N_{\min}-1}\log_2\left(\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left(1+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\cdot\lambda_i(k)\right)\right)^{N_c}\right)\\ &=\frac{1}{N_c}\sum_{i=0}^{N_{\min}-1}\log_2\left(1+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\lambda_i(k)\right)\right)^{N_c}=C_{fullMC}\end{aligned}. \quad (21)$$

From (21), it can be understood that the channel capacity of MC-CDMA with perfect ICIC is always larger than or equal to that of OFDM. If L=1 (frequency-nonselective channel), MC-CDMA provides the same channel capacity as OFDM.

IV. Channel Capacities of MIMO Multiplexing and Multiple SIMO

We compare the channel capacities of MIMO multiplexing and multiple (N_t)-SIMO. The capacity difference ΔC (bps/Hz) between (N_t,N_r)-MIMO multiplexing and $N_t\times(1,N_r)$-SIMO can be given as

$$\Delta C(\text{bps/Hz})=(N_t,N_r)\text{MIMO}-N_t\times(1,N_r)\text{SIMO}$$
$$=E\left[\begin{array}{l}\frac{U}{N_c}\sum_{n=0}^{\lfloor N_c/SF\rfloor-1}\log_2\det\left(\mathbf{I}_{N_t}+\frac{E_s}{N_tN_0}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\mathbf{H}^H(k)\mathbf{H}(k)\right)\right)\\ -\frac{U}{N_c}\sum_{n_t=0}^{N_t-1}\sum_{n=0}^{\lfloor N_c/SF\rfloor-1}\log_2\left(1+\frac{E_s}{N_tN_0}\left(\frac{1}{SF}\sum_{n_r=0}^{N_r-1}\sum_{k=nSF}^{(n+1)SF-1}\left|H_{n_r,n_t}(k)\right|^2\right)\right)\end{array}\right]. \quad (22)$$

ΔC is always lower than or equal to 0. This has been confirmed by our preliminary computer simulation (the proof for the case of N_t=N_r=2 is given in Appendix). Therefore, the capacity of (N_t,N_r)-MIMO multiplexing is always lower than or equal to $N_t\times(1,N_r)$-SIMO. This will be confirmed by the numerical evaluation in Sect. V.

V. Numerical Evaluation

The channel capacities of MC-CDMA MIMO and OFDM MIMO are numerically evaluated using (15) and (16). The numerical condition is summarized in Table 1. The number of sub-carriers is set to N_c=256. The spreading factor SF is varied from 4 to 256 and the full code-multiplexing (i.e., U=SF) is assumed. The channel for each pair of transmit and receive antennas is assumed to be a frequency-selective independent block Rayleigh fading channel having an L=16-path equal power delay profile. The channel capacity loss owing to the GI insertion is not considered since both OFDM and MC-CDMA require the same GI length.

TABLE I. SIMULATION CONDITION

		MC-CDMA	OFDM
Number of sub-carriers		N_c=256	
Spreading factor		SF=4~256	
Code multiplexing		U=SF	
ICIC		Perfect	
Channel Model	Fading	Block Rayleigh fading	
	Number of paths	L=16-path	
	Decay factor	γ=0dB	
Number of transmit/receive antennas		N_t/N_r=1~6	

The channel capacities of MC-CDMA and OFDM are compared in Fig. 2 as a function of the average E_s/N_0 with the number of transmit/receive antennas (N_t=N_r) as a parameter. It can be seen from Fig. 2 that MC-CDMA always provides higher channel capacity than OFDM irrespective of the number of transmit/receive antennas. As the number of antennas increases, both capacities of MC-CDMA and OFDM increase; however, the capacity difference between MC-CDMA and OFDM becomes larger.

Fig. 3 shows the channel capacity comparison between MC-CDMA and OFDM when the total number of transmit and receive antennas is kept to N_t+N_r=4. From Fig. 3, it can be seen that MIMO multiplexing provides slightly lower channel capacity than that of SIMO in a lower E_s/N_0 region since the transmission power per each antenna is reduced by a factor of N_t. However, the channel capacity of MIMO multiplexing increases greatly in a large E_s/N_0 region owing to the spatial diversity gain and spatial multiplexing gain. The channel capacity of STBC-MISO is much lower than those of SIMO and MIMO multiplexing even though the same diversity order of 3 as SIMO is obtained. It can also be seen from Fig. 3 that the capacity difference between MC-CDMA and OFDM is smaller for SIMO and STBC than for MIMO multiplexing. The reason for this can be explained as follows. The advantage of MC-CDMA over OFDM is the frequency diversity gain obtained from frequency domain spreading (as shown in (15) and (16)). However, the frequency diversity gain becomes relatively small compared to the spatial diversity gain when SIMO or STBC-MISO is used.

Fig. 4 plots ΔC of MC-CDMA, defined in (22), as a function of the number of transmit/receive antennas with SF as a parameter. Also plotted are ΔC of MC-CDMA with $SF\times\lfloor N_c/SF\rfloor$-frequency domain block interleaver and that of OFDM. As the number of antennas (N_t=N_r) increases, ΔC increases for OFDM and MC-CDMA (w/o interleaver) with SF=4 due to the residual inter-antenna interference (IAI). On the other hand, ΔC increases only slightly for MC-CDMA with SF=256 and MC-CDMA (w/ interleaver) with SF=16. This can be explained as follows. Here, we consider the case with N_t=N_r=2. The contribution of the channel matrix to the channel capacity is expressed as

$$\mathbf{H}^H(k)\mathbf{H}(k) = \begin{pmatrix} |H_{0,0}(k)|^2+|H_{1,0}(k)|^2 & H^*_{0,0}(k)H_{0,1}(k)+H^*_{1,0}(k)H_{1,1}(k) \\ H^*_{0,1}(k)H_{0,0}(k)+H^*_{1,1}(k)H_{1,0}(k) & |H_{0,1}(k)|^2+|H_{1,1}(k)|^2 \end{pmatrix}. \quad (23)$$

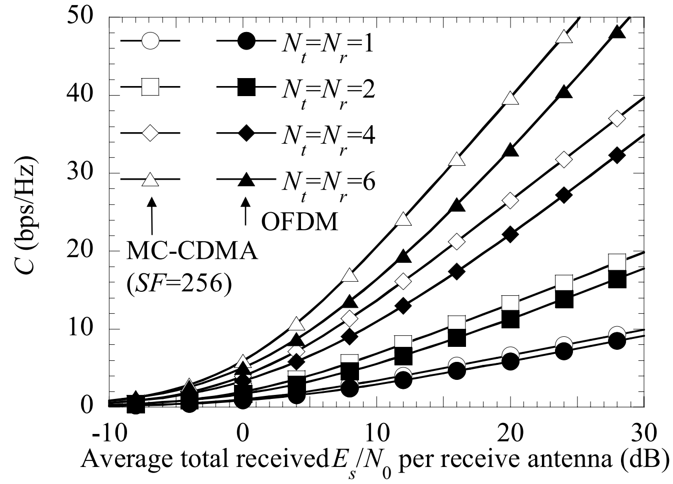

Figure 2. Impact of number of antennas.

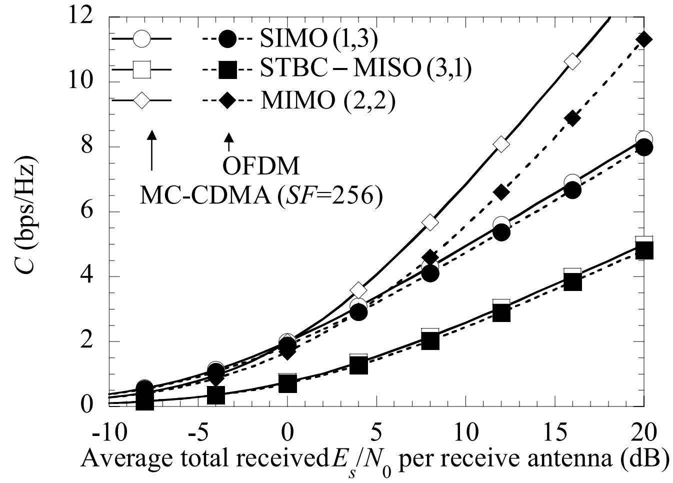

Figure 3. Comparison between spatial multiplexing and spatial diversity.

The northwest corner and southeast corner of $\mathbf{H}^H(k)\mathbf{H}(k)$ (which correspond to the channel correlation between the transmit antennas) are the interference between the transmit antennas. When MC-CDMA is used, $\mathbf{H}^H(k)\mathbf{H}(k)$ is averaged over SF sub-carriers; hence, as SF increases, because of the law of large number, the averaged channel correlation between the transmit antennas becomes $E[H_{n_r,n_t}(k)H^*_{n_r,n'_t\neq n_t}(k)]=0$ [11]. Since $\sum_{k=nSF}^{(n+1)SF-1}\mathbf{H}^H(k)\mathbf{H}(k)$ becomes a diagonal matrix, the IAI can be suppressed. As smaller SF is used (e.g., SF=4), the fading correlation between sub-carriers over which each data symbol is spread increases and hence, ΔC becomes almost the same as OFDM.

Fig. 5 plots the channel capacities of MC-CDMA and OFDM for the cases of (N_t,N_r)-MIMO and $N_t\times(1,N_r)$-SIMO. From the figure, it can be seen that MC-CDMA MIMO provides almost the same capacity as multiple SIMO while OFDM MIMO cannot. The reason for this is due to the residual IAI discussed earlier. On the other hand, MC-CDMA MIMO

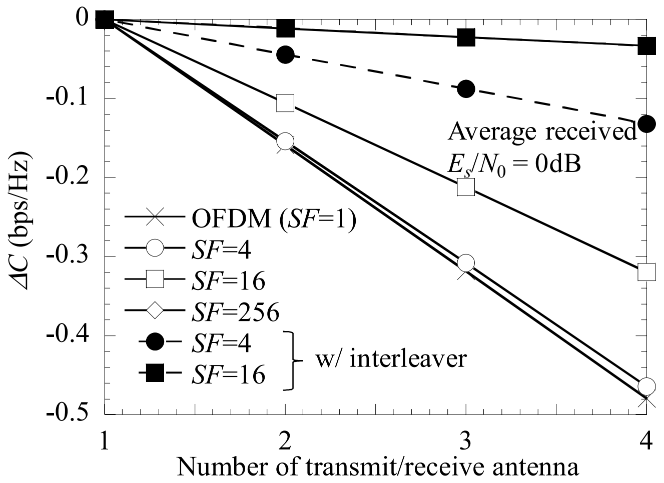

Figure 4. Channel capacity difference between MIMO and Multiple-SIMO.

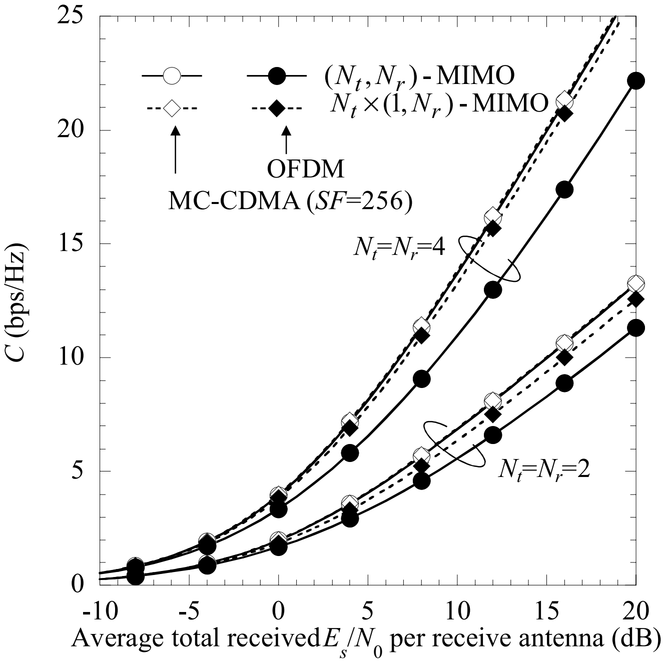

Figure 5. Comparison of MIMO and Multiple-SIMO.

can suppress sufficiently the IAI by using the frequency domain spreading.

VI. CONCLUSION

In this paper, we compared the channel capacity of MC-CDMA MIMO with perfect ICIC to that of OFDM MIMO by using the *Jensen's* inequality and showed that the channel capacity of MC-CDMA MIMO with perfect ICIC is always larger than or equal to that of OFDM MIMO. Also we showed that MC-CDMA MIMO can approach the capacity of multiple SIMO while OFDM MIMO cannot. The impact of imperfect ICIC on the channel capacity of MC-CDMA is left as an interesting future study.

APPENDIX.

For the simplicity purpose, we assume N_t=N_r=2 and N_c=SF=U=1. Equation (22) can be rewritten as

$$\begin{aligned}
\Delta C(\text{bps/Hz}) &= (N_t,N_r)\text{-MIMO} - N_t\times(1,N_r)\text{-SIMO}\\
&= E\left[\begin{array}{l}\log_2\det\left(\mathbf{I}_{N_t}+(E_s/(2N_0))\mathbf{H}^H(k)\mathbf{H}(k)\right)\\ -\sum_{n_t=0}^{1}\log_2\left(1+(E_s/(2N_0))\sum_{n_r=0}^{1}H_{n_r,n_t}(k)\right)\end{array}\right]\\
&= E\left[\begin{array}{l}\log_2\left\{\begin{array}{l}\left(1+(E_s/(2N_0))\left(|H_{11}(k)|^2+|H_{21}(k)|^2\right)\right)\\ \times\left(1+(E_s/(2N_0))\left(|H_{12}(k)|^2+|H_{22}(k)|^2\right)\right)\\ -(E_s/(2N_0))^2\left|H_{11}^*(k)H_{12}(k)+H_{21}^*(k)H_{22}(k)\right|^2\end{array}\right\}\\ -\log_2\left\{\begin{array}{l}\left(1+(E_s/(2N_0))\left(|H_{11}(k)|^2+|H_{21}(k)|^2\right)\right)\\ \times\left(1+(E_s/(2N_0))\left(|H_{12}(k)|^2+|H_{22}(k)|^2\right)\right)\end{array}\right\}\end{array}\right],
\end{aligned}\qquad\text{(A1)}$$

Since $(E_s/(2N_0))^2\left|H_{11}^*(k)H_{12}(k)+H_{21}^*(k)H_{22}(k)\right|^2$ becomes always larger than or equal to 0, ΔC (bps/Hz) is always smaller than or equal to 0.

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 Wirel. 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. 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.

[5] G. J. Foschini and M. J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," Wireless Personal Commun., pp. 311-335, Mar. 1998.

[6] K. Adachi, F. Adachi, and M. Nakagawa, "Cellular MIMO channel capacities of MC-CDMA and OFDM," Proc. IEEE VTC'08-spring, May 2008.

[7] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*, New York, Academic Press, 1965.

[8] K. Adachi and M. Nakagawa, "Iterative modified QRD-M based on CRC codes for OFDM MIMO multiplexing," IEICE Trans. Commun., vol.E90-B, no.6, pp.1433-1443, June 2007.

[9] A. Nakajima and F. Adachi, "Throughput performance of iterative frequency-domain SIC with 2D MMSE-FDE for SC-MIMO multiplexing," Proc. IEEE VTC'06-fall, Sept. 2006.

[10] 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.

[11] K. Adachi, F. Adachi, and M. Nakagawa, "Aproximate channel capacity of MC-CDMA MIMO," Proc. The 11th WPMC, Sept. 2008.