The 12th International Symposium on Wireless Personal Multimedia Communications (WPMC 2009)

CAPACITY OF MC-CDMA MIMO WITH IMPERFECT INTERFERENCE CANCELLATION

Koichi Adachi[†] Fumiyuki Adachi[‡] Masao Nakagawa[†]

[†]School of Science for Open and Environmental Systems,
Graduate School of Science and Technology, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522 Japan

[‡]Dept. of Electrical and Communication Engineering,
Graduate School of Engineering, Tohoku University
6-6-05 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579 Japan

ABSTRACT

Multi-carrier code division multiple access (MC-CDMA) is an attractive multiple access technique. For achieving a very high speed data transmission with a limited bandwidth, MC-CDMA can be jointly used with multiple-input multiple-output (MIMO) multiplexing. Among many signal detection methods, an iterative interference cancellation technique can be used. The presence of residual interference limits the performance improvement. In this paper, we consider the minimum mean squared error detection (MMSED) with imperfect cancellation of inter-code interference (ICI) and inter-antenna interference (IAI) and derive the capacity expression by taking into account the degrees of residual ICI and IAI. Then, we discuss how the imperfect interference cancellation impacts the achievable capacity of MC-CDMA MIMO.

I. INTRODUCTION

The next generation wireless communication systems require a very high speed data transmissions, e.g., up to 1Gbps with a limited frequency bandwidth [1]. The multi-carrier (MC) techniques, such as orthogonal frequency division multiplexing (OFDM) and multi-carrier code division multiple access (MC-CDMA) [2], are attractive for achieving high speed data transmission. MC-CDMA uses the frequency domain spreading and obtains the frequency diversity gain through the frequency domain equalization (FDE). Higher speed transmission can be achieved by using orthogonal code multiplexing. Full code multiplexing provides the same data rate as OFDM. Further increase in the data rate without bandwidth expansion can be achieved with multiple-input multiple-output (MIMO) multiplexing [3, 4].

High speed packet services will be dominated in the next generation systems. The channel capacity is the achievable upper bound of the packet based transmissions. In MIMO multiplexing, a superposition of different data streams simultaneously transmitted from different transmit antennas is received. As an efficient signal detection method for MC MIMO, maximum likelihood detection (MLD) [5], minimum mean squared error detection (MMSED) [6], MLD based on QR-decomposition and M-algorithm (QRD-M) [7], etc, can be used. An iterative frequency-domain interference cancellation based signal detection method has been proposed for single-carrier (SC) MIMO [8], SC multicode spread spectrum MIMO using FDE [9], and MC multicode spread spectrum MIMO [10]. In our previous papers [11, 12], assuming perfect inter-code interference (ICI) cancellation, we evaluated the channel capacity of MC-CDMA MIMO by using numerical computation method and using *Jensen's* inequality.

Interference cancellation cannot be perfect in practice and the presence of the residual interference limits the achievable performance improvement. In this paper, we discuss how the imperfect interference cancellation impacts the achievable capacity of MC-CDMA MIMO. The received signal-to-interference plus noise power ratio (SINR) is computed for MMSED with imperfect cancellation of ICI and inter-antenna interference (IAI). Two imperfect cancellation factors, ρ and η, are introduced which represent the degrees of residual ICI and IAI, respectively, after the interference cancellation.

The rest of the paper is organized as follows. In Sect. II, the transmission system model is presented. Assuming the Gaussian approximation of the residual interference, the conditional SINR with imperfect interference cancellation is derived for computing the capacity in Sect. III. Numerical results are presented and the impact of the imperfect interference cancellation on the achievable channel capacity of MC-CDMA MIMO is discussed in Sect. IV. Section V concludes the paper.

II. TRANSMISSION SYSTEM MODEL

Transmission system model is illustrated in Fig. 1. In this paper, the sample-spaced time representation is used. Without loss of generality, one MC-CDMA signalling interval is considered below.

The k-th sub-carrier component (k=0~(N_c–1)) of the data symbol stream $\{d_{n_t,u}(n);n=0\sim(\lfloor N_c/SF\rfloor-1)\}$, which is spread by the u-th spreading code (u=0~(U–1)) and is transmitted from the n_t-th antenna (n_t=0~(N_t–1)), can be expressed as

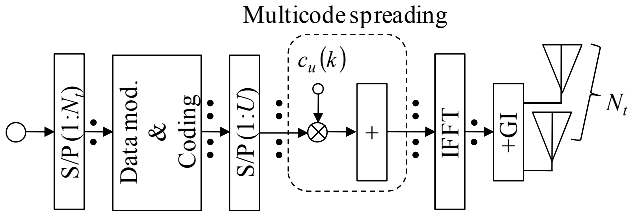
$$S_{n_t,u}(k)=\sqrt{\frac{2E_c}{N_t\cdot SF\cdot T_c}}\,d_{n_t,u}\left(\left\lfloor\frac{k}{SF}\right\rfloor\right)c_u(k\bmod SF),\qquad(1)$$

where E_c is the signal energy per fast Fourier transform (FFT) sample, SF is the spreading factor, T_c is the sample duration, N_t is the number of transmit antennas, and $\lfloor x\rfloor$ is the largest integer smaller than or equal to x. After the U-order code multiplexing, the time domain MC-CDMA signal $\{s_{n_t}(t);t=0\sim(N_c-1)\}$ is generated by applying N_c-point inverse fast Fourier transform (IFFT) as

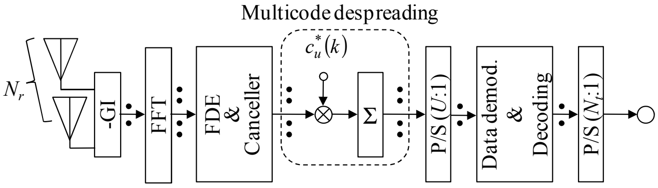
$$s_{n_t}(t)=\sum_{k=0}^{N_c-1}S_{n_t}(k)\exp\left(j2\pi\frac{t}{N_c}k\right),\qquad(2)$$

where

$$S_{n_t}(k)=\sum_{u=0}^{U-1}S_{n_t,u}(k).\qquad(3)$$



(a) Transmitter.



(b) Receiver.

Figure 1: Transmission system model.

After the insertion of N_g-sample cyclic prefix (CP) into the guard interval (GI), the multicode MC-CDMA signal $\{s_{n_t}(t \bmod N_c); t=-N_g \sim (N_c-1)\}$ is transmitted from each antenna.

The channel between each pair of transmit and receive antennas is assumed to be an independent L-path frequency-selective fading channel and its impulse response is given by

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

where $h_{n_r,n_t,l}$ and τ_l are respectively the complex-valued path gain and the time delay of the l-th path between the n_t-th transmit antenna and the n_r-th receive antenna with $E\left[\sum_{l=0}^{L-1}|h_{n_r,n_t,l}|^2\right]=1$ (E[.] represents the ensemble average operation).

The received signal at the n_r-th receive antenna (n_r=0~(N_r–1)) after the removal of CP is represented 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 complex-valued additive white Gaussian noise (AWGN) with mean 0 and variance $2\sigma^2=2N_0/T_c$ (N_0 is the one-sided power spectrum density of the AWGN).

The k-th sub-carrier component of the received signal is obtained by applying N_c-point FFT as

$$R_{n_r}(k)=\frac{1}{N_c}\sum_{t=0}^{N_c-1} r_{n_r}(t)\exp\left(-j2\pi\frac{k}{N_c}t\right). \tag{6}$$

Substituting (5) into (6) gives

$$R_{n_r}(k)=\sum_{n_t=0}^{N_t-1} H_{n_r,n_t}(k)S_{n_t}(k)+\Pi_{n_r}(k), \tag{7}$$

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

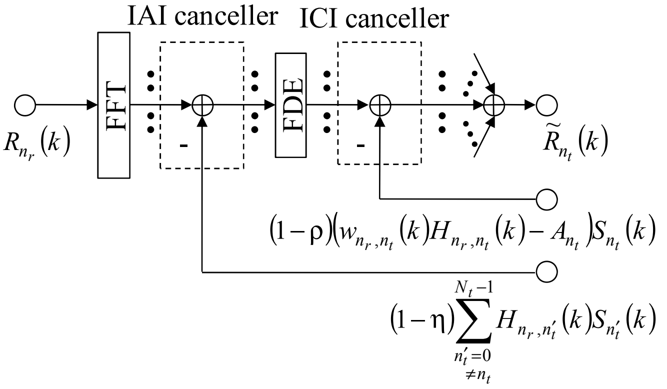


Figure 2: Structure of interference canceller for the n_t-th transmit antenna.

$$\begin{cases} H_{n_r,n_t}(k)=\sum_{l=0}^{L-1} h_{n_r,n_t,l}\exp\left(-j2\pi\frac{k}{N_c}\tau_l\right) \\ \Pi_{n_r}(k)=\frac{1}{N_c}\sum_{t=0}^{N_c-1} n_{n_r}(t)\exp\left(-j2\pi\frac{k}{n_c}t\right) \end{cases}. \tag{8}$$

III. IMPERFECT INTERFERENCE CANCELLATION

In MIMO multiplexing, the signals transmitted from N_t antennas interfere with each other (this is called the IAI). Furthermore, ICI is produced in a frequency-selective channel. In interference cancellation based signal detection, IAI cancellation, FDE, and ICI cancellation are successively performed as in Fig. 2. In this paper, we introduce the imperfect cancellation factors, η (η=0~1) and ρ (ρ=0~1), which represent the degrees of imperfect cancellation of IAI and ICI, respectively. The case ρ=η=1 represents the no interference cancellation, while the case ρ=η=0 represents the perfect ICI and IAI cancellation.

The IAI component associated with the n_t-th transmit antenna which should be subtracted from the received signal at the n_r-th receive antenna is given as

$$\mathrm{M}_{IAI,n_r,n_t}(k)=(1-\eta)\sum_{\substack{n_t'=0\\ \neq n_t}}^{N_t-1} H_{n_r,n_t'}(k)S_{n_t'}(k). \tag{9}$$

The residual ICI is defined as the deviation of the equivalent channel gain after FDE from the average equivalent channel gain [13]. The ICI component which is subtracted from the received signal is given as

$$\mathrm{M}_{ICI,n_r,n_t}(k)=(1-\rho)\cdot\left(w_{n_r,n_t}(k)H_{n_r,n_t}(k)-\frac{A_{n_t}}{N_r}\right)S_{n_t}(k), \tag{10}$$

where $w_{n_r,n_t}(k)$ is the FDE weight for the n_r-th receive antenna (which will be given by (17)) and A_{n_t} is the equivalent channel gain, given by

$$A_{n_t}=\frac{1}{SF}\sum_{n_r=0}^{N_r-1}\sum_{k=nSF}^{(n+1)SF-1} w_{n_r,n_t}(k)H_{n_r,n_t}(k). \tag{11}$$

After IAI cancellation, FDE, ICI cancellation, and diversity combining, the received *k*-th subcarrier component of the signal transmitted from the n_t-th transmit antenna can be expressed as

$$\widetilde{R}_{n_t}(k)=\sum_{n_r=0}^{N_r-1}\left(w_{n_r,n_t}(k)\left(R_{n_r}(k)-\mathrm{M}_{IAI,n_r,n_t}(k)\right)-\mathrm{M}_{ICI,n_r,n_t}(k)\right). \tag{12}$$

By substituting (7), (9), and (10) and introducing the imperfect cancellation factors, η and ρ, (12) can be rewritten

$$\begin{aligned}&\widetilde{R}_{n_t}(k)\\&=A_{n_t}S_{n_t}(k)+\sum_{n_r=0}^{N_r-1}\left(\begin{aligned}&\rho\cdot\left(w_{n_r,n_t}(k)H_{n_r,n_t}(k)-A_{n_t}/N_r\right)S_{n_t}(k)\\&+\eta\cdot w_{n_r,n_t}(k)\sum_{\substack{n_t'=0\\ \neq n_t}}^{N_t-1}H_{n_r,n_t'}(k)S_{n_t'}(k)\\&+w_{n_r,n_t}(k)\Pi_{n_r}(k)\end{aligned}\right).\end{aligned} \tag{13}$$

The decision variable can be obtained through frequency domain despreading as

$$d_{n_t,u}(n)=\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\widetilde{R}_{n_t}(k)c_u^*(k), \tag{14}$$

From (13) and (14), we have

$$d_{n_t,u}(n)=\sqrt{2P}A_{n_t}d_{n_t,u}(n)+\mu_{ICI}+\mu_{IAI}+\mu_{noise}, \tag{15}$$

where the 1st term is the desired signal component (the *u*-th data symbol stream transmitted from the n_t-th antenna is to be detected), the 2nd term is the residual ICI, the 3rd term is the residual IAI, and the 4th term is the noise. They are given by

$$\begin{cases}\mu_{ICI}\\=\rho\displaystyle\sum_{\substack{u'=0\\ \neq u}}^{U-1}\left(d_{n_t,u'}(n)\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\left(\begin{aligned}&\left(\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}(k)H_{n_r,n_t}(k)-A_{n_t}\right)\\&\times c_{u'}(k)c_u^*(k)\end{aligned}\right)\right)\\ \mu_{IAI}\\=\eta\displaystyle\sum_{\substack{n_t'=0\\ \neq n_t}}^{N_t-1}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}S_{n_t'}(k)\left(\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}(k)H_{n_r,n_t'}(k)\right)\cdot c_u^*(k)\right)\\ \mu_{noise}=\dfrac{1}{SF}\displaystyle\sum_{k=nSF}^{(n+1)SF-1}\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}(k)\Pi_{n_r}(k)c_c^*(k)\end{cases}. \tag{16}$$

The MMSE equalization weight taking into account the residual ICI and IAI can be derived as

$$\begin{aligned}\mathbf{w}_{n_t}(k)&=\left(w_{0,n_t}(k)\ \cdots\ w_{n_r,n_t}(k)\ \cdots\ w_{N_r-1,n_t}(k)\right)\\&=\mathbf{H}_{n_t}^H(k)\left(\mathbf{H}(k)\mathbf{G}_{n_t}(k)\mathbf{H}^H(k)+\left(\frac{U}{SF}\cdot\frac{E_s}{N_t\cdot N_0}\right)^{-1}\mathbf{I}_{N_r}\right)^{-1}\end{aligned} \tag{17}$$

where $\mathbf{H}(k)$ is an $N_r\times N_t$ channel matrix, $\mathbf{H}_{n_t}(k)=(H_{0,n_t}(k)\ \cdots\ H_{N_r-1,n_t}(k))^T$ is the n_t-th column vector of $\mathbf{H}(k)$, and $\mathbf{G}_{n_t}(k)=diag(g_0\cdots g_{n_t'}\cdots g_{N_t-1})$ is an $N_t\times N_t$ diagonal matrix representing the residual ICI and IAI with

$$g_{n_t'}=\begin{cases}\rho^2 & n_t'=n_t\\ \eta^2 & n_t'\neq n_t\end{cases}. \tag{18}$$

IV. CONDITIONAL RECEIVED SINR

There are $\lfloor N_c/SF\rfloor$ parallel code channels per transmit antenna. The channel capacity of MC-CDMA MIMO taking into account the residual ICI and IAI can be given as

$$C=\frac{U}{N_c}\sum_{n_t=0}^{N_t-1}\sum_{n=0}^{\left\lfloor\frac{N_c}{SF}-1\right\rfloor}\log_2\left(1+\gamma_{n_t,n}\left\{\frac{E_s}{N_0},\mathbf{H}(k)\right\}\right), \tag{19}$$

where $\gamma_{n_t,n}\{E_s/N_0,\mathbf{H}(k)\}$ is the conditional received SINR associated with the *n*-th code channel of the n_t-th transmit antenna.

In this paper, the sum of residual ICI, residual IAI, and noise is treated as a new zero-mean complex-valued Gaussian variable with variance $2\sigma^2$, which is given as

$$2\sigma^2=2\sigma_{ICI}^2+2\sigma_{IAI}^2+2\sigma_{noise}^2, \tag{20}$$

where $2\sigma_{ICI}^2$, $2\sigma_{IAI}^2$, and $2\sigma_{noise}^2$ are the variances of residual ICI, residual ICI, and noise component, respectively, and are given as

$$\begin{cases}2\sigma_{ICI}^2=E\left[\left|\mu_{ICI}\right|^2\right]\\=\dfrac{\rho^2}{SF}\cdot\dfrac{2E_c\cdot(U-1)}{N_t\cdot SF\cdot T_c}\left(\begin{aligned}&\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\left|\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}(k)H_{n_r,n_t}(k)\right|^2\\&-\left|A_{n_t}\right|^2\end{aligned}\right)\\ 2\sigma_{IAI}=E\left[\left|\mu_{IAI}\right|^2\right]\\=\dfrac{\eta^2}{SF}\cdot\dfrac{2E_c\cdot U}{N_t\cdot SF\cdot T_c}\displaystyle\sum_{\substack{n_t'=0\\ \neq n_t}}^{N_t-1}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\left|\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}(k)H_{n_r,n_t'}(k)\right|^2\right)\\ 2\sigma_{noise}^2=E\left[\left|\mu_{noise}\right|^2\right]\\=\dfrac{1}{SF}\cdot\dfrac{2N_0}{N_c\cdot T_c}\left(\dfrac{1}{SF}\displaystyle\sum_{k=nSF}^{(n+1)SF-1}\sum_{n_r=0}^{N_r-1}\left|w_{n_r,n_t}(k)\right|^2\right)\end{cases}. \tag{21}$$

Table 1: Numerical condition

Parameters		value
Number of transmit antennas		N_t=1~4
Number of receive antennas		N_r=4
Number of sub-carriers		N_c=256
Spreading factor		SF=256
Code multiplexing		U=SF
Channel model	Fading	Block Rayleigh fading
	Number of multipath	L=16-path
	Decay factor	γ=0dB
	Delay	l FFT samples

From (15), (20), and (21), the conditional received SINR becomes

$$\gamma_{n_t,n}\left(\frac{E_s}{N_0},\{\mathbf{H}(k)\}\right) = \frac{\frac{1}{N_t}\left(\frac{E_s}{N_0}\right)\left|\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}H_{n_r,n_t}(k)\right|^2}{\left(\begin{array}{l}\frac{\eta^2}{SF}\cdot\frac{U}{N_t}\left(\frac{E_s}{N_0}\right)\sum_{\substack{n_t'=0\\ \neq n_t}}^{N_t-1}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\left|\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}(k)H_{n_r,n_t'}(k)\right|^2\right)\\ +\frac{\rho^2}{SF}\cdot\frac{(U-1)}{N_t}\left(\frac{E_s}{N_0}\right)\cdot\left(\begin{array}{l}\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\left|\sum_{n_r=0}^{N_r-1}w_{n_r,n_t}H_{n_r,n_t}(k)\right|^2\\ -\left|A_{n_t}\right|^2\end{array}\right)\\ +\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\sum_{n_r=0}^{N_r-1}\left|w_{n_r,n_t}(k)\right|^2\end{array}\right)}. \quad (22)$$

By substituting (22) into (19), the capacity of MC-CDMA MIMO with MMSED and ICI/IAI cancellation can be computed. On the other hand, the channel capacity of OFDM MIMO is given as [14]

$$C_{OFDM}=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\log_2\det\left(\mathbf{I}_{N_r}+\frac{1}{N_t}\cdot\frac{E_s}{N_0}\mathbf{H}(k)\mathbf{H}^H(k)\right). \quad (23)$$

V. SIMULATION RESULTS

The impacts of residual ICI and residual IAI on the capacity of MC-CDMA are numerically evaluated. The numerical condition is summarized in Table 1. The number of sub-carriers is set to N_c=256 and spreading factor of SF=256 is used. Full code multiplexing is assumed, i.e., U=SF. The channel of transmit/receive antenna pair is assumed to be an independent block Rayleigh fading channel with an L=16-path uniform power delay profile. The l-th path time delay is assumed to be l FFT samples. The number of transmit antennas, N_t, is varied from 1 to 4 while the number of receive antenna, N_r, is set to 4.

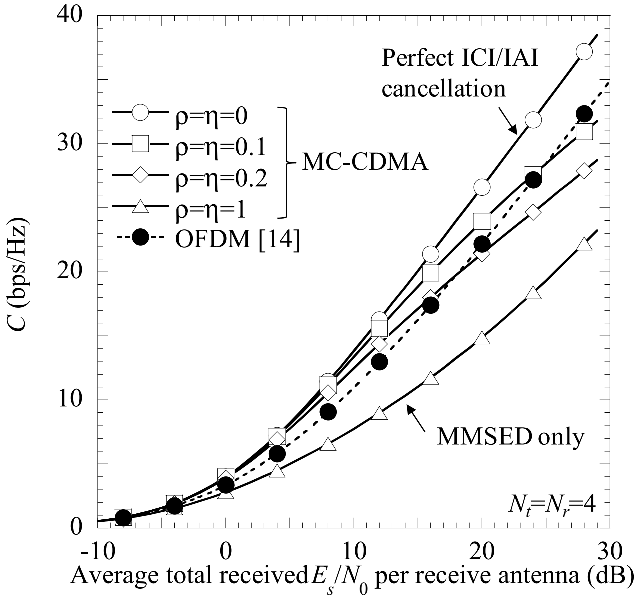


Figure 3: Channel capacities of MC-CDMA and OFDM.

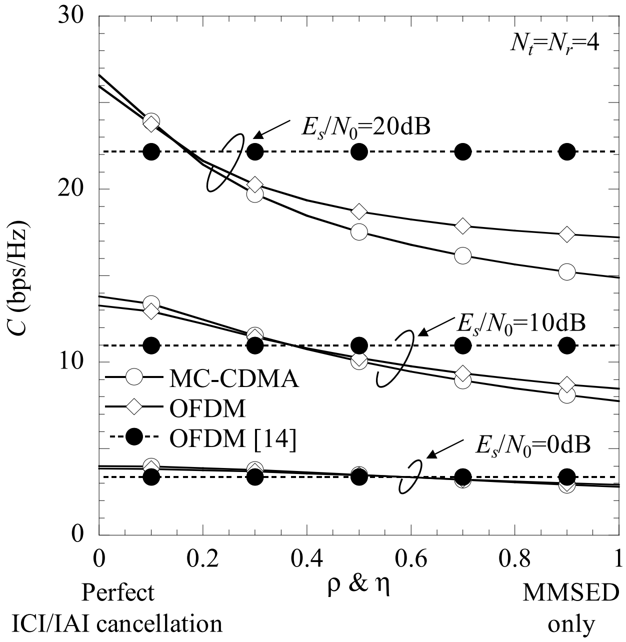


Figure 4: Impact of residual ICI/IAI on the channel capacity of MC-CDMA

A. Channel Capacities of MC-CDMA and OFDM

The capacity of MC-CDMA MIMO and that of OFDM MIMO [14] are plotted in Fig. 3 as a function of the average received E_s/N_0 per receive antenna (the GI insertion loss is not taken into account in E_s/N_0). It can be seen from the figure that the capacity of MC-CDMA MIMO increases as ρ and η reduce. MC-CDMA MIMO without interference cancellation (ρ=η=0) provides always smaller capacity than OFDM MIMO because of the presence of residual ICI and IAI. However, MC-CDMA MIMO can provide the same or larger

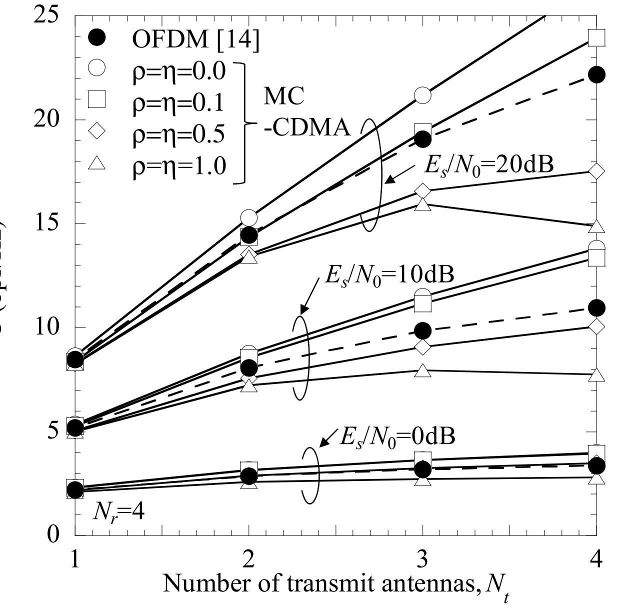


Figure 5: Effect of receive diversity.

capacity than OFDM MIMO when interference cancellation is used. Thus, we can say that the introduction of residual ICI/IAI cancellation is essential to increase the capacity of MC-CDMA MIMO.

B. Impact of Residual Interference

Fig. 4 shows how the imperfect interference cancellation impacts the achievable channel capacities of MC-CDMA MIMO and OFDM MIMO. Note that in the case of OFDM MIMO, no ICI is present (the channel capacity of OFDM MIMO is given by (19) and (22) with ρ=0) and only IAI cancellation is applied. Also plotted is the upper bound of OFDM MIMO given in [14]. It can be seen from the figure that the capacity of MC-CDMA MIMO is smaller than that of OFDM MIMO owing to the presence of the residual ICI. However, as the residual interference gets smaller (i.e., ρ and η reduce), the capacity difference between MC-CDMA and OFDM reduces. To achieve the capacity same as or larger than that of OFDM MIMO at E_s/N_0=20dB, the residual ICI and IAI need to be reduced to about 0.1.

C. Impact of Number of Transmit Antennas

It has been shown that since the variation of the equivalent channel seen after FDE and antenna diversity combining becomes narrower (i.e., the channel approaches the frequency-nonselective channel), the residual ICI reduces [15]. The channel capacity of MC-CDMA MIMO is plotted in Fig. 5 as a function of the number of transmit antennas, N_t, for N_r=4. It can be seen from the figure that when N_t is smaller than N_r, the capacity difference between MC-CDMA MIMO and OFDM MIMO is very small because the frequency selectivity of the channel becomes relatively weak owing to the receive antenna diversity. However, as N_t increases and approaches to N_r, the capacity difference between MC-CDMA MIMO and OFDM MIMO gets larger owing to the increasing residual IAI. Thus, the introduction of ICI/IAI cancellation is essential for MC-CDMA MIMO to achieve almost the same capacity as OFDM MIMO.

VI. CONCLUSION

In this paper, we derived the channel capacity expression of MC-CDMA with imperfect ICI/IAI cancellation by introducing the imperfect cancellation factors representing the degrees of residual ICI and IAI. We numerically evaluated the impact of residual ICI/IAI on the achievable channel capacity of MC-CDMA. We showed that MC-CDMA can provide almost the same channel capacity as OFDM if residual ICI/IAI can be suppressed to about 20%. Also we showed that when the receive antenna diversity is used, MC-CDMA can provide almost the same capacity as OFDM even without ICI/IAI cancellation. However, as the number of transmit antennas increases, the ICI/IAI cancellation should be introduced in MC-CDMA MIMO.

REFERENCES

[1] Y. Kim, B. J. Jeong, J. Chung, C. Hwang, J. S. Ryu, K. Kim, and Y. K. Kim, "Beyond 3G: vision, requirements, and enabling technologies," *IEEE Commun. Mag.*, vol.41, pp.120-124, Mar. 2003.

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

[3] G. Stüber, J. Barry, S. Mclaughlin, Y. Li, M. Ingram, and T. Pratt, "Broadband MIMO-OFDM wireless communications," *Proc. the IEEE*, vol.92, no.2, pp.271-294, Feb. 2004.

[4] M. Juntti, M. Vehkapera, J. Leinonen, V. Zexian, D. Tujkovic, S. Tsumura, and S. Hara, "MIMO MC-CDMA communications for future cellular systems," *IEEE Commun. Mag.*, vol.43, no.2, pp.118-124, Feb. 2005.

[5] A. van Zelst, R. van Nee, and G. A. Awater, "Space division multiplexing (SDM) for OFDM systems," *Proc. The 51st IEEE Vehicular Technology Conference (VTC2000)-spring*, pp.1070-1074, May 2000.

[6] J. G. Proakis, Digital Communications, 4th edition, McGraw-Hill, 2001.

[7] K. J. Kim, J. Yue, R. A. Iltis, and J. D. Gibson, "A QRD-M/Kalman filter-based detection and channel estimation algorithm for MIMO-OFDM systems," *IEEE Trans. Wirel. Commun.*, vol.4, no.2, pp.710-721, Mar. 2005.

[8] R. Dinis, R. Kalbasi, D. Falconer, and A. H. Banihashemi, "Iterative layered space-time receivers for single-carrier transmission over severe time-dispersive channels," *IEEE Commun. Lett.*, vol.8, no.9, pp.579-581, Sept. 2004.

[9] A. Nakajima, D. Garg, and F. Adachi, "Frequency-domain iterative parallel interference cancellation for multicode spread-spectrum MIMO multiplexing," *IEICE Trans. Commun.*, vol.E91-B, no.5, pp.1531-1539, May 2008.

[10] Y. Yuan-Wu and Y. Li, "Iterative and diversity techniques for uplink MC-CDMA mobile systems with full load," *IEEE Trans. Vehicul. Tech.*, vol.57, no.2, pp.1040-1048, Mar. 2008.

[11] K. Adachi, F. Adachi, and M. Nakagawa, "Approximate channel capacity of MC-CDMA MIMO," *Proc. The 11th International Symposium on Wireless Personal Multimedia Communications (WPMC'08)*, Sept. 2008.

[12] K. Adachi, F. Adachi, and M. Nakagawa, "A study on channel capacities of MC-CDMA MIMO and OFDM MIMO," *Proc. 11th IEEE International Conference on Communications Systems (ICCS 2008)*, Nov. 2008.

[13] 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.

[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, pp.225-234, Feb. 2002.

[15] T. Inoue, S. Takaoka, and F. Adachi, "Frequency-domain equalization for MC-CDMA downlink site diversity and performance evaluation," *IEICE Trans. Commun.*, vol.E88-B, no. 1, pp. 84-92, Jan. 2005.