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Statistical Characteristics of MIMO-OFDM Transmission Systems in a Multipath Environment Where the Delay Spreading Exceeds the Guard Interval

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SUMMARY

Orthogonal frequency division multiplex (OFDM) modulation systems can completely prevent intersymbol interference due to multipath propagation by providing a guard interval which is longer than the maximum delay hereafter we call "delay spreading." In an environment in which the delay spreading exceeds the guard interval, on the other hand, intersymbol interference occurs. This study considers a MIMO-OFDM system in which a MIMO configuration with high diversity gain is introduced into the OFDM modulation scheme, and discusses the transmission characteristics of maximal ratio combining transmission (single-stream transmission). It is shown that the MIMO-OFDM system is less affected by intersymbol interference due to the delay, even if the delay spread exceeds the guard interval, and that good performance is achieved. It is also shown that the channel response which is required in real-time control can be estimated with sufficient accuracy. © 2005 Wiley Periodicals, Inc. Electron Comm Jpn Pt 1, 88(12): 29–39, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ecja.20209

Key words: MIMO; OFDM; intersymbol interference; multipath fading; guard interval.

1. Introduction

The orthogonal frequency division multiplex (OFDM) modulation system is a multicarrier modulation system in which communication is performed by using multiple carriers. In a multipath environment, intersymbol interference (ISI) can be completely prevented by a guard interval (GI) introducing a cyclic prefix (CP) longer than the maximum delay of multipath waves. But in a propagation environment with a delay spreading (hereafter we use this term in place of the maximum delay) exceeding the GI length, a signal exceeding the GI length will also contain adjacent symbol information after OFDM demodulation, which will degrade communications quality due to intersymbol interference [1, 2]. If a guard interval that is sufficiently long compared to the delay spread is provided, immunity to delay spreading will be assured. When the GI length is increased, on the other hand, the problem arises that information transmission efficiency is degraded.

Consequently, this paper considers MIMO-OFDM, in which a MIMO (multi-input multi-output) configuration with diversity effect is introduced into the OFDM modulation system [3–6]. Computer simulations are used to investigate how immune the system is to intersymbol interference when maximal ratio combining transmission, which is a single-stream transmission, is used in a multipath environment in which the delay spreading exceeds the GI length.

In order to determine the transmission and reception weights in a MIMO system, the channel response characteristics must be determined; that is, the channel response must be estimated with a high accuracy. The estimation procedure for the channel response in a MIMO-OFDM system is discussed in the second half of this paper. It is then shown that the channel response can be estimated with sufficient accuracy even in a multipath environment in which the delay spreading exceeds the GI length.

2. Representation of a MIMO Multipath Channel

In an indoor or urban environment, a mobile communications channel is a multipath channel in which signals propagate over multiple paths. Consider a transmission and reception array system (MIMO) with M transmitting elements and N receiving elements (Fig. 1).

For the path connecting element m of the transmitting antenna with element n of the receiving antenna in a multipath propagation environment, the impulse response $h_{nm}(\tau)$ and the frequency transfer function $a_{nm}(f)$ are

$$h_{nm}(\tau) = \sum_{i=1}^{\infty} a_{nm}^{(i)} \delta\left(\tau - \tau_{nm}^{(i)}\right) \tag{1}$$

$$a_{nm}(f) = \sum_{i=1}^{\infty} a_{nm}^{(i)} \exp\left(-j2\pi f \tau_{nm}^{(i)}\right) \tag{2}$$

Here δ is the delta function, and $a_{nm}^{(i)}$ and $\tau_{nm}^{(i)}$ are the complex amplitude and the delay time of the multipath channel i. The number of paths is set as infinity (∞), but the actual number is finite.

Using the above expression, the channel based on the MIMO channel transfer function is represented as follows:

$$\boldsymbol{A}(f) = \begin{pmatrix} a_{11}(f) & a_{12}(f) & \cdots & a_{1M}(f) \\ a_{21}(f) & a_{22}(f) & \cdots & a_{2M}(f) \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1}(f) & a_{N2}(f) & \cdots & a_{NM}(f) \end{pmatrix} \tag{3}$$

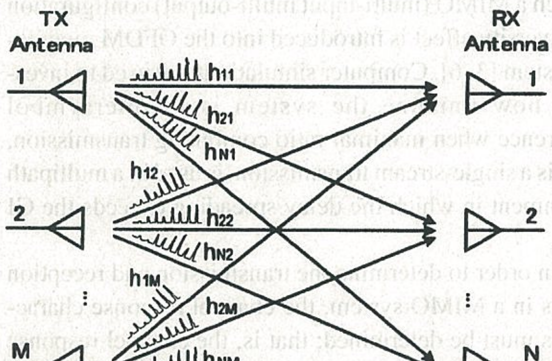


Fig. 1. Wideband multipath transmission channel of MIMO system.

The delay profile, which is the power average of the impulse response, is used in the statistical representation of the propagation environment. The delay profile $p(\tau)$ is expressed by the following exponential function in most of the indoor and mobile propagation environments:

$$p(\tau) = \frac{P_R}{\sigma_\tau} \exp\left(-\frac{\tau}{\sigma_\tau}\right) \tag{4}$$

Here σ_τ is the delay spread and P_R is the average power of the multipath wave.

When the number of paths is sufficiently large and the delay spread σ_τ is fairly large compared to the symbol length T_0 ($T_0 = T_s/K$, T_s is the effective symbol length, and K is the number of subchannels of OFDM), the profile can be approximated as follows, with discretization for each delay interval T_0:

$$p(\tau) = P_0 \sum_{i=0}^{L-1} \exp\left(-\frac{iT_0}{\sigma_\tau}\right) \delta(\tau - iT_0) \tag{5}$$

Here, the number of waves discretized with an interval T_0 is denoted as L and is called the multipath number. P_0 is a parameter used to adjust the total power to P_R. The amplitude of each discretized delayed multipath wave i follows an independent Rayleigh distribution. Figure 2 is an example of the impulse response of the channel.

In an indoor environment, the path direction spreads sufficiently around the transmitting and receiving stations. Thus, it is assumed in the discussion that a_{nm} is uncorrelated for paths with any n and m. In the above multipath environment, the above assumption is valid when the antenna distance is larger than a half-wavelength [7].

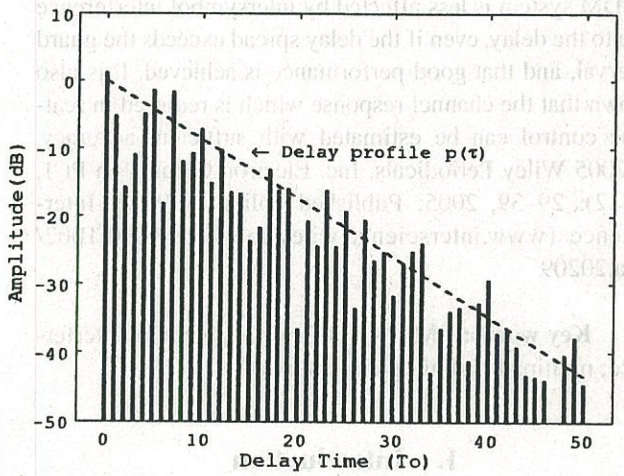


Fig. 2. Example of impulse response in the environment with exponential delay profile ($\sigma_\tau = 5T_0$).

3. Optimal Weight in Maximal Ratio Combining

3.1. Maximal ratio combining

When the channel characteristics are known (e.g., if it is measured by some means, such as a training sequence), the transfer function matrix A can be determined as in Eq. (3). Then the optimal weight that maximizes the SNR (signal-to-noise ratio) of the received signal is determined as follows [7].

Let the transmitted signal be $s(t)$. Then the average power of the transmitting signal before weighting in the transmitter is expressed by

$$P_s = \langle s^*(t)\, s(t) \rangle \tag{6}$$

The noise and the average noise power are given, respectively, by

$$\boldsymbol{n}(t) = [n_1(t), n_2(t), \ldots, n_N(t)]^T \tag{7}$$

$$P_{noise} = \langle n_n^*(t)\, n_n(t) \rangle \qquad (n = 1, 2, .., N) \tag{8}$$

Let the weight vectors of the transmitting and receiving antennas be

$$\boldsymbol{w_t} = [w_{t1}, w_{t2}, \ldots, w_{tM}]^T \tag{9}$$

$$\boldsymbol{w_r} = [w_{r1}, w_{r2}, \ldots, w_{rN}]^T \tag{10}$$

Then the received signal $y(t)$ and the average received power P_r are represented, respectively, as follows:

$$\boldsymbol{y(t)} = \boldsymbol{w_r^H}(\boldsymbol{A w_t} s(t) + \boldsymbol{n}(t)) \tag{11}$$

$$P_r \equiv \left\langle |\boldsymbol{y}(t)|^2 \right\rangle = \left|\boldsymbol{w_r^T A w_t}\right|^2 P_s + \boldsymbol{w_r^H w_r} P_{noise} \tag{12}$$

The condition is imposed that the total transmitted power P_s sent from the transmitting antenna remains constant, regardless of the transmitting weight. The condition is likewise imposed that the noise power P_{noise} in the received signal from the receiving antenna remains constant, regardless of the receiving weight. For this purpose, the weights are normalized as follows:

$$\|\boldsymbol{w_t}\| = \sqrt{\boldsymbol{w_t^H w_t}} = 1 \tag{13}$$

$$\|\boldsymbol{w_r}\| = \sqrt{\boldsymbol{w_r^H w_r}} = 1 \tag{14}$$

Then, the received power is obtained from the above expression as

$$P_r = \lambda P_s + P_{noise} \tag{15}$$

where

$$\lambda = \left|\boldsymbol{w_r^H A w_t}\right|^2 = \boldsymbol{w_r^H A w_t w_t^H A^H w_r} \tag{16}$$

Since the transmitted power P_s and the noise power P_{noise} remain constant, the received power P_r, that is, λ, should be maximized in order to maximize the SNR. The transmitting weight $\boldsymbol{w}_t$ and the receiving weight $\boldsymbol{w}_r$ that maximize the above λ are expressed, respectively, as follows:

$$\boldsymbol{w_t} = \boldsymbol{e_{t,max}} \tag{17}$$

$$\boldsymbol{w_r} = \boldsymbol{e_{r,max}} \tag{18}$$

Here $\boldsymbol{e}_{t,max}$ is the eigenvector corresponding to the maximum eigenvalue of matrix $A^H A$, and $\boldsymbol{e}_{r,max}$ is the eigenvector corresponding to the maximum eigenvalue of matrix AA^H. Thus, the weights of the transmitter and receiver are determined only from the channel response matrix A.

3.2. Weights in MIMO-OFDM

The transmitting and receiving weights given by Eqs. (17) and (18) are weights which are matched to the signal-carrier transmission MIMO system. However, the MIMO-OFDM system is a multicarrier transmission system in which the transmitted signal is sent by multicarrier modulation, and the received signal is received by multicarrier demodulation. For this purpose, the transmitting and receiving weights must be derived for each carrier.

In the equivalent low-pass system, let the carrier frequency of the 0-th subchannel be $f_0 = 0$. Then the carrier frequency f_k of the k-th subchannel is given by

$$f_k = \frac{k}{T_s} \qquad (k = 0, 1, 2, \ldots, K-1) \tag{19}$$

At this frequency f_k, the channel transfer function $a_{nm}(k)$ from the m-th transmitting antenna to the n-th receiving antenna is

$$a_{nm}(k) = \sum_{i=0}^{L-1} a_{nm}^{(i)} \exp(-j2\pi f_k i T_0) \tag{20}$$

Using the above transfer function $a_{nm}(k)$, the transfer function $A(k)$ of the k-th subchannel of the whole MIMO system can be determined by Eq. (3).

In maximum ratio combining transmission, the transmitting weight $\boldsymbol{w}_{tk}$ and the receiving weight $\boldsymbol{w}_{rk}$ for each subchannel are expressed as

$$\boldsymbol{w_{tk}} = \boldsymbol{e_{t,max}}(k) \tag{21}$$

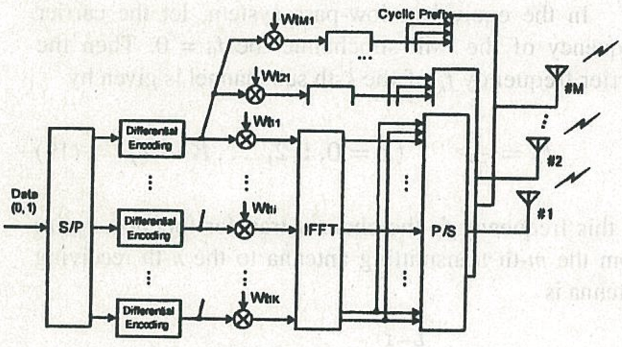
$$\boldsymbol{w_{rk}} = \boldsymbol{e_{r,max}}(k) \tag{22}$$

Here, $\boldsymbol{e}_{t,max}(k)$ is the eigenvector corresponding to the maximum eigenvalue of matrix $A^H(k)A(k)$, and $\boldsymbol{e}_{r,max}(k)$ is the eigenvector corresponding to the maximum eigenvalue of matrix $A(k)A^H(k)$. By using these transmitting and receiving weights, maximum ratio combining of the antenna output is realized.

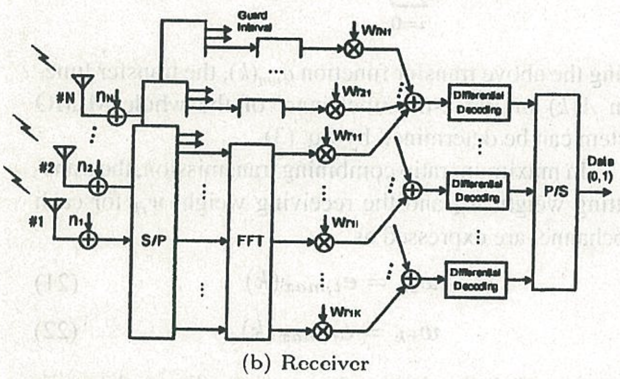
4. System Configuration

Figure 3 shows the transmitter and receiver configurations in the MIMO-OFDM system which is the object of performance analysis in this paper. The transmitter applies serial-parallel (S/P) conversion to the input data, dividing them into the data corresponding to each carrier. Then, differential coding PSK modulation is applied to the divided data sequence (DPSK is used in this study). The signal after the above primary modulation is used in common by the MIMO communication antenna elements. This shared signal is multiplied by the transmitting weights, and the inverse Fourier transform (IFFT) is applied to the resulting signal in order to perform OFDM modulation. In order to avoid intersymbol interference in the transmitted signal, a cyclic prefix is built in. After applying parallel-serial (P/S) conversion, the signals are sent from the antenna elements.

The receiver receives the signals arriving on the multipath channels by means of the receiving antenna elements.



(a) Transmitter



(b) Receiver

Fig. 3. MIMO-OFDM system.

Serial-parallel conversion is applied in each receiving antenna element, and the guard interval is removed. OFDM demodulation is performed by applying the Fourier transform (FFT). Then the received signal is obtained for each carrier. The received signals of the carriers are multiplied by the receiving weights and combined. The resulting signal is demodulated by delayed detection. Then, parallel-serial conversion is applied and the received data are obtained.

5. BER Floor Value in Multipath Environment with Delay Spread Exceeding the Guard Interval

In a multipath environment, if the delay spreading (the maximum delay τ_{delay}) stays within the GI length (τ_{GI}), intersymbol interference (ISI) due to the multipath can be avoided completely. Thus, the BER (bit error rate) depends only on thermal noise. Consequently, the BER can be reduced by increasing the value of E_b/N_0, resulting in the BER characteristics shown by the solid line in Fig. 4. However, when the delay spreading exceeds the GI length, waves exceeding the GI length produce ISI. Intercarrier interference (ICI) is also produced, which degrades the BER performance. In this case, the BER is not decreased by increasing E_b/N_0, resulting in a floor characteristic, as shown by the dashed line in Fig. 4.

In the case of Rayleigh fading, the floor value of the BER due to intersymbol interference is determined by the three parameters shown in Fig. 5 [8].

(1) τ_{GI}/σ_τ: the ratio of the guard interval length to the delay spread

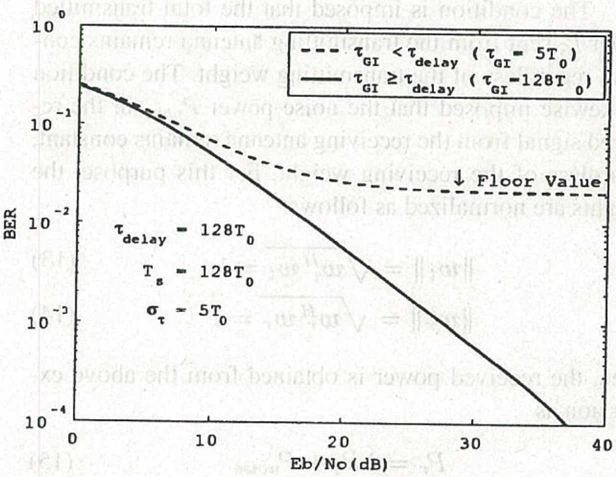


Fig. 4. Example of BER floor characteristic by ISI.

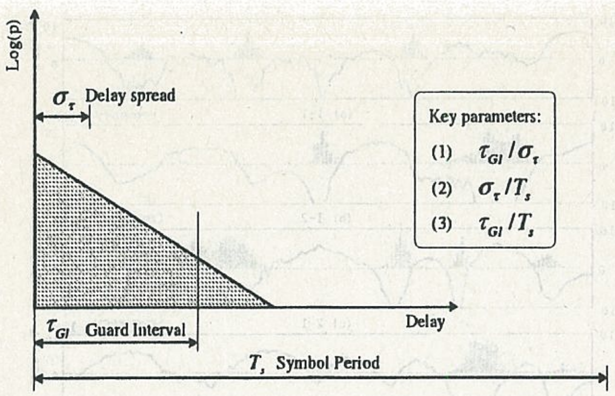


Fig. 5. Key parameters for errors due to ISI in OFDM.

(2) σ_τ/T_s: the ratio of the delay spread to the OFDM symbol length

(3) τ_{GI}/T_s: the ratio of the guard interval to the OFDM symbol length

In practice, the floor value is governed by two of the above three parameters.

Reference 8 considered a single-input single-output (SISO) multipath environment and analyzed the BER floor value due to intersymbol interference by using an equivalent channel model. This study investigates the BER floor characteristics due to intersymbol interference in a MIMO system, and uses a simulation to determine how much the floor value is reduced in MIMO.

6. Simulation for BER Floor Value Characteristics

Table 1 shows the simulation conditions. It is assumed that the channel characteristics are known. In order to investigate the statistical properties, the propagation environment is varied by using a random variable for each 100 symbol transmissions, constituting a session; 200 simulation sessions are performed.

Table 1. Simulation parameters

Number of OFDM symbols	20000 (= 100 × 200)
Number of subcarriers	128
Subcarrier modulation/demodulation	DQPSK
Delay spread	$5T_0$
Number of paths	128
Path amplitude	Independent Rayleigh distribution

6.1. BER floor value characteristics in OFDM with SISO configuration

The multipath propagation environment is a propagation environment with an exponential profile. In the propagation environment shown in Table 1, the number of paths is a constant value of 128. The system transmission characteristics are determined by varying the GI length τ_{GI} as 0, 5, 10, and $128T_0$, that is, as 0, 1, 2, and 25 times the delay spread σ_τ. When the GI length is sufficiently large ($128T_0$), the delay of each wave remains within the GI length, and there is no intersymbol interference.

Figure 6 shows the BER characteristics of the single-element receiving antenna for the single-element transmission antenna (SISO system). When the delay spread stays within the GI length ($\tau_{GI} = 128T_0$), there is no intersymbol interference, leaving only the effect of thermal noise. When τ_{GI} is decreased, intersymbol interference may be produced, depending on the ratio to σ_τ, and a floor value is produced in the BER characteristics. When the GI length is decreased, the floor value is increased, and the BER characteristics are remarkably degraded.

Figure 7 shows the BER floor characteristics as a function of τ_{GI}/σ_τ of OFDM with SISO configuration. The solid line and the dashed line are the characteristics calculated from the equivalent channel model in fading environments with continuous and discrete exponential delay profiles, respectively [8]. The curve with circles is the result obtained by simulation. The delay profile with the discrete

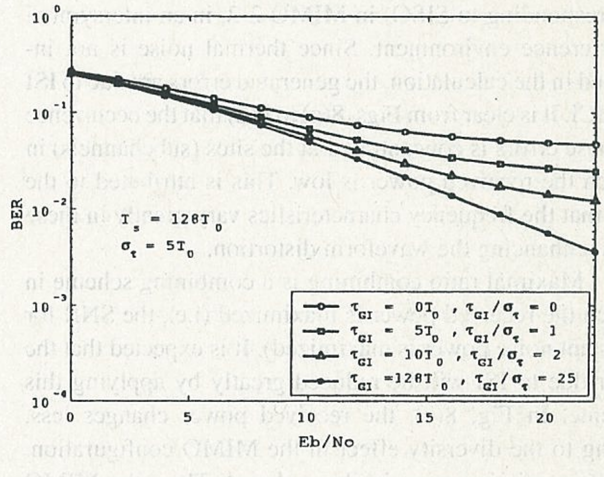


Fig. 6. BER characteristics of SISO.

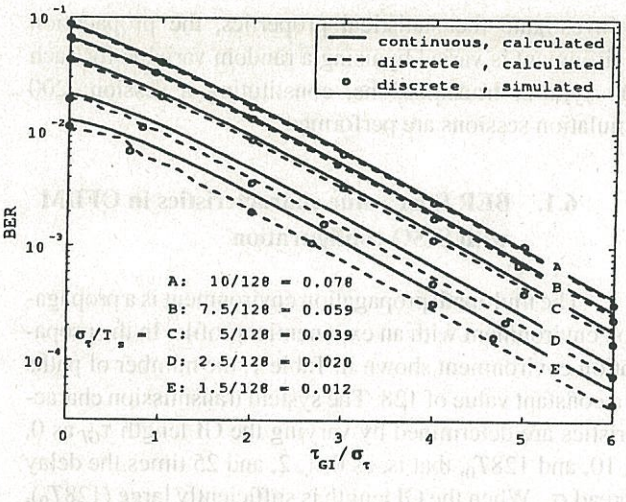


Fig. 7. BER floor value characteristics of SISO-OFDM system.

exponential function is used in the simulation. It can be seen that the simulation result agrees well with the calculation results for the discrete type.

The following observation is made from Fig. 7. In order to reduce the average BER to less than 10^{-3} in SISO transmission, even if the delay spread is approximately 4% of the symbol length (curve C), the GI length must be 4 times the delay spread, that is, 16% of the symbol length.

6.2. BER floor value characteristics in OFDM with MIMO configuration

Figures 8(a) to 8(d) are examples of the received power characteristics (power: solid line) and the error distribution characteristics (BER: bar graph) for the link connecting each transmitting antenna and receiving antenna (corresponding to SISO) in MIMO 2-2, in an intersymbol interference environment. Since thermal noise is not included in the calculation, the generated errors are due to ISI and ICI. It is clear from Figs. 8(a) to 8(d) that the occurrence of these errors is concentrated at the sites (subchannels) in which the received power is low. This is attributed to the fact that the frequency characteristics vary greatly in these sites, enhancing the waveform distortion.

Maximal ratio combining is a combining scheme in which the received power is maximized (i.e., the SNR for constant noise power is maximized). It is expected that the error due to ISI will be reduced greatly by applying this scheme. In Fig. 8(e), the received power changes less, owing to the diversity effect in the MIMO configuration. The transmission error is also reduced. Thus, the MIMO configuration is promising, since it is more robust to in-

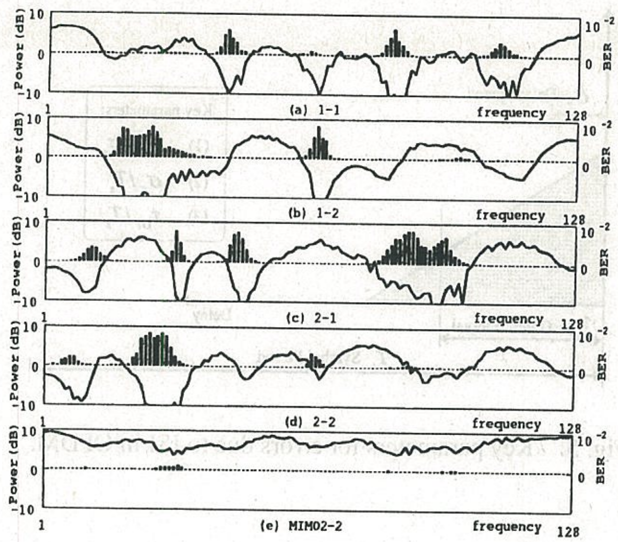


Fig. 8. Diversity effect of MIMO2-2 system.

tersymbol interference than the original SISO configuration.

Figure 9 shows the BER characteristics of the MIMO2-2 system. When the GI length is $128T_0$, the delay spread stays within the GI length due to the setting of (τ_{GI}/σ_τ) in Table 1. Consequently, there is no intersymbol interference and no floor occurs in the BER characteristics. On the other hand, when the GI length is 0, 1, or 2 times the delay spread, a floor is observed in the BER characteristics

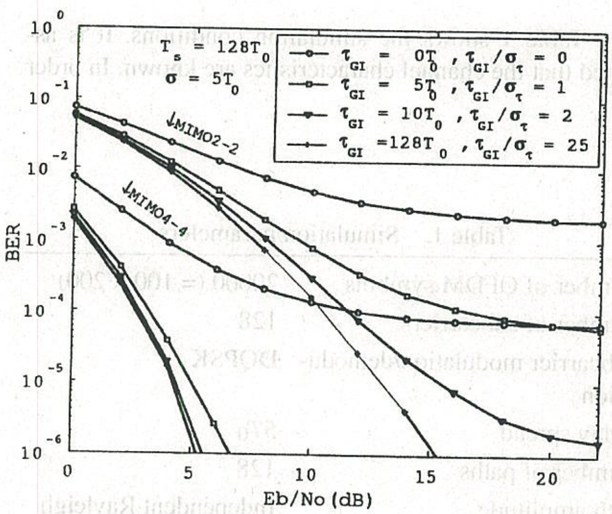


Fig. 9. MIMO2-2 and MIMO4-4 BER characteristics.

because of intersymbol interference. However, the floor value is smaller than that in the SISO1-1 characteristics.

It can be seen in the MIMO4-4 characteristics in Fig. 9 that the floor value is greatly improved compared to the MIMO2-2 characteristics. Thus, it is evident that even if the delay spreading exceeds the GI length, the maximum ratio combining transmission scheme of the MIMO system is effective in reducing the effect of intersymbol interference. The GI length can be set shorter, which improves the information transmission efficiency.

The floor value of MIMO2-2 is marked in Fig. 7 for comparison to the BER floor characteristics of SISO (Fig. 7), as shown in Fig. 10. It is evident from the figure that when the ratio τ_{GI}/σ_τ is increased, the BER is decreased, indicating that the effect of intersymbol interference is reduced. Compared to the SISO configuration, the BER floor value is lower in the MIMO2-2 configuration, and the characteristics depend strongly on τ_{GI}/σ_τ.

The BER characteristics of MIMO2-2 and SISO were compared for the case of $\sigma_\tau/T_s = 0.039$ (curve C), that is, for the case in which the delay spread σ_τ is approximately 4% of the symbol length T_s. In order to realize a BER of approximately 10^{-3}, it is required that $\tau_{GI}/\sigma_\tau = 0$, that is, the GI length is not needed in the MIMO2-2 configuration, while it must at least be approximately 3.5 times the delay spread, or 14% of the symbol length, in the SISO configuration. The latter represents a drastic degradation of transmission efficiency. Thus, the MIMO2-2 configuration is better than the SISO configuration in terms of transmission efficiency.

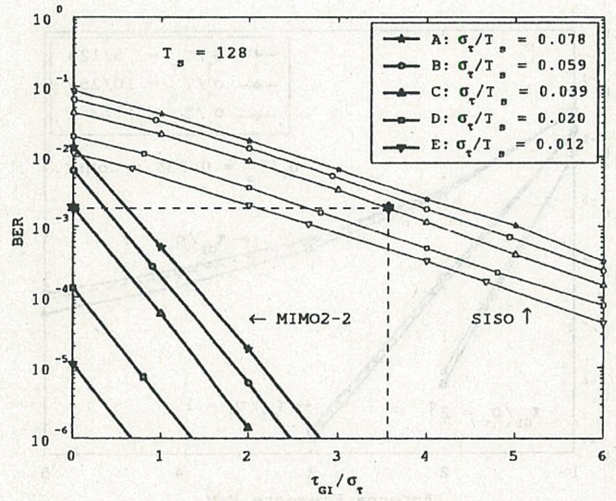


Fig. 10. BER floor value characteristics of MIMO2-2 system.

The number of transmitting antenna elements and the number of receiving antenna elements were varied as (1-1), (2-2), (3-3), (4-4), and (5-5), and the relation between the number of antenna elements and the BER floor value in MIMO system was investigated with τ_{GI}/σ_τ as the parameter. The propagation environment was set as follows. The conditions in Table 1 were kept unchanged. The number of paths was set as 128, and the delay spread was set as $\sigma_\tau = 5T_0$. The guard interval length was set as $\tau_{GI} = 0T_0, 5T_0$, and $10T_0$, that is, $\tau_{GI}/\sigma_\tau = 0$, 1, and 2.

Figure 11 shows the relation between the number of antenna elements and the BER floor value in the MIMO system. It is seen that a large floor value is produced in the SISO system ($M = N = 1$) when the guard interval is insufficient. In the MIMO system, on the other hand, the BER floor value is greatly improved with an increase in the number of antenna elements. In addition, the error due to intersymbol interference is greatly reduced with increasing τ_{GI}/σ_τ.

Next the delay spread σ_τ was varied as $10T_0$ and $15T_0$, and T_s was set as $256T_0$ and $384T_0$, respectively, so that the ratio σ_τ/T_s remained constant (= 5/128). As is evident from the figure, even if the delay spread σ_τ in the communications environment changes, the BER characteristics are maintained if the ratio σ_τ/T_s and the ratio τ_{GI}/σ_τ remain the same.

In the maximum ratio combining transmission (i.e., beamforming transmission) in OFDM, where a series of data is transmitted on subcarriers, as considered in this paper, the diversity effect is significant in BER evaluation, as is evident from Figs. 9 to 11. In the discussion of practical systems, however, comprehensive evaluation is needed, including the effects of error correction (FEC) and interleaving.

7. Estimation of Channel Response

7.1. Method of channel response estimation

In order to determine the transmitting weights and the receiving weights in maximal ratio combining, the channel response A in the transmission environment must be known. Up to this stage, the case of ideal channel estimation has been assumed. In a real situation, however, the channel characteristics must be estimated for an environment in which the delay spread exceeds the guard interval. Thus, it is necessary to ascertain whether the channel response can be well estimated. Various methods for channel response estimation have been proposed. In this study, estimation based on the least-square error [9] is used, since it uses a simple calculation and can be applied to OFDM. The method of channel response estimation is described below.

In OFDM, a channel transfer function is required for each subcarrier frequency. Consequently, the channel response matrix A should be treated as a function of the frequency (more precisely, the subcarrier number k). For subcarrier frequency k, let the signal transmitted from the m-th transmitting antenna ($m = 1, 2, \ldots, M$) be $s_m(t, k)$ and let the channel response be $a_m(k)$. Letting the noise be $n(t, k)$, the received signal $r(t, k)$ is

$$r(t,k) = \sum_{m=1}^{M} s_m(t,k)\, a_m(k) + n(t,k) \quad (23)$$

Let the estimate of $a_m(k)$ be $\hat{a}_m(k)$. $\hat{a}_m(k)$ is chosen so that the mean-square error of the error vector $\varepsilon(t, k)$ is minimized:

$$\varepsilon(t,k) = r(t,k) - \sum_{m=1}^{M} s_m(t,k)\, \hat{a}_m(k) \quad (24)$$

$$\begin{aligned} &\mathrm{E}\left[\varepsilon^H(t,k)\, \varepsilon(t,k)\right] \\ &= \mathrm{E}\left[r^H(t,k)\, r(t,k)\right] \\ &- \sum_{m=1}^{M} \mathrm{E}\left[s_m(t,k)\, r^H(t,k)\right] \hat{a}_m(k) \\ &+ \sum_{m=1}^{M} \sum_{m'=1}^{M} \mathrm{E}\left[s_m^*(t,k)\, s_{m'}(t,k)\right] \hat{a}_m^H(k)\, \hat{a}_{m'}(k) \\ &- \sum_{m=1}^{M} \mathrm{E}\left[s_m^*(t,k)\, r^T(t,k)\right] \hat{a}_m^*(k) \end{aligned} \quad (25)$$

Here, $\mathrm{E}[\cdot]$ is the ensemble mean, calculated as the time average over the training symbol period.

Forming the partial derivatives of both sides of Eq. (25) with respect to $\hat{a}_m$ ($m = 1, 2, \ldots, M$) and equating them to 0, the following equation is obtained:

$$\sum_{m=1}^{M} \hat{a}_m(k) \mathrm{E}\left[s_m(t,k)\, s_k^*(t,k)\right] = \mathrm{E}\left[r(t,k)\, s_k^*(t,k)\right] \quad (26)$$

where

$$s(t,k) = [s_1(t,k)\ s_2(t,k)\ \ldots\ s_M(t,k)]^T \quad (27)$$

$$r(t,k) = [r_1(t,k)\ r_2(t,k)\ \ldots\ r_N(t,k)]^T \quad (28)$$

$$\hat{a}_m(k) = [\hat{a}_{1m}(k)\ \hat{a}_{2m}(k)\ \ldots\ \hat{a}_{Nm}(k)]^T \quad (29)$$

Letting

$$\hat{A}(k) = [\hat{a}_1(k)\ \hat{a}_2(k)\ \ldots\ \hat{a}_M(k)] \quad (30)$$

$$R_{ss}(k) = \mathrm{E}\left[s(t,k)\, s^H(t,k)\right] \quad (31)$$

$$R_{rs}(k) = \mathrm{E}\left[r(t,k)\, s^H(t,k)\right] \quad (32)$$

Equation (26) is written as follows:

$$\hat{A}^T(k)\, R_{ss}(k) = R_{rs}(k) \quad (33)$$

$$\Rightarrow \quad \hat{A}(k) = \left[R_{rs}(k)\, R_{ss}^{-1}(k)\right]^T \quad (34)$$

Using this expression, $R_{ss}(k)$ and $R_{rs}(k)$ can be calculated from the transmitted signal $s(t, k)$ and the received signal $r(t, k)$ for the training symbol at subcarrier frequency k in OFDM, and the estimate $\hat{A}(k)$ of the channel response matrix $A(k)$ can be determined. The ensemble averages in Eqs. (31) and (32) are calculated as the time averages in the training symbol period.

7.2. Simulation for channel response estimation

Table 1 shows the simulation conditions. In order to derive the statistical properties, the propagation environment is varied for each 100 symbol transmissions, constituting a session, and 200 sessions are performed. By varying the parameters of the propagation environment, the channel response is estimated by using Eq. (34), based on 10 training symbols. Using the estimated channel response matrix, the transmitting weights and the receiving weights are calculated by using Eqs. (21) and (22), respectively, and the data transmission is performed by using the obtained weights.

The multipath propagation environment in the simulation is a propagation environment with an exponential function profile as shown in Fig. 2. The number of paths is set constant as 128. By varying the GI length τ_{GI} over

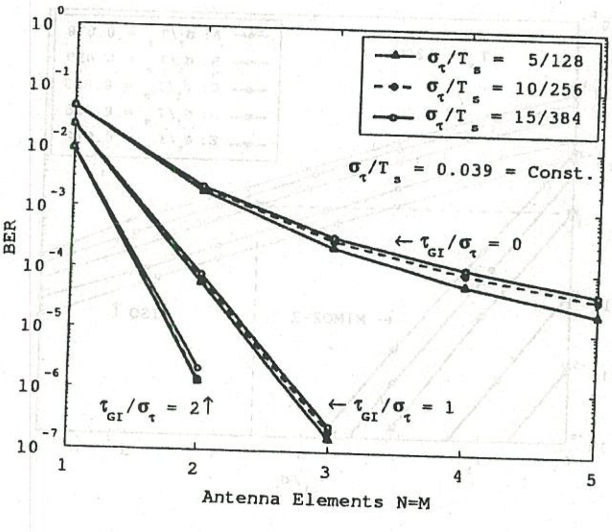


Fig. 11. BER floor value characteristics of MIMO-OFDM system.

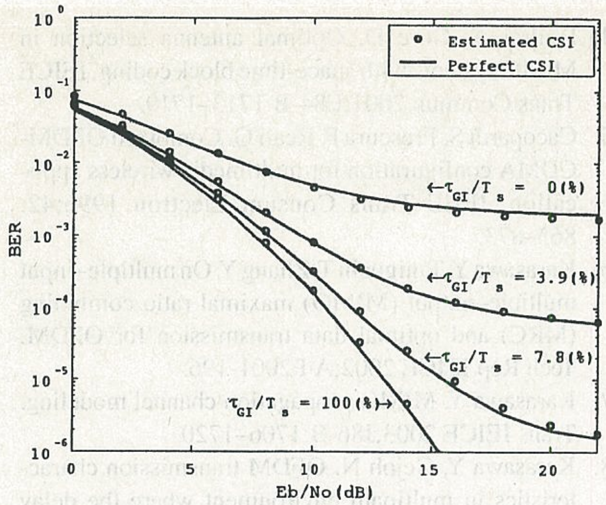


Fig. 12. BER characteristics of MIMO2-2 by channel estimation.

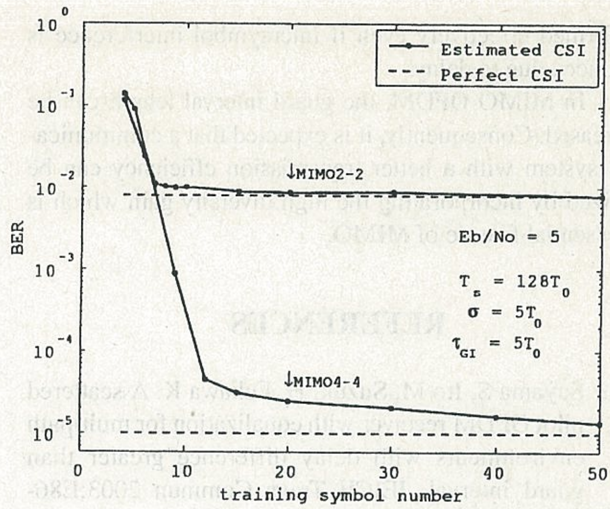


Fig. 13. BER characteristics for training symbol number of channel estimation.

values of 0, 5, 10, and $128T_0$, the transmission characteristics of the system are investigated. The transmission characteristics of MIMO2-2 are investigated in the simulation. Figure 12 shows the results. The points in the figure are the transmission characteristics based on channel estimation (estimated CSI), and the solid lines are the transmission characteristics for a completely known channel response (perfect CSI).

We see from the figure that the two characteristics agree rather well. Thus, good transmission characteristics can be obtained even if the delay spreading exceeds the guard interval. The reason seems to be as follows. The estimated weights ($\hat{w}_t$, $\hat{w}_r$) are the eigenvectors corresponding to the maximum eigenvalues of the correlation matrices, and are less affected by the interference wave (the average correlation coefficients $\langle|W_r\ \hat{W}_r^H|\rangle$ between the weight W_r derived from CSI for $\tau_{GI}/T_s = 3.9\%$ and the estimated weight $\hat{W}_r$ are 0.9729, 0.9744, 0.9945, 0.9960, and 0.9987 for $E_b/N_0 = 0, 5, 10, 15$, and 20, respectively). It is considered that the effect of the weight error on the characteristics degradation is smaller, even if it exists to some extent.

Figure 13 shows the BER characteristics in MIMO2-2 and MIMO4-4 channel estimation as functions of the number of training symbols. We see from the figure that the BER characteristics of MIMO2-2 approach the characteristics for the case in which the channel response is known, if the number of training symbols is at least 8. In MIMO4-4, the number of antenna elements is increased, which necessitates a larger number of training steps in order for the characteristics to converge. Generally, 2 to 3 times as many sample values as the number of transmitting antenna elements are needed in order to estimate the channel when determining the weights for the array antenna. For this reason, a larger number of samples, that is, training steps, are required in MIMO4-4 than in MIMO2-2.

It is evident from Fig. 13 that the channel response can be estimated with good accuracy in the MIMO4-4 system if 15 or more training symbols are used.

In a real radio wave propagation environment, there always exists a correlation between subcarriers. Since the weights differ less, the training signals of adjacent subchannels can be used in the determination. Thus, by utilizing the relations between subcarriers effectively, the number of samples can be increased by utilizing adjacent subchannels. The number of training symbols can be reduced accordingly.

8. Conclusions

This paper has considered OFDM with a MIMO configuration (MIMO-OFDM) in a multipath environment with the delay spreading exceeding the guard interval, and has investigated the maximal ratio combining transmission characteristics (single-stream transmission). It has been shown that even if the delay spreading exceeds the guard interval length in MIMO-OFDM, the effect of intersymbol interference due to delay is reduced by the diversity process. Thus, good transmission performance is realized without the use of special countermeasures such as an equalizer. It is also shown that the estimation of the channel characteristics, which is required in the real-time control, can be performed effectively even if intersymbol interference is produced due to delay.

In MIMO-OFDM, the guard interval length can be decreased. Consequently, it is expected that a communication system with a better transmission efficiency can be realized by incorporating the high diversity gain which is an essential feature of MIMO.

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