Electronics and Communications in Japan, Part 2, Vol. 90, No. 10, 2007
Translated from Denshi Joho Tsushin Gakkai Ronbunshi, Vol. J89-B, No. 9, September 2006, pp. 1746–1754

Multi-Keyhole Model for MIMO Repeater System Evaluation

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SUMMARY

Enhancement of service to closed spaces (independent spaces) via a repeater with several transmission lines is attracting attention as a means of expanding the service area of information transmission by MIMO. The propagation path in such environments becomes a multi-keyhole environment in the equivalent sense. The existence of a keyhole causes a reduction of communication capacity. However, in a multi-keyhole environment, the impact is reduced because multi-stream transmission becomes possible. In this paper, we propose a MIMO repeater system and a multi-keyhole model that realize repeater functions to a closed space while high-speed and high-reliability communication characteristic to MIMO are maintained. The eigenvalue distribution, average communication capacity, and average BER characteristics of the MIMO repeater channel are ascertained by computer simulations. The number of repeater antennas needed for relaying with the MIMO function maintained is determined. © 2007 Wiley Periodicals, Inc. Electron Comm Jpn Pt 2, 90(10): 40–48, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ecjb.20384

Key words: multi-keyhole; MIMO repeater system; eigenvalue; communication capacity; bit error rate.

1. Introduction

Research on MIMO (Multiple-Input Multiple-Output), intended for high-density information transmission in the presence of a finite frequency resource by using array antennas on both the transmission and reception sides, has been intensified [1–3]. Array realization of the terminals for wireless LAN has become realistic and thus research incentives for MIMO have been intensified. The number of papers published has increased dramatically.

The information transmission capability of MIMO is evaluated by the average communication capacity and average BER. However, the fundamental limit of the transmission capability of MIMO is expressed by the singular value of the channel response matrix or the eigenvalue of the correlation matrix [4].

In the future, due to expansion of the service area for information transmission by MIMO, enhanced service to closed spaces (or independent spaces) is expected. If the channels between the transmitter and the receiver are an independent and uncorrelated Rayleigh fading environment and if the relay to such a closed space is carried out with one relay antenna even though there are several transmitting and receiving antennas, such a channel is called a keyhole or a pinhole environment (this is called the keyhole environment below). In the channel in a keyhole environment, the multi-stream transmission characteristic of MIMO cannot be performed and hence high-speed, high-reliability communications can no longer be expected [5–7].

It is important to establish a model concept of the MIMO repeater system realizing the relay function to a closed space while maintaining the high-speed and high-reliability characteristic of MIMO and to study a system evaluation channel model [7]. This MIMO repeater system is a repeater with several transmission lines. For this reason, the channel environment becomes a multi-keyhole environment in the sense of equivalence.

In this paper, a multi-keyhole model is proposed. The channel eigenvalue distribution, average communication capacity, and the average BER are studied in a MIMO repeater system as an application of the multi-keyhole model. Also, the number of necessary repeater antennas K for repeating while MIMO function is maintained is determined.

2. MIMO Repeater System and Channel Model

2.1. MIMO repeater system

In order to deal with expansion of the service area with MIMO operation, let us consider the expansion of the MIMO function to a different closed space via a MIMO repeater system.

In this case, a relay to a closed space while maintaining the high-speed and high-reliability characteristic of MIMO is needed. Figure 1 shows a conceptual diagram of the MIMO repeater system. In order to provide service from the MIMO service space to a closed space while maintaining the high functionality of MIMO, a MIMO repeater system is needed in which the signals in the MIMO service space are received by several antennas and are then transmitted with several antennas toward the closed space (this is a multi-stream relay). The channel model of the system shown in Fig. 1 can be expressed in terms of the multi-keyhole model (Fig. 2), an expansion of the keyhole model.

Figure 3 presents the configuration of the MIMO repeater system. The MIMO repeater system in Fig. 3 retransmits the signals received by the MIMO repeater system from AP (Access Point) to the MS (Mobile Station) side. Then the signal processing of the MIMO repeater system performs only amplification of the signals received by K antennas and then retransmission takes place from K antennas. The AP in the MIMO service space and the MS in the closed space are connected via the MIMO repeater system. In this paper, it is assumed that the sections between the AP and the MIMO repeater system and between the MIMO repeater system and the MP are independent and are uncorrelated Rayleigh fading environments.

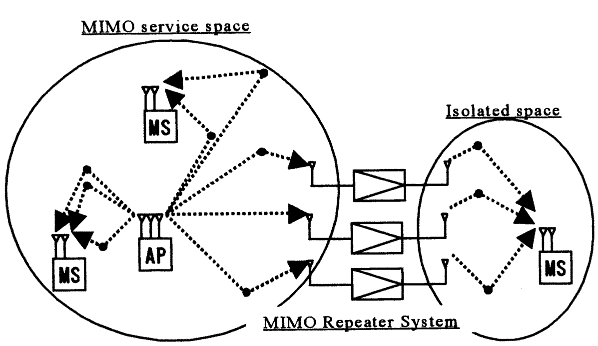


Fig. 1. Concept of MIMO repeater system.

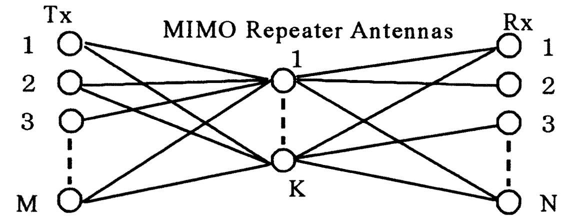


Fig. 2. MIMO channel model using MIMO repeater system.

2.2. Channel model

Let us consider a propagation channel for a MIMO repeater system consisting of M transmitting antennas, N receiving antennas, and K transmitting and receiving antennas (K keyholes) as shown in Fig. 3. The received signal $\boldsymbol{r}$ is

$$\boldsymbol{r} = \boldsymbol{H}_r \boldsymbol{G}(\boldsymbol{H}_t \boldsymbol{s} + \boldsymbol{n}_{rp}) + \boldsymbol{n}_{rv} \tag{1a}$$

Here the transmitted signal is $\boldsymbol{s}$, the thermal noise of the MIMO repeater system is $\boldsymbol{r}_{rp}$, the thermal noise of the receiver side is $\boldsymbol{n}_{rv}$, the channel response matrix between the AP and the MIMO repeater system is $\boldsymbol{H}_t$, the channel response matrix between the MIMO repeater system and the MS is $\boldsymbol{H}_r$, and the gain of the interior of the MIMO repeater system is $\boldsymbol{G}$. They are given by the following, where the superscript T denotes the transpose and *diag* denotes diagonal components:

$$\boldsymbol{r} \equiv [r_1, r_2, \cdots, r_N]^T \tag{1b}$$

$$\boldsymbol{s} \equiv [s_1, s_2, \cdots, s_M]^T \tag{1c}$$

$$\boldsymbol{H}_r \equiv \begin{bmatrix} h_{11}^r & h_{12}^r & \cdots & h_{1K}^r \\ h_{21}^r & h_{22}^r & \cdots & h_{2K}^r \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1}^r & h_{N2}^r & \cdots & h_{NK}^r \end{bmatrix} \tag{1d}$$

$$\boldsymbol{H}_t \equiv \begin{bmatrix} h_{11}^t & h_{12}^t & \cdots & h_{1M}^t \\ h_{21}^t & h_{22}^t & \cdots & h_{2M}^t \\ \vdots & \vdots & \ddots & \vdots \\ h_{K1}^t & h_{K2}^t & \cdots & h_{KM}^t \end{bmatrix} \tag{1e}$$

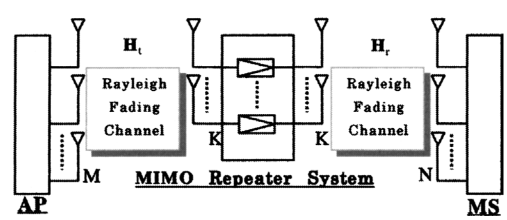


Fig. 3. Structure of MIMO repeater system.

$$\boldsymbol{n}_{rp} \equiv [n_1^{rp}, n_2^{rp}, \cdots, n_K^{rp}]^T \tag{1f}$$

$$\boldsymbol{n}_{rv} \equiv [n_1^{rv}, n_2^{rv}, \cdots, n_N^{rv}]^T \tag{1g}$$

$$\boldsymbol{G} \equiv diag[g_1, g_2, \cdots, g_K] \tag{1h}$$

In the initial stage of evaluation of the MIMO repeater system, it is assumed that the thermal noise $\boldsymbol{n}_{rp}$ inside the MIMO repeater system can be neglected. Then, the channel response matrix $\boldsymbol{H}_e'$ excluding the thermal noise $\boldsymbol{n}_{rv}$ on the receiver side is expressed as

$$\boldsymbol{H}_e' = \boldsymbol{H}_r \boldsymbol{G} \boldsymbol{H}_t \tag{2}$$

It is further assumed that the gain of each branch in the MIMO repeater system is constant and is normalized to the number of antennas K of the MIMO repeater system:

$$\boldsymbol{G} = \frac{1}{\sqrt{K}} \boldsymbol{I}_{K \times K} \tag{3}$$

Then the channel response matrix $\boldsymbol{H}_e$ between the transmitter and the receiver by way of the MIMO repeater system is

$$\boldsymbol{H}_e = \frac{1}{\sqrt{K}} \boldsymbol{H}_r \boldsymbol{H}_t \tag{4}$$

Channel response matrix (4) represents a multi-keyhole environment. In this paper, channel response matrix (4) will be discussed.

2.3. Distributions of the elements of channel response matrix

In a Rayleigh fading environment rich with independent and uncorrelated multiple paths without a need for repeater into a closed space, the amplitude distribution of the elements of the channel response matrix follows a Rayleigh distribution.

On the other hand, in an environment using a MIMO repeater system having one antenna ($K = 1$), the amplitude distribution of the elements of the channel response matrix follows a double Rayleigh distribution (a product of a Rayleigh distribution and a Rayleigh distribution) while the phase distribution follows a uniform distribution. This double Rayleigh distribution $p(r)$ can be expressed as follows [8]:

$$p(r) = \frac{r}{\sigma^4} K_0 \left(\frac{2r}{\sigma^2} \right) \tag{5}$$

where $K_0(\cdot)$ is the zeroth-order modified Bessel function of the second kind and σ^2 is the average power of the multipath component.

Figure 4 shows the numerical simulation values of the amplitude distributions of the elements in the channel response matrix when the number of antennas K in the MIMO repeater system is 1, 2, and 5 ($2 \times 1 \times 2$, $2 \times 2 \times 2$, $2 \times 5 \times 5$) and when there is no MIMO repeater system (2×2). Theoretical values are also presented in the cases of 2×2 and $2 \times 1 \times 2$. The theoretical values for 2×2 follow a Rayleigh distribution while those for $2 \times 1 \times 2$ follow a double Rayleigh distribution. The case in which there is no barrier for the electromagnetic wave between the closed space and the space with AP corresponds to the case without a MIMO repeater system (2×2). This can be considered as a metric for the performance of the MIMO repeater system. From the results in Fig. 4, it is found that distribution approaches the cumulative Rayleigh distribution, that is, the cumulative distribution of the amplitude of the channel in the case without a MIMO repeater system (2×2), as the number of antennas K in the MIMO repeater system is increased. As K is increased, the barrier to the electromagnetic wave in the closed space is effectively eliminated.

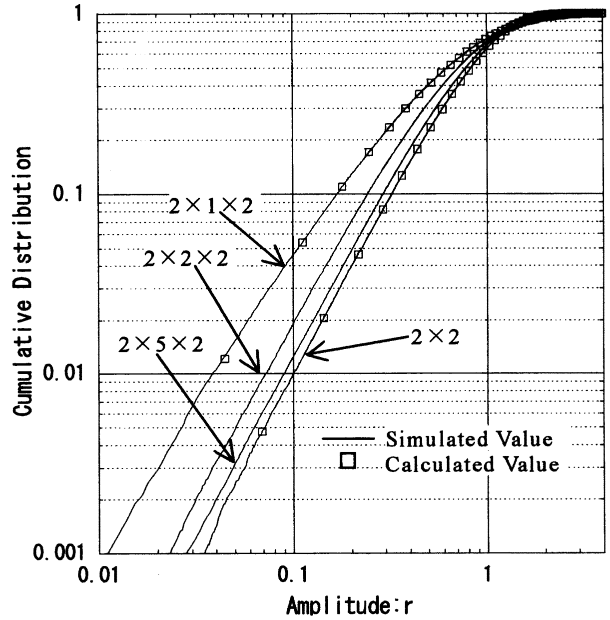


Fig. 4. Cumulative distribution of each element of channel response matrix.

3. Eigenvalue Distribution in Multi-keyhole Environment

3.1. Eigenvalue analysis

The channel response matrix $\boldsymbol{H}_e$ of a multi-keyhole environment can be expressed in the form of singular value decomposition (SVD) as follows:

$$\boldsymbol{H}_e = \boldsymbol{E}_r \boldsymbol{D} \boldsymbol{E}_t^H = \sum_{i=1}^{M_0} \sqrt{\lambda_i}\, \boldsymbol{e}_{r,i} \boldsymbol{e}_{t,i}^H \tag{6}$$

where

$$\boldsymbol{D} \equiv diag\left[\sqrt{\lambda_1}\ \ \sqrt{\lambda_2}\ \ \cdots\ \ \sqrt{\lambda_{M_0}}\right] \tag{7a}$$

$$\boldsymbol{E}_t \equiv \left[\boldsymbol{e}_{t,1}\ \ \boldsymbol{e}_{t,2}\ \ \cdots\ \ \boldsymbol{e}_{t,M_0}\right] \tag{7b}$$

$$\boldsymbol{E}_r \equiv \left[\boldsymbol{e}_{r,1}\ \ \boldsymbol{e}_{r,2}\ \ \cdots\ \ \boldsymbol{e}_{r,M_0}\right] \tag{7c}$$

$$M_0 \equiv \min(M, N, K) \tag{7d}$$

The superscript H denotes the complex conjugate transpose, λ_i is the i-th eigenvalue ($i = 1, 2, \ldots, M_0$ in descending order) of the correlation matrix $\boldsymbol{H}_e\boldsymbol{H}_e^H$ (or $\boldsymbol{H}_e^H\boldsymbol{H}_e$), $\boldsymbol{e}_{t,i}$ is the eigenvector belonging to the eigenvalue λ_i of $\boldsymbol{H}_e^H\boldsymbol{H}_e$, and $\boldsymbol{e}_{r,i}$ is the eigenvector belonging to the eigenvalue λ_i of $\boldsymbol{H}_e\boldsymbol{H}_e^H$.

3.2. Probability distribution of the eigenvalues

No analytical solution has been obtained for the probability distribution of each eigenvalue in a multi-keyhole environment. However, an analytical solution exists for the probability distribution of the eigenvalues if the number of antennas K in the MIMO repeater system is 1. In this case, channel response matrix (4) becomes

$$\begin{aligned}\boldsymbol{H}_e &= \boldsymbol{H}_r \boldsymbol{H}_t \\ &= \left[h_{11}^r\ h_{21}^r\ \cdots\ h_{N1}^r\right]^T \left[h_{11}^t\ h_{12}^t\ \cdots\ h_{1M}^t\right]\end{aligned} \tag{8}$$

The corresponding correlation matrix $\boldsymbol{R}$ is

$$\boldsymbol{R} = \boldsymbol{H}_e \boldsymbol{H}_e^H = \boldsymbol{H}_r \boldsymbol{H}_t \boldsymbol{H}_t^H \boldsymbol{H}_r^H \tag{9}$$

The rank of Eq. (9) is 1 and there exists only one eigenvalue. Therefore, the first eigenvalue λ_1 is given as

$$\lambda_1 = Trace[\boldsymbol{R}] = Trace(\boldsymbol{H}_r \boldsymbol{H}_r^H)(\boldsymbol{H}_t \boldsymbol{H}_t^H) \tag{10}$$

Since the corresponding $Trace(\boldsymbol{H}_r\boldsymbol{H}_r^H)$ follows the distribution of the sum of the exponential profiles, it follows the χ^2 distribution with $2M$ degrees of freedom $P_{2M}(u)$. Hence, the eigenvalue of the correlation matrix $\boldsymbol{R}$ is given by the product of $Trace(\boldsymbol{H}_r\boldsymbol{H}_r^H)$ (χ^2 distribution) and $\boldsymbol{H}_t\boldsymbol{H}_t^H$ (χ^2 distribution). The distribution $p(z)$ of the χ^2 distribution is

$$\begin{aligned}p(z) &= \int_0^\infty \frac{1}{u}\, p_{2N}(u)\, p_{2M}\left(\frac{z}{u}\right) du \\ &= \frac{2z^{\frac{N+M}{2}-1}}{\Gamma(N)\Gamma(M)} K_{M-N}(2\sqrt{z})\end{aligned} \tag{11}$$

Here, $\Gamma(\cdot)$ is the gamma function and $K_{M-N}(\cdot)$ is the M–N-th order modified Bessel function of the second kind. Equation (11) has been derived by an analysis of the probability density function of the Frobenius norm of the channel response matrix [9].

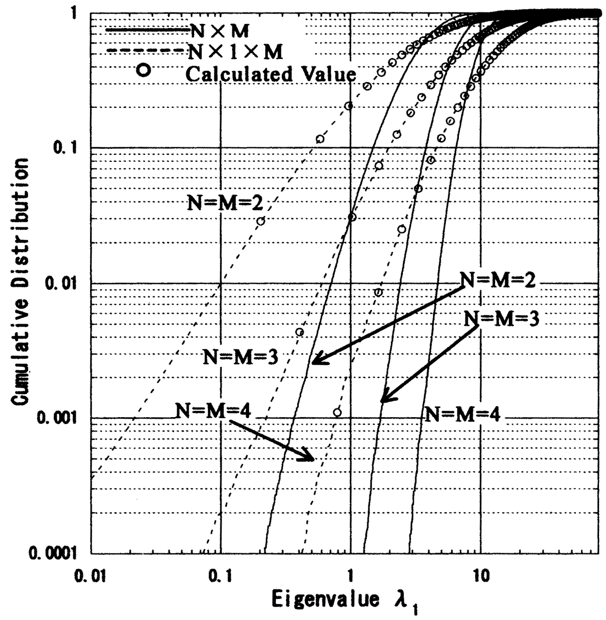


Fig. 5. Comparison of cumulative distribution of first eigenvalue ($N \times M$ versus $N \times 1 \times M$).

Figure 5 shows the cumulative distribution of the eigenvalues for the case with ($K = 1$) and without a MIMO repeater system. The numerical simulation values are shown for numbers of transmitting and receiving antennas

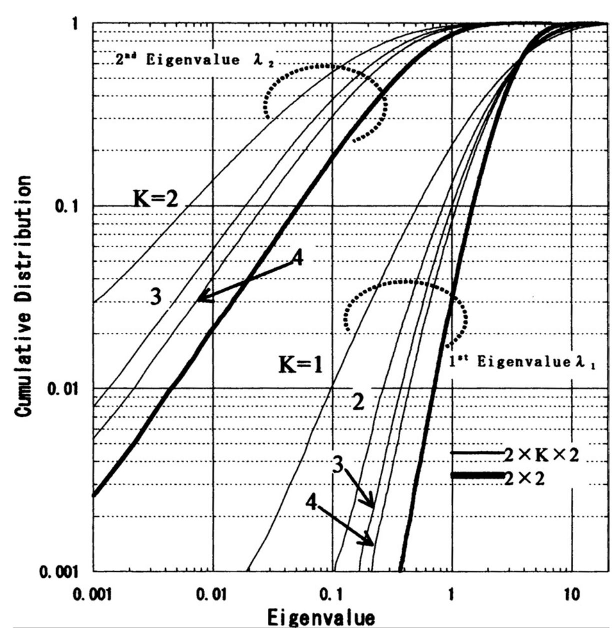


Fig. 6. Cumulative distribution of eigenvalues ($N = M = 2$, $K = 1 \sim 4$).

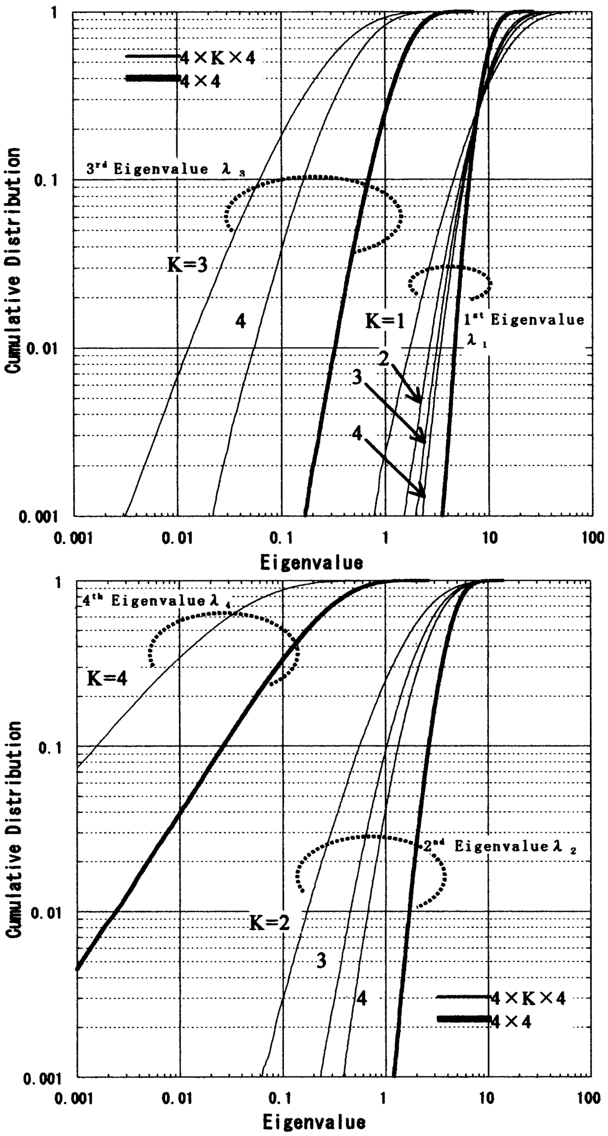


Fig. 7. Cumulative distribution of eigenvalues ($N = M = 4$, $K = 1 \sim 4$).

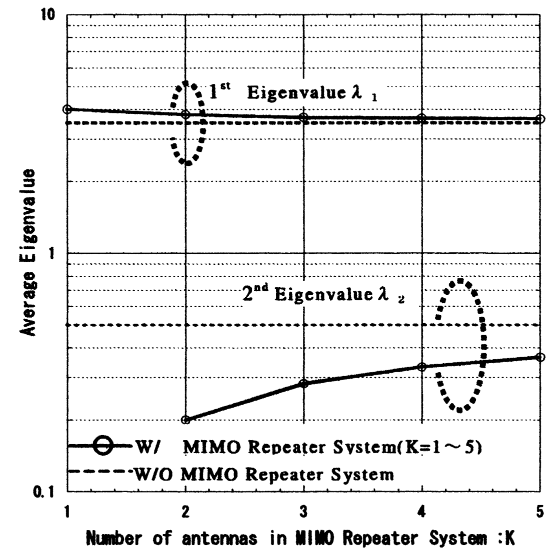
N, M = 2, 3, 4 for the AP and the MS and the theoretical values of Eq. (11) for the case with a MIMO repeater system (K = 1). The agreement between the simulation values and the theoretical values given by Eq. (11) is very good (the case without a MIMO repeater system is shown for comparison).

Figures 6 and 7 show the results of numerical simulations when Eq. (4) is applied for the cumulative distribution of the eigenvalue for the MIMO repeater system when the numbers of transmitting and receiving antennas of the AP and the MS are $N, M = 2, 4$. The numbers of transmitting and receiving antennas K in the MIMO repeater system are varied from 1 to 4.

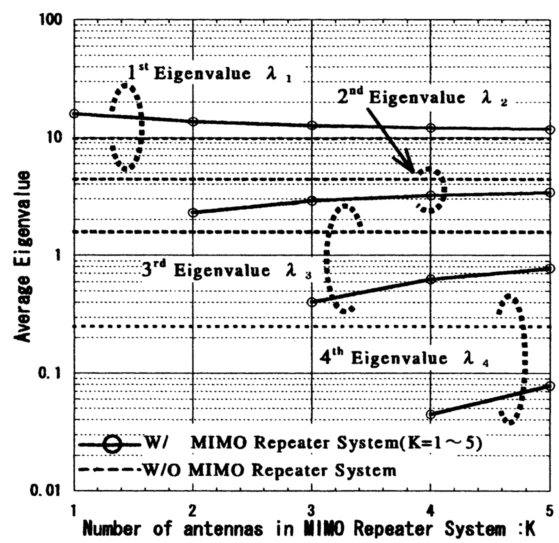
As indicated by the results shown in Figs. 6 and 7, the rank of the channel response matrix is increased and the diversity order is improved as the number of transmitting and receiving antennas K in the MIMO repeater system is increased. Hence, a MIMO repeater system extending the MIMO service to a closed space results in highly functional relay characteristics of MIMO by increasing the number of antennas K in the MIMO repeater system.

3.3. Distribution of average eigenvalues

Figure 8 shows a simulation result based on Eq. (4) for the relationship between the number of antennas K in



(a) Case of N, $M = 2$



(b) Case of N, $M = 4$

Fig. 8. Relationship between average eigenvalue of MIMO repeater system and number of antennas within MIMO repeater system.

the MIMO repeater system and the average eigenvalues. In Figs. 8(a) and 8(b), it is found that the rank of the channel response matrix increases and the average eigenvalues approach those for the case without a MIMO repeater as K is increased (the case without a MIMO repeater system is shown for comparison). Then, the number of antennas K in the MIMO repeater system corresponds to the number of keyholes in the multi-keyhole environment. In both Figs. 8(a) and 8(b), the number of keyholes is 1 and the number of eigenvalues is also 1 if K in the MIMO repeater system is 1. Then the average eigenvalue is NM if the number of the transmitting and receiving antennas are N and M.

4. Transmission Characteristics

4.1. Average communication capacity

The transmission path of information in the equivalent circuit obtained by SVD decomposition of the MIMO channel in the MIMO repeater system is different depending on whether or not the channel information is known for each of transmission and reception. When the channel information is available in both, maximum ratio combining (MRC) transmission in which all information is placed on the maximum eigenpath and also eigenmode transmission (ET) in which an optimum power is assigned to each eigenpath are possible. Assignment of the optimum power in the latter is based on the water filling (WF) theorem. Here, the upper limit of the average communication capacity in the case of eigenmode transmission is approximated by the following based on Shannon's information theory:

$$\langle C_{WF} \rangle \approx \sum_{i=1}^{M_0} \log_2(1 + \langle \lambda_i \rangle \gamma_i) \ (\text{bit/s/Hz}) \tag{12a}$$

$$\sum_{i=1}^{M_0} \gamma_i = \gamma_0 \tag{12b}$$

Here C_{WF} is the average communication capacity when optimum power distribution is performed on the basis of the WF theorem and $<C>$ is the average of C. γ_0 in Eqs. (12a) and (12b) is the SNR when all power on the transmitter side is radiated from a single antenna, arrives by a path with a path gain of 1, and is received by a single antenna.

Figure 9 shows the average communication capacity of the MIMO repeater system in eigenmode transmission when the numbers of transmitting and receiving antennas are N, M = 2 in the AP and the MS. In the eigenmode transmission shown in Fig. 9, the difference between the maximum and minimum of the average communication capacity is about 1 bit/s/Hz when the number of antennas K in the MIMO repeater system is 2 or more. If K in the MIMO repeater system is 2 or more, the second eigenvalue

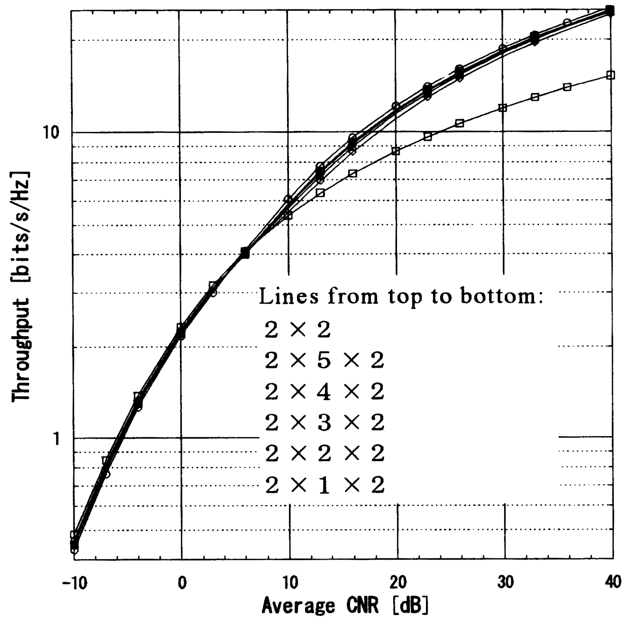


Fig. 9. Throughput performance of MIMO eigenmode transmission (case of N, M = 2) in MIMO repeater system.

appears and the deterioration of the average communication channel is improved as shown in Fig. 8(a). When K in the MIMO repeater system is 1 and 2 or more, the difference in the average communication capacity is increased as the CNR is increased. On the other hand, the MRC transmission depends little on the number of antennas K in the MIMO repeater system and the average communication capacity is almost constant.

Figure 10 shows the relationship between the average communication capacity and the number of antennas K necessary for the MIMO repeater system from the point of view of average communication capacity (the case without a MIMO repeater system is presented for comparison). The results in Figs. 10(a) and 10(b) show that the average communication capacity is not degraded significantly in comparison with the MIMO service area if K for the MIMO repeater system is set to more than the number of transmitting and receiving antennas N, where the numbers of transmitting and receiving antennas are N and M (= N).

4.2. Average BER

The average BER characteristics are evaluated by numerical simulation for eigenmode transmission (ET) in the MIMO channel of the MIMO repeater system shown in Fig. 3. In order to maximize the transmission rate, transmission rate control is needed in each stream. Here the trans-

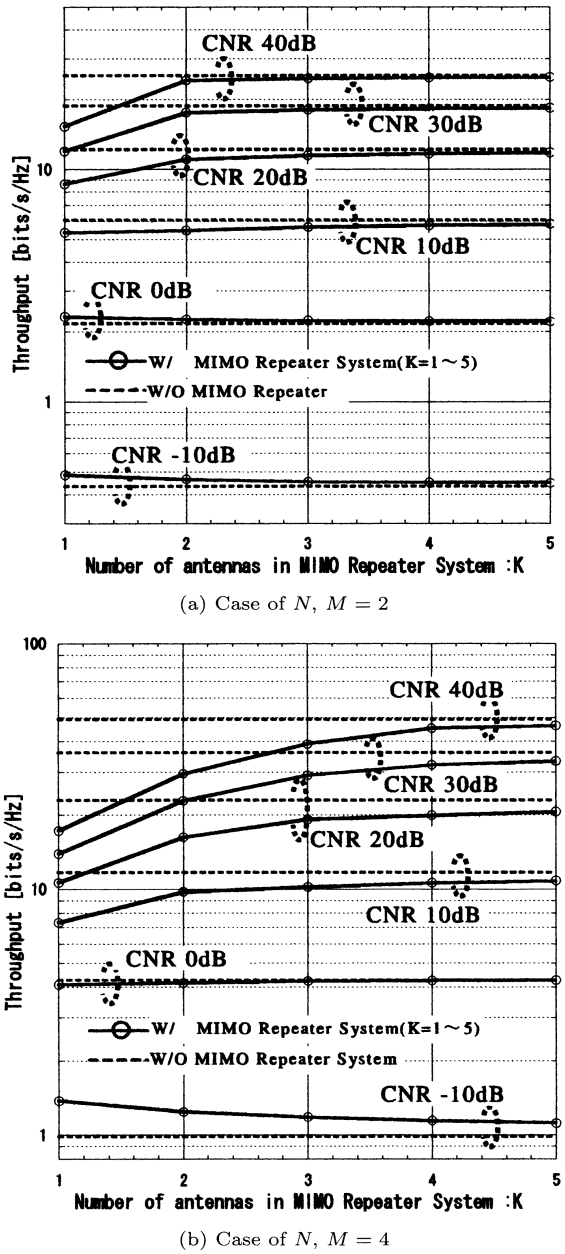


Fig. 10. Relationship between average throughput performance of MIMO repeater system and number of antennas within MIMO repeater system.

mission rate and the transmitted power are cooperatively controlled on the basis of the error rate minimization criterion.

Next, let us explain the cooperative control of the transmission rate and the transmitted power [10]. The modulation formats are QPSK, 16QAM, 64QAM, and 256QAM.

Let the number of bits per symbol for all substreams be L. Also, the error rate P of each Gray coded modulation format is approximately

$$P = \alpha \cdot erfc\left(\sqrt{\frac{\gamma}{\beta}}\right) \leq 2\alpha e^{-\frac{\gamma}{\beta}} \tag{13}$$

Here erfc(·) is the complementary error function, γ is the receiving SNR, and α and β are listed in Table 1.

When the number of bits per symbol in all substreams is L and the transmitted power of p_m and L_m bits are assigned to M_0 substreams, the average error rate P_{ava} is

$$P_{ava} \leq \frac{1}{L} \sum_{m=1}^{M_0} 2\alpha_m L_m e^{-p_m \gamma_m / \beta_m} \tag{14}$$

where

$$\sum_{m=1}^{M_0} L_m = L \tag{15a}$$

$$\gamma_m = \lambda_m \gamma_0 \tag{15b}$$

Therefore, the transmitted power minimizing the average error rate of all streams at constant total transmitted power is expressed as follows if the Lagrangian undermined coefficient method is applied:

$$p_m = \max\left\{\frac{\beta_m}{\gamma_m}\left(\log\frac{\alpha_m L_m \gamma_m}{\beta_m}\right) - \xi, 0\right\} \tag{16}$$

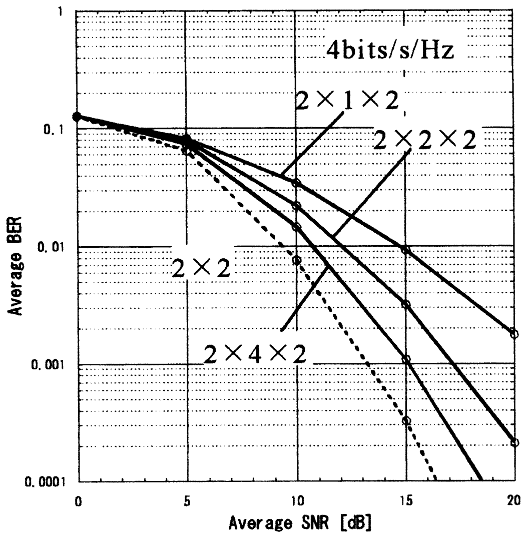
where ξ is a constant such that $\Sigma_{m=1}^{M_0} p_m = 1$.

For evaluation of the average BER characteristics, the transmission and reception control is performed on the basis of cooperative control of the transmission rate and the transmitted power described above and ZF (Zero Forcing) is applied to the receiving process. Here the numbers of antennas N and M of the AP and the MS are 2 and 4. The average BER characteristics of the MIMO repeater system are evaluated by numerical simulations in the cases where there is no MIMO repeater system (2 × 2 and 4 × 4) and where the number of antennas K in the MIMO repeater system is 1, 2, and 4. The results are shown in Fig. 11.

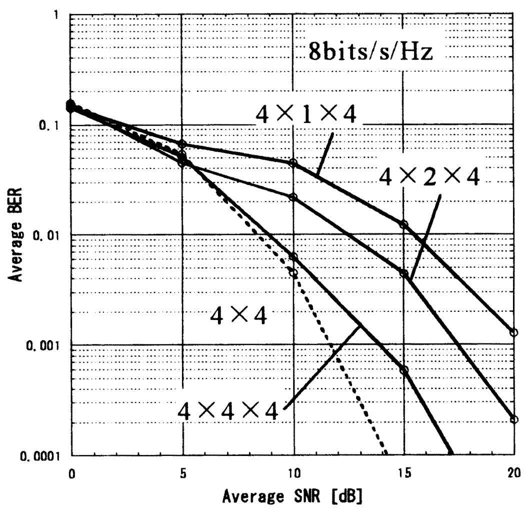
The number of bits L per symbol for all substreams is 4 and 8 bit/s/Hz. From the numerical simulation results

Table 1. Parameters of BER equation for each modulation type

Modulation format	α	β	No. of bits
QPSK	1/2	2	2
16QAM	3/8	10	4
64QAM	7/24	42	6
256QAM	15/64	170	8



(a) Case of N, $M = 2$



(b) Case of N, $M = 4$

Fig. 11. Average BER performance.

in Fig. 11, it is found that the average BER is improved as the diversity order is improved in the cumulative distribution of the eigenvalue as the number of antennas K in the MIMO repeater system is increased. Also, since the probability that the information is placed on all eigenpaths increases with increasing K in the MIMO repeater system, the required SNR is decreased. In addition, the improvement of the BER due to increased K of the transmitting and receiving antennas is considered to be mainly caused by improvement of the diversity order. The simulation results in Fig. 11 indicate that the required number of antennas K in the MIMO repeater system must be larger than that for the average communication capacity case in order to obtain an average BER comparable to that in the MIMO service area.

5. Conclusions

A multi-keyhole channel model is proposed and the propagation characteristics of the multi-keyhole model are analyzed. This multi-keyhole model is the channel model appearing when the high speed and high reliability of MIMO are maintained by a MIMO repeater system.

In this paper, the characteristics of the eigenvalues of the channel response matrix of the multi-keyhole model are analyzed and the distributions of the eigenvalues are found. For realization of a MIMO repeater system, the number of repeater antennas needed for maintaining the high speed and high reliability of MIMO is analyzed with regard to the eigenvalues, the average communication capacity, and the average BER by numerical simulation.

In the evaluations of the average communication capacity and the average BER, the characteristics depend strongly on the average SNR of the channel. This in turn depends on the channel characteristics and the internal gain of the MIMO repeater system, assumed constant. But the reality is very complicated and the comparison results presented in this paper may not be used directly. However, even in individual situations, the calculation formulas presented here can be effective for evaluation and the model has generality.

It is found sufficient that the number of antennas needed for the MIMO repeater system be equal to or greater than the number of degrees of freedom of the MIMO service space and the closed space, from the point of view of an average communication capacity equivalent to that in the independent and uncorrelated Rayleigh fading channel (in the case of $N = M = 2$, $K = 2$). On the other hand, from the point of view of obtaining the average BER equivalent to that in an independent and uncorrelated Rayleigh fading channel, more antennas than those assuring the average communication capacity are needed.

In the future, it is planned to generalize the channel model for the MIMO repeater system and to perform a theoretical analysis of the eigenvalue distributions.

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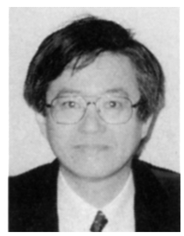

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