Optimizing Relay Selection in Distributed MIMO Relay System for Conservation of Transmit Power

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I. ABSTRACT

The research on distributed MIMO relay system has been attracting much attention. By optimizing the position of each relay, the channel capacity of such system is larger than that of original MIMO system. However, the propagation environment between each transceiver is simplified to be the same. In this paper, a decode-and-forward scheme distributed MIMO relay system is examined. The distance between each relay is optimized in propagation environment which is brought close to actuality. For upper bound of channel capacity, the number of relay is optimized whether total antenna element is fixed or not. When the number of relay is assumed to be infinite, the dynamic relay selection method based on the transmission rate is proposed. We represent that with such method the transmit power and relay is saving.

***Index Terms*—Distributed relay system, optimizing distance, Optimization antenna element, upper bound of channel capacity, dynamic relay selection.**

II. INTRODUCTION

In recent years, multiple-input multi-output (MIMO) technology using multiple antennas at both the access point (base station) and user terminal sides has become a popular research field of next-generation mobile communication systems. The increase of the system channel capacity under finite frequency bandwidth has made the MIMO system unique and efficient in data transmission.

In terms of the scientific underpinnings, a research on MIMO can be divided into three following areas, namely, 1) array antennas and adaptive signal processing for the implementation of antenna configurations and control methods, 2) information theory and coding schemes (space-time coding) for the implementation of an efficient data transmission, and 3) radio wave propagation for the modeling of MIMO channel [1]-[6].

The MIMO channel capacity can be decreased when the distance between a base station and an user terminal is much larger than the base station and user terminal scatterer radius, this leads to a waveguiding structure with a small rank of the MIMO matrix, even though the signals between antenna elements are uncorrelated. This effect has been termed "keyhole" or "pinhole" (hereafter, we call it keyhole). In the keyhole environment, the multi-stream transmission becomes impossible, and high-speed, high-reliability transmission cannot be expected [7]-[9].

In the future, it is believed that the MIMO service area will become fashionable. Thus, an expansion of an service area to an isolated area is anticipated. Based on this idea, the authors have proposed a general idea of a MIMO relay system that can maintain the ability of high-speed and/or high-reliability data transmission [10]. A MIMO relay system can relay radio signals from a MIMO service area to an isolated area. In general, when a MIMO relay system has only one relay, the whole channel in the MIMO relay system is equivalent to a MIMO multi-keyhole environment. In a multi-keyhole environment, the probability density functions (PDFs) of singular values of channel response matrix or eigenvalues of correlation matrix are important from a viewpoint of system designing such as transmission characteristic meaning channel capacity and bit error rate analysis. When the number of antenna element at relay is less than that at transmitter and receiver, the channel capacity of MIMO relay system is smaller than the one of original MIMO system. In addition, when the number of relay antenna is equivalent to the one of transmitter and receiver, a MIMO relay system can provide the same averaged channel capacity as a original MIMO system. However the number of the relay antenna is larger than the transmit and receive antennas, the channel capacity of a MIMO relay system cannot exceed the one of original MIMO system[10].

Therefore, in order to obtain the high propagation characteristic, the antenna element is distributed to many relays (RS), and those relays are arranged in series from transmitter to receiver. This system is called a distributed MIMO relay system (DMRS). With DMRS, when the distance between the transmitter and the final receiver (named total distance) is fixed, the distance between transmitter and the first relay, relay and relay, the final relay and receiver (called between each transceiver for short) is shorten, consequently the signal-to-noise ratio (SNR) as well as the channel capacity is increased. The upper bound of channel capacity is achieved by optimizing the distance between each transceiver. However, the propagation environment between each transceiver was assumed to be the same[11]. In this paper, we consider decode-and-forward scheme DMRS in the propagation environment that is brought close to actuality. In such environment, the upper bound of channel capacity is achieved by optimizing the distance between each transceiver in the case of fixing total

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transmit power and total distance. The optimum of antenna element number at each relay in the sense of the largest channel capacity is obtained when the total antenna element is fixed. Furthermore, when the number of relay is assumed to be infinite, the performance of system is analyzed and the dynamic relay selection method for conservation of transmit power is proposed.

III. Distributed MIMO relay system

A. Concept of system

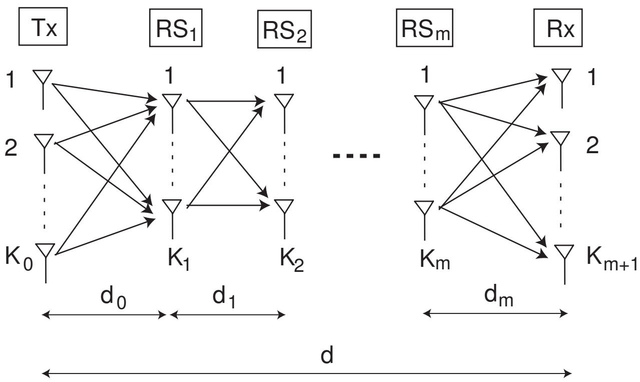

Fig. 1. Concept of Distributed MIMO relay system

In this section, we represent obviously the DMRS with m relays intervened. The structure of system is shown in Fig. 1. Here Tx, Rx and RS_i is the transmitter side, final receiver and the i^th relay, respectively. K_i denotes the number of antenna element and d_i denotes the distance between each transceiver. In such system, the signal is transmitted from the Tx to the RS_1. After that the signal is processed and transmitted to the RS_2. Similarly, the signal is transmitted over and over until to the final receiver.

The system parameters of each transceiver such as transceiver signal, transmit power matrix, noise vector, amplification factor of every relays are summarized in Table I.

TABLE I
System parameters of each transceiver

-	Tx	RS_1	$\cdots$	RS_m	Rx
Transceiver signal	$\mathbf{S}_0$	$\mathbf{S}_1$	$\cdots$	$\mathbf{S}_\mathrm{m}$	$\mathbf{S}_\mathrm{m+1}$
Transmit power	P_0	P_1	$\cdots$	P_m	-
Noise vector	-	$\mathbf{n}_1$	$\cdots$	$\mathbf{n}_\mathrm{m}$	$\mathbf{n}_\mathrm{m+1}$
Amplification factor	β_0	β_1	$\cdots$	β_m	-

As expressed in Fig. 2, let the channel capacity and the path loss between each transceiver is C_i and l_i $(i = 0 \cdots m)$, respectively. C denotes the channel capacity of system. Let $\mathbf{H}_\mathrm{ii+1}$ denotes a $K_{i+1} \times K_i$ channel matrix between each transceiver and $\mathbf{H}_\mathrm{ii+1}$ is a matrix with independent and identically distributed (i.i.d.), zero mean, unit variance, circularly symmetric complex Gaussian entries.

Since there are several schemes for interference cancellation by using array antenna such as linear (ZF) and nonlinear

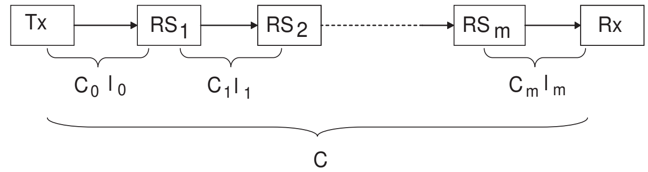

Fig. 2. Channel capacity of DF scheme distributed MIMO relay system

(SIC/DPC) algorithm, we assume that the interference signal from other transmitters can be ignored without loss of generality. Therefore, when the signal $\mathbf{S}_\mathrm{i-1}$ is transmitted from $RS_\mathrm{i-1}$, the received signal at the next relay is expressed as [10],

$$\mathbf{S}_\mathrm{i} = \mathbf{H}_\mathrm{ii+1}\beta_\mathrm{i}\mathbf{S}_\mathrm{i-1} + \mathbf{n}_\mathrm{i+1}, \quad (1)$$

where β_i denotes an amplification factor of RS_i. In this paper, since the decode-and-forward method is applied, the amplification factor is expressed as

$$\beta_\mathrm{i} = \sqrt{P_\mathrm{i} l_\mathrm{i}}. \quad (2)$$

Furthermore, the channel capacity is as follows,

$$C_\mathrm{i} = log_2(det(\mathbf{I}_{\mathrm{K_i}} + \frac{\mathrm{SNR}}{\mathrm{K_i}}\mathbf{H}_\mathrm{ii+1}\mathbf{H}^\mathrm{H}_\mathrm{ii+1})), \quad \mathrm{i} = 0 \cdots \mathrm{m}, \quad (3)$$

where $\mathbf{I}_{\mathrm{K_i}}$ is $K_\mathrm{i} \times K_\mathrm{i}$ unit matrix. However, as described in Sect. II, if the number of antenna elements at the least one relay is smaller than that of other relays, this relay will be the bottleneck of system. Therefore the channel capacity of system will be decreased. In order to obtain high propagation characteristic, we assume the number of antenna element at each relay to be the same. In addition, $\mathbf{H}_\mathrm{ii+1}\mathbf{H}^\mathrm{H}_\mathrm{ii+1}$ $(\mathrm{i} = 0 \cdots \mathrm{m})$ can be assumed to be an unit matrix. Consequently, the SNR can be examined instead of channel capacity. Since the channel capacity C_i $(i = 0 \cdots m)$ is independent of other ones, the channel capacity of the system is expressed as

$$C = \min(C_\mathrm{i}), \quad with\ i = 0 \cdots m. \quad (4)$$

Thus the upper bound of channel capacity of system is achieved when the channel capacity of every receivers meaning the SNR of every receivers is equivalent. Therefore, it is necessary to optimize the distance between each transceiver in order to obtain the upper bound of channel capacity of system.

B. Propagation environment

We assume that the transmit power of each relay is kept the same regardless of the total transmit power of relays as well as the number of relay is fixed or not. Therefore, the SNR is proportional to a propagation loss. Since the propagation channel is not necessary to be just in a free-space propagation, so it is necessary to consider being attenuated by the reflection, scattering, and so on. The path loss in this case is expressed as

$$l_\mathrm{i} = (\frac{\lambda a^\mathrm{ref}}{4\pi d_\mathrm{i}})^2. \quad (5)$$

Here, λ and ref denote the wavelength and the reflection times, respectively. The reflection loss a is assumed to be an amount of the attenuation by the only one reflection.

On the other hand, we consider the DMRS for several wireless network topology such as 1, Extension a MIMO service area from a base station in center of city to a receiver terminal in country side, 2, Transmission a health information from monitors implanted in body to a receiver of the outside, 3, Transmission information from terminals in isolated area to the near base station. For all of these scenario, the environment around the Tx has a lot of transmission obstacle, consequently the signal reflects many times before arriving the next relay. The times of reflection is decreased when the signal goes away from the Tx. In addition, the times of reflection is proportional to distance between each transceiver. Thus, we define the reflection times when the signal is transmitted from the RS_{i} to $RS_{\mathrm{i+1}}$ as follow,

$$ref_{\mathrm{i}} = \frac{4d_{\mathrm{i}}^2}{Dd_{\mathrm{t}}}, \tag{6}$$

where d_{t} denotes the distance between the Tx and the $RS_{\mathrm{i+1}}$. The propagation environment coefficient D is defined as the average distance from the Tx or a reflection point to a reflection point or RS_1. In other words, it is the average of line-of-sight (LOS) distance in the environment around the Tx. For validating the reflection times expressed in (6), we assume the distance between each transceiver is 250 m and 500 m, the propagation environment coefficient D is 500 m.

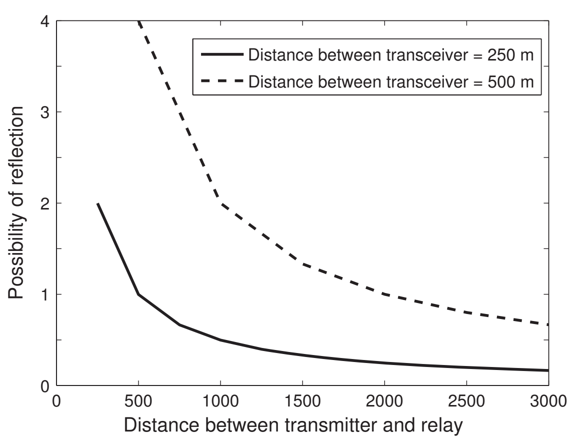

Fig. 3. Possibility of reflection with distance between transceiver is 250 m and 500 m

As the result shown in Fig. 3, the shorter distance between each transceiver is, or the more a relay is far from the Tx, the smaller possibility of reflection becomes. Naturally, for different propagation environment, the environment function meaning the equation of reflection times may be changed. However the function in (6) can describes the propagation environment that we consider to apply this research to, consequently the function in (6) is used in this paper.

IV. Upper bound of channel capacity with fixed transmit power and total distance

A. Optimizing distance

We assume that the total transmit power P_{t} is fixed in spite of the change in the number of relay and the number of antenna element at each relay. In order to simplify the composition of relay, the total transmit power is equally divided into each relay. Moreover, the transmit power of each relay is equally divided into each antenna element. Therefore, let $\bar{P}_{\mathrm{i}}$ $(i = 1 \cdots m)$ is assumed to be the transmit power of one antenna element, every transmit power is expressed as

$$P_{\mathrm{i}} \;=\; \bar{P}_{\mathrm{i}} K_{\mathrm{i}} = \frac{P_{\mathrm{t}}}{(m+1)K}, \tag{7}$$

where K is the number of antenna elements of a relay. In order to obtain the upper bound of channel capacity of system, all of SNR are necessary to be equal.

$$SNR_{\mathrm{i}} = SNR_{\mathrm{j}}, \quad for\ i \neq j,\ and\ i,j = 0 \cdots m, \tag{8}$$

where

$$SNR_{\mathrm{i}} = \frac{P_{\mathrm{t}} l_{\mathrm{i}}}{(m+1)K\sigma^2}, \quad with\ i = 0 \cdots m, \tag{9}$$

where σ^2 denotes the covariance of noise vector in each relays and final receiver. By solving (8), the optimized distances are obtained. The Fig. 4 shows the optimized distance of each relay in the case of 5 relays. The parameter is summarized in Table II.

TABLE II
NUMERICAL PARAMETERS

Antenna elements: K	4
Total transmit power: P_{t} [mW]	500
Total distance between Tx-Rx: d [m]	3000
Noise power: σ^2 [dBm]	-102
Reflection loss: a [dBm]	-8

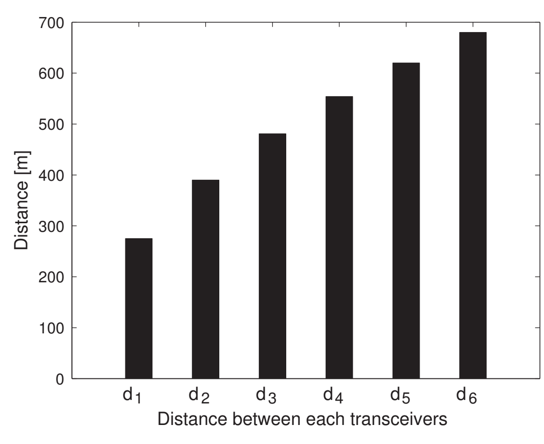

Fig. 4. Optimized distance between each transceiver in a sense of upper bound of channel capa city

As shown in Fig. 4, the distance between each transceiver is increased when the relay be far from the Tx. The reason can be explained that when the relay be far from the Tx, the reflection times become smaller than the one when relay be close to the Tx, therefore, with the same channel capacity, the signal can be transmitted farther.

B. Upper bound of channel capacity

In this section, we examine the upper bound of channel capacity in different condition. First, the propagation environment is changed. Fig. 5 shows the upper bound of channel capacity when D is 500 m and 1500 m. Since the reflection times is decreased when D is increased, the channel capacity when D is 1500 m, is larger than the one of D being 500 m. When the number of relay is increased, the distance between each transceiver is shorten, therefore the channel capacity is increased.

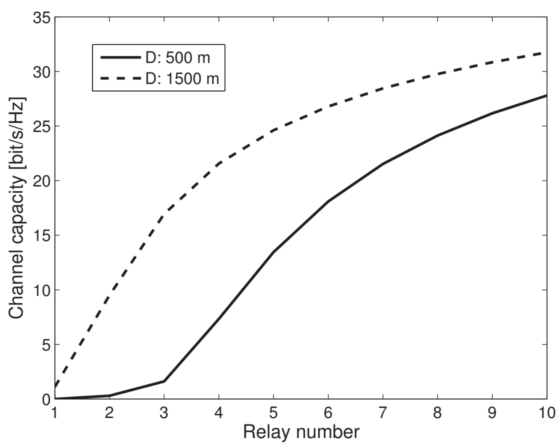

Fig. 5. Upper bound of channel capacity when propagation environment is changed

Then, we examine the upper bound of channel capacity when transmit power is changed, i.e., 100 mW, 300 mW, 500 mW. As the channel capacity shown in Fig. 6, the bigger the transmit power is, the higher the upper bound of channel capacity becomes. Therefore, for the same channel capacity, the smaller transmit power is, the more the necessary number of relay is demanded.

C. Upper bound of channel capacity with fixed total antenna element

Up to now, we analyze the performance of DMRS where the number of relay is assumed to be infinite. However from the viewpoint of the cost and the place to install many relays, the number of antenna element is assumed to be finite. As described in previous section, for high channel capacity, a lot of relay is demanded. However, for MIMO propagation, the number of antenna element at each relay plays an important rule as expressed in (3). Consequently, the relation between relay number and antenna element number at each relay is

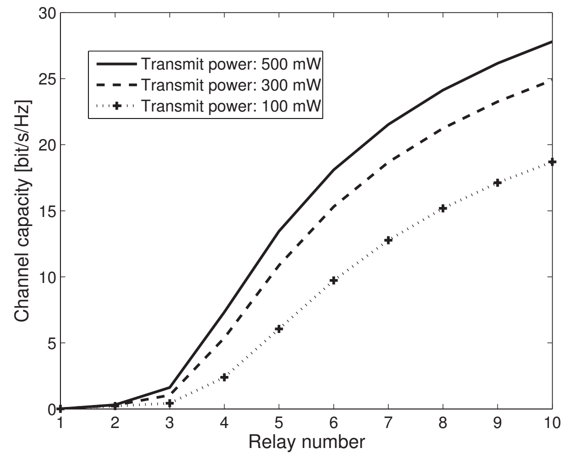

Fig. 6. Upper bound of channel capacity with changing of transmit power

necessary to be considered. Let us assume that the total antenna elements is T. Since the antenna elements at every relay is assumed to be equal, the antenna element at each relay becomes,

$$AN = \frac{T}{M}, \tag{10}$$

where M denotes the number of relay. In fact, the number of antenna element is an integral number. However, to analyze the performance of system easily, we assume the number of antenna element is a positive number. Exact number of antenna element can be obtained by rounding off the such positive number.

The channel capacity of each transceiver is changed as

$$C_{\rm i} = \frac{T}{M} log_2(1 + (\frac{\lambda a^{\rm ref_i}}{4\pi d_{\rm i_{max}}})^2 \frac{MP_{\rm t}}{(M+1)T\sigma^2}). \tag{11}$$

The parameter is summarized in Table II. The upper bound of channel capacity is shown in Figs. 7 and 8.

There is an optimal number of relay, meaning the optimal number of antenna elements at every relay in the sense of the largest channel capacity. If the number of relay is smaller than the optimal number, the antenna element at each relay is increased, moreover the distance between each transceiver is increased. As a result, the channel capacity is decreased. In other side, if the number of relay is higher than the optimal number, the distance between each transceiver is shorten, consequently the SNR is increased. However the antenna element at each relay is decreased, therefore the channel capacity is decreased. Furthermore, the optimal number of antenna element will be changed when the propagation environment or the total transmit power is changed. In the same propagation environment and total transmit power, the optimal number of relay is almost the same though total antenna elements is changed.

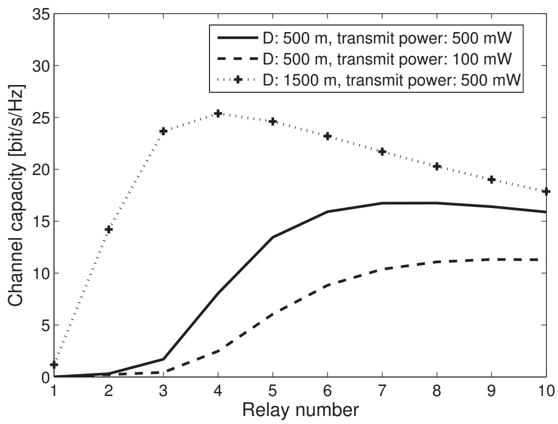

Fig. 7. Upper bound of channel capacity in several propagation condition, total antenna element is 10.

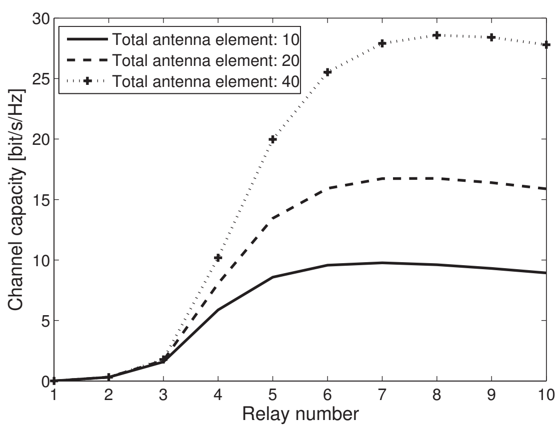

Fig. 8. Upper bound of channel capacity when fixed antenna element is 10, 20, and 40

V. Dynamic relay selection method for conservation of transmit power

A. Dynamic relay selection method

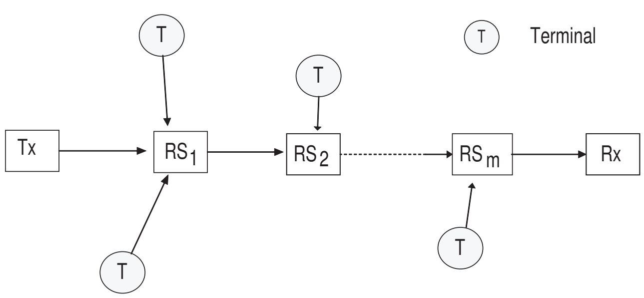

Fig. 9. Concept of dynamic relay selection method

As several scenario described in Sec. III-B, it is assumed the terminals that need to transmit an information signal, exist everywhere. These terminals transmit the signal to the relay that is the nearest from itself. Therefore, each relay receives the signal from not only the previous relay, but also the terminals around itself and sends the total signal to the next relay or the Rx.

Let the transmission rate of $RS_{\mathrm{i}-1}$ is $B_{\mathrm{i}-1}$, the total transmission rate of the terminals around RS_{i} is TB_{i}. Therefore, the transmission rate of RS_{i} must be $B_{\mathrm{i}} = B_{\mathrm{i}-1} + TB_{\mathrm{i}}$. In this section, we assume that there are many relays arranged from the Tx to the Rx and each relay knows the distance from itself to the others as well as the propagation environment. Each relay can selects the next relay to transmit the signal. The next relay is the one that the present relay can transmits total bits to. For saving the relay and the transmit power, the next relay is also assumed to be the farthest one from the present relay. In short, the distance from the present relay to the next relay must satisfies that,

$$B_{\mathrm{i}} = Klog_2(1 + (\frac{\lambda a^{\mathrm{ref_i}}}{4\pi d_{\mathrm{i}}})^2 \frac{P}{\sigma^2}). \quad (12)$$

This selection method is called dynamic relay selection method.

B. Conservation of transmit power

The dynamic relay selection method is compared to the optimizing distance method that described in Sec. IV-A. In the case of optimizing distance method, the total transmit power is fixed, and the link capacity between each transceiver is the same. In other side, in the case of dynamic relay selection method, the transmit power of each relay is fixed, however the total transmit power is infinite, and the link capacity between each transceiver is different. We assume that the bits received at the Rx in an unit time is the same in both cases of the dynamic relay selection method and the optimizing distance method, however the transmission rate of the Tx, as well as the terminals is random value. The parameter is summarized in Table II, and the propagation environment coefficient D is assumed to be 1500 m. The DMRS transmits the signal with capacity is expressed in Fig. 5. Therefore the transmit power and the relay number of optimizing distance method is as expressed in Fig. 5. The transmit power of each relay in the case of dynamic relay selection method P is assumed to be 100 mW and 50 mW. The Figs. 10, 11 show the necessary transmit power and relay number of system, respectively.

When the channel capacity is low, the transmit power in the case of dynamic relay selection method is considerably smaller than that of optimizing distance method. However when the channel capacity is increased, the transmit power of dynamic relay selection method is increased and be higher than the one of optimizing distance method as described in Fig. 10. On the contrary, when the channel capacity is low, the necessary relay number of dynamic selection method is larger than that of optimizing distance method. When the channel capacity is increased, the relay number of dynamic relay selection method is increased, however it becomes smaller than the one of

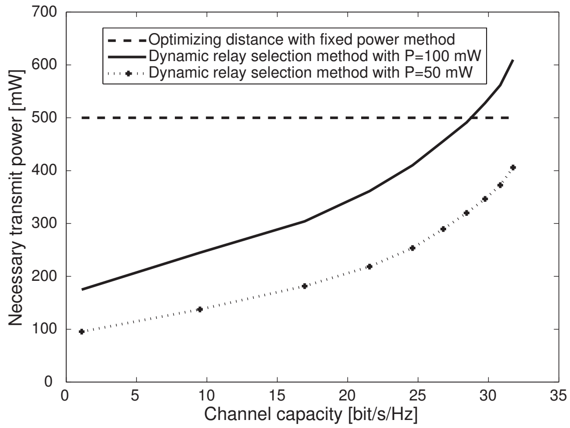

Fig. 10. Necessary transmit power of both methods with P=50 mW and 100 mW

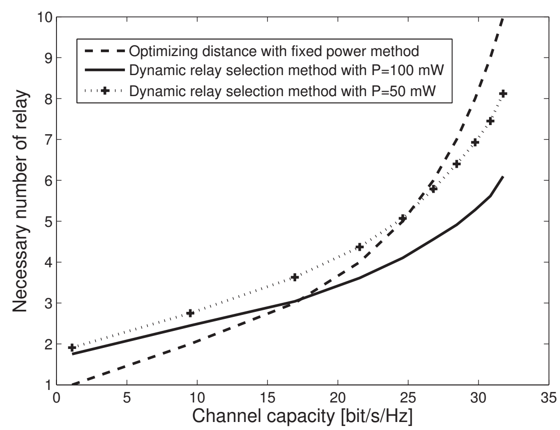

Fig. 11. Necessary relay number of both methods with P=50 mW and 100 mW

optimizing distance method as described in Fig. 10.
In one side, to consider dynamic relay selection method with P=100 mW, when the channel capacity is between 17 and 28 [bit/s/Hz], both the necessary transmit power and relay number are lower than the ones of optimizing distance method. Similarly, to consider dynamic relay selection method with P=50 mW, when the channel capacity is over 25 [bit/s/Hz], both the necessary transmit power and relay number are lower than the ones of optimizing distance method. As two examples mentioned before, by adjusting the transmit power of each relay, with lower total transmit power and the smaller relay number, the dynamic relay selection method can transmit the same channel capacity as the optimizing distance method.

VI. Conclusion

In this paper, we proposed the function that can brings the propagation environment to be close to an actuality. The performance of a DMRS with decode-and-forward method is examined. For upper bound of channel capacity of the system, the positions of all relays, meaning the distance between each relay was optimized in the case of fixing transmit power, total distance, also the total antenna elements. When total antenna element is fixed, there is the optimum of antenna element number in the sense of largest channel capacity, the optimum of antenna element number is changed by changing in condition of transmission. The dynamic relay selection method was proposed for conservation of transmit power and relay number.
The Peer-to-Peer(P2P) transmission method and the multiple-user to one-user (M2P) transmission method have been dealt in this paper. In the future, not only the P2P and M2P transmission method, but also multiple-user to multiple-user (M2M) transmission method is considered. In addition, the network coding will be applied to this research.

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