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Channel Capacity Maximization in a Distorted 2x2 LOS MIMO Link

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Abstract

This paper presents a novel channel capacity maximization method for a distorted 2×2 line-of-sight (LOS) multiple-input multiple-output (MIMO) link. A LOS MIMO link may be distorted by the influence of environmental factors such that the channel capacity of the LOS MIMO link may be degraded. By using the proposed method, the channel capacity of a distorted 2×2 LOS MIMO link can be the same as that of the ideal 2×2 LOS MIMO link. The proposed method employs an additional receiver antenna to maximize the channel capacity. In contrast to a 3×2 LOS MIMO link, a receiver circuit for a third receiving antenna is not necessary. Hence, the receiver for the proposed method is much simpler than that for a 3×2 LOS MIMO link. We determine the optimal position of the additional receiver antenna analytically. Simulation results show that the channel capacity can approach the ideal using the proposed method.

Index Terms: Antenna array, Channel capacity, LOS MIMO, Phase-shift-difference

I. INTRODUCTION

As high-speed wireless data services are becoming more widespread, high-speed and spectral-efficient networks are necessary. Higher-order modulation and/or multiple-input multiple-output (MIMO) techniques are generally used to increase channel capacity [1-4]. However, line-of-sight (LOS) environments may decrease the channel capacity of the MIMO link [5, 6]. Previous works have shown that a LOS MIMO link can achieve maximum capacity when antennas are placed in optimal positions [5, 7]. Various techniques for LOS MIMO communications considering their applications [8, 9], performance improvement [10, 11], and receiver architectures [12-14], have also been studied.

However, if an antenna array is shifted or rotated, the channel capacity may be decreased [5, 7, 15]. In [7], the authors examined the relationship between channel capacity and the rotation of an antenna array. It was shown that the channel capacity was significantly affected by the rotation of the antenna array (in the y-z plane, shown in Fig. 1). This means that if an antenna array rotates, the distance between the transmitter and receiver antenna array must be adjusted to maximize the channel capacity. However, in a real environment, it may not be possible to adjust the distance between the transmitter and receiver antenna-array due to the difficulty of installation in a limited environment.

This paper presents a novel channel capacity maximization method for a distorted 2×2 LOS MIMO link. The proposed method improves the channel capacity of a distorted 2×2 LOS MIMO link up to that of an ideal 2×2 LOS MIMO link by adding only a combiner and a receiver antenna without a receiver. Compared to the proposed method, the channel capacity of a 2×3 LOS MIMO link, using an additional antenna, additional receiver, and complex digital signal processing, is

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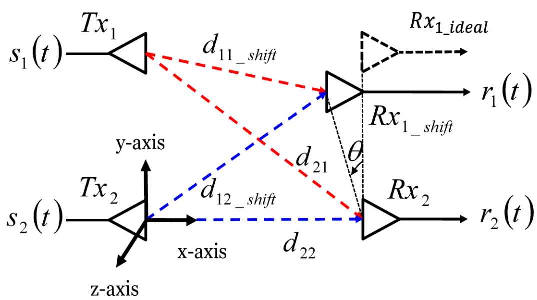

Fig. 1. A distorted 2×2 LOS MIMO link.

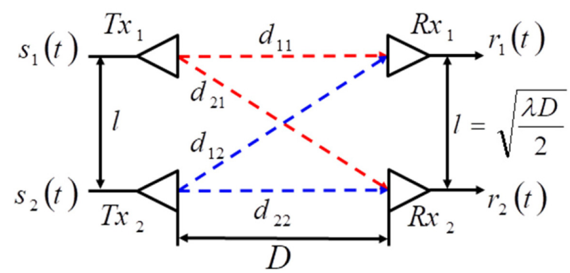

Fig. 2. A 2×2 LOS MIMO link.

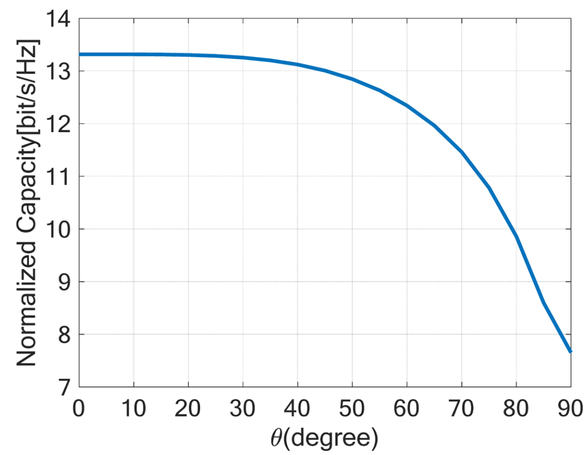

Fig. 3. Relationship between channel capacity of a distorted 2×2 LOS MIMO link and rotation angle θ.

theoretically larger than that of a 2×2 LOS MIMO link using the proposed method. However, the channel capacity of a 2×3 LOS MIMO link can also be decreased due to various distortions. The remainder of this paper is organized as follows. In Section II, we present the full rank 2×2 LOS MIMO link and a distorted 2×2 LOS MIMO link. In Section III, the proposed channel capacity maximization method is presented. The optimal position of the additional receiver antenna is determined analytically, even in various delay environments. The channel capacity of the proposed method is evaluated in Section IV. Finally, conclusions are presented in Section V.

II. 2×2 LOS MIMO LINK

Fig. 2 shows the configuration of a 2×2 LOS MIMO link. Here, D denotes the distance between the transmitter and receiver antenna-array, l denotes the distance between the Tx_1 antenna and Tx_2 antenna (and the Rx_1 antenna and Rx_2 antenna), d_{ji} (i,j=1,2) denotes the distance between the i-th transmitter antenna and the j-th receiver antenna, $s_1(t)$ and $s_2(t)$ denote signals transmitted at transmitters 1 and 2, respectively, and $r_1(t)$ and $r_2(t)$ denote the received signals at receivers 1 and 2, respectively. $r_1(t)$ and $r_2(t)$ are written as

$$\begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix} = \begin{bmatrix} e^{-j2\pi d_{11}/\lambda} & e^{-j2\pi d_{12}/\lambda} \\ e^{-j2\pi d_{21}/\lambda} & e^{-j2\pi d_{22}/\lambda} \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} = \begin{bmatrix} 1 & e^{j\theta} \\ e^{j\theta} & 1 \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix}, \quad (1)$$

where λ is the wavelength of the carrier. Using matrix notation, Eq. (1) is written as

$$\boldsymbol{r} = \boldsymbol{Hs}, \quad (2)$$

where $\boldsymbol{H}$ denotes the channel matrix. When l is equal to Eq. (3), the carrier phase difference between d_{ii} and d_{ji} (i, j = 1, 2; $i \neq j$) is equal to $\pi/2$, $\boldsymbol{H}$ has full rank, and the LOS MIMO link has the maximum capacity.

$$l = \sqrt{\lambda D/2}\,. \quad (3)$$

In this case, $\boldsymbol{H}$ is written as

$$\boldsymbol{H} = \begin{bmatrix} e^{j0} & e^{-j\pi/2} \\ e^{-j\pi/2} & e^{j0} \end{bmatrix}. \quad (4)$$

However, if a 2×2 LOS MIMO link is distorted, the channel capacity may be decreased. Fig. 1 shows a distorted 2×2 LOS MIMO link. We assume that the receiver antenna array is rotated in the y-z plane with the Rx_2 antenna as the center of rotation. The coordinates of the Tx_1 antenna, Tx_2 antenna, and Rx_2 antenna are (0, 0, 0), (0, l, 0), and (D, 0, 0), respectively. When the rotation angle is equal to θ, the coordinates of the Rx_{1_shift} antenna are (D, $l\cos\theta$, $l\sin\theta$). Fig. 3 shows the relationship between the channel capacity and rotation angle [5]. We find that the channel capacity decreases significantly as θ increases.

III. PROPOSED CHANNEL CAPACITY MAXIMIZATION METHOD

Herein, we propose an additional receiver antenna for a distorted 2×2 LOS MIMO link. Fig. 4 shows the configuration of the proposed method. In Fig. 4, the Rx_3 antenna denotes an additional antenna. There is no change in the receiver circuit because the proposed method combines the received signal at the rotated antenna, Rx_{1_shift}, and the received signal at the Rx_3 antenna using an RF combiner. To maximize the channel capacity, the optimal position of the Rx_3 antenna must be determined analytically. $\hat{r}_1(t)$ is written as

$$\hat{r}_1(t) = r_1(t)+r_3(t) = (e^{-j2\pi d_{11\_shift}/\lambda}+e^{-j2\pi d_{31}/\lambda})s_1(t) + (e^{-j2\pi d_{12\_shift}/\lambda}+e^{-j2\pi d_{32}/\lambda})s_2(t) \quad (5)$$

Using Eq. (5), the modified channel matrix $\hat{\boldsymbol{H}}$ is written as

$$\hat{\boldsymbol{H}} = \begin{bmatrix} \hat{h}_{11} & \hat{h}_{12} \\ \hat{h}_{21} & \hat{h}_{22} \end{bmatrix} = \begin{bmatrix} e^{-j2\pi d_{11\_shift}/\lambda}+e^{-j2\pi d_{31}/\lambda} & e^{-j2\pi d_{12\_shift}/\lambda}+e^{-j2\pi d_{32}/\lambda} \\ e^{-j2\pi d_{21}/\lambda} & e^{-j2\pi d_{22}/\lambda} \end{bmatrix} \quad (6)$$

To maximize the channel capacity, the following two conditions must be satisfied. First, as shown in Eq. (4), the phase difference between $\hat{h}_{11}$ and $\hat{h}_{12}$ must be equal to $\pi/2$. Utilizing the fact that $e^{j\phi_1} + e^{j\phi_2} = \cos((\phi_1 - \phi_2))/2)\ e^{j(\phi_1+\phi_2)/2}$, first condition is written as

$$\angle(e^{-j2\pi d_{11\_shift}/\lambda}+e^{-j2\pi d_{31}/\lambda})-\angle(e^{-j2\pi d_{12\_shift}/\lambda}+e^{-j2\pi d_{32}/\lambda}) = \pi/2$$
$$(2\pi d_{11\_shift}/\lambda+2\pi d_{31}/\lambda)-(2\pi d_{12\_shift}/\lambda+2\pi d_{32}/\lambda) = -\pi \quad (7)$$

The second condition is that $\hat{h}_{11}$ and $\hat{h}_{12}$ must have the same magnitude. Since the magnitude of all the signals received at the receiver antennas is the same, d_{11_shift}, d_{12_shift}, d_{31}, and d_{32} must satisfy the relationship shown in Eq. (8).

$$(2\pi d_{11\_shift}/\lambda-2\pi d_{31}/\lambda) = -(2\pi d_{12\_shift}/\lambda-2\pi d_{32}/\lambda) \quad (8)$$

Using Eqs. (7) and (8), d_{31} and d_{32} are written as

$$d_{31} = d_{12\_shift}-\lambda/4$$
$$d_{32} = d_{11\_shift}+\lambda/4 \quad (9)$$

If we assume that the Rx_3 antenna is positioned on the x-y plane, the coordinates of the Rx_3 antenna can be represented as $(x_3, y_3, 0)$. Then, using the coordinates of the Rx_1 antenna, Eq. (9) is written as

$$x_3^2+(y_3-l)^2 = (-\lambda/4+\sqrt{D^2+l^2})^2$$
$$x_3^2+y_3^2 = (\lambda/4+\sqrt{D^2+2l^2(1-\cos\theta)})^2 \quad (10)$$

Using Eq. (10), the coordinates of the Rx_3 antenna are determined as (Using, Eq. (11) and the measured relative rotation angle from the initial position of the Rx_1 antenna,

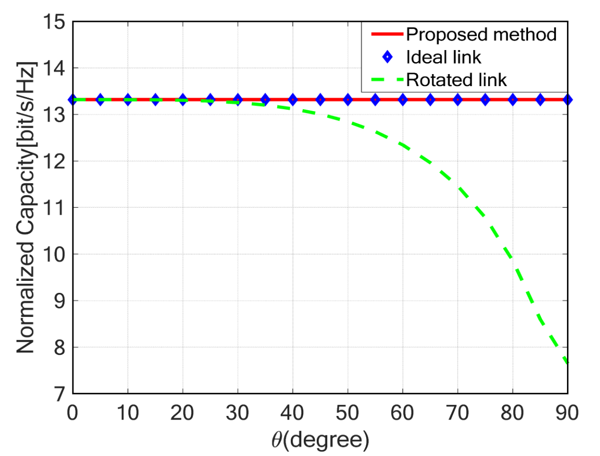

Fig. 5. Relationship between channel capacity of the proposed system and rotation angle θ (D = 4 m, f_c = 30 GHz, SNR = 20 dB).

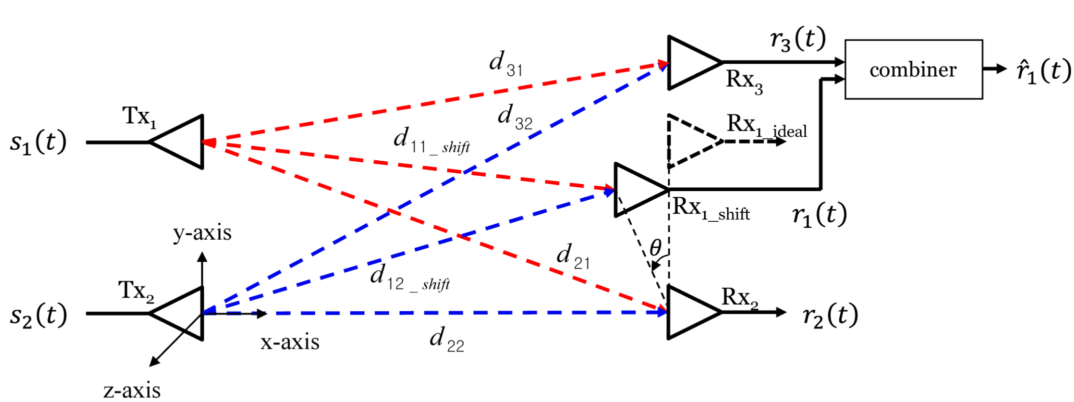

Fig. 4. A 2×2 LOS MIMO system using proposed method.

the Rx_3 antenna is moved and positioned in a pre-determined geometric path. To move the Rx_3 antenna, mechanical elements, such as an electric motor and gear, are necessary. However, if the rotation speed of θ is fast, the channel capacity may be decreased)

$$(x_3, y_3, 0) = (\sqrt{A-((A-B+l^2)/2l)^2}, (A-B+l^2)/2l, 0), \tag{11}$$

where

$$A = (\lambda/4+\sqrt{D^2+2l^2(1-\cos\theta)})^2$$

$$B = (-\lambda/4+\sqrt{D^2+l^2})^2.$$

More generally, if we assume that the Rx_3 antenna is positioned in a 3D space, the coordinate of the Rx_3 antenna can be represented as (x_3, y_3, z_3). Then, using the coordinates of the Rx_1 antenna, Eq. (9) is written as

$$\begin{aligned} x_3^2+(y_3-l)^2+z_3^2 &= (-\lambda/4+\sqrt{D^2+l^2})^2 \\ x_3^2+y_3^2+z_3^2 &= (\lambda/4+\sqrt{D^2+2l^2(1-\cos\theta)})^2 \end{aligned} \tag{12}$$

Using Eq. (12), the coordinate of Rx_3 antenna is determined as

$$\begin{aligned} x_3 &= \sqrt{A-((A-B+l^2)/2l)^2}\cdot\cos\varphi \\ y_3 &= (A-B+l^2)/2l \\ z_3 &= \sqrt{A-((A-B+l^2)/2l)^2}\cdot\sin\varphi,\ -\pi<\varphi\le\pi \end{aligned} \tag{13}$$

Comparing Eqs. (11) and (13), we find that y_3 is identical. Additionally, Eq. (13) shows that the coordinates x_3 and z_3 lie on a circle. Fig. 5 shows the channel capacity of the proposed system as a function of rotation angle θ. We find that the channel capacity can approach the ideal channel capacity regardless of rotation angle θ.

However, in the real-world, the time-delay of the signal path from the Rx_{1_shift} antenna to the combiner output and that from the Rx_3 antenna to the combiner output may not be the same due to the delay characteristics of the antenna, cable, and combiner. If these delay characteristics are considered, Fig. 4 and Eq. (5) must be modified to Fig. 6 and Eq. (14), respectively.

$$\begin{aligned} \hat{r}_1(t) &= r_1(t)e^{j\theta_1}+r_3(t)e^{j\theta_3} \\ &= (e^{-j2\pi d_{11\_shift}/\lambda}e^{j\theta_1}+e^{-j2\pi d_{31}/\lambda}e^{j\theta_3})s_1(t) \\ &= (e^{-j2\pi d_{12\_shift}/\lambda}e^{j\theta_1}+e^{-j2\pi d_{32}/\lambda}e^{j\theta_3})s_1(t) \end{aligned} \tag{14}$$

In Fig. 6 and Eq. (14), θ_1 and θ_3 are carrier phase rotations associated with the time-delay characteristics of the antenna, cable, and combiner in each signal path. Using Eq. (14) and $\theta_3 = \theta_1 + \Delta\theta$, the modified channel matrix $\hat{\boldsymbol{H}}$ is written as

$$\hat{\boldsymbol{H}} = \begin{bmatrix} \hat{h}_{11} & \hat{h}_{12} \\ \hat{h}_{21} & \hat{h}_{22} \end{bmatrix}$$

$$= \begin{bmatrix} \begin{pmatrix} e^{-j2\pi d_{11\_shift}/\lambda} \\ +e^{-j(2\pi d_{31}/\lambda-\Delta\theta)} \end{pmatrix} e^{j\theta_1} & \begin{pmatrix} e^{-j2\pi d_{12\_shift}/\lambda} \\ e^{-j(2\pi d_{32}/\lambda-\Delta\theta)} \end{pmatrix} e^{j\theta_1} \\ e^{-j2\pi d_{21}/\lambda} & e^{-j2\pi d_{22}/\lambda} \end{bmatrix}. \tag{15}$$

Second condition to maximize the channel capacity, presented in Eq. (8), is changed as follows:

$$\begin{aligned} &(2\pi d_{11\_shift}/\lambda-2\pi d_{31}/\lambda) \\ &= -(2\pi d_{12\_shift}/\lambda-2\pi d_{32}/\lambda)+2\Delta\theta \end{aligned} \tag{16}$$

Using Eqs. (7) and (16), d_{31} and d_{32} are changed as follows:

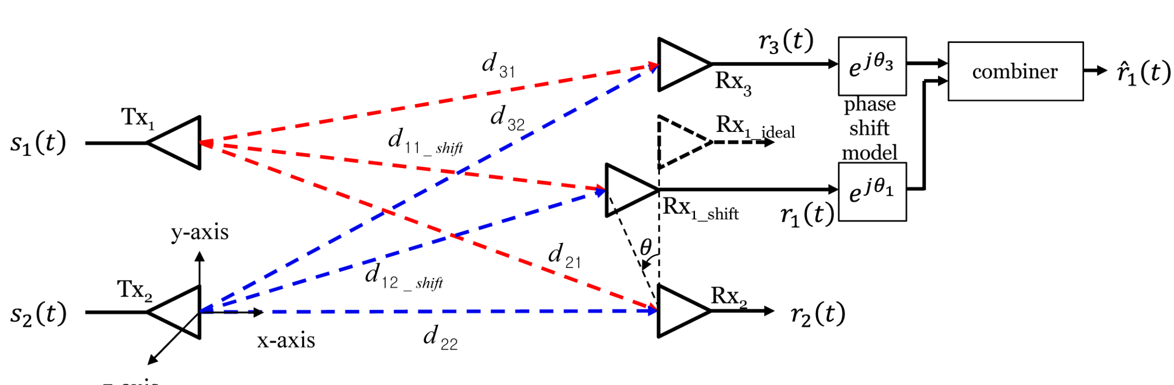

Fig. 6. A 2×2 LOS MIMO system using proposed method (including cable characteristic).

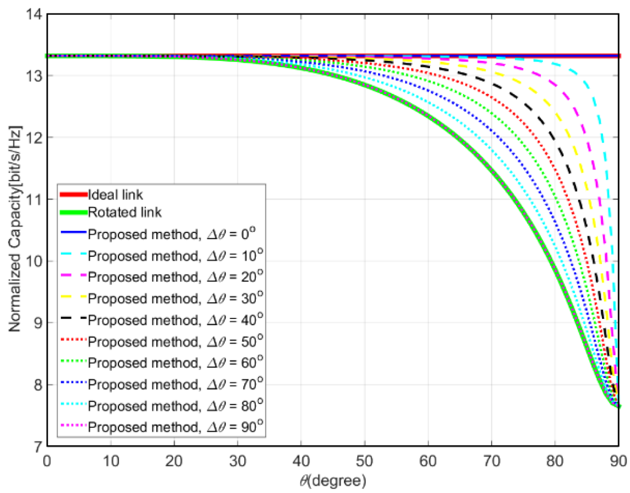

Fig. 7. Channel capacity of the proposed system without considering $\Delta\theta$.

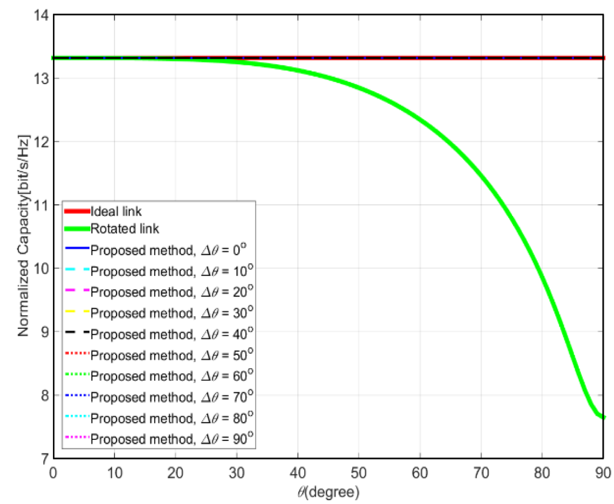

Fig. 8. Channel capacity of the proposed system taking into consideration of $\Delta\theta$.

$$d_{31} = d_{12\_shift} - (\Delta\theta/2\pi + 1/4)\lambda$$
$$d_{32} = d_{11\_shift} - (\Delta\theta/2\pi + 1/4)\lambda \qquad (17)$$

Utilizing Eq. (17), A and B in Eqs. (11) and (13) are changed as follows:

$$A = ((\Delta\theta/2\pi + 1/4)\lambda + \sqrt{D^2 + 2l^2(1-\cos\theta)})^2$$
$$B = (-(\Delta\theta/2\pi + 1/4)\lambda + \sqrt{D^2 + l^2})^2. \qquad (18)$$

By analyzing Eq. (18), we find that the optimal position of the additional receiver antenna is determined analytically by measuring $\Delta\theta$ (it can be measured when the system is installed).

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed method, we set D, the carrier frequency f_c, and the signal-to-noise ratio (SNR) to 4 m, 30 GHz, and 20 dB, respectively [15]. Fig. 7 shows the channel capacity of the proposed system as a function of rotation angle θ. In Fig. 7, the position of the Rx_3 antenna must be determined using Eq. (11). This shows that, since the position of the Rx_3 antenna is determined without considering $\Delta\theta$, the channel capacity decreases as $\Delta\theta$ increases. Fig. 8 shows that, since the position of the Rx_3 antenna is determined using Eq. (18), which takes into account $\Delta\theta$, the channel capacity of the proposed system can approach the ideal channel capacity regardless of $\Delta\theta$. Fig. 9 shows that the channel capacity of the proposed system decreases very slightly as the estimation error of θ increases. This means that a 2×2 LOS MIMO system using the proposed method is robust to the estimation error of θ.

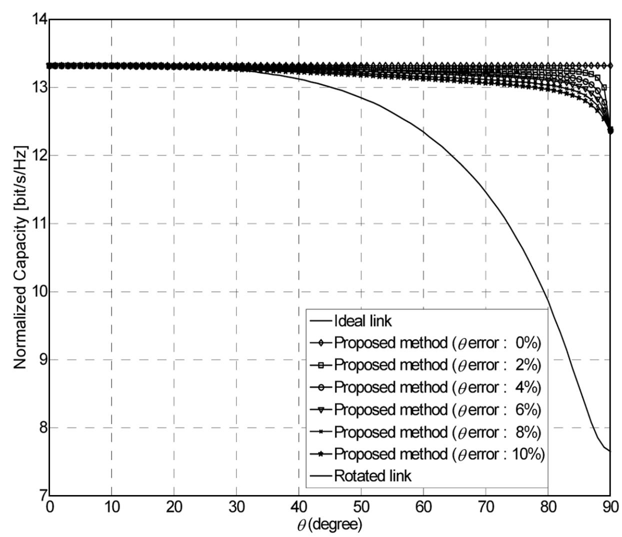

Fig. 9. Relationship between channel capacity of the proposed system and estimation error of θ.

V. CONCLUSION

In this paper, we presented a channel capacity maximization method for a distorted 2×2 LOS MIMO link by adding only an additional receiver antenna. We determined the optimal position of the additional receiver antenna analytically. Simulation results showed that the channel capacity of the proposed system can approach the ideal channel capacity regardless of rotation angle θ. Additionally, it was shown that a 2×2 LOS MIMO system using the proposed method is robust to the estimation error of θ and $\Delta\theta$ due to delay characteristics between signal paths.

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