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Capacity Loss From Localization Error in MIMO Channel Using Leaky Coaxial Cable

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ABSTRACT Leaky coaxial (LCX) cable has been employed as antennas for wireless traffic over many linear-cell scenarios such as railway station, tunnels and shopping malls. In addition, LCX can be used for user localization and wireless power transfer (WPT). Compared with the equal power allocation method, the power allocation method for LCX system using positional information (PI) can improve its capacity with the same level of computational complexity. In this paper, we will investigate the level of capacity loss on the 2.4 GHz and 5 GHz band for the conventional equal power (EP) allocation method, the water-filling (WF) based power allocation, and our proposed low-complexity power allocation method for LCX system with PI. The results show that LCX system with our proposed method using PI can reduce the capacity loss due to localization error than that of others.

INDEX TERMS Leaky coaxial cable (LCX), LCX-MIMO, positional information, channel capacity, power allocation.

I. INTRODUCTION

The 5th generation (5G) wireless technology has greatly promoted the development of real-time control, data acquisition and IoT technology by establishing the interactive connection among large numbers of devices, mobile terminals, various sensors and robots [1]. Some scenarios consider the wireless coverage for a long and shallow area named as linear-cell environment such as highway, manufacturing, railway station train or tunnel [2]. How to achieve high capacity and small localization error is one of major research topics on next generation wireless system over linear-cell environments.

Leaky coaxial cable (LCX) which can be used as antenna has been widely employed in diverse application scenarios because of its potential advantages. LCX has been researched for many years for wireless coverage over many environments with long and shallow shapes [3]. Compared with the conventional circular wireless coverage generated from omni-antennas, the handover process and interference from adjacent cells are reduced when mobile users move across cells. References [4] and [5] show the research of the coverage property and radiation characteristics of LCX with periodic slots over indoor environment. For high frequency bands, LCX can be designed and used for 2.4 GHz Industry Science and Medical (ISM) band [6], [7]. Reference [8] shows the research of LCX employed for train and the train ground communication system. In recent research, it has been found that LCX can be used for wireless power transfer (WPT) system [9].

With the increasing mobile terminals and IoT devices, the limitation of wireless traffic has become a serious problem. Cooperative communication and multiple-input-multiple-output (MIMO) are two of the key 5G techniques that can meet the high throughput requirements and improve the reliability of various dynamic networks such as IoT and Internet of Vehicles (IoV) communication networks [10], [11]. MIMO technique using LCXs is one of promising techniques to improve the spectral efficiency or capacity. The research about LCX-MIMO has just been promoted in recent years. In [12], it has realized a 2-by-2 LCX-MIMO system for office landscape and corridor scenarios with two LCXs. It shows that all measured LCX-MIMO channels are near to an independent and identically distributed (*i.i.d.*) channel. However, the quality of MIMO channel becomes worse when two cables are closely spaced. Different from a 2-by-2 LCX-MIMO system using two LCXs, the research results in [13]–[16] show that we can utilize one LCX as two antennas for the configuration of

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the 2-by-2 LCX-MIMO system. The results show that the peak directivity of propagation angles of LCX usually is highly relative to the signal wavelength, LCX slot period and relative permittivity of insulator. From that, we can control the propagation angle of the LCX by adjusting these parameters and design one LCX as two antennas when we input signals to two sides of LCX. In addition, a 4-by-4 LCX-MIMO system has been proposed in [17]. The idea of the proposal is that we can use two LCXs with different radiation characteristics to form a 4-by-4 MIMO channel.

Real-time control, robot work in automatic environment, wireless power transfer and various applications require not only high-speed wireless communication but also accurate users' locations. Compared with conventional monopole antennas, LCX can detect the location of the terminal in its wireless coverage area. Researches in [18]–[25] show several methods of position detection for LCX systems such as pulse signal technique and the method based on time of arrival (TOA). Reference [18] proposed a method for 1-D position detection with the TOA of the direct wave and the reflected wave from the end of LCX. Compared with 1-D location detection which only estimates the location information along the LCX, one improved method for 2-D localization method using TOA method from multiple LCXs has been researched in [19]. In addition to the TOA method, researches in [20] and [21] also developed a method using the time difference of arrival (TDOA) between the signal arrival at two ends of LCX to detect the location of the user. Several methods based on designed pulse signal are developed in user localization with LCX [22]–[25]. In [22] and [23], a method for 1-D position detection is employed using linear frequency modulation (LFM) pulse signal in zigzag-slotted LCX system. In [24] and [25], a wideband Boolean-chaos signal based on user localization has been studied for MIMO system with a pair of LCXs. References [26] and [27] show a localization detection method in LCX-MIMO using the multiple signal classification (MUSIC) algorithm. Reference [28] provided a different LCX combination for higher localization precision. With these good properties, LCX can be employed for many scenarios such as logistics management systems and manufacturing. In addition, compared with conventional monopole antennas, LCX usually has a constant coupling loss. This property can be further used for transmitting power allocation using the information of user locations.

In [29], a GBSB MIMO model was designed for LCX-MIMO system and the authors researched the capacity performance of LCX-MIMO system in tunnel environment. The result shows the MIMO channel with LCXs in the tunnel has a promising performance. In [30], the authors design and realize a 4-by-4 MIMO channel with one composite LCX. It has also proposed and analyzed a transmission power allocation method with low computational complexity utilizing the user's positional information. The proposed method can improve the capacity of the LCX-MIMO channel with almost the same computational complexity as the conventional equal power allocation method (EP). However, the research assumed that the position information of the user is known perfectly without any localization error. In a real environment, the localization error cannot be avoided because of many factors such as localization algorithm error and resolution of signal processing, etc.

In order to investigate the practicability of the proposed power allocation method and the level of system capacity loss, in this paper, we study the relationship between the LCX-MIMO channel capacity loss and the position detection error when using the proposed power allocation method. We will examine the capacity loss of LCX-MIMO system over the 2.4 GHz and 5 GHz bands with the conventional equal power allocation method, the water-filling (WF) algorithm based power allocation method, and the proposed power allocation method using positional information. In addition, our comparison also considers two different cases as multi-user case and single-user case.

On the other hand, as the experiments are finished in the anechoic chamber, the channel is equivalent to line of sight (LOS) propagation. In order to make the performance of the channel capacity more representative in this research, we also study the channel capacity under both LOS and non-line-sight (NLOS) propagation paths with the geometrically based single-bounce (GBSB) MIMO model for LCX-MIMO system [29].

The rest of paper is structured as follows. In Section II, we introduced the structure and the propagation property of LCX. Then the concept of MIMO channel capacity of two power allocation methods are explained in Section III. The low-complexity power allocation method with user positional information for LCX-MIMO system is shown in Section IV. We give the comparison results of capacity loss from localization error when using the proposed method and conventional methods in Section V, and end the paper with simple conclusions in Section VI.

II. LCX RADIATION PROPERTY AND LCX-MIMO STRUCTURE

A. THE RADIATION DIRECTIVITY OF LCX

Fig. 1 shows the structure of the LCX which is widely used as an antenna for wireless communication. The inner conductor is surrounded by an insulator. The outer conductor is on the outer layer of the insulator and then covered with an insulating coating of plastic resin. There are some slots arranged periodically over the outer conductor, and wireless radio waves can be received and radiated from these slots.

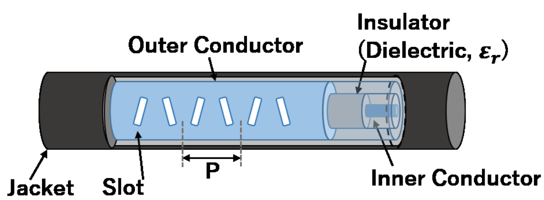


FIGURE 1. The structure of LCX.

When using LCX in basic mode, the radiation angle of the wireless signal from LCX which depends on its waves from all slots can be expressed as

$$\theta_m = \sin^{-1}(\sqrt{\epsilon_r} + \frac{m\lambda}{P}), \quad (m = -1, -2, \ldots) \tag{1}$$

where m is the harmonic order, the radiation angle θ_m is the angle related to the signal propagation direction of the LCX. P is the period of slots and ϵ_r is the LCX's relative insulator permittivity. λ is the wavelength related to the frequency band [4]. m is set as -1 to avoid radiated harmonics. It is possible to change the main radiation angle of the LCX by adjusting the direction of the slot and the value of P.

B. LCX-MIMO STRUCTURE

As shown in Fig. 2 (a), when signals A and B are fed to both sides of the cable simultaneously, the radiation direction of the peak directivity has a crossing angle $2\theta_{-1}$ degree. Therefore, their radiation characteristics have low correlation with each other. Based on this idea, as shown in Fig. 2 (a), radiation directivity in four directions can be obtained by selecting different V1 and V2 type LCXs and adjusting the value P and the slot direction. Furthermore, as shown in Fig. 2 (b), a 4-by-4 LCX-MIMO channel can be realized by combining two LCXs with different peak directivities and radiating crossing angles into one composite cable. Finally, it is possible to adjust the value of P or the type of LCX to obtain a good 4-by-4 MIMO channel.

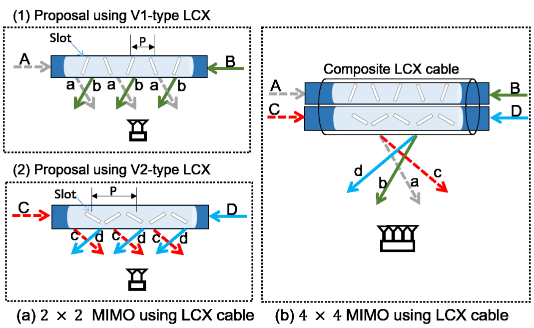


FIGURE 2. LCX-MIMO system.

C. GBSB MODEL FOR LCX-MIMO

GBSB model is established using the basic theory in communication fields as a classical model for channel analysis. In this paper, we provide a GBSB model for LCX-MIMO to show the LCX system over a multipath environment. To save paper's space, the complete theoretical analysis and mathematical formulas for GBSB-MIMO model are not cover here. Only the main content of the GBSB channel modeling for LCX-MIMO will be introduced here. For the content in details, reader can find it in [29].

We consider the LCX-MIMO system configuration in a $H \times W \times L$ space as the Fig. 3 shows. Two LCXs are set as the transmitters on the right side and the receiver is consists of four monopole antennas. It assumes that there are some scatterers on the wall on the left side and the jth scatterer is marked as S_j. The ith slot of one LCX is O_i. We set h_{lp} as the channel gain from one end of the LCX defined as the transmitters Tx_p $(1 \leq p \leq 4)$ to one of the receivers Rx_l $(1 \leq l \leq 4)$. Therefore, the channel between the transmitter and the receiver can be represented with a 4×4 complex matrix as $[\mathbf{H}]_{lp} = h_{lp}, (1 \leq l, p \leq 4)$. The signal propagation path from transmitter to receiver includes two parts as the LOS component and the NLOS component. From that, the channel gain h_{lp} can be written as

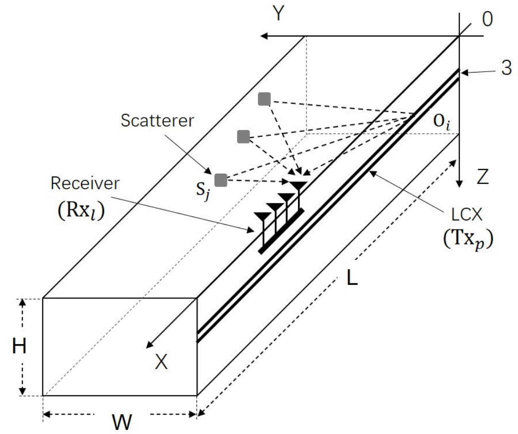


FIGURE 3. LCX-MIMO system configuration with GBSB model.

$$h_{lp} = h_{lp}^{LOS} + h_{lp}^{NLOS}, \tag{2}$$

where h_{lp}^{LOS} is deterministic process and h_{lp}^{NLOS} is stochastic process. According to GBSB model and LCX's radiation characteristics, we can epress the LOS and NLOS component by

$$h_{lp}^{LOS} = \sqrt{\frac{K_{lp} \cdot \Omega_{lp}}{K_{lp}+1}} \cdot \frac{1}{\sqrt{N}} \sum_{i=1}^{N} g_{lp,i}^{LOS} e^{-j(k_0 r_{lp,i} + \beta_i)} \tag{3}$$

$$h_{lp}^{NLOS} = \sqrt{\frac{\Omega_{lp}}{K_{lp}+1}} \cdot \frac{1}{\sqrt{NM}} \sum_{i=1}^{N} \sum_{j=1}^{M} g_{lp,ij}^{NLOS} \cdot e^{j\varphi_{ij}} \cdot e^{-j(k_0 r_{lp,ij} + \beta_i)}. \tag{4}$$

Here, Ω_{lp} is the received power from Tx_p to Rx_l and $\Omega_{lp} = E[|h_{lp}|^2]$. K_{lp} is Ricean K-factor which represents the ratio between LOS component power and NLOS component power. N and M are the number of the slots and scatterers. $g_{lp,i}^{LOS}$ is the normalization amplitude of LOS signal wave from one LCX end Tx_p via slot O_i to Rx_l. $g_{lp,ij}^{NLOS}$ is the normalization amplitude of NLOS signal wave from one LCX end Tx_p via slot O_i and scatterer S_j to Rx_l. k_0 is the propagation constant of electrical wave in free space. The distance from slot O_i of Tx_p to Rx_l is $r_{lp,i}$ and the distance from slot O_i of Tx_p via scatterer S_j to Rx_l is $r_{lp,ij}$. β_i is the phase variation and φ_{ij} is the i.i.d random variables with uniform distributions at $[0,2\pi)$.

III. CAPACITY OF MIMO CHANNEL

MIMO channel capacity named as Shannon ergodic channel capacity generally shows a fundamental property and limitation of MIMO system [31]. Here, the channel capacity can be described under two conditions. The first one is that the channel state information (CSI) **H** is not known on the transmitter side. In such a case, the channel capacity becomes optimal if the transmitter side allocates power to each stream using the equal power (EP) allocation method. We assume that **H** is only knows at the receiver side, the MIMO capacity using the equal power (EP) allocation method can be expressed by the following equation

$$C_{EP} = \mathbb{E}_{\mathbf{H}}\left[\log_2(\det[\mathbf{I} + \frac{\zeta}{N}\mathbf{H}\mathbf{H}^H])\right], \tag{5}$$

where ζ is the average signal-to-noise ratio (SNR) at receiver, N and $\mathbf{I}$ are the antenna number at transmitter and the identity matrix. We use the superscript H to represent the Hermitian transpose.

On the other hand, if the CSI is known at the transmitter, the optimal Shannon ergodic capacity of the MIMO channel can be achieved by the power allocation method based on the water-filling (WF) algorithm [32], and the channel capacity can be expressed as

$$C_{WF} = \mathbb{E}_{\mathbf{H}}\left[\sum_{i=1}^{N}\log_2(1 + \lambda_i P_i)\right]. \tag{6}$$

Here λ_i is the corresponding eigenvalue of CSI matrix. P_i is the power allocated for the ith MIMO eigenchannel as

$$P_i = (\mu - \frac{1}{\lambda_i})^+, \tag{7}$$

where μ is water-fill level and x^+ means the result of $\max(x, 0)$. The WF algorithm fills each eigenchannel with power to the level μ iteratively and the MIMO channel capacity is represented as

$$C_{WF} = \mathbb{E}_{\mathbf{H}}\left[\sum_{i=1}^{N}(\log_2(\lambda_i \mu))^+\right]. \tag{8}$$

Equations (5) and (8) above are normalized by bandwidth.

The Shannon ergodic capacity of a MIMO channel using the WF method is generally larger than the capacity using the EP power allocation method. However, the power allocation method based on WF has the drawback of requiring CSI feedback from receiver side and enormous amount of calculation, so this capacity is hard to realize in a real environment, and is often used as the upper bound of MIMO channel capacity.

IV. LCX-MIMO CHANNEL CAPACITY USING USER POSITION INFORMATION

A. THE PROPOSED POWER ALLOCATION METHOD USING USER POSITION INFORMATION

Localization with LCX system has been researched for many years. It has developed several methods for LCX localization such as methods based on TOA and pulse signal compression technique [18]–[25]. References [20] and [21] show the TDOA method using time difference between the arrived signal at two ends of the cable. Therefore, we can have a good accuracy of user location detection for application. In addition, compared with wireless transmission over air, the signal transmission over the LCX has a fixed power loss and these properties can be used for power allocation to improve the channel capacity of the communication system.

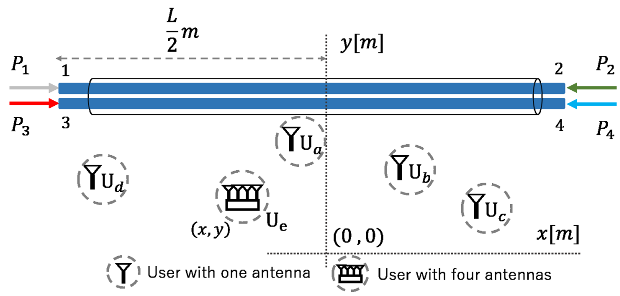


FIGURE 4. The power allocation method with positional information.

The power allocation method using positional information is based on the fact that the power loss rate is constant when signal is transmitted over the LCX. The main idea of the method is adjusting the power at LCX side in considering of the known constant cable loss. Here we use the Fig. 4 to show the power allocation method for the single-user case and the multi-user case. As shown in Fig. 4, in the case of the single user, only a single user U_e with four antennas is set to utilizes 4-by-4 LCX-MIMO channel for wireless communication. On the other hand, in the case of the multi-user, U_a, U_b, U_c, U_d are four users with one antenna and we assume that these four single-antenna users are accessed to the LCX-MIMO simultaneously. Power is allocated to each port of the cable according to the ratio of the distance between the user and both ends of the cable. Here, the length of the LCX is L [m], where the known position of the user is (x,y). First, in the case of the single user, the power allocation method using positional information (x,y) is shown as

$$\begin{cases} \sum_{i=1}^{i=4} P_i = P \\ P_1 = P_3; P_2 = P_4 \\ \dfrac{P_1}{\frac{L}{2} + x} = \dfrac{P_2}{\frac{L}{2} - x}. \end{cases} \tag{9}$$

On the other hand, for the multi-user case, the system calculates the distance from each user to both sides of the cable along the X-axis firstly. Next, it chooses the port closest to each user. In Fig. 4, it provides 4 streams between U_a and port 1, U_d and port 3, user U_b and port 2, U_c and port 4, respectively. We assume that the users' position information are x_a, x_b, x_c, x_d, the power allocation method using the positional information is expressed as the following formula

$$\begin{cases} \dfrac{P_1}{L/2+x_a} = \dfrac{P_3}{L/2+x_d} \\ = \dfrac{P_2}{L/2-x_b} = \dfrac{P_4}{L/2-x_c} \\ \sum\limits_{i=1}^{i=4} P_i = P. \end{cases} \tag{10}$$

B. LCX LOCALIZATION ALGORITHM AND COMPLEXITY OF THE POWER ALLOCATION METHOD

We give a brief introduction on the localization method in LCX-MIMO system. The main idea of the proposed method is based on the fact that the times of the signals from user to both ends of the LCX are different. We can measure the difference time of arrival (DToA) of both signals to estimate the user's location. For time arrival estimation, the method based on multiple signal classification (MUSIC) algorithm is used in LCX-MIMO system in our recent researches [26]–[28]. We used the orthogonality between the signal and noise to analyze the signal samples from the limited bandwidth and then employed the MUSIC method to estimate the ToA of signal.

For the complexity of the power allocation method, equal power (EP) allocation method which allocates power to each stream equally has low computational complexity. The power allocation methods based on the water-filling (WF) algorithm require the feedback of the real-time CSI from the receiver side, and it needs high computational complexity in practical application. From (9) and (10) above, our proposed power allocation method using positional information (PI) just requires the positional information of users and allocates the power according to the radio of the distances from the user to the ends of the cable, so the proposed PI method in LCX-MIMO system has low computational complexity as that of the EP method.

C. LCX-MIMO CHANNEL CAPACITY WITH POWER ALLOCATION METHOD

Let us use Fig. 5 to show the reason of that PI power allocation method using positional information (PI) has a larger capacity than that of the EP power allocation method over the low SNR range. We assume a 2-by-2 LCX-MIMO channel $\mathbf{H}$ and λ_1, λ_2 ($\lambda_1 > \lambda_2$) as the corresponding eigenvalue of the $\mathbf{HH}^H$. As the user is approaching near to one side of the LCX, the channel power from the other side of the LCX becomes weaker and the difference between λ_1 and λ_2 will get larger. The purpose of the proposed PI method is to reduce the value of λ_1 and increase the value of λ_2 by adjusting the transmission power from both sides of the LCX.

To simplify the analysis, the total power and the noise power are assumed to be unit and N, respectively. From this, the channel capacity obtained by the EP method will be expressed by the following equation as

$$C_{EP} = \log(1+\frac{\lambda_1}{2N}) + \log(1+\frac{\lambda_2}{2N}). \tag{11}$$

In the case of the PI allocation method, it is assumed that k (k>0.5) power is allocated to λ_2, and the power $(1-k)$ is allocated to λ_1. The equation for the channel capacity obtained by the PI allocation method is as

$$C_{PI} = \log(1+\frac{(1-k)\lambda_1}{N}) + \log(1+\frac{k\lambda_2}{N}), \tag{12}$$

When $k = 0.5$, both methods have the same capacity.

As shown in Fig. 5, the capacity of the EP method is $C_{EP} = C_1 + C_4$, and the PI method ($C_{PI} = C_2 + C_3$) increases EP method from C_1 to C_2, but reduces from C_4 to C_3. Due to the property of the logarithmic function, when the SNR value is small, the capacity increment is larger than the capacity decrement as $(C_2-C_1) > (C_4-C_3)$. Therefore, the PI method can achieve better capacity than the EP method as $C_{PI} > C_{EP}$. However, when the SNR value is large, the allocation of the PI method increases the capacity from C_5 to C_6 but reduces the capacity from C_8 to C_7. The capacity increment is smaller than the decrement as $(C_6 - C_5) < (C_8 - C_7)$. As a result, the total capacity of the PI method is smaller than that of the EP method as $C_{PI} < C_{EP}$.

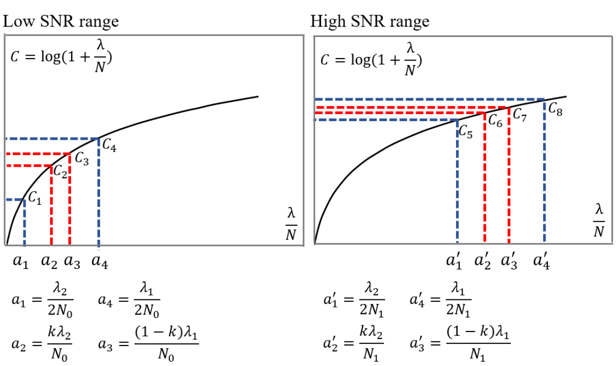


FIGURE 5. The mechanism of the PI power allocation method.

D. THE POWER ALLOCATION WITH USER's LOCALIZATION ERROR

LCX can detect user position, However, it is impossible and impractical to obtain the correct PI of the user. Over the real environment, estimation error often occurs when the user location information detected using LCX. In this paper, we evaluated the capacity of the LCX-MIMO channel with the proposed PI based power allocation method. However, the location information includes error item shown in Fig. 6.

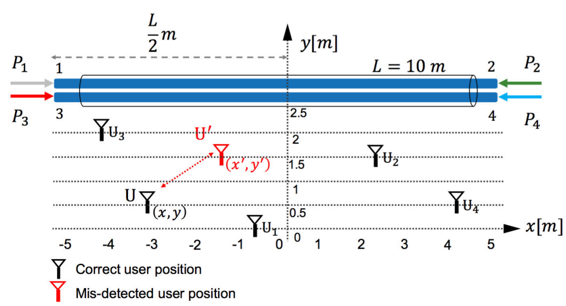


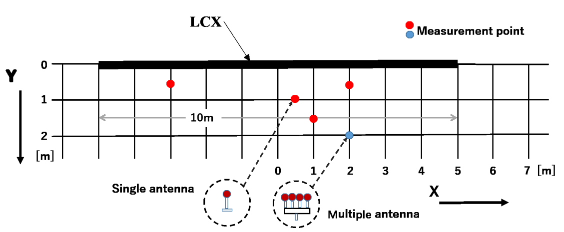
FIGURE 6. Detection error in user's location.

Suppose user U is a terminal in the wireless coverage area with (x, y) as its correct positional information. When localization error occurs, the correct location of this terminal is mis-detected as U$'$ with the wrong positional information (x', y'). When operating the power allocation, the system uses the wrong positional information (x', y') as for algorithm as in formula (9) and (10). For the single-user case, the position (x, y) of each user U is detected as (x', y'). For the multi-user case, the X-axis positional information (PI) of all users U_1, U_2, U_3, U_4, as (x_1, x_2, x_3, x_4) will be mis-detected as (x_1', x_2', x_3', x_4').

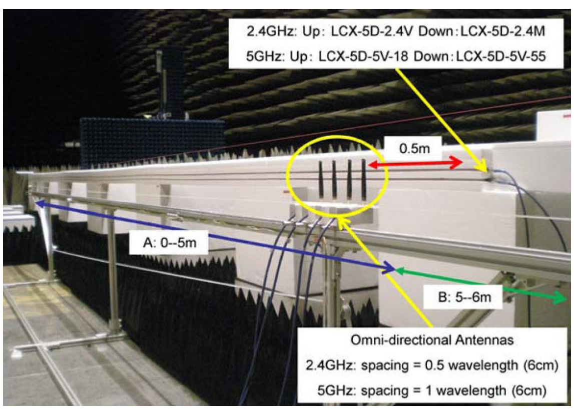
V. MEASUREMENT AND CAPACITY RESULTS

A. MEASUREMENT OF LCX-MIMO CHANNEL IN ANECHOIC CHAMBER

The channel matrix between the LCX and the receiving antenna was measured with a multi-port vector network analyzer in an anechoic chamber. The configuration of the measurement is shown in Fig. 7(a). The length of the LCX is 10 m. The X- and Y-axis are the longitudinal direction along the LCX and the direction from the cable to the receiving antenna. Here, it is assumed that the center of the LCX is the origin point. Each user receiving antenna was a monopole antenna. Measurement points are set at equal intervals of 25.4 mm over the X-axis range of [−6 m, 6 m]. The Y-axis values are fixed at 0.5 m, 1 m, 1.5 m, 2.0 m, and 2.5 m, respectively. Receiving antennas are set at each measurement point to measure the channel between the LCX and the receiving antenna and then the average channel capacity will be calculated.



(a) The measurement configuration of LCX-MIMO channel



(b) The measurement configuration in the anechoic chamber

FIGURE 7. The measurement configuration of LCX-MIMO channel.

Table 1 shows the specifications of the selected composite LCX for experiments in the 2.4 GHz frequency band. The distance between the two cables is set to 3 cm. The antenna gain of the user's monopole type is 1 dBi. The measurement frequency range is set to a bandwidth of 500 MHz centered at 2.452 GHz, the frequency interval is set to 1.25 MHz, and 401 frequency samples are obtained at each measurement point. Table 2 shows the specifications of the selected composite LCX for the experiment in the 5 GHz frequency band. The distance between two LCXs is set to 3 cm. The measurement frequency range is set to the bandwidth from 5.15 GHz to 5.65 GHz, the frequency interval is set to 1 MHz, and 501 samples are obtained at each measurement point. The distance between the receiving antennas of the user is set to 0.5 wavelength over the 2.4 GHz frequency band and 1 wavelength over the 5 GHz frequency band. Fig. 7(b) shows the experiment environment in the anechoic chamber.

TABLE 1. Specifications of LCX (2.4GHz).

Cable type	M-type, V-type
Slot spacing P	80 mm
Coupling loss	60 dB ± 5 dB @1.5m
Cable loss	V-type: 0.4 dB/m, M-type: 0.3 dB/m
Inner copper wire diameter	2mm
Insulator (foamed polyethylene) diameter	5mm
Outer sheathe thickness	1mm
Cable diameter	7mm
VSWR	1.1

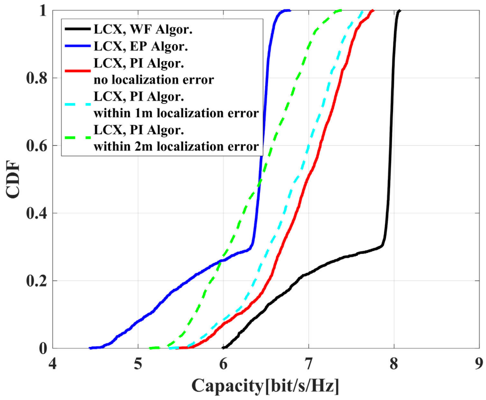
TABLE 2. Specifications of LCX (5GHz).

Cable type	V-type for both
Slot spacing P	40mm for 18Deg., 30mm for 55Deg.
Coupling loss	60dB ± 5 dB @1.5m
Cable loss	0.6dB/m
Inner copper wire diameter	2mm
Insulator (foamed polyethylene) diameter	5mm
Outer sheathe thickness	1mm
Cable diameter	7mm
VSWR	1.2

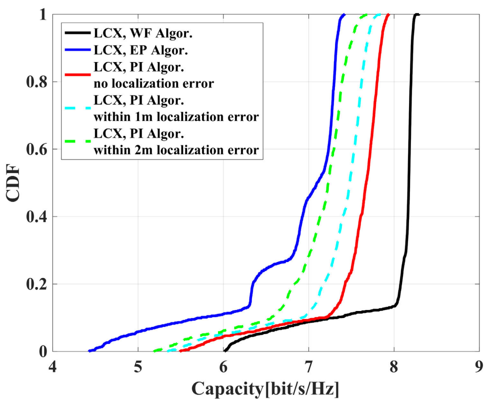
B. LCX-MIMO CHANNEL WITH GBSB MODEL

In order to study the capacity loss in the environment with both LOS and NLOS propagation paths, we investigate the channel capacity by simulating the LCX-MIMO channel using the GBSB-MIMO channel model.

For the simulation, we set the scale of the space as 3(m) × 5(m) × 10(m) as shown in Fig. 3. The height of the LCX upside is fixed to 2.5 m above the ground and the distance between two cables is set as 3 cm. The height of the user is fixed to 1.8 m above the ground. We set the measurement points and the measurement frequency as same as the experiment in anechoic chamber in above section. The slot spacing

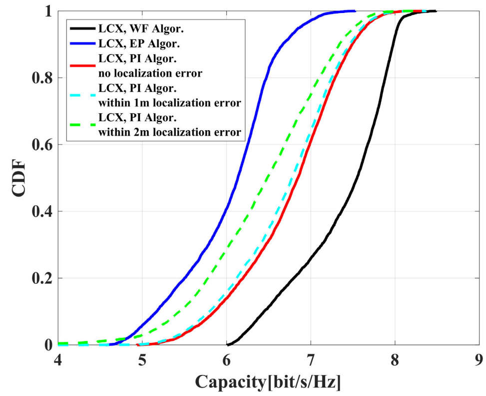


(a) CDF of the capacity result over 2.4GHz band (SNR=6dB, single-user case, anechoic chamber environment)

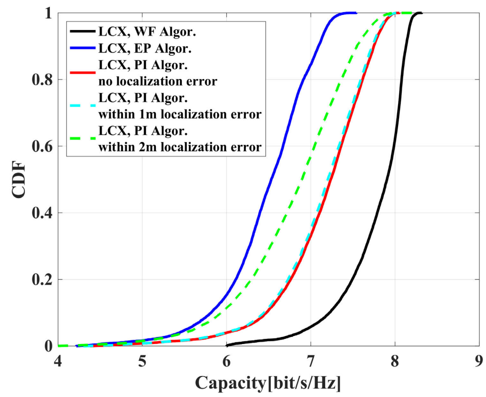


(b) CDF of the capacity result over 5GHz band (SNR=6dB, single-user case, anechoic chamber environment)

FIGURE 8. The capacity results of LCX-MIMO channel over 2.4 GHz and 5 GHz band in anechoic chamber environment (single-user case).



(a) CDF of the capacity result over 2.4GHz band (SNR=6dB, multi-user case, anechoic chamber environment)



(b) CDF of the capacity result over 5GHz band (SNR=6dB, multi-user case, anechoic chamber environment)

FIGURE 9. The capacity results of LCX-MIMO channel over 2.4 GHz and 5 GHz band in anechoic chamber environment (multi-user case).

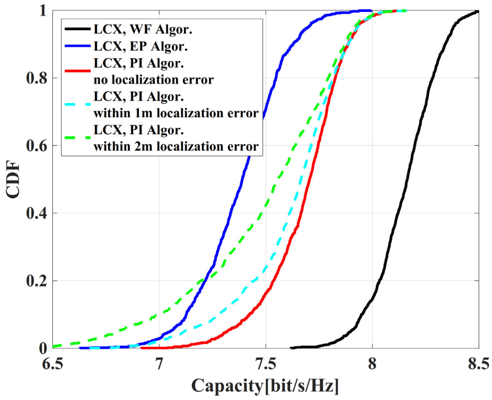
and cable loss of the LCX are set as same as the specifications in Table 1 and Table 2. We assume that $M = 100$ scatterers are uniformly distributed over the wall on the left side.

C. CHANNEL CAPACITY RESULTS OF LCX-MIMO

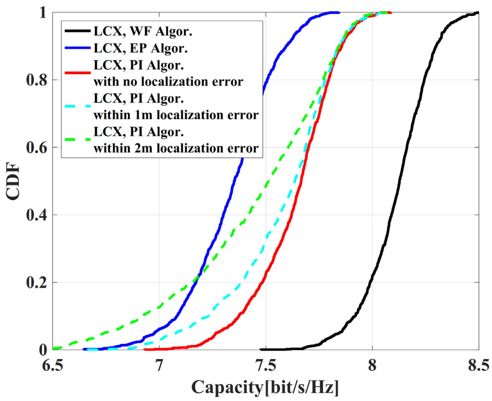
In this paper, in order to observe the loss of the channel capacity of LCX-MIMO using PI power allocation method due to the user positional information error, the channel capacity is evaluated under three conditions where the position error was 0 m, within 1 m, and within 2 m. The position error here is the coordinate error on the X axis in Fig. 3 or Fig. 7(a) and does not include the error on the Y axis. Position error within 1 m means that the position error is set randomly within the range from 0 m to 1 m. On the other hand, SNR is one of the important factors affecting both channel capacity and localization error. The capacity gets larger and the localization error gets smaller when SNR is over the high range. Conversely, in the low SNR range, the capacity and the localization error become worse. Considering the communication with a large number of low-power IoT devices in the future application scenarios, we mainly evaluate the channel capacity of LCX-MIMO in low SNR range in this research. In addition to the capacity results of PI method with location error, we also provide the capacity results of EP method and WF method. The results of all channel capacities are shown by the cumulative distribution function (CDF).

Fig. 8(a) and Fig. 9(a) show the channel capacity results of single-user case and multi-user case over 2.4 GHz frequency band. Here, the SNR value is fixed to 6 dB. When the position error is 0 m, in the single-user case of Fig. 8(a), PI method has 80% of the samples measured that have the value of channel capacity exceeding 6.5 bit/s/Hz. However, EP method has only 20% under the same conditions. PI method has 70% of the samples measured that have the value of channel capacity exceeding 9.5 bit/s/Hz, where EP method only has 10%. In the multi-user case of Fig. 9(a), it was found that the PI method is 0.5 bit/s/Hz higher than the EP method on average. From these results, LCX-MIMO can increase the channel capacity by easily adjusting the power allocation based on the known power loss of the cable and using the user's positional information.

When the positional information error is within 1 m, the capacity obtained by the PI method drops slightly, but

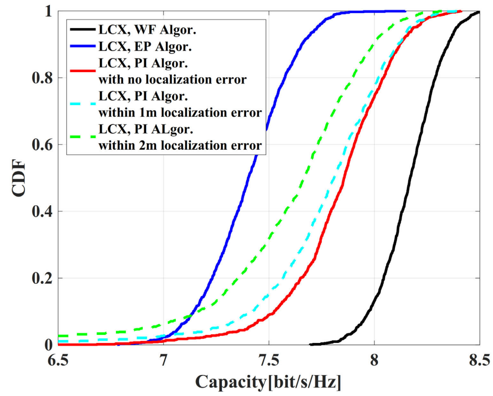


(a) CDF of the capacity result over 2.4GHz band (SNR=6dB, single-user case, simulation with GBSB model)

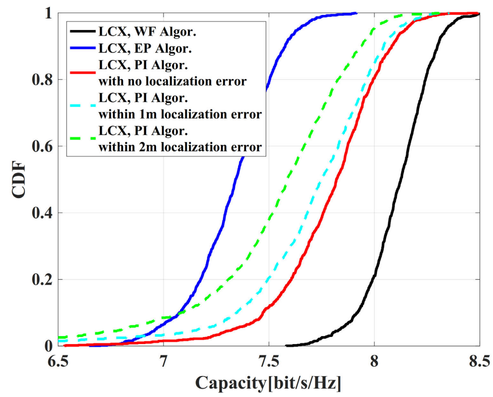


(b) CDF of the capacity result over 5GHz band (SNR=6dB, single-user case, simulation with GBSB model)

FIGURE 10. **The capacity results of LCX-MIMO channel over 2.4 GHz and 5 GHz band in simulation with GBSB model (single-user case).**



(a) CDF of the capacity result over 2.4GHz band (SNR=6dB, multi-user case, simulation with GBSB model)



(b) CDF of the capacity result over 5GHz band (SNR=6dB, multi-user case, simulation with GBSB model)

FIGURE 11. **The capacity results of LCX-MIMO channel over 2.4 GHz and 5 GHz band in simulation with GBSB model (multi-user case).**

it is still close to the capacity without position error and is superior to the capacity of the EP method. When the error is within 2 m, for the single-user case of Fig. 8(a), the PI method has a large decrease in the obtained capacity, but it is slightly better than the EP method. In the multi-user case of Fig. 9(a), it is shown that the PI method is 0.3 bit/s/Hz higher than the EP method on average. LCX-MIMO using the PI method can obtain a good channel capacity even if user positional information error occurs, and is superior in fault tolerance of position error to a MIMO system composed of ordinary monopole antennas.

Fig. 8(b) and Fig. 9(b) show the results of single-user and multi-user channel capacities over 5 GHz frequency band. Although the results are similar to the 2.4 GHz frequency band, the channel capacity of the 5 GHz frequency band is a little higher than the 2.4 GHz frequency band as a whole.

Fig. 10 and Fig. 11 show the capacity results of the simulation with GBSB model under single-user case and multi-user case. It is also operated over 2.4 GHz and 5 GHz frequency band and SNR value is fixed to 6 dB. The channel capacity distribution of three power allocation methods is roughly same as the measurement experiment in anechoic chamber. As the result of single-user case in Fig. 10, when the positional information error is 0 m or within 1 m, the PI method can obtain promising capacity. However, when the error increase, the capacity of PI method become worse. From the comparison of Fig. 10 and Fig. 11, we find that the capacity of PI method in multi-user case is a little better than that in single-user case.

VI. CONCLUSION

In this paper, based on the power allocation method using positional information, we investigated the channel capacity of the LCX-MIMO channel considering the user location error and we carried out measurements in the anechoic chamber and simulated the LCX-MIMO channel over multipath environment using GBSB model. From the experimental results, LCX-MIMO can increase the channel capacity by easily adjusting the power allocation using the user's positional information. In addition, PI method can obtain a good channel capacity even if the user positional information error occurs. In other words, this research aims to find the tolerance of localization error for the LCX-MIMO system with the acceptable capacity loss. From the simulated results using GBSB model, we can find the LCX-MIMO channel capacity is promising over multipath environment. Furthermore, it was shown that the multi-user case is less affected by the position information error than the single-user case. LCX-MIMO can be expected to be an effective communication system that meets these technical requirements in scenarios such as automated factories that require real-time control, position localization, multi-user connection, and high-speed communication.

It will be our future research work to observe how the channel capacity of LCX-MIMO changes in a real environment. As an important part of the future research, we will also put our attention on improving the accuracy of user localization with multiple LCXs.

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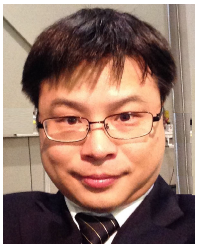

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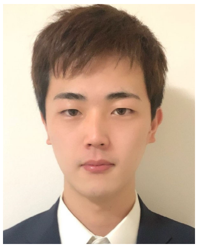

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