Capacity Evaluation of MIMO Channel With One Leaky Coaxial Cable Used as Two Antennas Over Linear-Cell Environments

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Abstract—Leaky coaxial (LCX) cable is widely used in wireless communication systems as an antenna, especially for a long and narrow area called the linear-cell environment. The general usage of LCX cable is that it can be treated as one antenna. To configure a multiple-input–multiple-output (MIMO) system, it requires more than one LCX cable. In this paper, we propose a simple design in which one single LCX cable can be used as two antennas. Therefore, the proposal reduces the cost and spacing requirement and releases the space requirement of MIMO deployment for wireless application over linear-cell environments. We will study the capacity of the proposed LCX–MIMO system using equal power (EP) allocation and water-filling power allocation and compare its capacity with the conventional MIMO system using monopole antennas. The capacity results over the 2.4 GHz band and the 5 GHz band show that the proposed LCX–MIMO channel has better capacity than that of using monopole antennas over linear-cell environments. In particular, it can achieve more capacity improvement than that of channel using monopole antennas with the simple EP allocation. The throughput experiments over 5 GHz also show that our proposal can achieve the higher and stable throughput over the radiation coverage of LCX cable.

Index Terms—Channel capacity, channel measurement, leaky coaxial (LCX) cable, multiple-input–multiple-output (MIMO) channel.

I. INTRODUCTION

WIRELESS technologies have been widely designed for many special wireless coverage areas and applications using antenna technique. Different from the general assumption that the wireless coverage of the monopole antenna is circle like, some scenarios are considered with a long and shallow places called the linear-cell environment. The linear-cell environment includes many scenarios, such as tunnel, along a railway, underground shopping mall, interior of vehicles, such as railway carriage or airplane, etc. For the linear-cell environment, a wireless system using a leaky coaxial (LCX) cable as an antenna for radio communication is widely used because LCX has many potential advantages. For example, its coverage is uniform and the installation might be simpler [1]. In addition, the frequency of the handover process can be reduced from omni-cell with the same service area when users are moving along the LCX.

Since the wireless traffic is rapidly increasing due to the popularization of high-performance mobile terminals, improvement in spectral efficiency is an important research topic. To achieve this purpose, the multiple-input–multiple-output (MIMO) technique is proposed to increase the channel capacity, which is a key part of the current and evolving wireless access systems, such as long-term evolution (LTE), wireless local area networks (WLANs), Worldwide Interoperability for Microwave Access (WiMAX), and LTE-Advanced that can be deployed both in a large cell and in the picocell or femtocell systems [2].

The theoretical research of coverage and radiation characteristics of an LCX cable has been studied for many years. Using a ray tracing model, Morgan [3] has researched its coverage characteristics over indoor environment. The radiation characteristics of the LCX cable with periodic slots have been discussed in [4], and further researched with the finite-difference time-domain method and mode expansion method in [5]. In addition, the LCX cable has been utilized for many real systems. The LCX cable has been largely used for train system [6], [7] and train ground communications system [8]. Although the LCX was used for lower frequency bands, some LCXs have been developed for higher frequency bands, such as 2.4 GHz ISM band [8], [9]. Suzuki et al. [9] show the characteristics of 2.4 GHz LCX cable through simulations and field tests. The results show that the communication through 2.4 GHz frequency band using an LCX can provide stronger radio signals and thus better throughput compared with free space in tunnels. On the other hand, compared with other type of antennas, the transmission delay between LCX cables can be utilized to detect the position of users [10], [11] that largely benefits the applications over linear-cell environments. The research of configuring the
MIMO system using LCX cables just started recently. In [12], two independent LCXs are utilized to configure 2-by-2\textsuperscript{1} indoor MIMO system, and some experimental studies of this type of MIMO system were reported for a corridor scenario and an office landscape scenario. The measurement results in [12] show that LCXs are suited for MIMO in indoor scenarios and the observed channel MIMO quality is close to an independent and identically distributed (i.i.d.) channel quality for all measurement cases. In addition, Medbo and Nilsson [12] also point out that the observed channel MIMO quality becomes worse than the i.i.d. quality when the cables were closely spaced.

However, until now, all other works assumed that one LCX cable is treated only as one antenna. To configure an MIMO system, it needs more than one LCX cable that requires more cost for the configuration of MIMO and large spacing between LCXs. Therefore, we will propose a method that one single LCX cable can be used as two antennas [13]–[17]. The main idea comes from that the propagation angles with peak directivity of LCX cable usually depend on the relative permittivity of insulator, wavelength of input radio-frequency (RF) signal, and the period of slots of LCX. Therefore, we can design the propagation angle using these parameters. When different RF transmit signals are fed to each end of the cable, the single LCX can work as two antennas. On the other hand, by adjusting the inclination angle of slot and its period, we can use one composite cable, which consists of a pair of LCX cables with different radiation directivities, to configure a 4-by-4 MIMO channel [16], [17].

This paper will show the proposal that a single LCX can work as two antennas, investigate the Shannon ergodic capacity of the proposed LCX–MIMO channel, and compare its capacity with the MIMO system using monopole antennas over the 2.4 GHz band and the 5 GHz band. The capacities of each channel are evaluated and compared using the two power allocations methods, namely, equal power (EP) allocation and the water-filling (WF) power allocation. The capacity results show that the proposed LCX–MIMO channel has better capacity than that of using monopole antennas at both sides over linear-cell environments. The proposed LCX–MIMO channel using the WF allocation scheme can also have the capacity near to that of i.i.d. channel over the 2.4 GHz and 5 GHz bands. On the other hand, the capacity can be improved using the simple EP allocation scheme if the system utilizes LCX cables to configure MIMO systems. The throughput experiments also confirm that our proposal can provide high-speed wireless access services for our dairy living.

This paper is organized as follows. The fundamental idea of that a single LCX can work as two antennas and how to configure the LCX–MIMO system is explained in Section II. Then, the capacity of the MIMO channel using the EP allocation and the WF power allocation is introduced in Section III. The capacities of each 2-by-2 MIMO channel are evaluated and compared using the two power allocations over the 2.4 GHz and 5 GHz bands in Section IV. The effect on MIMO channel condition due to decay over the LCX cable is also evaluated in Section IV. The capacity and experiment results of throughput of the proposed LCX–MIMO system over the 5 GHz band are given in Section V. This paper ends with the conclusions presented in Section VI.

II. PROPOSED LEAKY COAXIAL MULTIPLE-INPUT–MULTIPLE-OUTPUT STRUCTURE

A. LCX Cable and Its Propagation Directions

An LCX cable has two fundamental uses: One is used as a feeder, and the other is treated as an antenna. Fig. 1(a) shows an example structure of the LCX cable. Radio wave is radiated and received from slots, which are periodically located along the outer conductor in the cable. Signal strength of radio waves at far-field region from the LCX cable is related to sum of the radiated radio waves from the slots. Radiation angles with peak directivity are

\[
\theta_m = \sin^{-1} \left( \sqrt{\varepsilon_r + \frac{m\lambda}{P}} \right), \quad (m = -1, -2, \ldots) \tag{1}
\]

[1] We use “\(N_t\)-by-\(N_r\)” to represent a MIMO system with \(N_t\) transmitter antennas and \(N_r\) receiver antennas.
where \( m \) is an order of harmonic, \( \epsilon_r \) is relative permittivity of an insulator in the LCX cable, \( \lambda \) is wavelength, \( P \) is the period of slots [4], and \( \theta_m \) is an angle relative to the direction of the RF signal propagation in the LCX. To avoid radiation of harmonics, LCX cable is typically designed as taking value \( m = -1 \). By changing the direction of a slot and the spacing between the slots \( P \), the dominant radiation area of LCX is accordingly changed.

### B. Proposed LCX–MIMO Structure

For any LCX cable with \( \theta_{-1} \neq 0 \), as shown in Fig. 1(b), the radiation patterns of two different input RF signal propagations have different directions. It means that the radiation angles with peak directivity from two different input RF signal propagations will have about 2\( \theta_{-1} \) degree in the area. Therefore, we can adjust the value \( P \) to change the radiation characteristics and directions to achieve promising MIMO channel condition.

It is usually assumed that one LCX is only applied as one antenna. However, as shown in Fig. 2(a), the radiation pattern of an LCX at the 5.35 GHz band. In this measurement, an LCX of 3 m length was put on a turntable. Measurement signal was fed from each end of the LCX, and the opposite end was terminated by a 50-\( \Omega \) resister, respectively. We evaluated LCX cables with the intersection angle \( \theta_{-1} \) as \(-18^\circ\) and \(-55^\circ\) which marked the LCX cables as LCX-5D-5V-18 and LCX-5D-5V-55, respectively. Fig. 3 shows measurement results at a 5-m distance from the center of the LCX at the 5.35 GHz in an anechoic
chamber. An arrow beside the figure gives a direction of an RF signal propagation in the LCX. The angle of dominant radiations which is perpendicular to the LCX cable can be found around $\pm 18^\circ$ and $\pm 55^\circ$, as shown in Fig. 3(a) and (b), that are measured from signal input side. These results suggest that the single LCX can be used as two antennas. To further show different angles of dominant radiation, we measured the received power along the LCX cable with 0.5 m distance, as shown in Fig. 3(c) in an anechoic chamber. The LCX cable is 10 m and the middle position is defined as 0 m (the measurement configuration is also shown in Fig. 6 and here Y-axis is 0.5 m). We can find that the LCX cable with the larger angle of dominant radiation will have higher power decay at the border of LCX cable.

C. LCX–MIMO System Using the Proposed LCX Cable

Based on previous explanation, we can design an LCX–MIMO system using the proposed LCX cable. Fig. 4 shows a proposed 2-by-2 LCX–MIMO system. Here, each user equipment has two conventional antennas.\(^2\) The base station can send symbols using two ends of an LCX cable as Tx1 and Tx2, which has two different directions of RF signal propagation as A and B. The radiation patterns of input RF signal propagations have different propagation directions. Therefore, the signal at one receiving antenna can have low correlation with that at the other one if two receiving antennas have appropriate distance $w(\lambda)$ between each other and appropriate distance $d$ from the LCX cable. The proposed LCX–MIMO system has the identical practical structure of that of using conventional monopole antennas instead of two conventional antennas with one LCX cable. Both input signal A and B will simultaneously use this LCX cable but radiate with different propagation directions which can generate the equivalent MIMO channel condition.

III. SHANNON ERGODIC CAPACITY OF MULTIPLE-INPUT–MULTIPLE-OUTPUT CHANNEL

The Shannon ergodic capacity of an MIMO channel usually provides a fundamental understanding and limitations of the MIMO channel [18]. It depends heavily on the statistical properties and antenna element correlations of the channel. Generally, the capacity of two kinds of conditions gives important fundamental limitations for the design of the MIMO system. The first one assumes that transmitter side has no channel status information (CSI) $\mathbf{H}$ for transmission process. In this case, the channel capacity can be optimal if the transmitter allocates the EP for each stream transmission. On the other hand, if CSI is known at transmission side, which is a practical assumption for the multiuser MIMO system, the optimal capacity can be achieved using a power allocation algorithm called the WF algorithm [19].

At first, we assume that the channel $\mathbf{H}$ is unknown at transmitter. As a result, the Shannon ergodic capacity of the MIMO channel under the EP allocation [18] is expressed as

$$C = \mathbb{E}_H \left[ \log_2 \left( \det \left( \mathbf{I} + \frac{\zeta}{N \mathbf{H}^H \mathbf{H}} \right) \right) \right]$$

(2)

where $\zeta$ is the average SNR at receiver side, and $N$ is the number of transmitting antennas. $\mathbf{I}$ is the identity matrix. The superscript $H$ in (2) represents the Hermitian transpose.

If the CSI is known at transmitter, the maximum of Shannon ergodic capacity of the MIMO channel can be achieved with the WF power allocation and the channel capacity can be expressed as

$$C = \mathbb{E}_H \left[ \sum_{i=1}^{N} \log_2(1 + \lambda_i P_i) \right]$$

(3)

where $\lambda_i$ is the corresponding eigenvalue. Here, $P_i$ is the power allocated to the $i$th MIMO eigen channel and can be calculated as

$$P_i = \left( \mu - 1 \lambda_i \right)^+$$

(4)

where $\mu$ is WF level, and $x^+$ is defined as max($x$, 0). After each eigen channel is iteratively filled with the common level $\mu$, the MIMO channel capacity can be computed as [20] follows:

$$C = \mathbb{E}_H \left[ \sum_{i=1}^{N} (\log_2(\lambda_i, \mu))^+ \right].$$

(5)

It is noted that the above-mentioned capacity equations are normalized with respect to the bandwidth. On the other hand, EP algorithm can be treated as a special case of WF algorithm with $P_1 = P_2 = \cdots = P_N = \frac{\zeta}{\lambda}$. The correlation level of channel matrix $\mathbf{H}$ will largely impact the value of the corresponding eigenvalue $\lambda$, and then the capacity of the MIMO channel.

The Shannon ergodic capacity of the MIMO channel using WF allocation algorithm is generally larger than that of EP allocation scheme. However, it requires CSI feedback to achieve accurate CSI at transmitter side which needs large feedback resource of uplink, especially when the number of antenna at both sides are large.

IV. CAPACITY RESULTS OF 2-BY-2 LEAKY COAXIAL MULTIPLE-INPUT–MULTIPLE-OUTPUT CHANNEL

A. Measurement Configuration of 2-by-2 LCX–MIMO Channel

We considered 2-by-2 channel of the proposed LCX–MIMO and compared with that of the MIMO channel using monopole
antennas in an anechoic chamber where no reflection path exists. It should be noted the channel condition will be improved if the proposed LCXs are put on a real environment with more reflection paths. The configuration of the experiment is shown in Fig. 5. The LCX is laid on the edge of foaming polystyrene that is placed on the radio wave absorber. It is around 0.5 m above the floor. Fig. 6 shows the geographical setup of a measurement area and also depicts measurement points within the area. Here X-axis is the direction along the LCX and Y-axis is the direction from the LCX to the receiving antenna that is perpendicular from the LCX. An origin point is defined as the center of the LCX. Each receiving antenna was monopole half-wavelength monopole type for 2.4 GHz band and one wavelength for the 5 GHz band. The separated distance between the user equipment (UE’s) antennas is one wavelength. Since there is no reflection path and the channel propagation is static in an anechoic chamber, a shape of a cell that is formed by the LCX is assumed to be symmetric against X-axis and Y-axis. Given this assumption, the measurement area was reduced to a quarter from the entire cell area. The measurement positions including outside the end of the LCX are selected for measurement. For each measurement point, the average ergodic capacity is calculated for all 401 frequency samples with different SNR value.

For the proposed system over 2.4 GHz band, we choose two types of LCX, one is a horizontally polarized (H-type) LCX with radiation angle \( \theta_{-1} \) as 25°, and the other one is a vertically polarized (V-type) LCX with radiation angle \( \theta_{-1} \) as 20°. The major specifications of LCX are listed in Table I. In addition, the efficiency for monopole antenna is 1 dBi for comparison. The measurement frequency and the bandwidth were 2.452 GHz and 125 MHz, respectively. Four hundred and one frequency samples were obtained in each measurement. For each fixed value of Y-axis, 13 positions including 3 positions outside the end of the LCX are selected for measurement. For each measurement point, the average ergodic capacity is calculated for all 401 frequency samples with different SNR value.

For evaluating the LCX–MIMO channel condition over the 5 GHz band, to show the channel condition for LCX with different radiation angles \( 2\theta_{-1} \), we choose two types of vertically polarized (V-type) LCX for comparison. By designing the slot spacing \( P \) using (1), the angle \( 2\theta_{-1} \) between peak directivity from two different input RF signal propagations can be set as 36° (\( \theta_{-1} = -18^\circ \)) and 110° (\( \theta_{-1} = -55^\circ \)), respectively. The specifications are listed in Table II. Measurement bandwidth is 500 MHz which is from 5.15 to 5.65 GHz. The frequency res-

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SPECIFICATIONS OF LCX (2.4 GHz)</th>
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<tbody>
<tr>
<td>Cable type</td>
<td>H-type; V-type</td>
</tr>
<tr>
<td>Slot spacing ( P )</td>
<td>80 mm</td>
</tr>
<tr>
<td>Coupling loss</td>
<td>60 dB ± 5 dB at 1.5 m</td>
</tr>
<tr>
<td>Cable loss</td>
<td>V-type: 0.4 dB/m; H-type: 0.3 dB/m</td>
</tr>
<tr>
<td>Inner copper wire diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Insulator (foamed polyethylene) diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td>Outer sheathe thickness</td>
<td>1 mm</td>
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<tr>
<td>Cable diameter</td>
<td>7 mm</td>
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<td>VSWR</td>
<td>1.1</td>
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<tr>
<th>TABLE II</th>
<th>SPECIFICATIONS OF LCX (5 GHz)</th>
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<tr>
<td>Cable type</td>
<td>V-type</td>
</tr>
<tr>
<td>Slot spacing ( P )</td>
<td>40 mm for 18°, 30 mm for 55°</td>
</tr>
<tr>
<td>Coupling loss</td>
<td>60 dB ± 5 dB at 1.5 m</td>
</tr>
<tr>
<td>Cable loss</td>
<td>0.6 dB/m</td>
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<tr>
<td>Inner copper wire diameter</td>
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<td>Insulator (foamed polyethylene) diameter</td>
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<td>7 mm</td>
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<td>VSWR</td>
<td>1.2</td>
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olution is 312.5 KHz. Therefore, 1635 samples were obtained in each measurement position. The measurement area is similar to Fig. 6, which includes three areas. For each fixed value of Y-axis, 41 positions including eight positions outside the end of the LCX are selected for measurement, and these positions are divided into three areas, as shown in Fig. 6.

B. 2-by-2 LCX–MIMO Channel Capacity Results

We compare the average capacity of 2-by-2 LCX–MIMO channel using H-type and V-type with that of MIMO channel using monopole antennas at both sides with spacing about 12 cm for the 2.4 GHz band and 6 cm for the 5 GHz band, respectively. We also measured the capacity where the transmitting monopole antennas has 10 m spacing as distributed antennas setting for better MIMO condition. On the other hand, we also provide the capacity of 2-by-2 i.i.d. channel, where the spacing between all antennas is large enough and each antenna can receive an independent signal. The capacity results for all cases in three areas are shown in Fig. 7 for 2.4 GHz band and in Fig. 8 for the 5 GHz band.

As shown in Fig. 7, the proposal of that one LCX can be utilized as two antennas has to be confirmed. Compared with the MIMO channel using monopole antennas with 12 cm spacing at transmitter, LCX–MIMO can achieve better capacity on all three kind of areas. In addition, both types of LCX cable can achieve the channel capacity similar or better to that of 2-by-2 i.i.d. MIMO channel regardless of EP allocation or WF power allocation in Area 1 and Area 2. On the other hand, the capacity of the LCX–MIMO channel using EP allocation and WF power allocation can outperforms with maximum capacity improvement to about 30% than that of channel using monopole antennas. If considering that WF power allocation needs accurate CSI from feedback which is difficult target, LCX–MIMO can achieve better capacity than that of MIMO system using monopole antennas over linear cell with some simple multiplexing algorithms. The results also show that V-type LCX has better capacity than that of H-type LCX over all areas. The reason is that the type of receiver antennas is the conventional V-type monopole one, which has better antenna gain for the V-type wave. Therefore, if the H-type monopole antennas are selected as receiver antennas, the capacity for H-type LCX will be increased.

For the 5 GHz band shown in Fig. 8, similar to that in Fig. 7, the proposal that one LCX can be utilized as two antennas has to be confirmed. Compared with the MIMO channel using monopole antennas with 6 cm spacing at transmitter, the proposed LCX–MIMO can achieve better capacity on all three kind of areas. The results also show that the LCX cable with the angle $\theta_1$ as 55° has better capacity than that of the LCX cable with the angle $\theta_1$ as 18° over all areas. The reason is that LCX cable with the angle $\theta_1$ as 55° has a better propagation angle between two signals, which generates better channel condition than that of the LCX cable with the angle $\theta_1$ as 18°.

On the other hand, when the spacing between the transmitter monopole antennas is increased to 10 m, the capacity of MIMO channel is largely increased compared with that of one wavelength (12 cm for 2.4 GHz band and 6 cm for the 5 GHz band) spacing. Therefore, it shows that by adjusting the position setting of monopole antennas, the capacity of conventional MIMO channel can be improved. However, our proposed LCX–MIMO still has better capacity than that of conventional one over Area 1 and comparable capacity to that of conventional monopole one over Area 2 because the proposed LCX have stable propagation angles along the cables, which can be easy to
optimize the MIMO capacity over linear-cell scenarios. In an anechoic chamber, for linear-cell scenarios, the MIMO channel with short distance using monopole antennas, it is, perhaps, difficult to achieve an efficient distinguishable signal between antennas with small spacing. The proposed LCX–MIMO has good channel condition when the LCX and UEs are in a scenario like the line of sight (LOS) one. When the distance between LCX and UEs is increased, the path loss of channel is increased which may reduce the efficiency of LCX. However, for linear-cell scenario, most of UEs can communicate with LCX within a short distance. On the other hand, when the receiving antennas are close to each other, due to the special radiation pattern of LCX at breaking strength (BS) side, the channel condition may be better compared with that BS utilizes monopole antennas. Therefore, the proposed LCX–MIMO can be more efficient for some scenarios that have less paths and short distance, such as femtocell or picocell. In addition, for more high-frequency band such as millimeter-wave system over 60 GHz band, the channel can be modeled as a major LOS with very small number of paths [21]. The MIMO system with the proposed LCX cable will have more advantages for configuration of any linear-cell shape of wireless coverage.

C. Two-by-2 LCX–MIMO Channel Capacity Variation Over 20 MHz Bandwidth

We have utilized the average capacity to show the LCX–MIMO channel with 125 MHz bandwidth over the 2.4 GHz band and with 500 MHz bandwidth over the 5 GHz band. The frequency resolution is about 312.5 kHz for each frequency point. In this section, we will show how the channel capacity varies for different center frequency with 20 MHz bandwidth. For the 2.4 GHz band, we choose three kinds of frequency range as low band (2.452–2.472 GHz), middle band (2.512–2.532 GHz), and high band (2.557–2.577 GHz). For the 5 GHz band, the three kinds of frequency range as selected as low band (5.15–5.17 GHz), middle band (5.30–5.52 GHz), and high band (5.63–5.65 GHz).

The average capacity over Area 1 and Area 2 with each 20 MHz bandwidth for different type of LCX cable are shown in Fig. 9. Here the power allocation method is EP algorithm. As shown in Fig. 9(a) and (b), the average capacities over low, middle, and high bands have almost the same value regardless of the LCX type and frequency band. The results are perhaps the same for the higher operating band, which supports our major proposal that one LCX cable can be utilized as two antennas.

D. Effect on MIMO Channel Condition From LCX Cable Loss

When LCX cable has a long size, the cable loss will largely impact the proposed channel condition. As shown in Fig. 10, compared with the short LCX which has been measured in an anechoic chamber, the long LCX cable has a larger cable loss due to the signal decays over the cable from two ends. In this section, we will show the effect on the proposed LCX–MIMO channel condition from a long LCX cable.

For a 10 m short LCX cable, as shown in Fig. 10, the UE in middle positions will get the signal with almost identical cable loss, and each element $h_{ij}$ represents the channel signal between the LCX end $i$ and receiver antenna $j$. When LCX cable is increased to $L + 10$ [m], the received signal for $h_{L1}$ and $h_{L2}$ will be reduced with about $\rho L$ [dB], where $\rho$ is cable loss. In addition, the transmitted signal also has a phase shift with about $2\pi \frac{m}{\lambda}$, where $\lambda$ is the wavelength of signal transmitted in the LCX cable and can be
Fig. 9. Two-by-2 LCX–MIMO channel capacity with 20 MHz bandwidth. (a) LCX for the 2.4 GHz band. (b) LCX for the 5 GHz band.

calculated as
\[ \lambda = \frac{C}{f_c \sqrt{\epsilon_r}} \]  
(6)

where \( C \) is the wave speed, \( f_c \) is the center frequency of signal, and \( \epsilon_r \) is relative permittivity of the insulator in the LCX cable. Therefore, we can approximately calculate the channel matrix \( H_L \) using the value of channel matrix \( H_1 \).

Usually we can use condition number (CN) \( \gamma \) as a metric of 2-by-2 MIMO condition which can be calculated as \( \gamma = 10\log_{10}(\lambda_1/\lambda_2) \), where \( \lambda_1 \) and \( \lambda_2 \) are the maximum and minimum eigenvalue of channel \( HH^H \). A matrix with a low CN is said to be well-conditioned channel, whereas a matrix with a high CN is said to be ill-conditioned one. To show the effect of cable loss on channel condition, we utilize CN \( \gamma_1 \) and \( \gamma_L \) to represent the channel condition of \( H_1 \) and \( H_L \) with different value of \( L \). Then, we can use the ratio of \( \gamma_L / \gamma_1 \) to show the variation of channel condition when the length of cable is enlarged.

Fig. 11 shows the average value of \( \gamma_L / \gamma_1 \) over all frequency samples for all four kinds of LCX cables and \( L \) is increased from 0 to 30 m. Here \( \epsilon_r \) is 1.44. As shown in Fig. 10, for 2.4 GHz band, the cable loss will dramatically deteriorate the LCX–MIMO channel condition when \( L \) is larger than 20 m, especially for V-type LCX with large cable loss value. For 5 GHz band, due to the larger cable loss of LCX cable, when \( L \) is larger than 10 m, channel condition will be dramatically deteriorated for both kind of LCX cables. Therefore, for usage of the proposed LCX–MIMO over a long linear-cell scenarios, it should consider how to adjust the transmit power from LCX to UE according to the position of UE. For the proposed LCX–MIMO, it is possible to detect the position of UE in an easy way using the information of transmission delay between two ends of LCX cable [22], [23].

V. THROUGHPUT EXPERIMENTS OF THE LEAKY COAXIAL SYSTEM

To further confirm the effectiveness of proposal, we have operated some experiments on the throughput of the LCX–MIMO system in the anechoic chamber. The configuration of experiment is shown in Fig. 12. Here, we select V-type with radiation angle \( \theta \) as 55° for experiments and test its throughput using the conventional Buffalo Air Station product with IEEE 802.11b/g/n standard over the channel of W52 36ch (5.17–5.19 GHz). The
transmitter and receiver are about 82.5 cm over the ground. Here, we use a shield box to shield the RF signal from the conventional access point but radiate the RF signal from the LCX cable. The receiver has two monopole antennas with one wavelength as the spacing, as shown in Fig. 13. Some parameters for experiments on the Buffalo Air Station are given in Table III. When the experiments are operated with one LCX cable that is only used as one antenna, the RateSet of Air Station is selected with the average transmission speed of 45 Mb/s.

Fig. 14 shows the throughput results when LCX cable is utilized as a transmitter antenna. We compare three kinds of usage. That is, the signal is input at left side, right side of LCX, and at both sides as the proposed LCX–MIMO system. When only one side of LCX cable is input, it only sends one stream data to the receiver. As shown in Fig. 14, when the location of receiver is between 0 and 3 m, the throughput of the signal that is input from left side is almost same to that of the signal that is input from right side. Due to the radiation angle (55° for LCX-5D-5V-55), when the receiver is 1.5 m from LCX cable, the radiation energy is largely varied after 3 m, which makes the throughput decrease [24]. When the signal is input from the right side, with the similar reason, the radiation angle of LCX cable can ensure the steady throughput till 6 m. For our proposal where two sides of LCX cable are input with signal, the throughput is almost doubled when the location of receiver is between 0 and 3 m. When the receiver is between 3 and 6 m, the throughput is still steady due to the radiated signal from the input of right side. Therefore, compared with that of conventional methods, our proposal can achieve the higher throughput for most of radiation coverage of LCX cable. It also realize stable transmission performance, even if the UEs are at the edge of LCX cable.

### VI. Conclusion

In this paper, we have proposed a simple method to realize that one single LCX cable can be used as two antennas. The proposal can reduce the cost of LCX–MIMO configuration and releases the space requirement of MIMO deployment over linear-cell environments. The capacity results in an anechoic chamber showed that the proposed LCX–MIMO channel has better capacity than that of using monopole antennas over linear-cell environments. In particular, it can achieve more capacity improvement than that of channel using monopole antennas with some simple power allocation algorithms. The throughput experiments also showed that the proposal can achieve the higher and stable throughput over the radiation coverage of LCX cable. We will study its channel model and capacity in a real environment with more multipath reflection with more LCX cables in future research.
REFERENCES


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