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2×2 LCX-MIMO System in Real Indoor Linear-cell Environment

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Abstract

Leaky coaxial (LCX) cable is utilized in wireless communication systems as an antenna for long and narrow areas called as linear-cell environment. Conventional usage of LCX cable is generally treated as one antenna. Recently a 22 multiple-input multiple-output (MIMO) system using single LCX cable as two antennas has been proposed by inputting signals in both ends of LCX cable. However, until now, all research results were measured and compared in an anechoic chamber where reflection paths did not exist. This thesis reports the measured throughput performance of proposed 2×2 LCX-MIMO system under 5GHz band in an indoor linear-cell environment. The measurement results demonstrate that 2×2 LCX-MIMO can double the system throughput compared with that of system using LCX cable as conventional way. In addition, compared with the 2×2 MIMO system employing two omni-directional antennas at transmitter and receiver, 2×2 LCX-MIMO system can achieve higher throughput performance at some measurement positions over the indoor linear-cell environment.

Keywords:

Leaky Coaxial Cable, LCX-MIMO, MIMO System, Indoor Linear-environment,Channel Capacity

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Contents

List of Figures iv

List of Tables v

1 Introduction 1

1.1 Background 1

1.2 Problem Statement and Motivation 2

1.3 Contribution 2

2 Review of Leaky Coaxial Cable 4

2.1 Introduction 4

2.2 Characteristic of LCX Cable 4

2.2.1 Structure of LCX Cable 4

2.2.2 Radio Propagation and Direction Angle 5

2.2.3 Coupling Loss 7

3 LCX-MIMO System 9

3.1 Introduction 9

3.2 Structure of LCX-MIMO System 9

3.2.1 MIMO system 9

3.2.2 Proposed LCX-MIMO System 11

4 Experiment and Results Analysis 13

4.1 Introduction 13

4.2 Experiment Configuration 13

4.2.1 Experiment Environment 13

4.2.2 S-parameters 16

4.2.3 Network Layer Throughput 18

4.3 Results Analysis 19
4.3.1 Channel Condition Number of LCX-MIMO 19
4.3.2 Shannon Channel Capacity of LCX-MIMO 20
4.3.3 Network Layer Throughput of LCX-MIMO 22

5 Conclusion **28**
5.1 Conclusion 28
5.2 Future works 28

References **30**

List of Figures

2.1 Structure of LCX cable 5
2.2 Radio direction angle 5
2.3 Relationship between radio direction and wave front 6

3.1 Block Diagram of MIMO System 10
3.2 Radiation Pattern of LCX Cables in Anechoic Chamber 11
3.3 LCX-MIMO system with two input signals 12

4.1 Experiment Environment in Office 14
4.2 Experiment Environment in Area A 14
4.3 Experiment Environment in Area B 15
4.4 Experiment Environment in Area C 15
4.5 Condition Number in Y=0.5m 20
4.6 Condition Number in Y=2m 21
4.7 Channel Capacity in Y=0.5m 22
4.8 Channel Capacity in Y=2m 23
4.9 Throughput comparison for MIMO system using LCX cable with 18Deg. 24
4.10 Throughput comparison for MIMO system in Area A Y=1m . . . 25
4.11 Throughput comparison for MIMO system in Area A Y=2.1m . . 26
4.12 Throughput comparison for MIMO system in Area C Y=3.5m . . 26
4.13 Throughput comparison for MIMO system in Area B 27

List of Tables

4.1 Parameters of LCX cables 18
4.2 Configuration of Access Point 18

1 Introduction

1.1 Background

Wireless terminals are affecting our daily life everywhere. And more and more applications in smartphone provide different kinds of service and make our life more convenient. The IoT (Internet of Things) are also playing more important roles in various industrial fields. In this decade, the explosive increment of wireless terminals is urgently demanding the growth of wireless systems. As the successor of 4G (4th Generation), 5G (5th Generation) solution, planned to offer the commercial service in 2020, will provide higher channel capacity and lower network latency. 5G solution may utilize wider bandwidth, higher carrier frequency and larger number of antennas, but it also will increase the interference amoung radio signals from multiple terminals and base stations.

LCX (Leaky Coaxial) cable has already been deployed in tunnel of subway and highway for transmitting radio signal. With a special structure, LCX cable can feed radio frequency as an feeder and transmit the radio to the air as an antenna at same time. Thence in those scenarios, by LCX cables wireless signal can easily cover long distance and narrow area. Compared with conventional omnidirectional antennas, LCX cables are able to provide more stable and steady radio waves to improve the performance.

MIMO(Multiple-iput Multiple-output) system is a key technique in the 5th generation system. In MIMO system, several of antennas are placed at the transmitter sides to create multiple dimensions in spatial domain[1-5]. Spatial domain can be used to provide diversity or opportunities of spatial multiplexing which can improve the system performance dramatically. On the other hand, LCX cables can also build a MIMO system, called LCX-MIMO system. When LCX cables send radio wave to around space, the radio wave shows a directional characteristic with different angle. This angle directivity provides extra spatial multiplexing and it also reduces the interference between each signal transmitter[6-8]. Therefore, LCX-MIMO system is expected to be used in 5G system especially in some long and narrow scenarios, known as linear-cell environments.

The property of LCX cable has been studied for many years in both theory and applications[3]. A 2×2 LCX-MIMO system has been evaluated by two closely-spaced LCX cables in 2.4GHz [9]. However, until now, for most researchers of LCX and LCX-MIMO, they always assumed that one LCX cable only has been utilized as one antenna. Thus to configure a MIMO system, they have to use more than one LCX cable. This will cost more resource and space to deploy multiple cables. Hence, a novel method to realize a 2×2 MIMO using only one LCX cable as two antennas has been proposed in [5] and given the performance comparison between LCX cables and the monopole antennas [10].

1.2 Problem Statement and Motivation

Until now, all research results of our proposed method of aforementioned LCX-MIMO system were measured and compared in an anechoic chamber where reflection paths did not exist. Even they have already proved this method feasible and effective. However, because of the evident difference between the anechoic chamber and real environments, we complete some experiments and show the effectiveness of LCX-MIMO system in this thesis for investigating the performance of this method in a real office environment and comparing with the conventional MIMO system using omni-directional antennas.

1.3 Contribution

In this thesis, we compare the network throughput and channel capacity of 2×2 MIMO system using three kinds of antennas at base station (BS), there are two kinds of LCX cables but with different radiation properties and conventional omni-directional antennas. The measurement results demonstrate that the proposed configuration of LCX cables can achieve good channel condition of 2×2

MIMO system in the real office environment and the throughput performance of proposed method can achieve about two times of system using LCX cable as one antenna for transmitting signals. Moreover it also shows that our proposed LCX-MIMO system has similar and even better throughput at some position than the system using conventional omni-directional antennas. The measurement results in a real indoor linear-cell environments confirm that this 2×2 LCX-MIMO system can achieve the promising and stable MIMO throughput over the radiation coverage of LCX cable just using one single LCX cable.

The organization of this thesis is as follows: Chapter 2 describes the details of LCX cables in structure and electric-magnetic characteristic. Chapter 3 gives the brief information of MIMO system and the 2×2 LCX-MIMO system used in this study. Chapter 4 represents our experiments and the analysis of results. Finally, Chapter 5 summarizes this work and suggestion to the future works.

2 Review of Leaky Coaxial Cable

2.1 Introduction

Leaky coaxial cable (LCX) is developed from coaxial cable which is normally used in transmission of television broadcasting signal. By cutting some periodic gaps, called slots, on the outer conductor of the coaxial cable, the signal when it is transmitted in the cable, will be able to send to the around environment so that the LCX will be used as a wireless antenna. Because of the special property of LCX that it allows signal to transmit in cable and send to air at same time, in some long distance scenarios LCX has been widely installed especial in tunnels, and carriage of trains.

In 1960s, the planning stage of Tokaido Shinkansen had already considered the application of LCX systems in Japan. In 1989, to improve the quality of wireless signal in tunnels, LCX systems were deployed for analog communication systems. With the development of communication system, latest LCX systems for digital communication have been replaced to connect the trains and BS(Base Station). Recently LCX system also started to provide the Internet service and high speed communication for passengers. In other fields, such as underground shopping mall or subway station, LCX systems also show advantage than conventional wireless system.

2.2 Characteristic of LCX Cable

2.2.1 Structure of LCX Cable

LCX cable can be used as an antenna in wireless communication system. Fig.2.1 shows an example of LCX cable structure. A LCX cable is constructed by inner conductor, insulator, outer conductor and Jacket what is same with coaxial cable. To send the radio wave to the air, some periodic slots on the outer conductor was opened. The shape and interval of slots will decide the propagation property of a cable. Moreover a LCX cable with given slots can be analyzed as an array antenna.

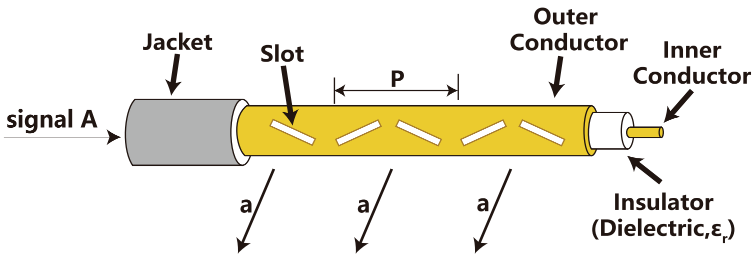


Figure 2.1: Structure of LCX cable

2.2.2 Radio Propagation and Direction Angle

Normally, the design process of LCX cables with periodic slots includes two steps, the design of carrier frequency and the coupling loss. The arrangement of slots mainly determine the carrier frequency of the cable and it has been studied for long years[7]. In this section, we elaborate the radiation characteristics of the LCX cables.

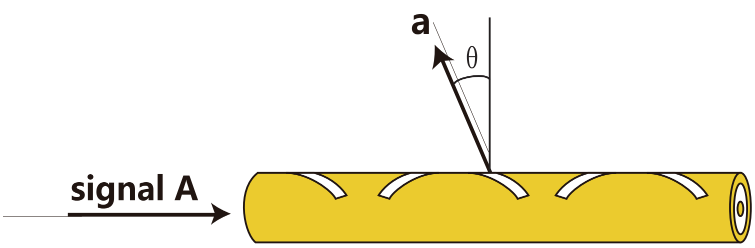


Figure 2.2: Radio direction angle

For a LCX cable with periodic slots in Fig.2.2, the electric field around the cable can be shown by

$$E(r, \gamma, z) = E_p(r, \gamma, z)e^{-jk_z z} \tag{2.1}$$

where $k_z = \beta - j\alpha$. α and β are the attenuation and propagation constant respectively.In this terms, the parameter can be shown by constants of unperturbed cable, as $\alpha = \alpha_0\kappa'$ and $\beta = \beta_0\kappa$. $\beta_0 = k_0\sqrt{\epsilon_r}$, where k_0 is the wave number of free space, and ϵ_r is the relative permittivity of the dielectric material in the cable. κ and κ' are the functions of many factors, slot arrangement, slot size and shapes, the operation frequency and so on.

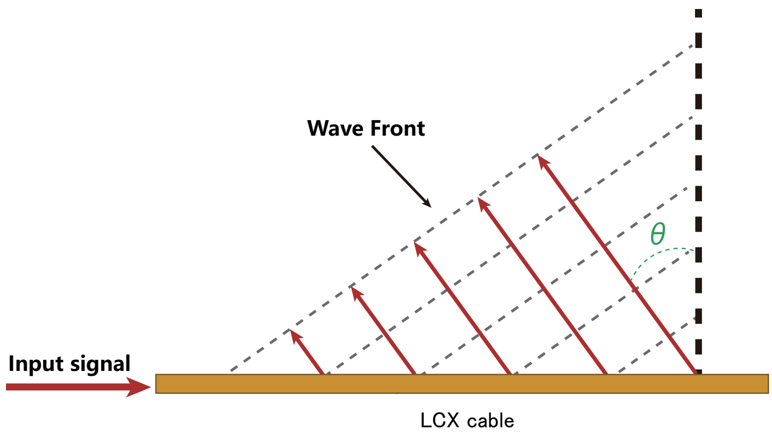


Figure 2.3: Relationship between radio direction and wave front

The attenuation of the LCX cables are designed to be as low as possible for maximizing the effective distance. Usually the dielectric used in the cable is foamed PE(Polyethylene) with a permittivity of around 1.25, where the wave velocity in the cable is about 88% of that in free space. So the κ and κ' are almost 1 and because α_0 is very small comparing to β_0, it is negligible in the analysis that follows.

$E_p(r, \gamma, z)$ in (2.1) is the periodic functions of z, and can be expanded into Fourier series

$$E(r, \gamma, z) = e^{-z\alpha} \sum_{m=-\infty}^{\infty} E_p m(r, \gamma)e^{-j\beta_m z} \tag{2.2}$$

where

$$\beta_m = \beta + \frac{2m\pi}{P} \tag{2.3}$$

β_m is the propagation constant of the mth spatial harmonic in the z direction. P is the period of slots. Usually, the LCX cables are designed only to allow radiation in their -1th harmonic to avoid the large fluctuation caused by the radiation of high order harmonics. The propagation angles are determined by

$$\theta_m = \sin^{-1}(\sqrt{\epsilon_r} + \frac{m\lambda}{P}), \qquad (m = -1, -2, \ldots) \tag{2.4}$$

2.2.3 Coupling Loss

Coupling loss L_c of LCX cable is the parameter which can distinguish the LCX cables and normal RF cables[11]. It is defined as follows:

$$L_s = L_f + L_t + L_c \tag{2.5}$$

where L_s is system loss, L_f is feeder loss, and L_t is transmission power loss in cable inner where:

$$L_c = L_{co} + L_r \tag{2.6}$$

and

$$L_t = \alpha Z \tag{2.7}$$

Standard coupling loss L_{co} is defined by the quotient of transmission power inside the LCX and received power with a standard dipole antenna placed 1.5m from the LCX, and it is in general from 50 to 80 dB [reference:design of a tunnel]. And L_r is lateral power attenuation, Z is cable length in km, and α is the cable transmission power loss in dB/km, depending on the resistance loss between inner conductor and outer conductor α_r, the dielectric loss α_g and radiation loss α_R where

$$\alpha = \alpha_r + \alpha_g + \alpha_R \tag{2.8}$$

In some condition that the power loss by the radiation α_R is relatively negligible to resistance loss α_r and dielectric loss α_g, the LCX transmission power loss α

can be considered as a normal coaxial cable. However, if the radiation increases largely, the electric current will also increase and lead to increase of the influence by resistance loss α_r.

3 LCX-MIMO System

3.1 Introduction

First of all the MIMO system using LCX cable will be introduced in this chapter. Secondly the structure of 2×2 LCX-MIMO system and the experiment will be discussed. To build a LCX-MIMO system, more than 2 cables are necessary in the past, and we have proposed a method that One LCX cable can be used as two wireless antennas so that for building a simplest 2-by-2 MIMO system, we can only use one LCX cable. Until now this method was only proved its effectiveness and feasibility in the anechoic chamber where the reflection radiation doesn't exist[10]. In this chapter, we design an experiment for measuring the properties of LCX cables in a real indoor environment. Finally, we compare the LCX cable with conventional Omni-directional antenna in several fields.

3.2 Structure of LCX-MIMO System

3.2.1 MIMO system

Multiple Input Multiple Output(MIMO) technology, first introduced in1984, was key technology in the next generation wireless communication system. MIMO systems consist of a number of antennas in both transmitter sides(BSs) and receiver sides(Terminals). Those antennas were combined for providing multiplex or diversity or both of them, which can improve the system with bit error rates(BER) or upper bound data rates. MIMO also is a kind of smart antenna technology. Unlike conventional antenna systems, MIMO systems are able to improve system diversity and bandwidth efficiency by multi-path components[9].

Figure3.1 shows a MIMO system with multiple antennas in transmitter and

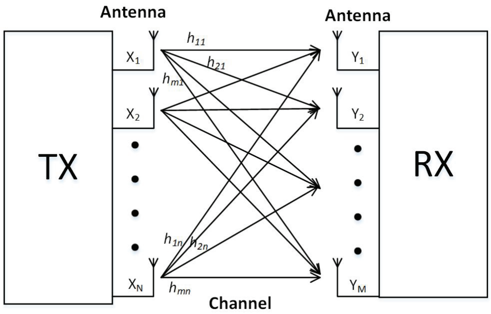


Figure 3.1: Block Diagram of MIMO System

receiver. The signal what is sent from $k-$th antenna in transmitter to $l-$th antenna in receiver is given by

$$y_l(t) = \sum_{k=1}^{N} h_{lk}(t)x_k(t) + n_l(t); k \in [1, ..., N], l \in [1, ..., M] \tag{3.1}$$

where N and M are the number of antennas in transmitter and receiver respectively, and $h_{lk}(t)$ is the complex channel factor between $k-$th transmitter antenna and $l-$th receiver antenna. $n_l(t)$ is the additive white Gaussian noise. It is also given in

$$y_l(t) = \mathbf{H}(t)x(t) + n(t) \tag{3.2}$$

where

$$\mathbf{H}(t) = \begin{pmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1N}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1}(t) & h_{M2}(t) & \cdots & h_{MN}(t) \end{pmatrix} \tag{3.3}$$

Matrix H is called as MIMO transmission matrix which is estimated from transmission channel. This matrix will be used for retrieving the information at the receiver. Basically the information signal can be obtained by multiplying the inverse matrix of H with the received signal

$$\mathbf{H}^{(-1)}(t)y(t) = \mathbf{H}^{-1}(\mathbf{H}(t)x(t) + n(t)) = \tilde{x} \tag{3.4}$$

Usually the types of antennas play a important roll in the channel model. And the statistical characters of MIMO Fading Channel ($\mathbf{H}$ matrix) has significant influence in system performance[12-15].

3.2.2 Proposed LCX-MIMO System

Usually one LCX cable is applied as a normal antenna for construct a MIMO system. In a widely used method, LCX cables are installed in mime tunnels for covering whole area by one cable Fig 3.3(a). However by measuring the radiation characteristic of LCX cables in anechoic chamber, it is identified that the electrical signal is loaded in a end of LCX cable, the wireless signal will spread to the around space with different direction. For example, a LCX-5D-5V-18D cable, designed by (2.4) $\theta_{-1} = 18°$ in center frequency 5.35GHz band, was measured in anechoic chamber and the radio signals, fed from each ends of the cable are propagating with two opposite direction in Fig 3.2 marked by the purple lines and blue lines [16][17].

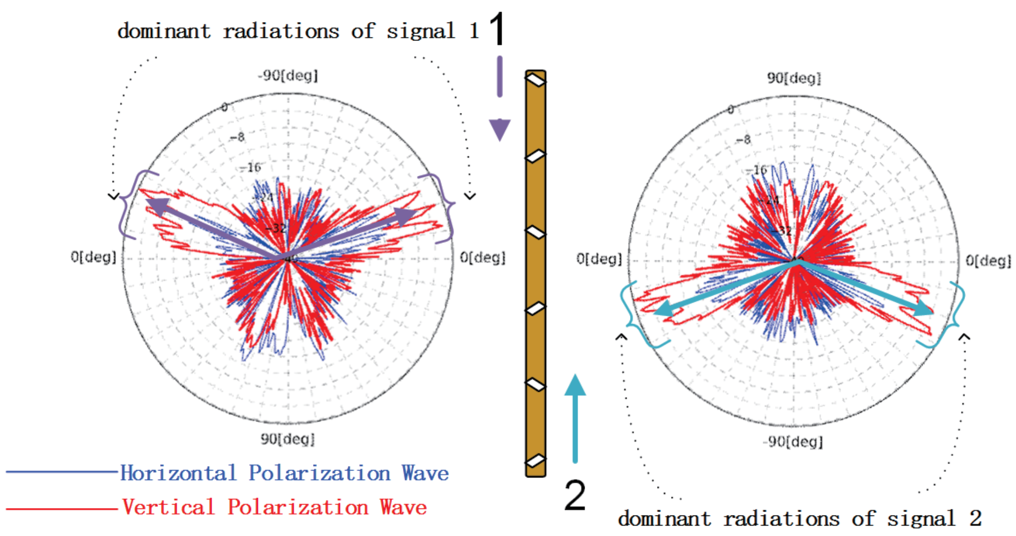


Figure 3.2: Radiation Pattern of LCX Cables in Anechoic Chamber

In the spatial domain, there is a 36° angle between two signals and the receiver side can distinguish different signals because of their spatial multiplex as a normal MIMO system. Compared with the MIMO systems using conventional Omni-directional antennas, even the signals, fed by two ends, are propagated from almost same slots positions on the cable, but this congenital property of directional angles can provide an extra spatial multiplex and lead the MIMO transmission matrix H(t) to distinction of different signals. Eventually a LCX cable can be used as two transmitter antenna for realizing a good LCX-MIMO system Fig 3.3(b).

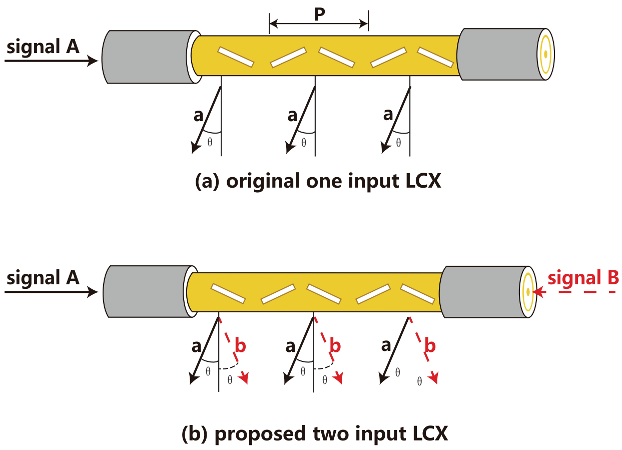


Figure 3.3: LCX-MIMO system with two input signals

By this proposal, for building a simplest 2-by-2 LCX-MIMO system, only one LCX cable is necessary. Since the required cables are reduced to half numbers, this proposal can save commercial cost and decrease the interference between antennas in reality environment.

4 Experiment and Results Analysis

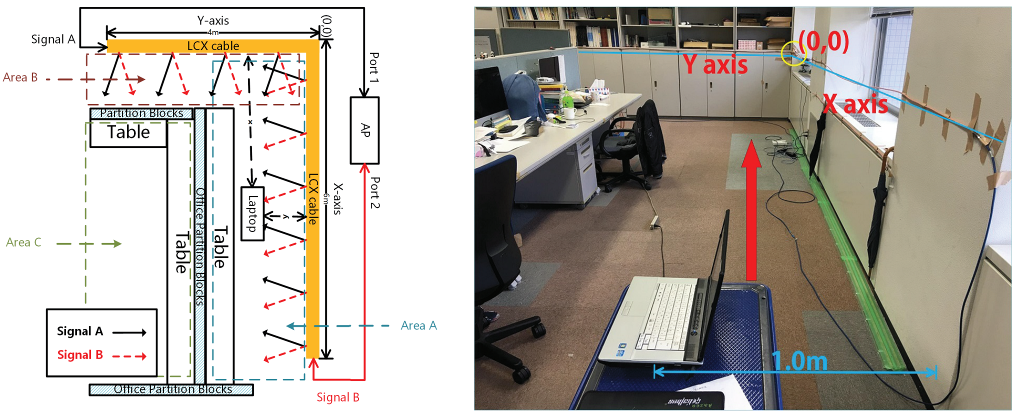
4.1 Introduction

In the previous researches, usually one LCX cable is assumed as one antennas in MIMO systems [14]. And the proposal, one LCX cable is used as two antennas, has been verified in anechic chamber where the reflection electromagnetic waves don't exist makes evident difference in MIMO systems. Therefore, we have designed some experiments and measurements in a real indoor typical office environment for confirming the feasibility and performance of proposed LCX-MIMO system.

4.2 Experiment Configuration

4.2.1 Experiment Environment

We measure the throughput performance of the LCX-MIMO system in an office environment (Fig 4.1) of 4th floor of one building of graduate school of information science in Nara Institute of Science and Technology (Naist) and the linear-cell layout is similar to that of Fig 4.1(a). To cover the area shown in the Fig 4.1(b), in the window side as X axis, we set the LCX cable along the wall and keep the cable as straight as possible. In the cabinet side as Y axis, we fix the LCX cable on the cabinet and ensure that all slots are facing to the passageway (arrow line in Fig 4.1(b)). Here the corner is assumed as the origin point $(0, 0)$ (the circle in Fig 4.1(b)). The height of LCX cable is about 1.1m from the floor, and the length of the cable in the X direction is 6m, another side Y direction is



(a) (b)

Figure 4.1: Experiment Environment in Office

4m.

As the comparison, we have two type LCX cable with different radiation angle θ_{-1} as 18° and 55°. Therefore, the angles $2\theta_{-1}$ between peak directivity of RF signal propagation from two different input can reach 36° and 110°, respectively. We also measure the performance of omni-antennas with 3dBi absolute gain in the same environment by deploying them in the origin point. Between the two omni-antennas, the spacing in 20cm is larger than two wavelengths for system over 5GHz band which is efficient distance to achieve good channel condition.

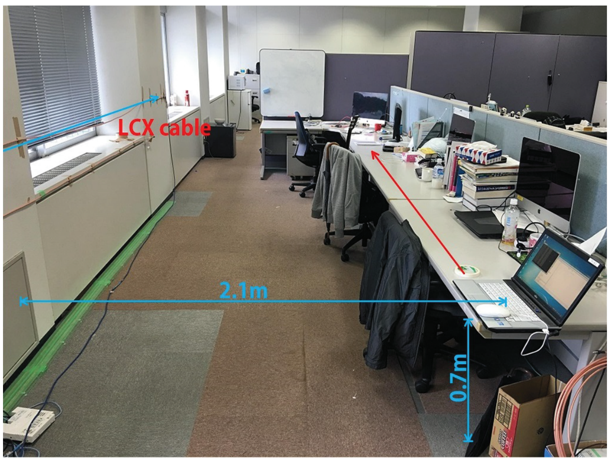


Figure 4.2: Experiment Environment in Area A

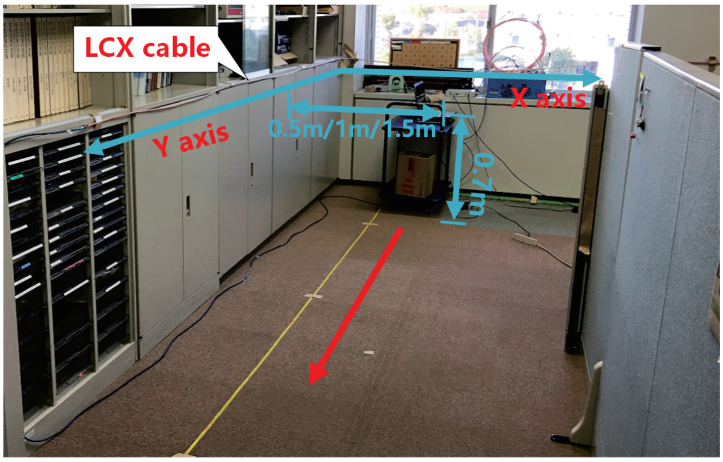


Figure 4.3: Experiment Environment in Area B

Figure 4.4: Experiment Environment in Area C

We set the laptop on a cart with 0.7m height from the floor and measure the throughput over 3 main areas, Area A, Area B and Area C(Fig 4.1(a)). In Area A, we fix the Y in 1m and 2.1m and move the receiver along the X axis from 0,2m to 6.8m as shown in Fig 4.1(b) and Fig 4.2. In this scenario, we investigate the system performance where the receiver is near to the LCX cable or beside the table.

In Area B, the receiver is nearer to reflection objects, such as the partition wall and cabinet, over this narrow passageway. And we arrange the receiver in three distances to Y axis where X is fixed in 0.5m, 1m and 1.5m.

In addition, to survey the influence caused by some blocks which generate the non-light-of-sight (NLOS) scenario between transmitter and receiver, we also do the experiment in Area C where the Y keeps 3.5m and X begins from 2.8m to 6.8m in Fig.9. Because the partition wall is 1.2m height taller than LCX cable at 1.1m and laptop at 0.7m, it is possible to build a NLOS environment in Area C shown in Fig.9. Otherwise, all the interval between adjacent measurement positions is 20cm.

4.2.2 S-parameters

Scattering parameters(S-parameters) is a convenient way to describe a given network in terms of waves rather than voltages or currents[15]. In a n-by-n MIMO system, the waves going towards the n-port are $a = (a_1, a_2, ..., a_n)$, and the waves traveling away from the n-port are $b = (b_1, b_2, ..., b_n)$. The relation between a_i and b_i can be wtritten as a system of n linear equations

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \tag{4.1}$$

or in matrix formulation

$$\mathbf{b} = \mathbf{Sa} \tag{4.2}$$

The physical meaning of S_{11} is the input reflection coefficient with the output of the network terminated by a matched load ($a_2 = 0$). S_{21} is the forward transmission from port 1 to port 2, S_{12} the reverse transmission from port 2 to port 1 and S_{22} the output reflection coefficient.

When measuring the S-parameters of an n-port, all n ports must be terminated by a matched load, including the port connected to the generator.

Moreover we can write the reflection coefficient of a signle impedance Z_L connected to a generator of source impedance Z_0

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} = \Gamma = \frac{Z_L/Z_0 - 1}{Z_L/Z_0 + 1} \tag{4.3}$$

which is the familiar formula for the reflection coefficient Γ. And in a similar form we get

$$S_{21} = \frac{b_2}{a_1} = \frac{2Z_0}{2Z_0 + Z} \tag{4.4}$$

Due to the symmetry of the element $S_{22} = S_{11}$ and $S_{12} = S_{21}$, and assuming $Z_L = Z_0$ the full S-matrix of the elements is then

$$\mathbf{S} = \begin{Bmatrix} \frac{Z}{2Z_0+Z} & \frac{2Z_0}{2Z_0+Z} \\ \frac{2Z_0}{2Z_0+Z} & \frac{Z}{2Z_0+Z} \end{Bmatrix} \tag{4.5}$$

A generalized n-port S-matrix has n^2 scattering coefficients. While the S_{ij} may be all independent, in general due to symmetries. The number of independent coefficients is much smaller. The **S** matrix has some properties as follow,

- An n-port is reciprocal when $S_{ij} = S_{ji}$ for all i and j and most passive components are reciprocal, active components such as amplifiers are generally non-reciprocal.
- A two-port is symmetric, when it is reciprocal ($S_{21} = S_{12}$) and when the inpurt and output reflection coefficients are equal ($S_{11} = S_{22}$).
- An n-port is passive and lossless if its **S** matrix is unitray, $\mathbf{S}^\dagger\mathbf{S} = \mathbf{1}$, where $\mathbf{x}^\dagger = (\mathbf{x}^*)^{\mathbf{T}}$ is the conjugate transpose of $\mathbf{x}$ and for a two-port means

$$(\mathbf{S}^*)^T\mathbf{S} = \begin{pmatrix} S_{11}^* & S_{21}^* \\ S_{12}^* & S_{22}^* \end{pmatrix} \begin{pmatrix} S_{11} & S_{21} \\ S_{12} & S_{22} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{4.6}$$

In general the S-parameters are complex and frequency dependent. Their phase change when the reference plane is moved. Often the S-parameters can be determined from considering symmetries and, in case of lossless networks, energy conservation[16].

Cable type	V-type for both
Slot period P	40mm for 18Deg., 30mm for 55Deg.
Coupling loss	60dB $\pm$ 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

Table 4.1: Parameters of LCX cables

Mode	IEEE 802.11n
Channel	36
Bandwidth	20MHz
Guard Interval	Short(1/16)
Fragmentation Threshold	2346 Bytes
Transmit Power	15 dBm for 1 antenna 10 dBm for 2 antenna
Modulation Coding Scheme(Rate)	Automatic

Table 4.2: Configuration of Access Point

4.2.3 Network Layer Throughput

In this experiment, we measure the system throughput under 802.11n in 5GHz band 36 channel. The AP can choose the modulation and coding scheme (MCS) automatically to maximize the throughput. Furthermore, we occupy only 20MHz bandwidth and use a short guard interval. Here we utilize a network test software, called 'IPERF', for measuring the throughput by sending the TCP packets. At each measurement position, the throughput measurement last 30 seconds and record the average speed as result. Eventually we get 34 points in Y = 1m and Y = 2.1m, 21 points in Y = 3.5m. To confirm the capability of the proposed 2-by-2 LCX-MIMO system, we also measure the system throughput of one transmitter antenna and two receiver antennas (1-by-2) by input port 2 of LCX cable as shown in Fig. 2 but from X = 2.8m. The parameters of LCX cables and AP are given in Table 4.1 and 4.2.

4.3 Results Analysis

4.3.1 Channel Condition Number of LCX-MIMO

Condition Number(CN) is a parameter of matrix that we can use it for measuring the MIMO channel matrix by numbers. For example, a 2-by-2 MIMO matrix **H** usually using the S-matrix, the elements between the transmitter and receiver antennas are represented as

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{21} \\ h_{21} & h_{22} \end{pmatrix} \tag{4.7}$$

First the measured matrix **H** can be decomposed by singular value decomposition (SVD) method as follow:

$$\mathbf{H} = \mathbf{U\Sigma V}^* = \mathbf{U} \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \mathbf{V}^* \tag{4.8}$$

where **U** and **V** are unitary matrices of **H** and λ_i is ith eigenvalue. The condition number γ [dB] is defined by

$$\gamma = 20 * \log_{10} \left(\frac{\lambda_1}{\lambda_2} \right) \tag{4.9}$$

Generally a matrix with a low CN is considered as a well conditioned matrix while a matrix with a CN is an ill-conditioned one. Similarly a MIMO matrix with a lower CN means good cannel condition and will lead a higher channel capacity in theory, since a channel matrix with lower CN provides a larger spatial multiplexing in MIMO systems.

Fig 4.5 and 4.6 shows the cumulative distribution function (CDF) of CN in $Y = 0.5m$ and $2m$. If receiver is very close to the transmitter, the Omni-directional antennas show a good results than LCX cables due to the strong straight signal waves. However, if the receiver is far from the transmitter and near to other blocks in the environment, the LCX cables show a outstanding performance than Omni-directional antennas where the straight signals become weaker and reflection becomes stronger.

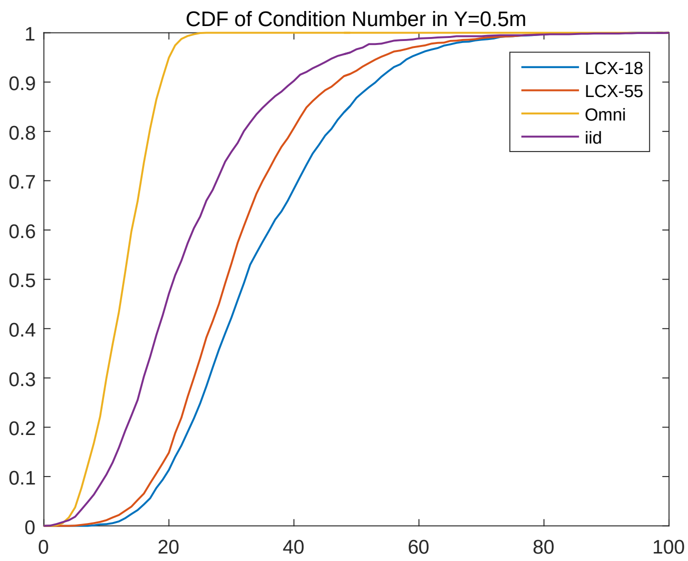


Figure 4.5: Condition Number in Y=0.5m

4.3.2 Shannon Channel Capacity of LCX-MIMO

Usually the Shannon capacity of an MIMO channel describes the upper rate limitation of the MIMO channel and provides a direct number of the system performance in theory [18-20]. Generally the Shannon capacity depends on the statistical properties and inter-antenna element correlations of the channel. There are two kinds of conditions for design of a MIMO system.

The first one assumes that Channel State Information **H** is known in transmitter side. In this case, the channel capacity can be optimal if the transmit power is allocated to each sub-carrier by a power allocation algorithm called Water-filling (WF) algorithm[21][22]. And the channel capacity can be expressed as

$$C = \mathbf{E}_{\mathbf{H}} \left[\sum_{i=1}^{N} \log_2 \left(1 + \lambda_i P_i\right) \right] \tag{4.10}$$

where λ_i is the corresponding eigenvalue and P_i is the power allocated to the ith MIMO eigen channel and can be calculated

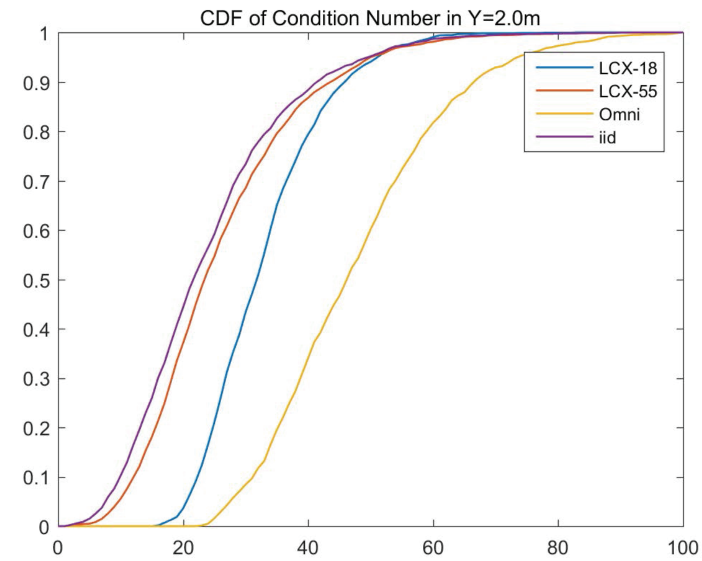


Figure 4.6: Condition Number in Y=2m

$$P_i = (\mu - \frac{1}{\lambda_i})^+ \tag{4.11}$$

where μ is known as WF level and x^+ is defined as $max(x, 0)$. After each eigen channel is iteratively filled wkith the common level μ, the MIMO channel capacity can be computed as follows:

$$C = \mathbf{E_H}\left[\sum_{i=1}^{N} \log_2(\lambda_i \mu)^+\right] \tag{4.12}$$

In more general case that the CSI is not known as transmitter side, the channel capacity can be optimal if the transmitter allocated the uniform power allocation equal power(EP) algorithm to each stream transmission. The Shannon capacity is expressed as

$$C = \mathbf{E_H}\left[\log_2\left(\det\left[\mathbf{I} + \frac{\zeta}{N}\mathbf{H}\mathbf{H}^H\right]\right)\right] \tag{4.13}$$

where ζ is the average Signal-to-Noise Rate(SNR) at receiver side, and N is the number of transmitter antennas. $\mathbf{I}$ is the identity matrix[23]. The superscript H represents the Hermitian transpose.

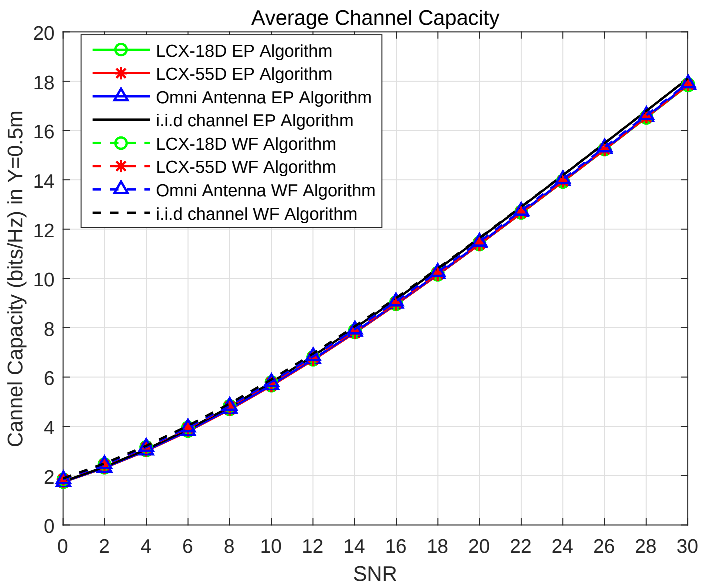


Figure 4.7: Channel Capacity in Y=0.5m

As well known, the channel capacity is related to the occupied bandwidth. By S-parameters measured from the experiments, we calculate the mean channel capacity in bits/Hz. The Fig 4.7 gives the comparison of all three antennas in Y position equal to 0.5 meters where the receiver is close to transmitter. Depending on good channel condition, all antennas have almost same performance in this area and also near to the independent and identically distributed(i.i.d) channel.

In the Fig 4.8, the distance in Y axis becomes farther to 2 meters. The LCX cables shows improvement than Omni-directional antennas about 1.5% in channel capacity. Furthermore, the system using WF algorithm has a better performance in bad SNR[24][25].

4.3.3 Network Layer Throughput of LCX-MIMO

As the previous description, the network throughput is the most direct numerical result for showing the system performance in reality. Fig 4.9 gives the

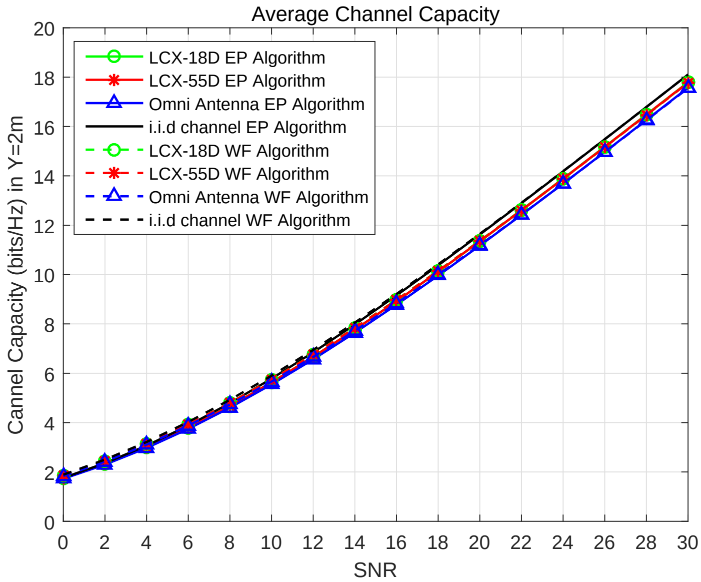


Figure 4.8: Channel Capacity in Y=2m

experiment throughput results of system using 18Deg. LCX cable with the proposed two inputs method and conventional one input method over 3 different Y positions in Area A and C. The horizontal axis means the space positions in the X axis and the origin point means the measurements begin from the origin point. Comparing with the conventional method (dash lines), our proposed method (solid lines) demonstrates a great improving of throughput performance. In most measurement positions, the proposal can achieve two times of conventional one input system using one LCX cable as one antenna in transmitter side. Moreover, it even can achieve more than twice throughput than that of conventional method at some position especially where are far from origin point. Those facts prove this method using one LCX cable as two antennas can realize MIMO system in real indoor environment.

The measurement results of 2-by-2 MIMO system using three kinds antennas, 18Deg. LCX cable, 55Deg. LCX cable and omni-directional antennas, for $Y = 1\text{m}$ in Area A are compared in Fig 4.10. In this scenario, three kinds antennas all have rapidly fluctuated over all coverage. However, comparing with the omni-directional antennas, the LCX-cables show relatively stable and promising

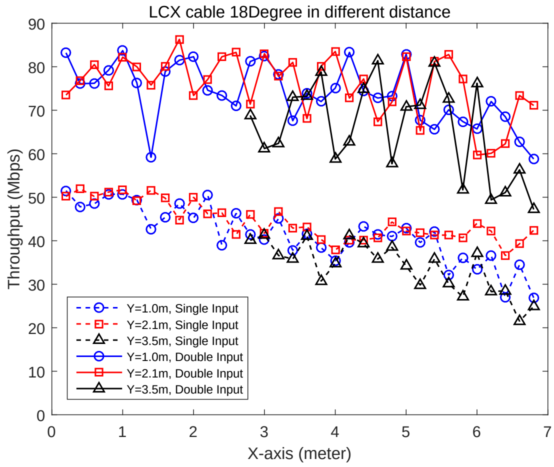


Figure 4.9: Throughput comparison for MIMO system using LCX cable with 18Deg.

throughput performance, especially for 55Deg. LCX-cable at the positions from 0.2m to 1.8m. Moreover, due to positions out of range of cable, the throughput performance of both 18Deg. and 55Deg. LCX cable cannot overtake omni-directional antennas after X=6m.

We increase the distance between the laptop and the antenna from Y = 1m to Y = 2.1m as shown in Fig 4.7. The laptop moves along the arrow line on the table. In this case, the laptop is nearer to many blocks which lead to more reflection and attenuation impact. Therefore, there are more fluctuation causing large delay and phase shift. The results are shown in Fig.8. In this scenario, the LCX cables also can reach similar and even better throughput performance than the system using omni-directional antennas in most positions. Due to larger signal loss in inner of LCX cables, the performance tends to exhibit larger attenuation around the boundary where is far from the center of cable.

When the distance between the transmitter and receiver increases to 3.5m in Area C, the RF signals pass through some metal office partition blocks with 1.2m height and other reflection blocks, such as computer screens. Due to the antennas arranged at 1.1m and the laptop arranged at 0.7m, it can generate NLOS scenario and cause more attenuation. The environment is shown in Fig

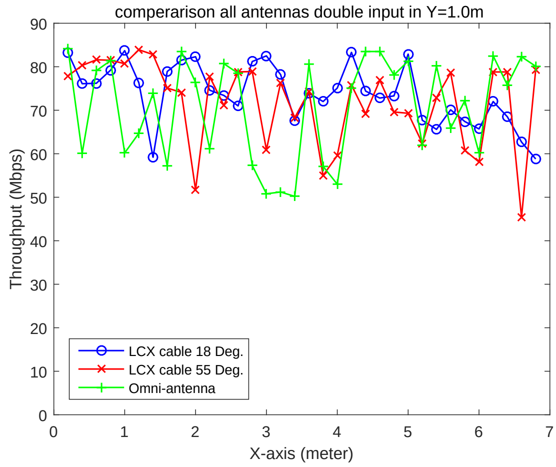


Figure 4.10: Throughput comparison for MIMO system in Area A Y=1m

4.8. The laptop also moves along the arrow line on the table at 0.7m height from X = 2.8m to 6.8m. From the results shown in Fig.10, the system using omni-directional antennas shows better throughput performance than system using LCX cables proves the system of LCX cables have more attenuation caused by blocks. However, those results also confirm the effectiveness of our proposed LCX-MIMO over linear-cell environment where is a long and narrow coverage area.

In the Last Area B, we move the receiver along the Y axis in X=0.5m/1m/1.5m shown in Fig 4.9. This Area B is more narrow than Area A and C. It is really near to reflection objects, such as metal cabinet and partition wall. Consequently, according to Fig.12, we can conclude the LCX cable present better and stabler performance than omni-directional antennas in this scenario.

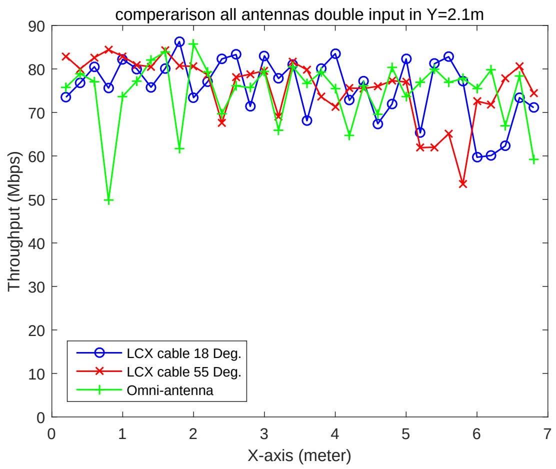


Figure 4.11: Throughput comparison for MIMO system in Area A Y=2.1m

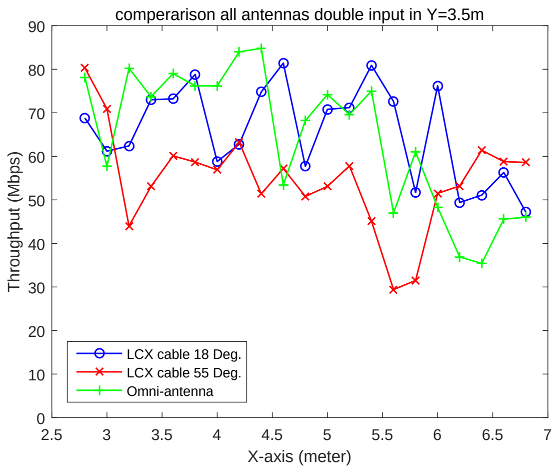


Figure 4.12: Throughput comparison for MIMO system in Area C Y=3.5m

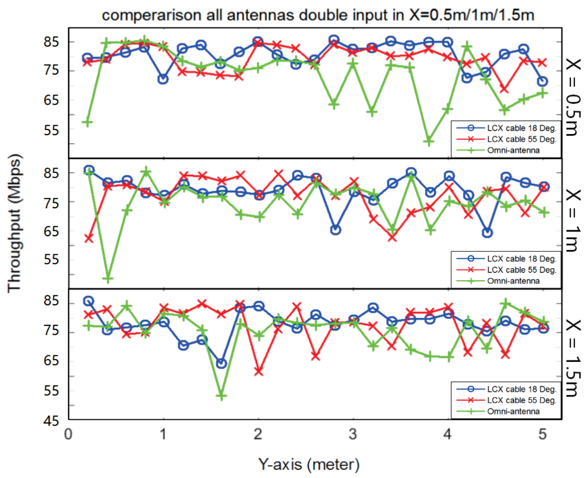


Figure 4.13: Throughput comparison for MIMO system in Area B

5 Conclusion

5.1 Conclusion

In this paper, we have introduced a throughput measurement experiment of the proposed LCX-MIMO system comparing with conventional MIMO system using two omni-directional antennas in a real office environment. By several typical analysis methods, CN, channel capacity, and network throughput, the measurement results prove that our proposed MIMO system using one LCX cable as two antennas can be utilized in the real environment and the LCX-MIMO systems can perform well in indoor linear-cell environments. In addition, comparing with conventional omni-directional antennas, our proposal can achieve similar or even better performance in most measurement positions. Therefore, our proposed LCX-MIMO system is proved as a promising solution for linear-cell environment with a long and narrow wireless coverage area.

5.2 Future works

This study is focusing the 2-by-2 LCX-MIMO system by only one LCX cable as a transmitter antenna. But for the further improvement in both spectral efficiency and channel capacity, the case with more transmitter antennas should be studied in the future. Moreover the interference between difference LCX cables did not be considered. For the future research, we will try to realize a 4-by-4 LCX-MIMO system by a parallel coupled LCX cables and it maybe achieve better performance than other antennas.

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