FULL-DUPLEX SINGLE-CHANNEL COMMUNICATION FOR MIMO SYSTEMS

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Telecommunication Engineering

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FULL-DUPLEX SINGLE-CHANNEL COMMUNICATION

FOR MIMO SYSTEMS

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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ปัจจุบันระบบการสื่อสารไร้สายได้ถูกคิดค้นและพัฒนามาอย่างต่อเนื่อง เนื่องจากความต้องการของผู้ใช้บริการที่ต้องการรูปแบบการสื่อสารที่สามารถรองรับการรับส่งข้อมูลที่มีความรวดเร็วและมีความแม่นยำมาก หนึ่งในเทคโนโลยีการสื่อสารไร้สายที่กำลังพัฒนาอยู่ในขณะนี้ คือ เครือข่ายการสื่อสารไร้สายยุคที่ 5 ซึ่งหนึ่งในแนวทางนี้ได้รับความสนใจมากคือการสื่อสารที่สามารถรับและส่งพร้อม ๆ กันได้ อีกทั้งยังสามารถทำให้อัตราการรับส่งข้อมูลได้อย่างรวดเร็วขึ้น งานวิจัยที่มีอยู่ในปัจจุบันได้มุ่งเน้นไปที่การแก้ปัญหาการเกิดสัญญาณแทรกสอดของตนเองบนช่องทางการสื่อสารสองทางเต็มอัตรา โดยสร้างอุปกรณ์ที่สามารถลดระดับสัญญาณแทรกสอดของตนเองได้ อย่างไรก็ตามงานวิจัยดังกล่าวยังไม่ได้พิจารณาในแง่ของประสิทธิภาพในการรองรับการสื่อสารความเร็วสูงซึ่งใช้เพียงแค่สายอากาศต้นเดียวบนช่องสัญญาณเดียว ด้วยเหตุนี้ผู้วิจัยได้จึงเกิดแนวคิดที่จะปรับปรุงประสิทธิภาพการสื่อสารไร้สายให้มีประสิทธิภาพในการรับสัญญาณที่ดีขึ้น โดยการนำระบบไมโมมาประยุกต์ใช้ ถึงแม้ว่าจะมีงานวิจัยที่มุ่งเน้นไปที่การพัฒนาเกี่ยวกับระบบรีเลย์ไมโม แต่งานวิจัยดังกล่าวไม่ได้พิจารณาถึงปัญหาสัญญาณแทรกสอดร่วม ซึ่งเกิดจากสัญญาณที่ถูกส่งออกระหว่างภาคส่งกับภาคส่งต้นอื่นๆ ในโนดเดียวกัน และการลดสัญญาณแทรกสอดในส่วนดิจิตอลอาจไม่เพียงพอ เพราะระดับความแรงของสัญญาณแทรกสอดของตนเองและสัญญาณแทรกสอดร่วมนั้น แรงกว่าสัญญาณที่รับได้ที่ภาครับ ซึ่งปัญหาเหล่านี้ทำให้ระบบเกิดความผิดพลาดที่ภาครับ ดังนั้นวิทยานิพนธ์นี้จึงนำเสนอการพัฒนาระบบสื่อสารสองทางเต็มอัตราบนช่องสัญญาณเดียวสำหรับระบบไมโม โดยใช้เทคนิคการลดสัญญาณแทรกสอดทั้งแบบแอนาลอกและดิจิตอล การลดสัญญาณแทรกสอดแบบแอนาลอกถูกออกแบบเพื่อลดระดับพลังงานของสัญญาณแทรกสอดของตนเองและสัญญาณแทรกสอดร่วมโดยการปรับเฟสและแอมพลิจูด การลดสัญญาณแทรกสอดแบบดิจิตอลถูกดำเนินการภายในบอร์ด USRP เพื่อลดปัญหาระดับความแรงของสัญญาณแทรกสอดของตนเองและสัญญาณแทรกสอดร่วมไปพร้อมๆ กัน ผลจากการจำลองแบบและการสร้างชุดทดสอบในการปฏิบัติการแสดงให้เห็นว่าระบบที่นำเสนอสามารถให้การส่งผ่านข้อมูลเป็นสองเท่าของระบบเดิมและภาครับสามารถรับข้อมูลได้อย่างมีประสิทธิภาพมากขึ้น

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FULL-DUPLEX COMMUNICATION/MIMO SYSTEMS/SELF-INTERFERENCE/MUTUAL-INTERFERENCE

Nowadays, the wireless communication systems have been developed continuously. Since the requirement of users prefer a form of communication that can transfer data very fast and very accurate. One of the most recent technologies being developed right now is a network of 5G wireless communication, which in this approach has received much attention that can transmit and receive simultaneously. The work in literature has focused on solving the problem of self-interference full-duplex communication, by creating a device that can reduce the self-interference. However, the literature has not considered in terms of performance to support high-speed communication, which uses only a single antenna on a single channel. For this reason, researchers have an idea to improve the performance of wireless communication to attain better signals by introducing MIMO applications. Although, the literature has focused on the development of the MIMO relay system, but the literature does not consider problems associated mutual-interference. This is caused by the transmitted signal between antenna elements in the same node and the interference reduction in digital domain being not enough due to the strength of the self-interference and mutual-interference with the received signal strength at the receiver. These problems cause the system to crash at the receiver. Finally, this thesis proposes the development of full-duplex communication on a single channel for MIMO systems by using a technique to reduce the interference of both analog and digital domains. Analog cancellation is designed to reduce the power levels of self-interference and mutual-interference signals by adjusting phase and amplitude. Digital cancellation is implemented inside the Universal Software Radio Peripheral (USRP). To reduce the strength of the self-interference and mutual-interference simultaneously. The simulation and experimental results show that the proposed system can double throughput of the conventional system and the receiver can receive data more efficiently.

School of Telecommunication Engineering Student's Signature______________

Academic Year 2017 Advisor's Signature______________

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SYMBOLS AND ABBREVIATIONS

ADC	=	Analog-to-Digital Converter
BER	=	Bit Error Rate
BS	=	Base Station
CR	=	Circulator
DAC	=	Digital-to-Analog Converter
DBPSK	=	Differential Binary Phase Shift Keying
D2D	=	Device to Device
EMF	=	Electromagnetic Force
FDD	=	Frequency Division Duplex
FDSC	=	Full Duplex Single Channel
FPGA	=	Field-Programmable Gate Array
GRC	=	GNU Radio Companion
MIMO	=	Multiple Input Multiple Output
MISO	=	Multiple Input Single Output
M2M	=	Machine to Machine
MMSE	=	Minimum Mean Square Error
RF	=	Radio Frequency
TDD	=	Time Division Duplex
UHD	=	USRP Hardware Driver
USRP	=	Universal Software Radio Peripheral

SYMBOLS AND ABBREVIATIONS (Continued)

SDR	=	Software-Defined Radio
SVD	=	Singular Value Decomposition
SNR	=	Signal to Noise Ratios
SIMO	=	Signal Input Multiple Output
SIR	=	Signal to Interference Ratio
SISO	=	Single Input Single Output
STBC	=	Space Time Block Code
ZF	=	Zero Forcing

CHAPTER I

INTRODUCTION

1.1 Background and problems

At the moment, the wireless communication system is one of the key technologies of the human life such as the mobile communications and other entertainment. The users demand to send video and audio data of large sizes. But nowadays, the technologies have limited frequency that cannot respond the requirement of increasing users. The demand of transmitting and receiving information require faster data rates. From the words of Andrea Goldsmith (2005), “It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results”. In this sentence, the main idea is to improve the performance of communication systems that transmit and receive data at the same time on the same frequency band.

A communication channel can be defined as a pathway for the transmission and reception. There are three modes of duplex communication systems such as the simplex communication system, the half-duplex communication system and the full-duplex communication system. In these duplex communications, the most applications of wireless communications are half-duplex and full-duplex. Half-duplex provides communication in both directions, but only one direction will be allowed through at a time. For example, a walkie-talkie uses only one single frequency for bidirectional communication, one party speaks while the other person listens, and vice versa. On the other hand, full-duplex is bi-directional which is used for transmitting and receiving simultaneously. The full-duplex communication systems are one of the most effective technologies because they provide double throughputs and capacities over the conventional system. There are two basic forms of full-duplexing such as Frequency Division Duplex (FDD) and Time Division Duplex (TDD). For the reasons mentioned above, a full-duplex communication is the most interesting technologies for researchers (Zhang Z., et.al, (2016); Bharadia D., and Katti S., (2014)) to develop and design new types of wireless communications. The researchers want to increase the performance of a communication system which supports and facilitates users to transmit and receive at the same time on the same frequency. Moreover, the wireless communication systems have reliability and good quality. The communication systems should have to transmit and receive signals simultaneously, i.e., the full-duplex communication.

The most effective concept is to transmit and receive at the same time on the same frequency. Moreover, the main challenge of the design of full-duplex communication system is the interference signal cancellation. Because the strong interference signals generated from transmitter at the same side of receiver. This interference signal is called as self-interference signal. It directly affects the quality of transmitting and receiving signals. In (Liempd B. V., et.al., (2014); Korpi D., et.al., (2014); Hong S., et.al., (2014)), authors have focused on the design of the full-duplex communication system which can transmit and receive simultaneously at the same frequency and the same channel, so called as Full Duplex Single Channel (FDSC). It is designed by using only one antenna for both the transmitting and receiving sessions. The designed FDSC uses a circulator for the separation of the signals. It can separate two paths of transmitting and receiving signals at the same time. Due to imperfection of circulator, when the signal is transmitted to circulator, there will be a signal leakage. Hence, the self-interference cancellation is the challenge in the implementation of the FDSC communication system which causes the strength of the interference signal at the receiving antenna. Full-duplex communication has been a source of interest for the researchers. Most of the self-interference cancellation techniques were presented in the literatures in order to reduce the self-interference signal. However, most of the current research present two techniques for self-interference cancellation which are both analog cancellation (Choi J. II, et.al., (2010); Zhou Z., et.al., (2015); Kolodziej K. E., and McMichael J. G. et.al., (2016); Kolodziej K. E., and Doane J. P. et.al., (2016)) and digital cancellation (Korpi, et.al., (2014); Zhou Z., et.al., (2015)). In (Kolodziej K. E., and Doane J. P. et.al, (2016)), the isolation-improvement technique is presented to cancel interference by using the adjusting phase shifter. In (Choi J. II, et.al, (2010)), the antenna cancellation have been proposed by using two transmitting antennas and one receiving antenna. For a wavelength λ, the transmitting antenna is placed at distance d from receiving antenna and the other transmitting antenna is placed at $\lambda + \frac{\lambda}{2}$ from the receiving antenna. This technique has limitation on physical implementation. The other techniques using RF circuits are more practical but they need more complex design for cancellation circuits. In (Zhou Z., et.al, (2015)), the Qh $\times 220$ chip is used for cancelling a reference signal, which is called RF canceller technique. The digital cancellation is done after transforming signal into the digital domain. That is why many fancy techniques can be proposed to digitally eliminate the interference signals (Liang, et.al, (2015); Masmoudi, et.al, (2016)).

As above mentioned, the researchers study the new technologies in order to respond to the demand of users by using more and more antennas at the transmitter and receiver. The improved quality of the received signal means better performance of the system to communicate well together. The researchers have studied the multiple-input multiple-output (MIMO) system in order to develop the wireless communication system. The mobile communication systems have deployed the MIMO technologies on the third generation (3G), the fourth generation (4G), as well as beyond the fifth generation (5G) (Albreem M. A. M., et.al, (2015); Gupta, et.al, (2015); Alves H, et.al, (2015)). In the literature, researchers have improved the wireless communication systems that can transmit and receive data coverage the area of use increases. The FDSC MIMO system is more number of antennas on the transmitter and receiver. The self-interference and mutual-interference signals occurs due to transmitting and receiving simultaneously. However, if the interference signal is happened at the same antenna, so called the self-interference signal. In other words, if the interference signals are present at the neighboring antennas, so called the mutual-interference signal. This problem cannot be solved by all techniques in literatures because the interference signals are the combination of the self-interference and mutual-interference. The MIMO relay was presented by researchers. A relay station is used to assist communication between the base station and the mobile station. The problem of MIMO relay is self-interference signal because the relay transmits and receives simultaneously. In (Lioliou P., et.al, (2009); Zhang J., et.al, (2013); Liu H., et.al, (2013); Shang C. Y. A., et.al, (2014)), authors have presented only the self-interference cancellation. In (Lioliou P., et.al, (2010), the self-interference signal is cancelled by using weight filters technique at the relay's transmit and receive sides. They aim at maximizing the signal- to- interference ratio (SIR) between the desired signal to the self-interference signal at the reception and transmission. In (Shang C. Y. A., et.al, (2014)), authors have presented loopback interference cancellation by using weight vector based on zero-forcing (ZF) technique. From the above literature, the real interference power is ignored in the proposed cancellations and it is impossible to perform any digital cancellation. In fact, the self-interference and mutual-interference signals are still stronger than desired signal. Thus, the main key of interference cancellation consists of both analog and digital cancellations.

Finally, the real interference power is not considered for the full-duplex MIMO system in literatures. Therefore, this thesis presents the FDSC communication for MIMO systems by considering the real interference power. Moreover, the main problem of this concept is the strong self-interference and mutual-interference signals. The interference cancellation techniques are proposed in this thesis, which are analog and digital cancellations. For the analog cancellation, it is designed to reduce the power levels of self-interference and mutual-interference signals by using RF circuit. It can suppress interference power by adjusting phase and amplitude of signals. For digital cancellation, it uses the subtraction of known transmitted data which is operated inside Universal Software Radio Peripheral (USRP) board.

1.2 Thesis objectives

(i) To study the theories and to design the full-duplex single-channel communication for MIMO systems.

(ii) To propose the technique to reduce the self-interference and mutual-interference signals on both analog and digital domains.

(iii) To investigate the performance of the proposed interference cancellation technique on the full-duplex single-channel communication for MIMO systems.

1.3 Scope of study

(i) Due to limitations of test kits, this thesis uses two antennas for the transmitter and receiver.

(ii) All simulation results are performed using MATLAB.

(iii) A test kit is designed to transmit and receive signals simultaneously, named as two-way communication.

(iv) For experimentation, this thesis is to reduce the strength of self-interference and mutual-interference in both analog and digital domains.

(v) A test kits of the proposed full-duplex single-channel communication for MIMO systems consist of two nodes which can transmit and receive simultaneously.

(vi) The measured power and Bit Error Rate (BER) are considered.

1.4 Contributions

(i) To obtain the concept of the full-duplex single-channel communication for MIMO systems.

(ii) The proposed techniques can suppress self-interference and mutual-interference signals.

(iii)Experimental results show the significance of the proposed technique regarding cancellation of self-interference and mutual-interference signals.

1.5 Thesis organization

The remainder of this thesis is organized as follows. Chapter II presents the background theory including the development of wireless communication system in the future, the utilization of duplex communication systems, MIMO systems, the effective of mutual-coupling and the main problem of interference signal. This chapter presents the interference cancellation techniques.

Chapter III presents the development of full-duplex single-channel communication for MIMO systems. This chapter presents the interference cancellation techniques in the FDSC for SISO and the MIMO systems.

Chapter IV presents the analog cancellation part. The proposed technique is designed to reduce the power levels of self-interference and mutual-interference signals by using modified hybrid coupler and phase shifter. The designed modified hybrid coupler and simulation results of the proposed technique are presented in this chapter.

Chapter V presents the digital cancellation part, the subtraction of known transmitted data is implemented inside the Universal Software Radio Peripheral (USRP). The space time block coding (STBC) technique is used for the estimation of the received data. A full test kit is constructed. The test kit consists of two nodes of the simultaneous transmitting and receiving for FDSC 2×2 MIMO system which are developed under Software-Defined Radio (SDR) technology. The experimental results show that the proposed technique can eliminate the interference power in the real-time. In addition, it can provide double throughputs in the system.

Chapter VI provides the conclusion of the research work and suggestion for further study.

CHAPTER II

BACKGROUND THEORY

2.1 Introduction

This chapter refers to the theory of full-duplex communication and MIMO technology which assists in the development of wireless communication systems in the future. MIMO is a technology to use multiple antennas for transmission and reception. The full-duplex communication for MIMO system is to transmit and receive at the same time on the same frequency. The main problem of this system is the interference signals including self-interference signal and mutual-interference signal. Therefore, this chapter discusses the interference cancellation techniques which can solve the mentioned problem. Section 2.1 is an introduction of this chapter which presents the main problem of full-duplex MIMO systems. Section 2.2 discusses the development of wireless communication in the future. Section 2.3 discusses the types of communication technologies. Section 2.4 presents the theory of the MIMO technology which shows the effect of mutual coupling presented in Section 2.5. Section 2.6 presents the FDSC communication for MIMO systems. The problem of self-interference and mutual-interference signals is explained in Section 2.7. Many techniques for cancelling interference were presented in previous literatures which are discussed in Section 2.8. The last section concludes this chapter.

2.2 The development of wireless communication in the future

Nowadays, the wireless communication systems have become an essential part of everyday life, the demand of more users, and the data or information can be transmitted faster and with a high speed. In (Osseiran A., et al., (2014); Albreem M.A.M., et al., (2015); Gupta and Jha R.K., (2015), authors study and develop the communication technologies in order to support transmitting and receiving with high speed. They show the evolution and development of various generations of mobile wireless technology in terms of data, mobility and spectral efficiency. The wireless technologies have evolved from 1G to 4G, and to beyond 5G networks. The first generation (1G) technology uses analog telecommunication standard which transmit voice signals only. The second generation (2G) technology differed from the previous generation in their use of digital transmission instead of analog transmission which can be transmitted both voice and data signals. The third generation (3G) support services that provide an information transfer rate of at least 2 Mbps. It can be applied to transmit and receive higher data such as mobile Internet access, video calls and mobile TV technologies. Speed of fourth generation (4G) are increased to keep up with data access demand used by various services. This generation has been continuously developing and improving mobile technologies like MIMO systems. To achieve the expected capacity, coverage, reliability, latency and improvements in energy consumption until fifth generation (5G). Simultaneously, research toward 5G is one of the most attractive topics of mobile communication as shown in Figure 2.1. Researchers in the world have been doing research on enabling technologies for both evolution and revolution routes (Gupta, and Jha R. K., (2015); Zhang X., et al, (2015); Al-Falahy N., and Y. Alani O., (2017); Hossain E. and Hasan M., (2015); Talwar S., et al, (2014) including massive

MIMO, Device to Device (D2D), Machine to Machine (M2M) communications and mmWave communication. Massive MIMO techniques are the use of a very large number of service antennas, very large MIMO (Al-Falahy N., and Y. Alani O., (2017)). The benefits of massive MIMO include the extensive use of inexpensive low-power components, reduced latency and a solution to both capacity and energy efficiency demands. Device to Device (D2D) technique is the communication between devices (Talwar S., et al, (2014)), which allow two nearby devices to communicate with each other in licensed cellular bandwidth without a Base Station (BS). Simultaneously, authors present the designed full-duplex communication MIMO relay system using single antenna (Lioliou P., et al, (2010); Shang C. Y. A., et al, (2014); Xiong X., et al, (2016)). The simultaneous transmitting and receiving simultaneously are provided the high capacity of MIMO communication with the coverage extension capability of relay transmission.

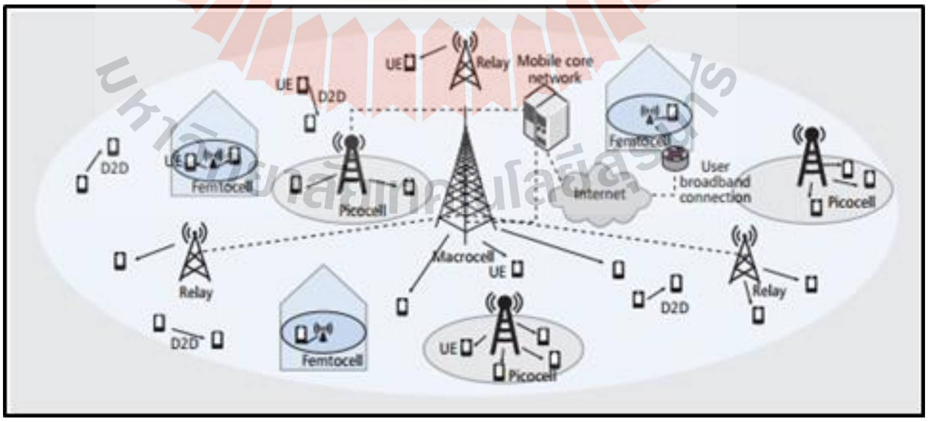

Figure 2.1 5G landscape and performance requirements (Hossain E. et al, (2014)).

2.3 Types of communication technologies

The transmission on communication channel defines the direction of the flow of information between two communication devices. There are three types of communication systems such as simplex, half-duplex and full-duplex.

2.3.1 Simplex

The system operates in one direction, as shown in Figure 2.2. This method is not complicated. Communication is unidirectional when the transmitting device does not require a response from the receiving device such as a communication between a computer, radio and a keyboard, television and remote.

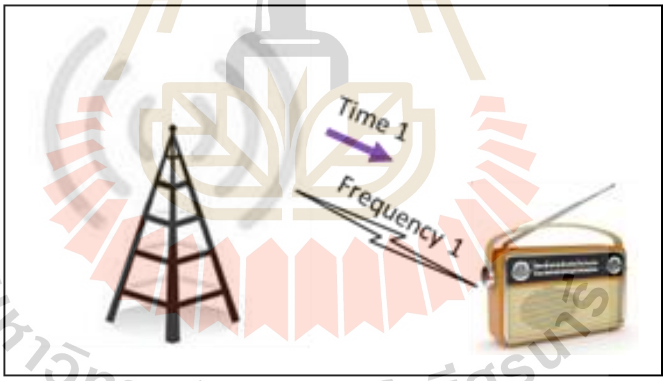

Figure 2.2 Simplex communication system.

2.3.2 Half-duplex

Half-duplex data transmission means that data can be transmitted in both directions on the same frequency, but not at the same time. The transmitting and receiving information cannot happen simultaneously, as shown in Figure 2.3. For example, a walkie-talkie operates in half-duplex mode which message is sent one at a time. It can only send or receive information which cannot do both at the same time.

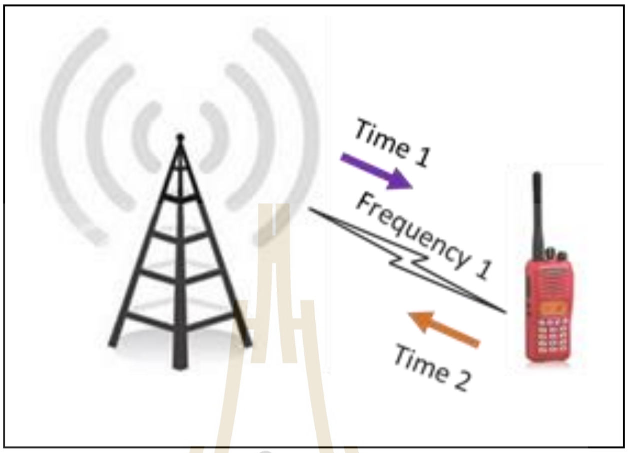

Figure 2.3 Half-duplex communication system.

2.3.3 Full-duplex

In Figure 2.4, a full-duplex system can transmit and receive data simultaneously in both directions on transmission path. Full-duplex transmission, the channel capacity is shared by both communicating devices at all times. The connected devices can transmit and receive at the same time. Therefore, it represents truly bi-directional system. For example, telephone networks operate in full-duplex mode when two persons talk on telephone line, both can listen and speak simultaneously. There are two basic forms of full-duplex such as Frequency Division Duplex (FDD) and Time Division Duplex (TDD).

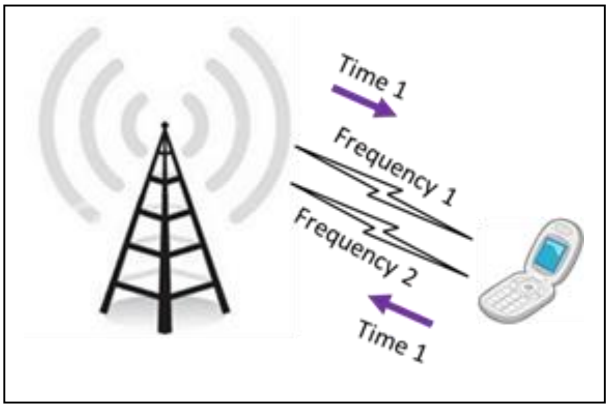

Figure 2.4 Full-duplex communication system.

Frequency Division Duplex (FDD) is a technique where separate the frequency bands are used at the transmitter and receiver. The FDD technique uses two separate frequency bands or channels for transmitting and receiving operations. A sufficient amount of guard band separates the two bands so transmitter and receiver do not interfere with another.

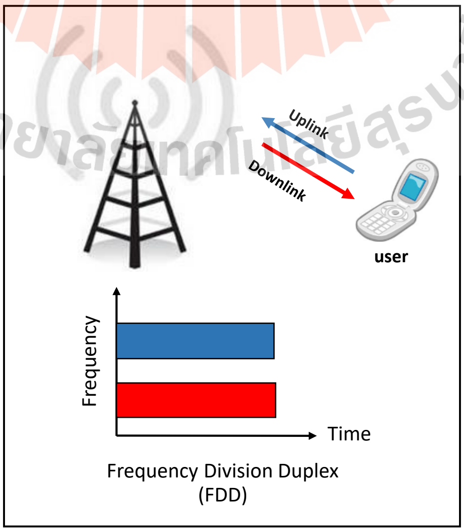

Figure 2.5 Full-duplex communication system using FDD.

Time Division Duplex (TDD) uses the allocation of different time slots on a single frequency band for both transmitting and receiving. Then it shares that band by assigning alternating time slots to transmit and receive operations. TDD separates uplink and downlink signals by matching full-duplex communication over a half-duplex communication. Users are allocated by time slots for uplink and downlink transmission.

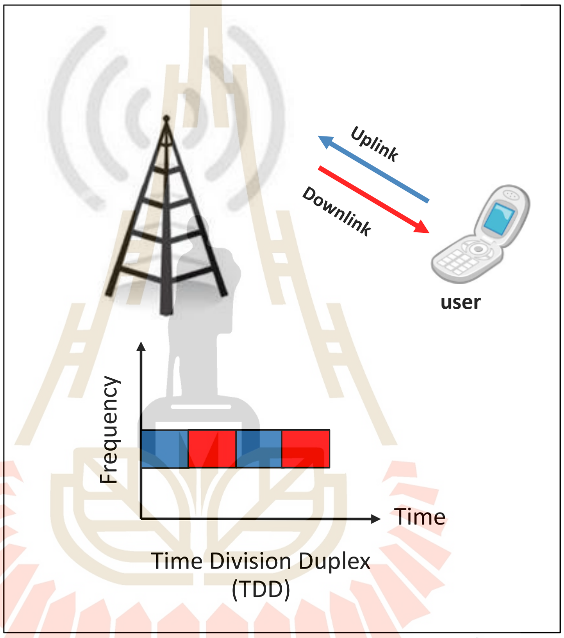

Figure 2.6 Full-duplex communication system using TDD.

2.3.3.1 Full-duplex communication system by using single channel

Normally, the wireless communication cannot transmit and receive simultaneously at the same channel. Andrea Goldsmith (2005) mentioned the full-duplex communication, "It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results". Therefore, the full-duplex system needs to separate uplink and downlink by transmitting and receiving through one switchable channel. The channel need to share between transmitting and receiving which requires either time or frequency to be switched, named as Time Division Duplex (TDD) or Frequency Division Duplex (FDD), respectively. As shown in Figure 2.7, the information is sent between both node 1 and node 2 at the same frequency. The main problem of full-duplex system is signal leakage on the same side which is the undesired signal, so called as self-interference. In order to eliminate self-interference signals, many techniques are proposed in (Choi J. II, et.al, (2010); Zhou Z., et.al, (2015); (Korpi, et.al, (2014); Zhou Z., et.al, (2015)). The advantage of FDSC communication is to efficiently utilize the channel which results in improvement of throughputs and data rate. When node1 and node 2 transmits and receives simultaneously at the same time and then the receiver will receive the bad information. Furthermore, it is the fact that the problem of interference signal is happened, stronger than the desired signal at the same node. This interference signal is named as self-interference signal. In (Choi J. II, et al, (2010); Liempd B. V., et al, (2014); Zhou Z., and Zhang X. (2015)), authors have presented the FDSC communication system using single antenna to transmit and receive simultaneously. However, the problem of MIMO system is more pronounced because it has more single antenna than SISO system.

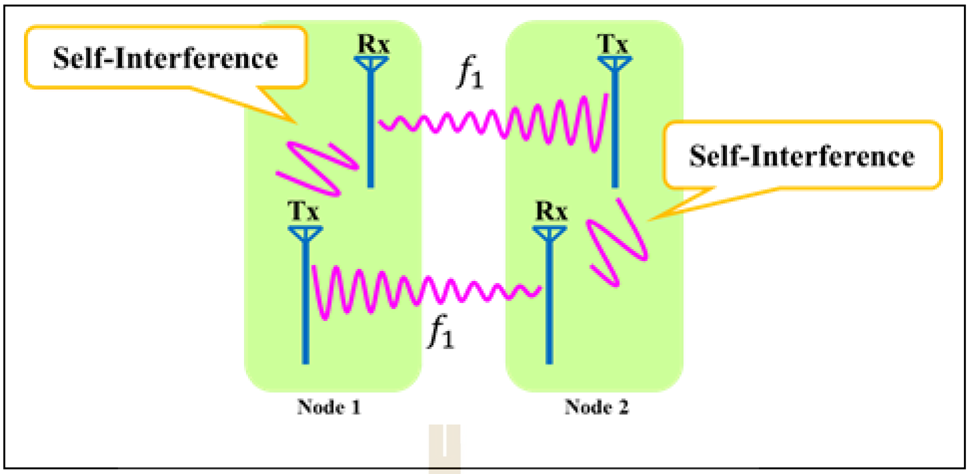

Figure 2.7 The effect of self-interference signals.

2.4 Multiple-Input Multiple-Output (MIMO) System

Nowadays, the MIMO technology is developed in order to improve the wireless communications and spectrum efficiency. In radio, multiple-input multiple-output (MIMO) system is a technique for multiplying the channel capacity of a radio link using multiple antennas at both the transmitter and receiver to improve communication performance. MIMO technology is one of the most interesting technologies in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. Because of these properties, MIMO is an important part of modern wireless communication standards. MIMO technology has been developed and implemented in some standards, e.g. 802.11n products. SISO/ SIMO/ MISO are special cases of MIMO

- Single-input and single-output (SISO) is a radio system where neither the transmitter nor receiver has multiple antennas.

- Single-input and multiple-output (SIMO) is the transmitter has a single antenna.
- Multiple-input and single-output (MISO) is the receiver has a single antenna.

MIMO system consists of the received signal vector with N transmitting antennas and M receiving antennas which can be formulated as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}, \qquad (2.1)$$

where $\boldsymbol{y}$ is the received signal vector, $\boldsymbol{H}$ is the channel matrix between transmitting and receiving antennas, $\boldsymbol{x}$ is the transmitted signal vector, and $\boldsymbol{n}$ is the adding noise vector.

2.4.1 Types of MIMO system

MIMO can be separated two main categories such as Open-loop systems and Closed-loop systems. The difference of both systems are that the closed-loop systems are the feedback channel between the transmitter and receiver. Closed-loop systems are more complex than the open-loop systems but better quality.

2.4.1.1 Open-loop systems

The receiver does not require knowledge of the channel at the transmitter. As a result, this operation occurs when the access network does not have information from the receiver. These systems are called open-loop system.

2.4.1.1.1 Spatial multiplexing

Spatial multiplexing is a well-known open-loop MIMO technique widely used in wireless systems. Different data streams are sent via each transmit antenna. The spatial multiplexing system is depicted in Figure 2.8.

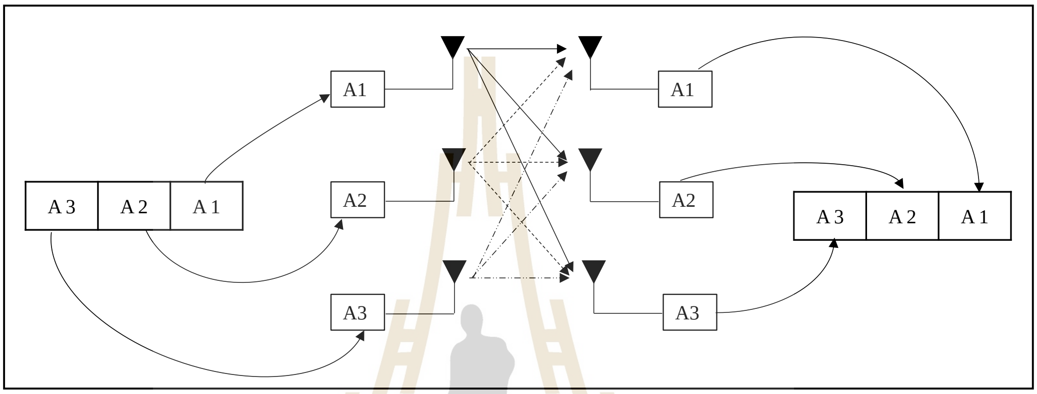

Figure 2.8 Spatial multiplexing system.

2.4.1.1.2 Space-Time Block Code

In the space-time code, a single data stream is transmitted from multiple transmit antennas, but the signal is coded to exploit independent fading in multiple antennas to achieve space diversity as shown in Figure 2.9. The most popular space-time code is Alamouti, which is adopted by many wireless standards. Typical Alamouti code is expressed by (2.2) and rearranged by (2.3)

$$\begin{bmatrix} y_{11} & y_{21} \\ y_{12} & y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix} + \begin{bmatrix} n_{11} & n_{21} \\ n_{12} & n_{22} \end{bmatrix}, \tag{2.2}$$

and

$$\begin{bmatrix} y_{11} \\ y_{12} \\ y_{21}^* \\ y_{22}^* \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{12} \\ n_{21}^* \\ n_{22}^* \end{bmatrix}, \quad (2.3)$$

where the signals x_1 and x_2 are transmitted independently. Then, in the second time, the signals $-x_2^*$ and x_1^* are transmitted simultaneously from the two antennas. Compared with spatial multiplexing, using Alamouti code provides higher diversity gain and does not require complicated receiver detection. The spatial multiplexing targets spatial multiplexing gain, space-time code targets diversity gains.

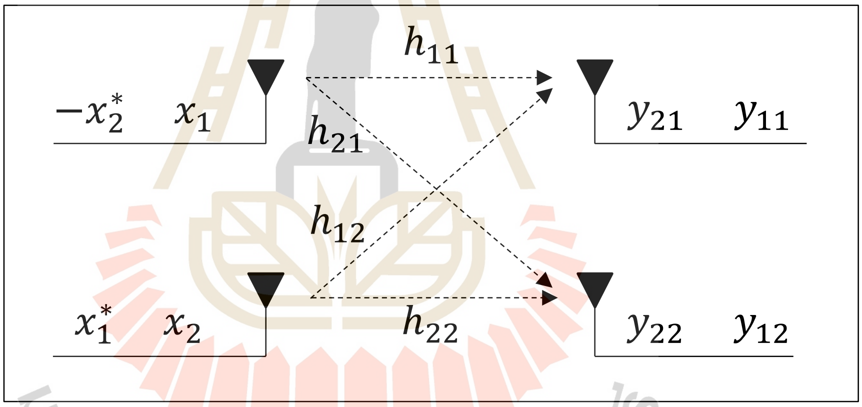

Figure 2.9 Space-Time Block Code system.

2.4.1.2. Closed-loop systems

As the mentioned above, the difference between closed-loop and open-loop of MIMO system is that the closed-loop systems require channel knowledge at the transmitter. Moreover, the main problem is how to obtain channel knowledge at the transmitter. Most current wireless standards allocate a feedback channel to transmit channel knowledge to the base transceiver station. This feedback solution can work in Frequency Division Duplex (FDD) and Time Division Duplex (TDD) systems. Because the redundant channel information puts heavy overhead on the uplink, channel information is usually quantized to reduce the feedback message size. This quantized information feedback is called as a limited feedback.

2.5 Mutual coupling phenomena on MIMO systems

The electromagnetic interaction between the antenna elements in an antenna array is called mutual coupling. Antenna to antenna mutual coupling describes energy absorbed by one antenna's receiver when another nearby antenna is operating. The mutual coupling is typically undesirable because it reduces the performance of the system. Hence, mutual coupling reduces the antenna efficiency and performance of antennas in both transmit and receive modes. The interactions between the entries set of antennas and scatters are initially described by the impedance matrix $\boldsymbol{z}$. In general, $\boldsymbol{z}$ can be determined using numerical techniques. For dipoles, the mutual impedance can easily be calculated using classical induced Electromagnetic Force (EMF) method (Uthansakul P., (2009); Lykhograi V. G., et al, (2013)). The value of the mutual impedance between the m^{th} and n^{th} dipoles can be written as

$$z_{mn} = \begin{cases} 30[0.5772 + \ln(kl) - c_i(kl)] + \\ j[30 s_i(kl)] & m = n \\ 30[2c_i(u_0) - c_i(u_1) - c_i(u_2)] - \\ j\left[30\left(2s_i(u_0) - s_i(u_1) - s_i(u_2)\right)\right] & m \neq n, \end{cases} \tag{2.4}$$

where $k = \frac{2\pi}{\lambda}$ is the wave number, $l = \frac{\lambda}{2}$ is the dipole length and the constants u_0, u_1, u_2 are given by

$$u_0 = kd_h, \tag{2.5}$$

$$u_1 = k\left(\sqrt{d_h^2 + l^2} + l\right), \tag{2.6}$$

$$u_2 = k\left(\sqrt{d_h^2 + l^2} - l\right), \tag{2.7}$$

where d_h is the distance between the two dipole antennas and $c_i(u)$ and $s_i(u)$ are the Cosine and Sine integrals respectively, defined as

$$c_i(u) = \int_{\infty}^{u} \frac{\cos(x)}{x} dx, \tag{2.8}$$

$$s_i(u) = \int_{0}^{u} \frac{\sin(x)}{x} dx. \tag{2.9}$$

In general, mutual can be characterized by numerical modeling techniques. However, for dipoles, we can use analytical expression to introduce mutual coupling into the designed MIMO system. The coupling matrix of transmitting antenna array $\boldsymbol{C}_T$ can be written using fundamental electromagnetic and circuit theory. $\boldsymbol{C}_T$ is the transfer function matrix for the transmitting array and can be written as

$$\boldsymbol{C}_T = (Z_A + Z_T)\left(\boldsymbol{Z} + Z_T\boldsymbol{I}_{N_T}\right)^{-1}, \tag{2.10}$$

where Z_A is the element's impedance in isolation for half wavelength dipole, $Z_A = 73 + j42.5$ ohm. $Z_T = Z_A^*$ is determined for the purpose of achieving the maximum power. $\boldsymbol{Z}$ is defined by using the EMF method as described in (2.4). Also, the coupling matrix of receiving antenna array $\boldsymbol{C}_R$ can be determined in a similar manner. $\boldsymbol{C}_R$ has the meaning of transfer function matrix for the receiving array and can be written as

$$\boldsymbol{C}_R = (Z_A + Z_T)\left(\boldsymbol{Z} + Z_T \boldsymbol{I}_{N_R}\right)^{-1}. \tag{2.11}$$

The channel matrix $\boldsymbol{H}$ obtained from the case that this effect is absent has to be pre and post multiplied by coupling matrices $\boldsymbol{C}_R$ and $\boldsymbol{C}_T$. As a result, the new channel matrix is given by $\boldsymbol{H}_{mc} = \boldsymbol{C}_R \boldsymbol{H} \boldsymbol{C}_T$. This inclusion leads to the modified signal model (2.1), can be written as

$$\boldsymbol{y} = \boldsymbol{H}_{mc}\boldsymbol{x} + \boldsymbol{n}. \tag{2.12}$$

2.6 Full-duplex communication for MIMO systems

Due to the trend of users, there is more demand the data transmission. In (Talwar S., et al, (2014)), this work has presented the development of MIMO system in order to increase the transmitting and receiving data efficiency, the demand of the increased high-data rate and capacity. Many methods were presented such as the transmitting and receiving data through relay in (Lioliou P., et al, (2010); Shang C.Y. A., et al, (2014); Xiong X., et al, (2016)). As shown in Figure 2.10, a relay station is used to assist communication between the base station and the mobile station. The relay receives data from the base station and transmits data into the mobile station. Due to the relay, there is that the simultaneous transmitting and receiving at the same time. The problem of relay is the effect of self-interference signal. The self-interference elimination techniques are presented in literatures which the real interference power is ignored. But in the fact, the power levels of self-interference signal is still stronger than the desired signal. The work in literatures present the MIMO technology and the problem of self-interference signal but the mutual coupling phenomena is ignored. The mutual coupling phenomena is called mutual-interference signal. In fact, the mutual coupling phenomena in FDSC communication for MIMO system is stronger than desirable received signal so it cannot be ignored. For this reasons, the channel capacity efficiency is reduced due to not having the desired signal.

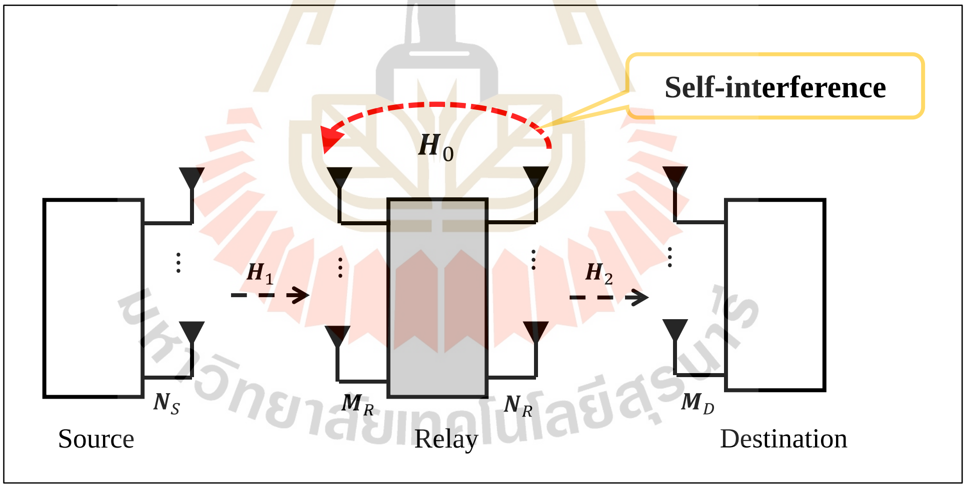

Figure 2.10 Full-duplex MIMO relay model.

2.7 The problem of interference signals for MIMO system

In the literature review, the main problem of self-interference and mutual-interference signals are happened when the full-duplex communication for MIMO system transmits and receives simultaneously at the same time on the same frequency. As shown in Figure 2.11, the difference of self-interference and mutual-interference is on which antenna that interference signal occurs. If the interference signal is happened at the same antenna, then it is called as self-interference. In other hand, if the interference signal occurs at the neighboring antennas is called as mutual-interference. Hence, the interference signal results can be written as

$$\boldsymbol{H}_I \boldsymbol{s} = \boldsymbol{H}_{SI} \boldsymbol{s} + \boldsymbol{H}_{MI} \boldsymbol{s}, \tag{2.13}$$

where $\boldsymbol{H}_{SI}$ is self-interference signal vector, $\boldsymbol{H}_{MI}$ is mutual-interference signal vector, $\boldsymbol{H}_I$ is the combination of self-interference and mutual-interference signals, then it is called as interference signals. The power levels of both interference signals are still stronger than desirable received signal which can be shown by (2.14)

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{H}_I \boldsymbol{s} + \boldsymbol{n}. \tag{2.14}$$

The main problem of full-duplex MIMO system is self-interference and mutual-interference signals which affect with the desired signal and distortion signals. In (Lioliou P., et al, (2010); Shang C. Y. A., et al, (2014)), authors have presented the interference cancellation techniques in digital cancellation part. But in fact, it is not enough for the power levels of interference signals with the real interference powers. Hence, this thesis proposed two types of interference cancellation for FDSC MIMO systems, which is analog cancellation and digital cancellation in the next chapter.

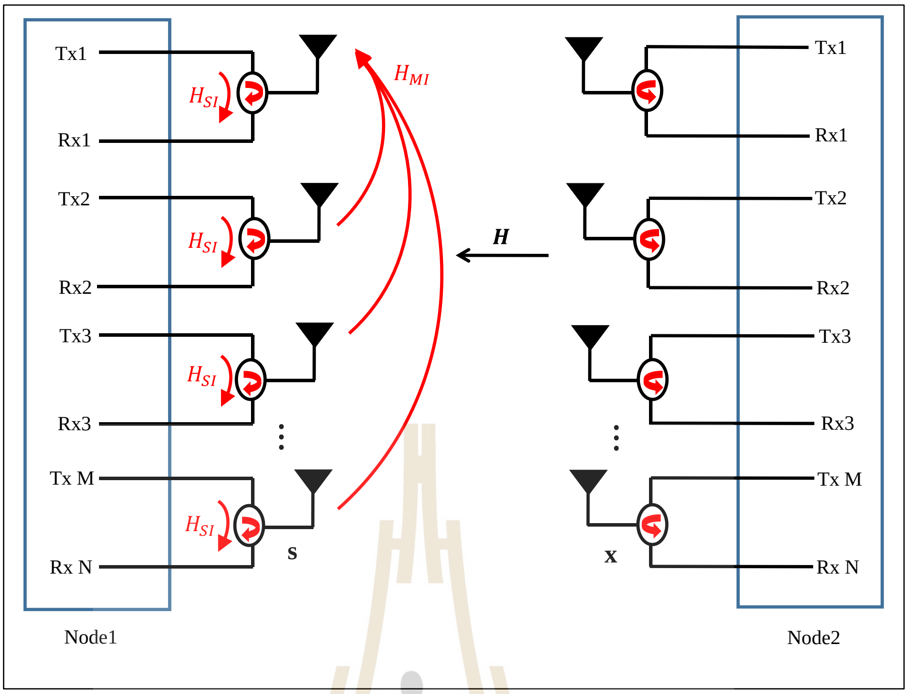

Figure 2.11 MIMO system model with the problem of interference signals.

2.8 Interference cancellation techniques

For FDSC communication, the main problem of FDSC is the strong interference signal which is generated from transmitter on the same side of receiver. Many techniques are presented in the literatures such as zero forcing algorithm, minimum mean square error algorithm, analog cancellation technique and digital cancellation. All the presented techniques have been concluded in Table 2.1.

Table 2.1 Comparison between different proposed techniques for full-duplex communication.

Literatures	Self-interference	Mutual-interference	Analog cancellation	Digital cancellation	Measurement results	MIMO systems
(Choi J.II, et al., (2010); Jain M., et al., (2011); Knox M. E., (2012); Phungamngern N., (2013))	✓		✓	✓	✓	
(Lioliou P., et al., (2010); Liu H. et al., (2013); Shang C. Y. A. et al., (2014))	✓			✓		✓
(Li S., and Murch R. D., (2011); Sahai A., et al., (2011))	✓			✓		
Proposed	✓	✓	✓	✓	✓	✓

2.9 Chapter summary

This chapter describes wireless communication, full-duplex communication systems, advantages and benefits of MIMO systems. The development of communication systems can transmit and receive simultaneously at the same time on the same frequency. The main concept of FDSC communication is one of many possible approaches to occupy the highest spectrum efficiency. However, the main problem of this concept is the effect of self-interference signals. For full-duplex MIMO relay technology, this technology is considered the effect of self-interference signals.

Furthermore, the MIMO system uses to transmit and receive multiple antennas which occurs the mutual coupling phenomena. Hence, this concept supports the wireless communication systems and more usage. The development of a FDSC communication for MIMO system is the method to transmit and receive signals simultaneously at the same time and on the same frequency. Consequently, a critical issue involved in such an operation is the resulting self-interference and mutual-interference signals. The next chapter describes the method to eliminate self-interference and mutual-interference.

CHAPTER III

DEVELOPMENT OF FULL-DUPLEX SINGLE-CHANNEL COMMUNICATION FOR MIMO SYSTEMS

3.1 Introduction

This chapter describes the development of FDSC communication for MIMO systems which show the processes and principles used in designing equations. The main problem of FDSC MIMO system is self-interference and mutual-interference signals. Self-interference and mutual-interference affect the signals in different ways. If the interference signal is happened at the same antenna, then it is called as self-interference. Otherwise, the interference signals are happened at the neighboring antennas, it is called as mutual-interference. In order to eliminate self-interference signal, many techniques have been proposed in literatures. Many techniques have suggested to reduce self-interferences in case of MIMO relay system which are discussed in the Section 3.2. The strong interference signals are generated from transmitter on the same side of receiver which are presented in the Section 3.3. Section 3.4 presents the comparison of self-interference and mutual-interference cancellation techniques. Interference signals are reduced by using the proposed analog and digital techniques for FDSC communication in MIMO system, as discussed in Section 3.5. The first part is the analog cancellation which discusses the method to eliminate interference signals on RF domain. The second part is mentioned in the next chapter which includes the digital cancellation part. Finally, the last section concludes the chapter.

3.2 Interference cancellation on the MIMO relay system

Many methods in the literature are discussed regarding full-duplex communication for MIMO relay system. Relay node receives signal from the signal source and transmits the signal to the destination. However, the problem of full-duplex communication is the effect of a self-interference signal which occurs at the transmitter and receiver of relay node. The main problem of MIMO relay system is only self-interference signal which is presented in the literatures. In (Lioliou P., et al., (2010)), authors propose lot of techniques in order to eliminate self-interference signal, for example, Zero-Forcing (ZF) technique and Minimum Mean Square Error (MMSE) technique. The designed full-duplex communication for MIMO relay system is shown in Figure 3.1. The singular value decomposition (SVD) of the self-interference channel $\boldsymbol{H}_0$ can be written as

$$\boldsymbol{H}_0 = \boldsymbol{U}_0 \boldsymbol{D}_0 \boldsymbol{V}_0^H, \tag{3.1}$$

where $\boldsymbol{D}_0$ is a diagonal matrix, $\boldsymbol{U}_0$ and $\boldsymbol{V}_0$ are unitary matrices that contain the left and right singular vectors, respectively. For zero forcing, the self-interference cancellation matrices, $\boldsymbol{W}_r$ and $\boldsymbol{W}_t$ are selected in such way that the row space of $\boldsymbol{W}_r$ lies in the left null space of $\boldsymbol{H}_0$, and the column space of $\boldsymbol{W}_t$ lies in the right null space of $\boldsymbol{H}_0$. Therefore, the self-interference cancellation matrices can be expressed as

$$\boldsymbol{W}_r = \boldsymbol{U}_0^H, \tag{3.2}$$

$$\boldsymbol{W}_t = \boldsymbol{V}_0. \tag{3.3}$$

The designed signal at the destination can be written as

$$\boldsymbol{y}_d = \{\boldsymbol{H}_2\boldsymbol{W}_t\boldsymbol{G}\boldsymbol{W}_r\boldsymbol{H}_1\boldsymbol{x}_s + \boldsymbol{H}_2\boldsymbol{W}_t\boldsymbol{G}\boldsymbol{W}_r\boldsymbol{H}_0\boldsymbol{x}_r + \boldsymbol{H}_2\boldsymbol{W}_t\boldsymbol{G}\boldsymbol{W}_r\boldsymbol{n}_r\}\boldsymbol{x}_s + \boldsymbol{n}_D. \quad (3.4)$$

The work in literature aimed to design full-duplex communication for MIMO relay system (Lioliou P., et al, (2010)). The challenge of this concept is self-interference signal by proposing zero forcing technique. Many techniques for self-interference cancellation are proposed in the literature by neglecting the real interference power. In fact, the interference signal is still much stronger than the desired signal and cannot be ignored. The results will be revealed in the next section.

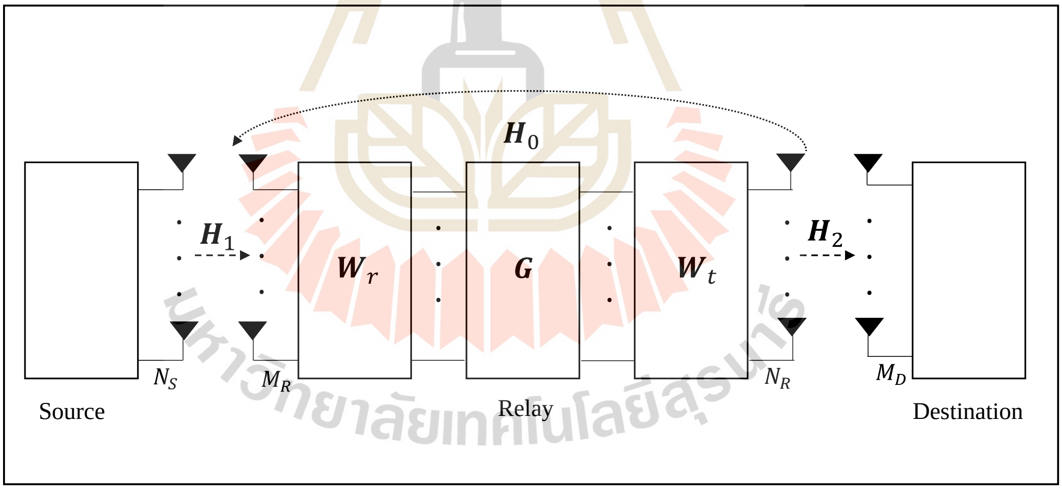

Figure 3.1. The full-duplex communication for MIMO relay system.

3.3 Strength of interference signals

The works in literatures discuss full-duplex communication for MIMO relay system to cancel the self-interferences but they have neglected the real interference power. In fact, the power of interference signal is still much stronger than the power of desired signal which cannot be ignored. However, this thesis considers the interference signals and the desired signals which the real power is measured. The power levels of interference signals are still stronger than the desired signals. This problem focuses on the interference cancellation method in only digital domain, which is not enough. Figure 3.2 shows channel capacity of MIMO system at different input powers. For zero-forcing technique, the normalized power shown by blue line in the Figure 3.2 is compared with the real power of the interference signal shown by dashed blue line. After the measurement results, the ZF technique is not enough to cancel the real interference power of the signal. For this reason, the interference cancellation techniques are proposed into two types, which are analog cancellation and digital cancellation. We have used the modified hybrid coupler and phase shifters to cancel the analog cancellation and STBC technique for digital cancellation which basically the idea is to subtract the interference from the original signal. These techniques are discussed in details in the next chapters.

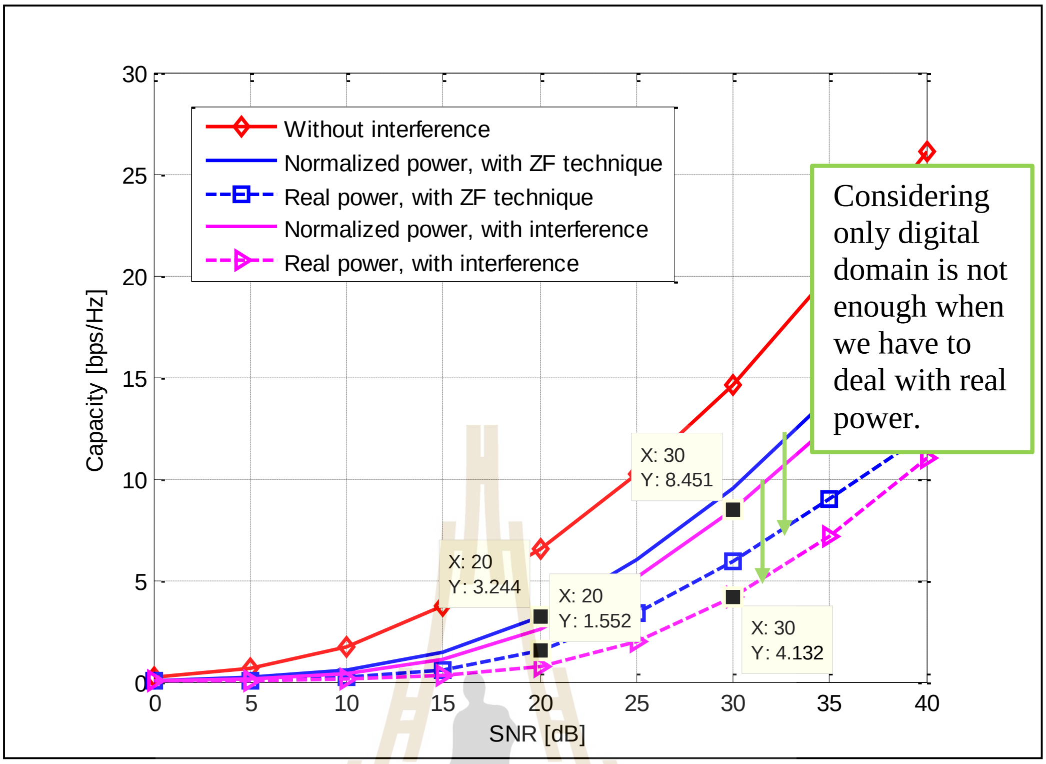

Figure 3.2 Channel capacity of MIMO system at different power levels by using ZF technique.

3.4 The comparison of self-interference and mutual-interference cancellation techniques

As shown in Figure 3.3, the design of FDSC for $M \times N$ MIMO system uses the channel compensator (**W**). Purpose of the compensator (**W**) is to get to know the response of self-interference and mutual-interference in order to cancel them. The channel compensation of interference signals (**W**) can be written as equation (3.5)

$$\boldsymbol{W} = -\boldsymbol{H}_I. \tag{3.5}$$

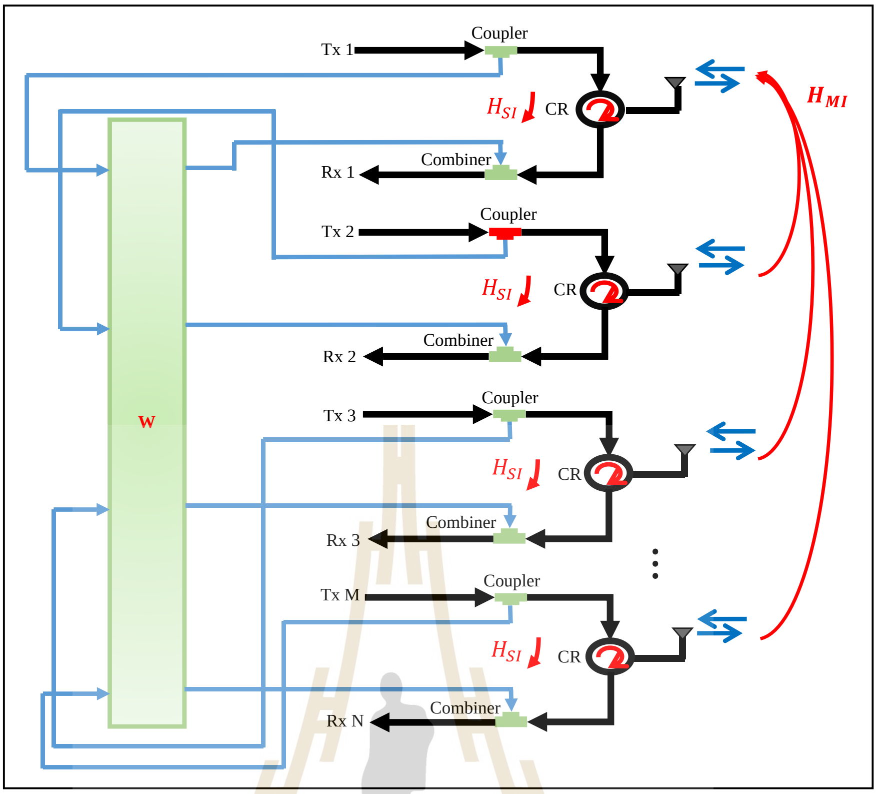

Figure 3.3 FDSC communication for $M \times N$ MIMO system model using the channel compensation.

The designed signal at the destination can be written as

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{H}_I\boldsymbol{s} + \boldsymbol{Ws} + \boldsymbol{n}. \tag{3.6}$$

The interference cancellation techniques are proposed in literatures. So, the main idea of this system is that the elimination of self-interference and mutual-interference signals are pre-known. The interference cancellation technique is written as equation 3.6. For simulation results, the channel compensation and ZF techniques are compared to eliminate interference signals by using the MATLAB programming.

Figure 3.4 and Figure 3.5 show the channel capacity of 2×2 and 4×4 MIMO system respectively. For 2×2 and 4×4 FDSC MIMO systems, this thesis have proposed the channel compensation technique in order to eliminate the interference cancellation. The channel compensation technique is the evaluation of interference channel by defining the evaluation of channel compensation equal the interference channel. For measurement of real interference power, the proposed channel compensation technique is better than the ZF technique. The ZF technique eliminates the interference signal in digital domain only, which is not enough. However, the proposed technique is poorer than that of the system without interference.

Figure 3.6 and Figure 3.7 show the system BER versus E_b/N_0 for different interference cancellation techniques. In the interference signals, the ZF performance is poorer than that of the channel compensation technique, and their declining tendency becomes gradually slow with the increase of E_b/N_0 because we have considered the interference signals in the ZF technique as compared to the channel compensation technique by using the same condition. In addition, with the increase of E_b/N_0, the BER difference between the two techniques would gradually increase. In Figure 3.6 and Figure 3.7, the interference signals are cancelled by using the channel compensation technique. As seen in these figures, the 2×2 MIMO system is worse than the 4×4 MIMO system because BER of 2×2 MIMO system is more than the 4×4 MIMO system.

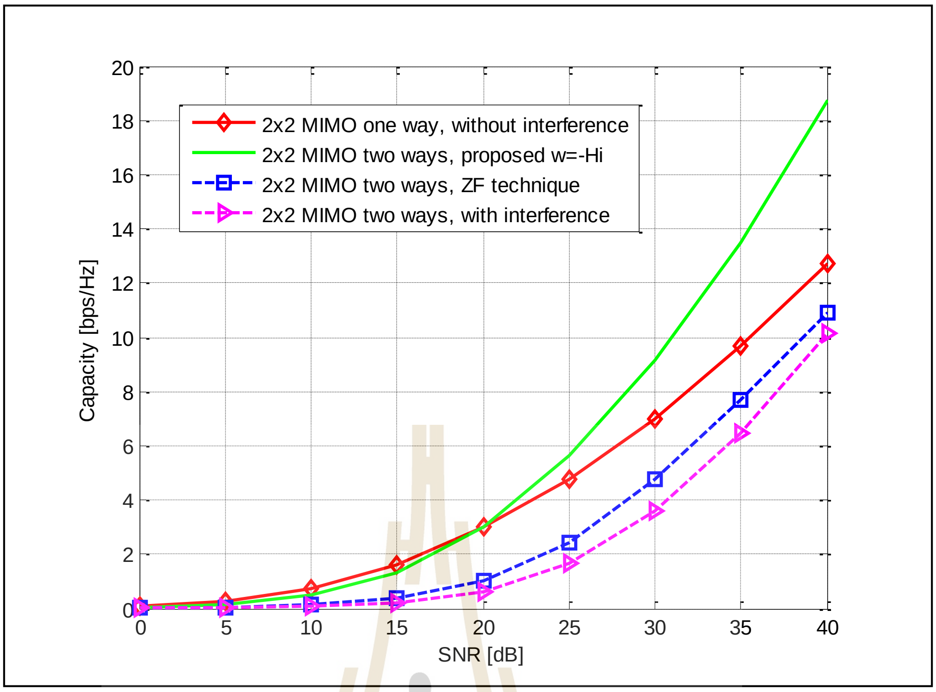

Figure 3.4 Channel capacity of 2 × 2 MIMO system.

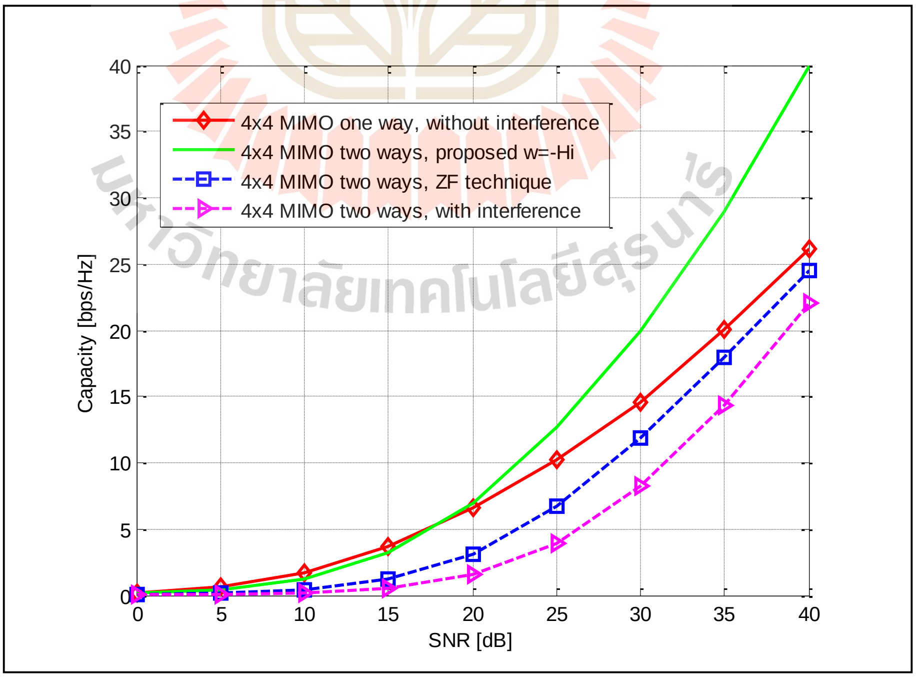

Figure 3.5 Channel capacity of 4 × 4 MIMO system.

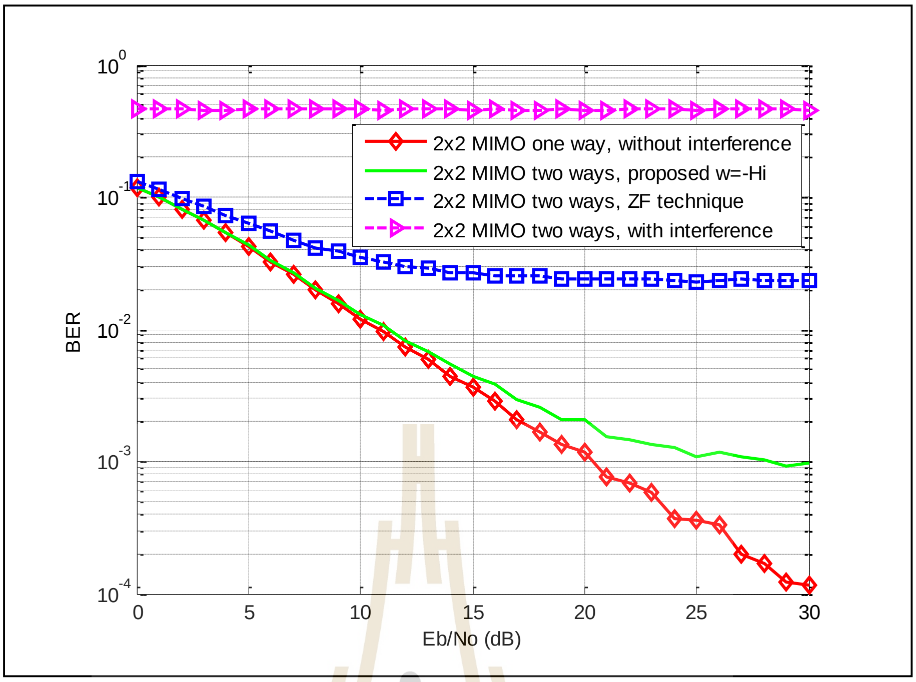

Figure 3.6 BER of 2 × 2 MIMO system.

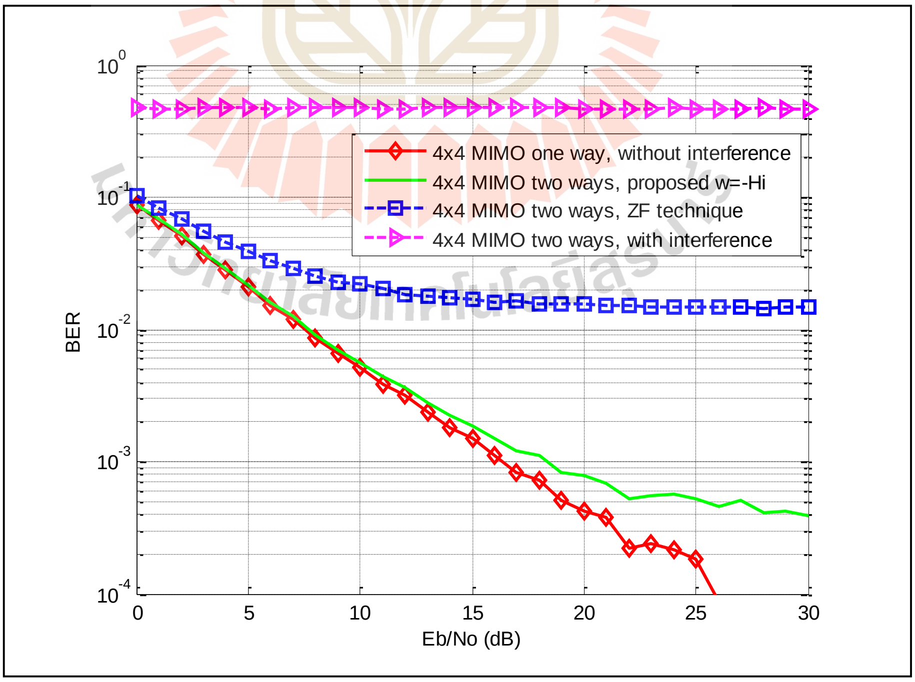

Figure 3.7 BER of 4 × 4 MIMO system.

3.5 Proposed test kit for 2×2 FDSC MIMO system

The author designs FDSC communication for MIMO system. The advantages of this system are double throughputs, reduced delays and the simultaneous transmitting and receiving signal at the same time on the same frequency. As shown in Figure 3.8, the N^{th} antennas at node 1 and M^{th} antennas at node 2 are designed to employ a single antenna for both transmitting and receiving which implemented with the help of Circulator (CR). The circulator can separate two paths of transmitting and receiving signals. As shown in Figure 3.9, the designed FDSC communication for 2×2 MIMO system can be transmitted and received simultaneously at the same time and on the same frequency. The main problem of FDSC is the strong self-interference and mutual-interference signals which generated from transmitter on the same side of receiver.

For self-interference signal, it is the imperfection of circulator that leaks the transmitting signal to the receiving path. In this case, a single antenna is connected to a circulator at the 2^{nd} port, which is a 3-port device that provides limited isolation between the 1^{st} port and the 3^{rd} port. The transmitted signals are fed from the 1^{st} port to the 2^{nd} port which are connected with antenna. The received signal from the antenna is passed from the 2^{nd} port to the 3^{rd} port. Circulator cannot imperfectly isolate the 1^{st} port and the 3^{rd} port. Inevitably, the transmitted signal leaks (self-interference) from the 1^{st} port to the 3^{rd} port and it interferes with the received signal.

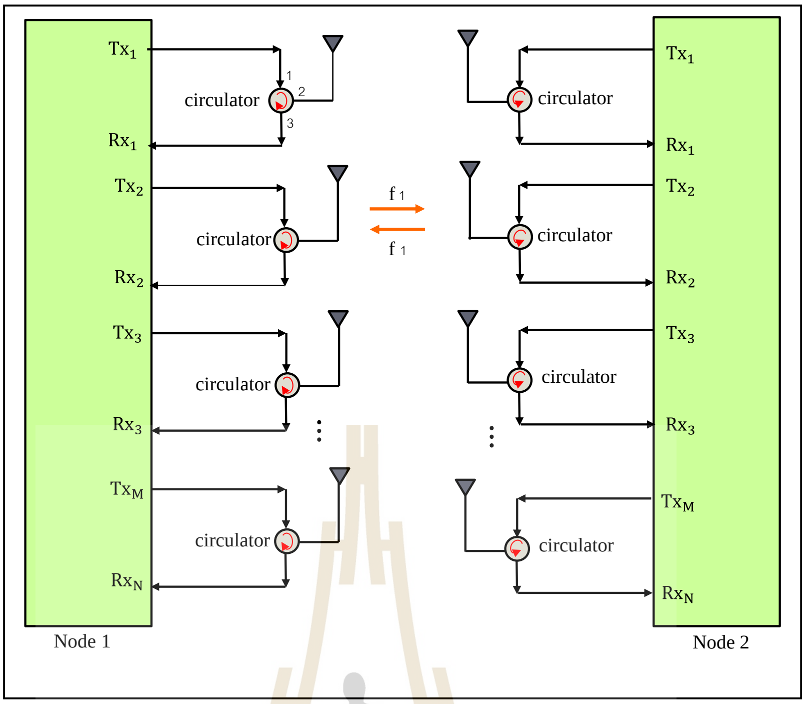

Figure 3.8 Full-duplex single-channel communication for $M \times N$ MIMO system.

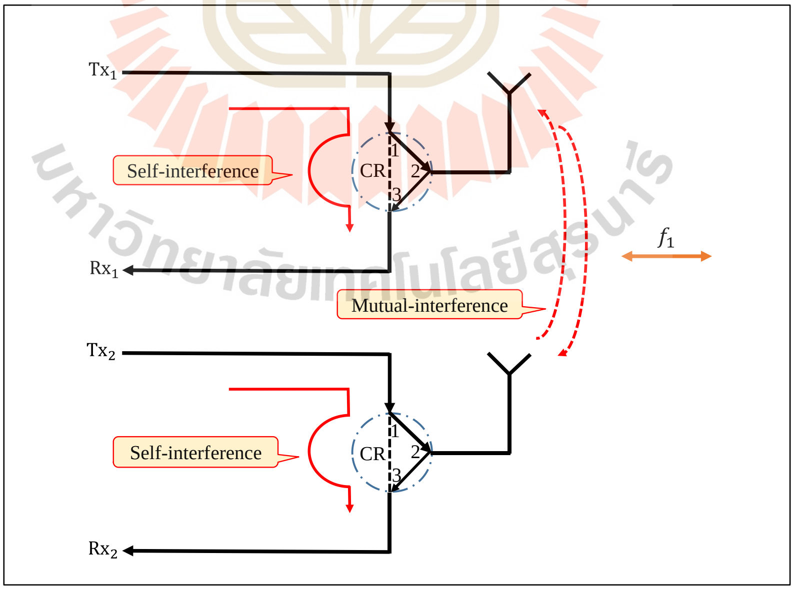

Figure 3.9 The illustration of self-interference and mutual-interference in FDSC 2×2 MIMO system.

Moreover, for mutual-interference, there is mutual coupling phenomena happened by many antennas locating nearby. The mutual coupling is the disinterested signal because the transmitted signals would be radiated away to a nearby antenna. Hence, the mutual coupling reduces the antenna efficiency and performance of antenna in both transmitting and receiving modes. Therefore, the challenge of this designed system is the power levels reduction of self-interference and mutual-interference signals. The interference cancellation has two important techniques by proposing both analog and digital cancellations, which is described in the next section.

3.5.1 Design of analog cancellation

In the first part, the design of analog cancellation is very important. Hence, the analog cancellation technique is proposed to eliminate interference signals, which based on pre-defined RF circuit network. The advantages of this communication system are self-interference and mutual-interference signals, which use knowledge of the transmission signal to cancel interference signals from the receiving analog signal. The circuit is designed to adjust the phase and amplitude of the primary and secondary routes. For analog cancellation, in order to completely cancel the self-interference and mutual-interference signals, the phase of these two output routes must differ from the phase of interference signals by π. In addition, the amplitudes of primary and secondary routes must have comparable power levels. This research presents to design FDSC communication for 2×2 MIMO system. Figure 3.10 shows the block diagram of analog interference cancellation for FDSC 2×2 MIMO system by using the modified hybrid coupler and phase shifters.

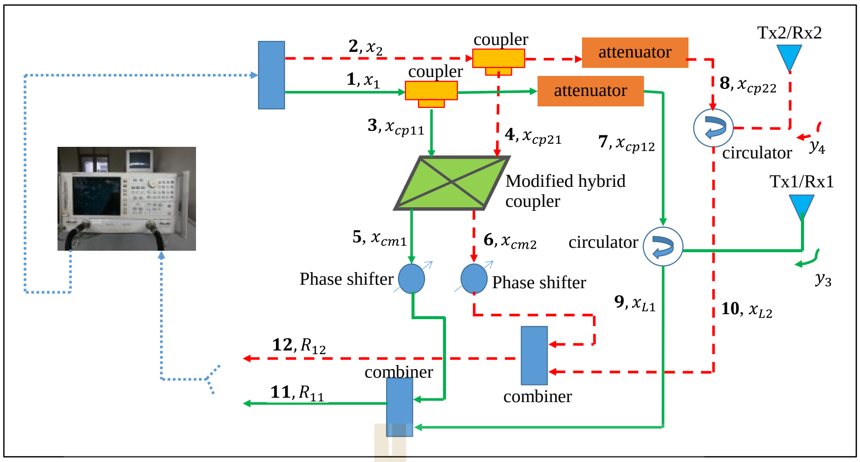

Figure 3.10 The block diagram of analog interference cancellation for FDSC 2 × 2 MIMO system.

The design and implementation of analog cancellation is verified by measurements. The block diagram of FDSC 2 × 2 MIMO system is shown in Figure 3.10. The adjacent antennas should be $\lambda/2$ apart in MIMO system for best performance. If they be placed closer, there will be stronger correlation between their signals (mutual coupling), therefore the utility of MIMO is reduced. The interference cancellation circuit consists the modified hybrid coupler, attenuators, phase shifters and combiners. The parameters are used to design this model, as shown in Table 3.1.

Table 3.1 The parameters are used to model of FDSC communication for MIMO system.

Parameters	Values
Number of antenna at node1	2
Number of antenna at node2	2
Antenna distance	$\lambda/2$
Frequency (GHz)	2.45

As shown in Figure 3.10, the green lines denote the signals at the first antenna. The signals of the 1^{st} port can be written as

$$x_1 = A_1 e^{-j(\omega t+\emptyset_1)}, \tag{3.7}$$

where A_1 is amplitude of the 1^{st} port and $\emptyset_1$ is phase of the 1^{st} port. When the x_1 signal is transmitted to coupler and be divided into two ways. The major power of x_1 signal transmits through the antenna and the remainder in the 3^{rd} port becomes the input of modified hybrid coupler. As seen in (3.8) and (3.9), the x_1 signal transmits through a coupler into the 7^{th} port and the 3^{rd} port, respectively as follows:

$$x_{cp12} = \left(1-\alpha_{cp_{11}}\right)A_1 e^{-j\left(\omega t+\emptyset_1+\emptyset_{cp12}\right)}, \tag{3.8}$$

$$x_{cp11} = \alpha_{cp_{11}} A_1 e^{-j\left(\omega t+\emptyset_1+\emptyset_{cp11}\right)}. \tag{3.9}$$

From the viewpoint of the first antenna, the signal in the 3^{rd} port is the reference signal for self-interference signal and the signal in the 4^{th} port is the reference signal for mutual-interference signal. Then, the summation of reference signals of self-interference and mutual-interference at the first antenna is written as

$$x_{cm1} = \frac{1}{\sqrt{2}}\Big(\alpha_{cp_{11}}\alpha_{cm_1}A_1e^{-j(\omega t+\emptyset_1+\emptyset_{cp_{11}}+\emptyset_{cm_1})} + \alpha_{cp_{21}}\alpha_{cm_2}A_2e^{-j(\omega t+\emptyset_2+\emptyset_{cp_{21}}+\emptyset_{cm_2})}\Big), \quad (3.10)$$

where $\alpha_{cp_{11}}$ and $\alpha_{cp_{21}}$ are the attenuation coefficients of the 3^{rd} and the 4^{th} ports respectively. $\emptyset_{cp_{11}}$ and $\emptyset_{cp_{21}}$ are the phases of the 3^{rd} and the 4^{th} ports respectively. α_{cm_1} and α_{cm_2} are the attenuation coefficients of the received signals at the first and second antennas respectively. $\emptyset_{cm_1}$ *and* $\emptyset_{cm_2}$ are the phases of the received signals at the first and second antennas respectively. At the 7^{th} port, when the signal is transmitted to circulator, there is a signal leakage due to imperfection of circulator circuits and the reflection of signals due to the effect of an antenna. This leakage is called self-interference signal, which can be written as

$$x_{L1} = (1-\alpha_{cp_{11}})A_1e^{-j(\omega t+\emptyset_1+\emptyset_{cp_{12}})}\left[\alpha_L e^{-j\emptyset_L} + \alpha_R e^{-j\emptyset_R}\right] + (1-\alpha_{cp_{21}})\alpha_t\alpha_{mc}\alpha_t A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{cp_{22}}+\emptyset_t+\emptyset_{mc}+\emptyset_t)}, \quad (3.11)$$

where α_L is the attenuation coefficient of the signal leakage from circulator, $\emptyset_L$ is the phase of the signal leakage from circulator, α_R is the attenuation coefficient of the reflection of signal from an antenna, $\emptyset_L$ is the phase of the reflection of signal from an antenna, α_t is the attenuation coefficient of the coaxial cable, $\emptyset_t$ is the phase of the coaxial cable, α_{mc} is the attenuation coefficient of the mutual-interference signals and $\emptyset_{mc}$ is the phase of the mutual-interference signals. The key success of analog interference cancellation is the appropriate design of modified hybrid coupler and phase shifters. The task is to make the phase of the 5^{th} port differ from the phase of the 9^{th} port by π. Note that the amplitude of both signals must be controlled to have approximately the same level.

The received signal R_{11} is given by

$$R_{11} = y_3 + x_{cm1} + x_{L1}. \tag{3.12}$$

The received signal R_{11} must be equal to incoming signal y_3 under the condition that the interference signals are perfectly suppressed that is x_{cm1} must be equal to x_{L1}. By equating (3.10) to (3.11), the attenuation coefficients and phase shifts can be written as

$$(1 - \alpha_{cp_{11}})A_1 e^{-j(\omega t + \emptyset_1 + \emptyset_{cp12})}\left[\alpha_L e^{-j\emptyset_L} + \alpha_R e^{-j\emptyset_R}\right] = -\frac{1}{\sqrt{2}}\alpha_{cp_{11}}\alpha_{cm_1}A_1 e^{-j(\omega t + \emptyset_1 + \emptyset_{cp_{11}} + \emptyset_{cm_1})}, \tag{3.13}$$

and

$$(1 - \alpha_{cp_{21}})\alpha_t \alpha_{mc} \alpha_t A_2 e^{-j(\omega t + \emptyset_2 + \emptyset_{cp_{22}} + \emptyset_t + \emptyset_{mc} + \emptyset_t)} = -\frac{1}{\sqrt{2}}\alpha_{cp_{21}}\alpha_{cm_2}A_2 e^{-j(\omega t + \emptyset_2 + \emptyset_{cp_{21}} + \emptyset_{cm_2})}. \tag{3.14}$$

Therefore, based on (3.13) and (3.14), it is possible to design the modified hybrid coupler for cancelling both self-interference and mutual-interference.

As shown in Figure 3.10, the red dash lines denote the signals at the second antenna. The signals of the 2^{nd} port can be written as

$$x_2 = A_2 e^{-j(\omega t + \emptyset_2)}, \tag{3.15}$$

where x_2 is amplitude of the 2^{nd} port and $\emptyset_2$ is phase of the 2^{nd} port. When the x_2 signal is transmitted to coupler and be divided into two ways. The major power of x_2 signal transmits through the antenna and the remainder in the 4^{th} port becomes the input of modified hybrid coupler. As seen in (3.16) and (3.17), the x_2 signal transmits through a coupler into the 8^{th} port and the 4^{th} port attaining the following signals, respectively,

$$x_{cp22} = \left(1 - \alpha_{cp_{21}}\right) A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{cp22}\right)}, \tag{3.16}$$

$$x_{cp21} = \alpha_{cp_{21}} A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{cp21}\right)}. \tag{3.17}$$

From the viewpoint of the second antenna, the signal in the 4^{th} port is the reference signal for self-interference signals and the signal in the 3^{rd} port is the reference signal for mutual-interference signals. Then, the summation of reference signals of self-interference and mutual-interference at the second antenna is written as

$$x_{cm2} = \frac{1}{\sqrt{2}}\Big(\alpha_{cp_{11}}\alpha_{cm_1}A_1 e^{-j\left(\omega t+\emptyset_1+\emptyset_{cp_{11}}+\emptyset_{cm_1}\right)} +$$

$$\alpha_{cp_{21}}\alpha_{cm_2}A_2 e^{-j\left(\omega t+\emptyset_2+\emptyset_{cp_{21}}+\emptyset_{cm_2}\right)}\Big). \quad (3.18)$$

Next, the signal leakage due to circulator and the reflection of signal due to the effect of an antenna at the 8^{th} port can be written as

$$x_{L2} = \left(1-\alpha_{cp_{21}}\right)A_2 e^{-j\left(\omega t+\emptyset_2+\emptyset_{cp_{22}}\right)}\left[\alpha_L e^{-j\emptyset_L} + \alpha_R e^{-j\emptyset_R}\right] +$$

$$\left(1-\alpha_{cp_{11}}\right)\alpha_t\alpha_{mc}\alpha_t A_1 e^{-j\left(\omega t+\emptyset_1+\emptyset_{cp_{12}}+\emptyset_t+\emptyset_{mc}+\emptyset_t\right)}. \quad (3.19)$$

The key success of analog interference cancellation is the appropriate design of modified hybrid coupler and phase shifters. The design reference signal is to make the phase of the 6^{th} port differ from the phase of the 10^{th} port by π. Note that the amplitude of both signals must be controlled to have approximately the same level.

The received signal R_{12} is given by

$$R_{12} = y_4 + x_{cm2} + x_{L2}. \quad (3.20)$$

The received signal R_{12} must be equal to incoming signal y_4 under the condition that the interference signals are perfectly suppressed that is x_{cm2} must be equal to x_{L2}. Therefore, the attenuation coefficients and phase shifters of signals are matched in (3.21) and (3.22)

$$(1-\alpha_{cp_{21}})A_2e^{-j(\omega t+\emptyset_2+\emptyset_{cp_{22}})}[\alpha_L e^{-j\emptyset_L}+\alpha_R e^{-j\emptyset_R}] =$$

$$-\frac{1}{\sqrt{2}}\alpha_{cp_{21}}\alpha_{cm_2}A_2e^{-j(\omega t+\emptyset_2+\emptyset_{cp_{21}}+\emptyset_{cm_2})}, \quad (3.21)$$

and

$$(1-\alpha_{cp_{11}})\alpha_t\alpha_{mc}\alpha_t A_1e^{-j(\omega t+\emptyset_1+\emptyset_{cp_{12}}+\emptyset_t+\emptyset_{mc}+\emptyset_t)} =$$

$$-\frac{1}{\sqrt{2}}\alpha_{cp_{11}}\alpha_{cm_1}A_1e^{-j(\omega t+\emptyset_1+\emptyset_{cp_{11}}+\emptyset_{cm_1})}. \quad (3.22)$$

For a modified hybrid coupler, the 3^{rd} and the 4^{th} ports represent the input ports and the 5^{th} and the 6^{th} ports represent the output ports as shown in Figure 3.10. The green line of first antenna represents the direction of the 3^{rd} and the 5^{th} ports that they are self-interference signals of the first antenna. The red dash line represents the direction of the 4^{th} and the 5^{th} ports which are mutual-interference signals of the first antenna. The red dash line of second antenna represents the direction of the 4^{th} and the 6^{th} ports that they are self-interference signals of the second antenna. The green line represents the direction of the 3^{rd} and the 6^{th} ports which are mutual-interference signals of the second antenna. Then, the amplitude and phase of modified hybrid coupler to cancel self-interference signals can be determined according to equation (3.23) and (3.24)

$$\alpha_{cm,SI_j} = \frac{(1-\alpha_{cp})(\alpha_L+\alpha_R)\sqrt{2}}{\alpha_{cp}}, \quad (3.23)$$

where α_{cm,SI_j} denotes the attenuation coefficient of the received self-interference signal at the j^{th} antenna. Thus, at the first antenna, equation (3.23) is calculated from (3.13) that is α_{cm,SI_j} must be equal to α_{cm_1}. At the second antenna, equation (3.23) is calculated from (3.21) that is α_{cm,SI_j} must be equal to α_{cm_2}. The parameter α_{cp} is the attenuation coefficient of signal in the secondary route.

$$\emptyset_{cm,SI_j} = \emptyset_{cp} + \emptyset_L + \emptyset_R - \emptyset_{cp} + \pi, \tag{3.24}$$

where $\emptyset_{cm,SI_j}$ is the phase of self-interference signals at the j^{th} antenna. Thus, at the first antenna, equation (3.24) is calculated from (3.13) that is $\emptyset_{cm,SI_j}$ must be equal to $\emptyset_{cm_1}$. At the second antenna, equation (3.24) is calculated from (3.21) that is $\emptyset_{cm,SI_j}$ must be equal to $\emptyset_{cm_2}$. The parameter $\emptyset_{cp}$ is the phase of signals in secondary route.

The amplitude and phase of modified hybrid coupler to cancel the mutual-interference signals can be written as

$$\alpha_{cm,MI_j} = \frac{(1-\alpha_{cp})\alpha_t \alpha_{mc} \alpha_t \sqrt{2}}{\alpha_{cp}}, \tag{3.25}$$

$$\emptyset_{cm,MI_j} = \emptyset_{cp} + \emptyset_t + \emptyset_{mc} + \emptyset_t - \emptyset_{cp} + \pi, \tag{3.26}$$

where α_{cm,MI_j} is the attenuation coefficient of the received mutual-interference signal at j^{th} antenna. Thus, at second antenna, equation (3.25) and (3.26) are calculated from (3.14) that is α_{cm,MI_j} must be equal to α_{cm_2} and the $\emptyset_{cm,SI_j}$ must be equal to $\emptyset_{cm_2}$, respectively. At the first antenna, equation (3.25) and (3.26) are calculated from (3.22) that is α_{cm,MI_j} must be equal to α_{cm_1}. Thus, Table 3.2 can be concluded the values of the attenuation coefficient and phase order to reduce self-interference and mutual-interference signals.

Table3.2 The conclusion of the values attenuation coefficient and phase order to reduce self-interference and mutual-interference signals as shown in Figure 3.10.

		Attenuation coefficient	Phase
First antenna	Self-interference signal	$\alpha_{cm_1} = \frac{(1-\alpha_{cp_{11}})(\propto_L + \alpha_R)\sqrt{2}}{\alpha_{cp_{11}}}$	$\emptyset_{cm_1} = \emptyset_{cp_{12}} + \emptyset_L + \emptyset_R - \emptyset_{cp_{11}} + \pi$
	Mutual-interference signal	$\alpha_{cm_1} = \frac{(1-\alpha_{cp_{11}}) \propto_t \propto_{mc} \propto_t \sqrt{2}}{\alpha_{cp_{11}}}$	$\emptyset_{cm_1} = \emptyset_{cp_{12}} + \emptyset_t + \emptyset_{mc} + \emptyset_t - \emptyset_{cp_{11}} + \pi$
Second antenna	Self-interference signal	$\alpha_{cm_2} = \frac{(1-\alpha_{cp_{21}})(\propto_L + \alpha_R)\sqrt{2}}{\alpha_{cp_{21}}}$	$\emptyset_{cm_2} = \emptyset_{c_{22}} + \emptyset_L + \emptyset_R - \emptyset_{c_{21}} + \pi$
	Mutual-interference signal	$\alpha_{cp_2} = \frac{(1-\alpha_{cp_{21}}) \propto_t \propto_{mc} \propto_t \sqrt{2}}{\alpha_{cp_{21}}}$	$\emptyset_{cm_2} = \emptyset_{cp_{22}} + \emptyset_t + \emptyset_{mc} + \emptyset_t - \emptyset_{cp_{21}} + \pi$

3.6 Chapter summary

The FDSC 2×2 MIMO system model is designed and simulated by using the MATLAB programming. The advantage of this concept is knowledge of self-interference and mutual-interference signals. The channel compensation technique is proposed for the basic to eliminate interference signals by comparing with other many techniques. In order to eliminate self-interference signal, many techniques have been proposed any digital cancellation in literatures by neglecting the real interference power. However, in fact, the self-interference and mutual-interference are still much stronger than desirably received signal and they cannot be ignored.

Finally, the above equations are the guideline to design the modified hybrid coupler and phase shifter due to the effect of self-interference signals at the first and second antennas by matching $\alpha_L \alpha_R \angle(\emptyset_L + \emptyset_R + \pi)$ and the effect of mutual-interference signals at the first and second antennas by matching $\alpha_t \alpha_{mc} \alpha_t \angle(\emptyset_t + \emptyset_{mc} + \emptyset_t + \pi)$. Please note that the advantage of this proposed method is that the amplitude and phase of self-interference and mutual-interference signals can be pre-defined by calculating from just only one measurement. After implementing all components with specific positions, the values of amplitude and phase of interference signals will not change. Hence, the proposed circuit can work very well to eliminate interferences by pre-defining at the manufacturing process. This technique is proposed to eliminate both self-interference and mutual-interference signal by designing two types of interference cancellation for FDSC 2×2 MIMO system, which are an analog cancellation and digital cancellation. The experimental results of an analog cancellation and digital cancellation will be mentioned the next chapter.

CHAPTER IV

ANALOG CANCELLATION FOR FDSC

2×2 MIMO SYSTEM

4.1 Introduction

The interference cancellation technique for FDSC 2×2 MIMO system is discussed in this chapter. For FDSC 2×2 MIMO system, the problem of interference signals is larger amplified because of the more number of antennas on the both transmitter and receiver. The interference signals are named as self-interference and mutual-interference signals. Therefore, an analog cancellation is proposed to reduce the power levels of the interference signals by using RF circuit networks technique which is described in Section 4.2. Section 4.3 describes the design of the modified hybrid coupler circuit by calculating the amplitude and phase of an appropriate hybrid coupler from theory. The experiment of interference cancellation techniques separate two types which are analog cancellation and digital cancellation. In Section 4.4, the measurement results of FDSC 2×2 MIMO system presents the interference cancellation technique by analog cancellation. Finally, Section 4.5 concludes the chapter.

4.2 Design of interference cancellation technique

This section discusses to design FDSC communication for 2×2 MIMO system. It transmits and receives simultaneously at the same time and on the same frequency.

The main problem of FDSC 2×2 MIMO system is the strong self-interference and mutual-interference signals. From the problem above, this research proposes the interference cancellation technique. The proposed system consists both analog and digital cancellations. For analog cancellation, it is designed to reduce the power levels of self-interference and mutual-interference signals by using the combination of a modified hybrid coupler and phase shifters. The modified hybrid coupler is proposed to differentiate phase between self-interference and mutual-interference signal. The design modified hybrid coupler is shown as Figure 4.1. The green lines denote the signals at the first antenna and the red dash lines denote the signals at the second antenna. The major signal is transmitted to coupler which separated into two ways through the antenna and the modified hybrid coupler. For the modified hybrid coupler, the 3^{rd} and 4^{th} ports are the input ports. The 5^{th} and 6^{th} ports are the output ports. From Figure 4.1, at the first antenna, the signal in the 3^{rd} port is the reference signal for self-interference signals and the signal in the 4^{th} port is the reference signal for mutual-interference. At the second antenna, the signal in the 4^{th} port is the reference signal for self-interference signals and the signal in the 3^{rd} port is the reference signal for mutual-interference. Then, the 5^{th} and 6^{th} port of reference signals are the summation of self-interference and mutual-interference at the first and second antennas, respectively.

Moreover, the demonstration of FDSC2×2 MIMO system has been presented. From this design system, the full-duplex communication can be designed more antennas such as the design FDSC 4×4 MIMO system, the design FDSC 8×8 MIMO systems etc. The design FDSC MIMO system as mentioned above, the RF circuit network is proposed to reduce the power levels of interference signals by using the butler matrix technique. The advantage of this proposed method is that the amplitude and phase of self-interference and mutual-interference signals can be pre-defined by calculating from the only measurement. For the FDSC 2×2 MIMO system, hybrid coupler technique is proposed to reduce the interference signals.

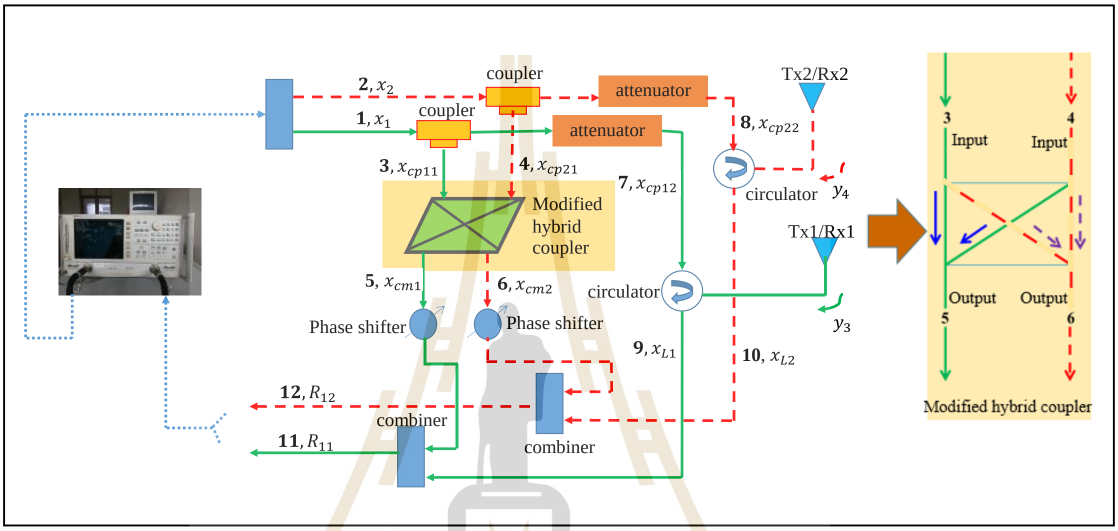

Figure 4.1 The design modified hybrid coupler for FDSC 2×2 MIMO system.

4.3 Design of hybrid coupler

Hybrid couplers are the special case of a four-port directional coupler that is designed to split power. The design basic of 90° hybrid coupler is shown as Figure 4.2. The signal at outputs are attenuated by three decibels (-3dB) and have a 90-degree phase difference with respect to each other. For the design of hybrid couplers using FR-4, thickness of the substrate is taken as 1.6 mm and dielectric constant (ε_r) 4.6. Operating frequency has chosen as 2.45 GHz with impedance (Z_0) is 50Ω. The design of hybrid coupler shown in Figure 4.2.

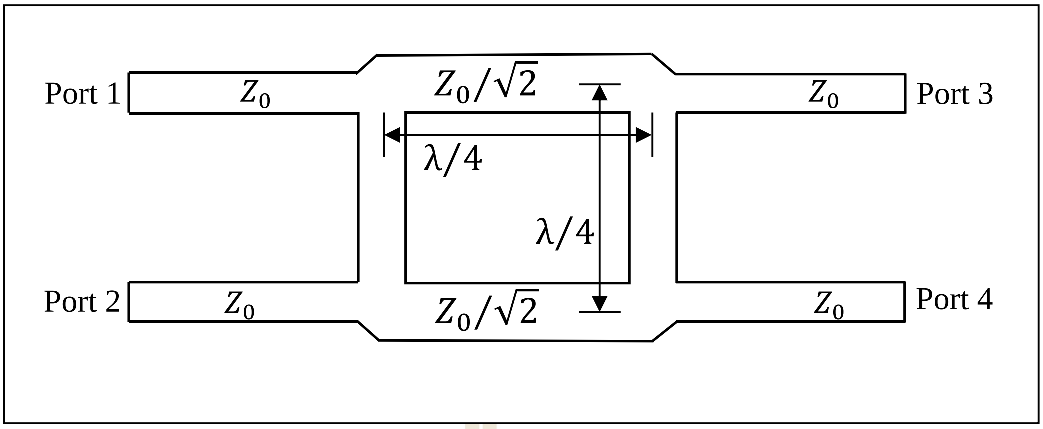

Figure 4.2. Hybrid coupler.

In order to solve for the width (W) and height (h) of the transmission line, the factor A must be determined first by Z_0=50Ω.

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right). \tag{4.1}$$

$$A = \frac{50}{60}\sqrt{\frac{4.6+1}{2}} + \frac{4.6-1}{4.6+1}\left(0.23 + \frac{0.11}{4.6}\right) = 1.56$$

$$\frac{W}{h} = \begin{cases} \frac{8e^A}{e^{2A}-2} & ; \frac{W}{h} < 2 \\ \frac{2}{\pi}\left[B - 1 - ln(2B-1) + \frac{\varepsilon_r-1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right] & : \frac{W}{h} > 2. \end{cases} \tag{4.2}$$

Consider A = 1.56, h = 1.6 mm

$$\frac{W}{h} = \frac{8e^A}{e^{2A}-2} \qquad \text{for } \frac{W}{h} < 2$$

$$\frac{W}{h} = \frac{8e^{1.56}}{e^{2(1.56)}-2} = 1.84$$

Thus, width of the hybrid, W is 2.94 mm

The effective dielectric constant of microstrip line (ε_e) is written as

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\sqrt{\frac{1}{1+\frac{12h}{W}}}. \tag{4.3}$$

$$\varepsilon_e = \frac{4.6+1}{2} + \frac{4.6-1}{2}\sqrt{\frac{1}{1+\frac{12(1.6)}{2.94}}} = 3.46$$

The wavelength (λ) on the substrate is defined as

$$\lambda = \frac{c}{f\sqrt{\varepsilon_e}}, \tag{4.4}$$

$$\lambda = \frac{3\times10^8}{2.45\times10^9\sqrt{3.46}} = 65.83 \text{ mm}$$

where c is the speed of light in free space about 3×10^8 m/s, f is the operating frequency of 2.45 GHz. Thus, for frequency 2.45 GHz, the wavelength $\left(\frac{\lambda}{4}\right)$ is calculated as $\frac{\lambda}{4} = 16.46$ mm.

In order to solve for the width (W) and height (h) of the transmission line, the factor B must be determined first by $\frac{Z_0}{\sqrt{2}} = \frac{50}{\sqrt{2}} = 35.36\Omega$

$$B = \frac{377\pi}{2Z_0(\sqrt{\varepsilon_r})}. \tag{4.5}$$

$$B = \frac{377\pi}{2\times35.36(\sqrt{4.6})} = 7.81$$

Consider B = 7.81, h = 1.6 mm

$$\frac{W}{h} = \frac{2}{\pi}\left[B - 1 - ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right] \quad \text{for } \frac{W}{h} > 2$$

$$\frac{W}{h} = \frac{2}{\pi}\left[7.81 - 1 - ln(2(7.81) - 1) + \frac{4.6 - 1}{2(4.6)}\left\{\ln(7.81 - 1) + 0.39 - \frac{0.61}{4.6}\right\}\right] = 3.24$$

Thus, width of the hybrid, W is 5.18 mm

The effective dielectric constant of microstrip line (ε_e) is written as (4.3)

$$\varepsilon_e = \frac{4.6+1}{2} + \frac{4.6-1}{2}\sqrt{\frac{1}{1+\frac{12(1.6)}{5.18}}} = 3.63.$$

The wavelength (λ) on the substrate is calculated similar to (4.4) as follows

$$\lambda = \frac{3\times10^8}{2.45\times10^9\sqrt{3.63}} = 64.27 \text{ mm}$$

Thus, for phase difference of 90°, the wavelength $\left(\frac{\lambda}{4}\right)$ is equal to 16.07 mm.

The basic of 90° hybrid coupler is designed by using CST Microwave Studio programming after that the author adjusted the size of microstrip lines (width and length) in order to modify for 256° hybrid coupler (the empirical method). Each line is adjusted in order to get the appropriate phase for the desired hybrid coupler. In the FDSC 2×2 MIMO system, the analog cancellation is firstly implemented. From the mathematics analysis, it can be calculated to find the amplitude and phase of appropriate hybrid coupler. In this technique, the solution is modified 256° hybrid coupler which is suitable to cancel the phase difference between self-interference and mutual-interference signals. All dimensions of modified 256° hybrid coupler is illustrated in Figure 4.3. Note that the appropriate amplitude and phase of modified hybrid coupler are varied by the specific design of many factors such as the length of feeding line, the specification of circulator, and the loss of transmission line. However, this solution can be pre-defined and always work because there is nothing changed after operating. It means that the proposed system can be manufactured as a mass production because amplitude and phase of modified hybrid couple are fixed. Thus, the modified hybrid coupler operating at 2.45 GHz was designed and simulated using CST Microwave Studio programming as shown in Figure 4.4.

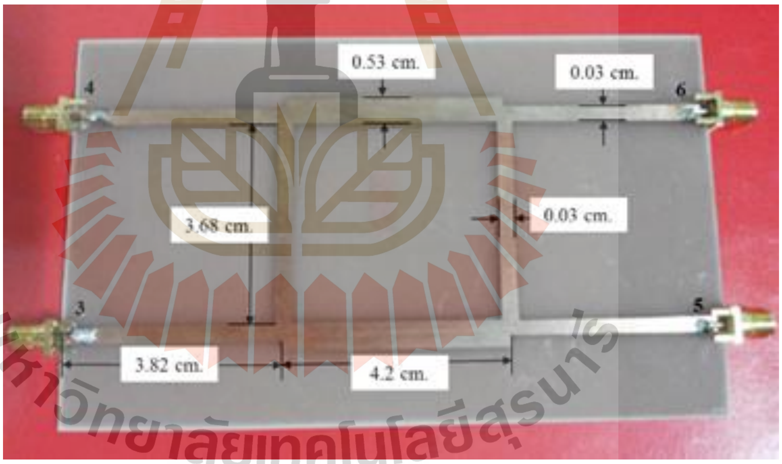

Figure 4.3 Modified hybrid coupler.

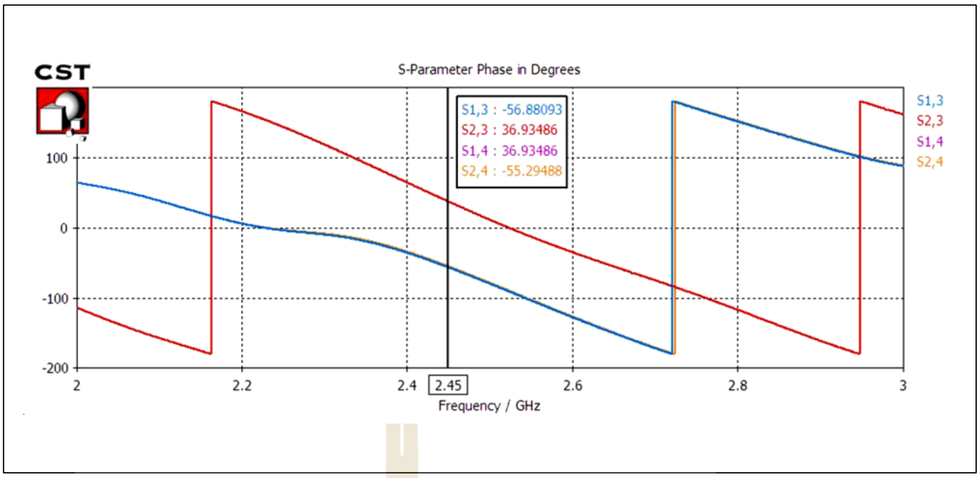

Figure 4.4 Phase angle of modified hybrid coupler.

4.4 Analog cancellation

From analog cancellation mentioned above, the test kit is designed to measure the results self-interference and mutual-interference signals. The design of analog cancellation is based on pre-defined RF circuit network by using the combination of a modified hybrid coupler and phase shifters, which as shown in Figure 4.5. In the designed FDSC 2×2 MIMO system, the analog cancellation technique consists modified hybrid coupler and phase shifters. The details of each component are shown as follows. The first component is modified hybrid coupler which as mentioned above. The photograph of phase shifter is shown in Figure 4.6 which is model number JSPHS 2484 from Mini Circuits®. Each phase shifter operate the range of frequency from 2.15 to 2.484 GHz and control voltage from 0-15 volts.

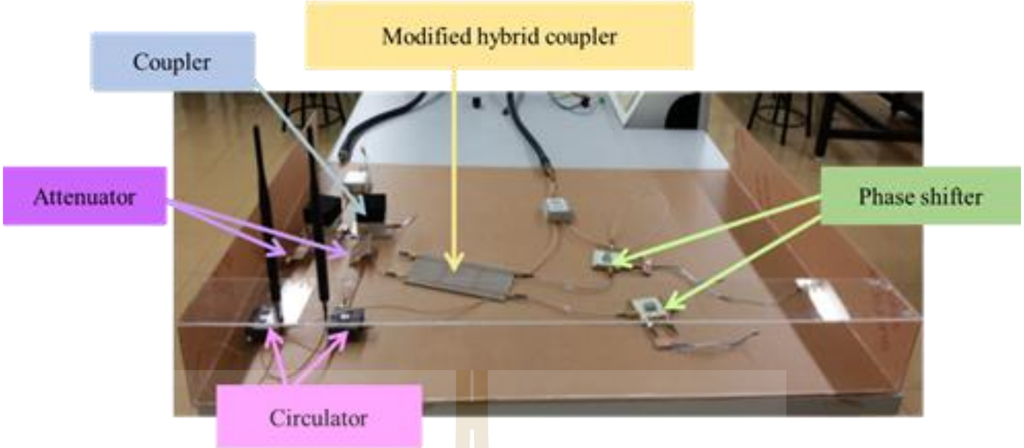

Figure 4.5 Implementation of analog cancellation for FDSC 2 × 2 MIMO system.

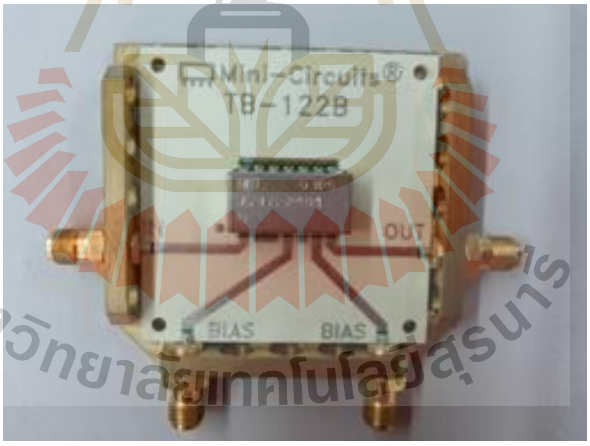

Figure 4.6. Photograph of phase shifter.

Figure 4.7 shows the power of self-interference and mutual-interference signals before and after cancellation. For self-interference measurement, the authors feed the transmitted power into the 1^{st} port and measure the power output of the 9^{th} port while terminating the 2^{nd} port with 50 ohms. The output power is the power of self-interference which is approximately -42.16 dB as shown in Figure 4.7. When operating the self-interference cancellation, the reference signal passes to the modified hybrid coupler and phase shifter combined with interference signal. For the reference and self-interference signals, the phase shifter is adjusted to make phases of two signals differ by π. The power of self-interference after cancellation at the 11^{th} port is -61.28 dB. It means that the self-interference signal is significantly reduced. The blue dashed line represents to reduce self-interference signal for analog cancellation technique which the best range of self-interference cancellation have bandwidth about 2.42 to 2.48 GHz. For mutual-interference measurement, the authors feed the transmitted power into the 2^{nd} port and measure the power output of the 9^{th} port while terminating the 1^{st} port with 50 ohms. The measured power of mutual-interference signal is -21.75 dB as shown in Figure 4.7. When operating for the mutual-interference cancellation, the reference signals through the modified hybrid coupler and phase shifter combined with interference signal. For the reference and mutual-interference signals, the phase shifter is adjusted to make phases of the two signals differ by π. The power of mutual-interference after cancellation at the 11^{th} port is -45.12 dB. The results confirm the success of proposed analog cancellation as follows.

In Figure 4.8, the full operation of analog cancellation is investigated. The power of self-interference signal due to circulator leakage is about -42.16 dB. The power of mutual-interference signal due to coupling effect between antennas is about -21.49 dB. After using the proposed analog cancellation, it is clearly seen that the magnitude of interference signals are significantly decreased. The interference power reduced to -61.42 dB for the first antenna and -62.06 dB for the second antenna.

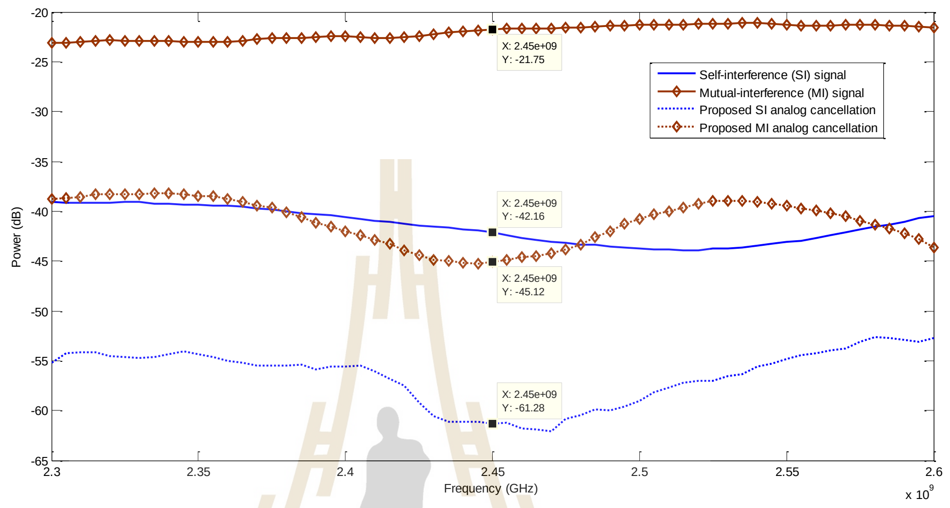

Figure 4.7 The power of self-interference and mutual-interference signals, before and after cancellation.

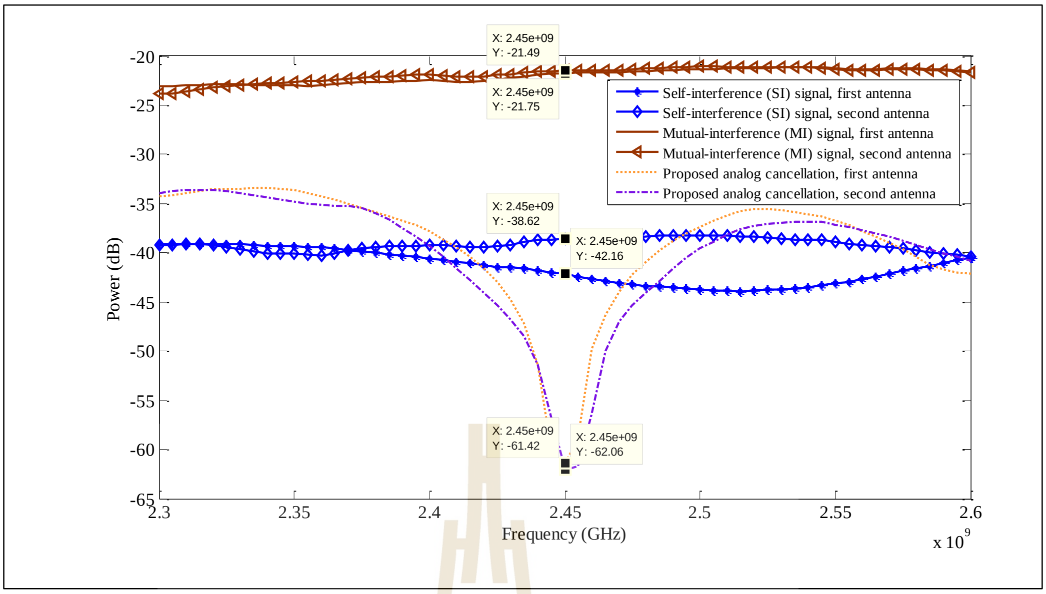

Figure 4.8 The power of received signals using analog cancellation for FDSC 2 × 2 MIMO system.

In Figure 4.9, the interference channels are pre-known from the signal leakage and the effect between antennas (mutual coupling). This is the average of capacity in bits per second per Hertz (bps/Hz). Hence, the uniform transmitting power is assumed for each antenna, $\left(E\{\boldsymbol{x}\boldsymbol{x}^{\boldsymbol{H}}\} = \frac{P_o}{M_s}\boldsymbol{I}_x\right)$. The capacity of FDSC 2 × 2 MIMO system can be written by (4.6)

$$C = \log_2 det[\boldsymbol{I} + \frac{P_o}{M_s}\boldsymbol{H}_I\boldsymbol{H}_I^H \times \left(\boldsymbol{\sigma}_I^2\boldsymbol{H}_I'\boldsymbol{H}_I'^H + \boldsymbol{\sigma}_d^2\boldsymbol{I}\right)^{-1}], \quad (4.6)$$

where P_o denotes the maximum available power at the transmitter, M_s denotes the number of transmit antennas. Figure 4.9 shows the performance of capacity by considering three cases. In first case, there is no the self-interference and mutual-interference signals in the system, so called as without interference. The second case is that the analog cancellation is proposed on the FDSC 2×2 MIMO system (by using modified hybrid coupler and phase shifters technique) for self-interference and mutual-interference signals. In last case, we have not used any cancellation technique to eliminate the self-interference and mutual-interference signals. So there will be interference.

The simulation of MATLAB programming can be described as follows. The source and destination are assigned with two transmitting and two receiving antennas; $x = s = 2$. The interference channels H_I consist self-interference and mutual-interference channels H_{SI} and H_{MI}. Figure 4.9 shows the channel capacity versus SNR for the 2×2 MIMO system. As seen in Figure 4.9, the proposed technique lies between with and without the interference cancellation. The capacity of the proposed technique is about 3.907 bps/Hz (at SNR = 20 dB) higher than the system with interference signals. Thus, Figure 4.10 shows Capacity versus SNR for the FDSC 2×2 MIMO system. In the two-way for MIMO system, the proposed technique demonstrates that the double capacities can be achieved in practice when employing the proposed concept. The capacity of the proposed technique is about 22.63 bps/Hz (at SNR = 20 dB) higher than the capacity of the interference signals about 15.237 bps/Hz (at SNR = 20 dB).

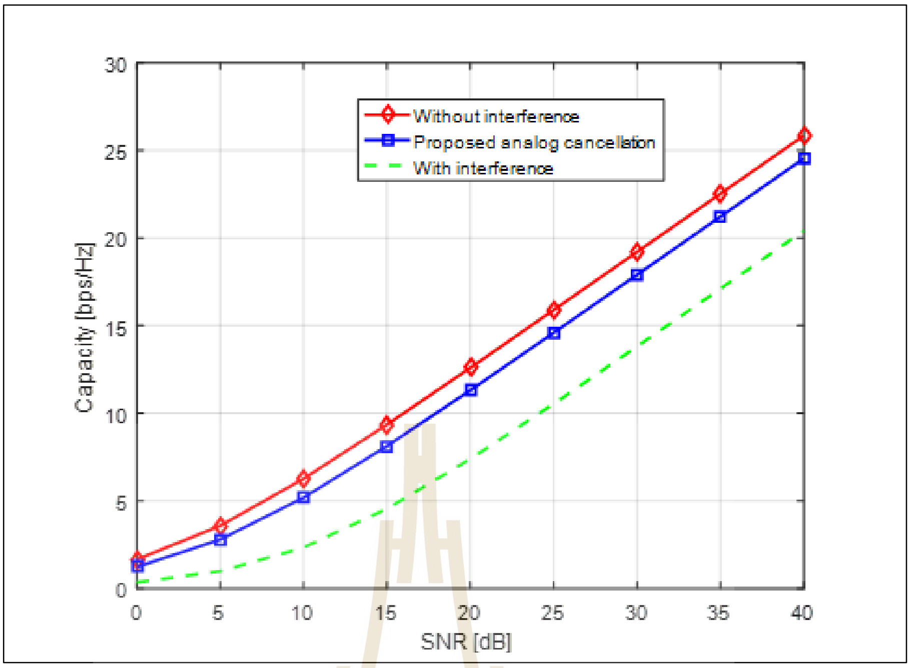

Figure 4.9 Capacity versus SNR for the 2 × 2 MIMO system.

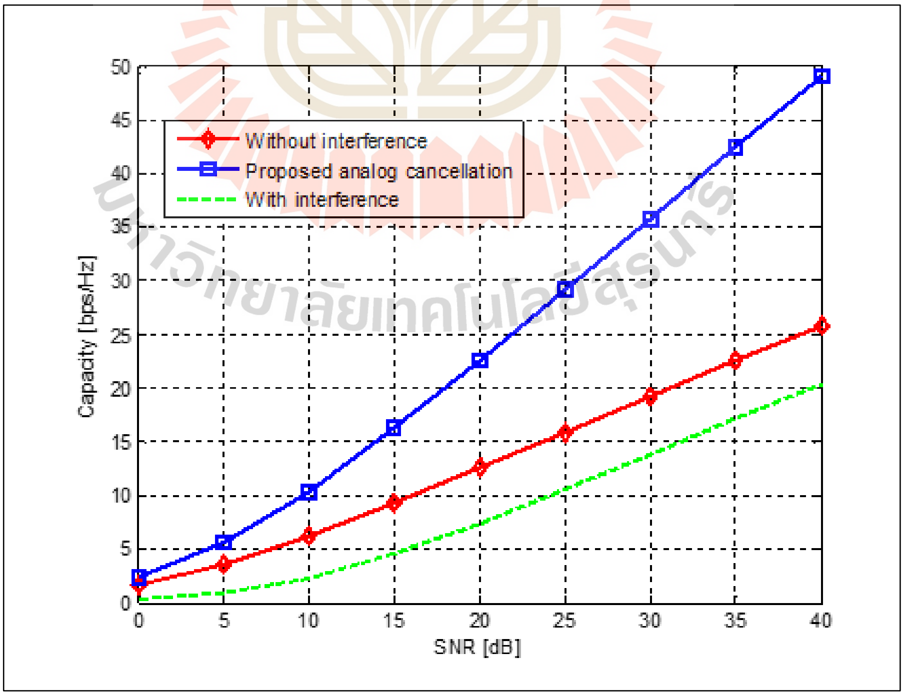

Figure 4.10 Capacity versus SNR for the full-duplex 2 × 2 MIMO system.

4.5 Chapter summary

This chapter proposed the method of self-interference and mutual-interference cancellations for FDSC MIMO system. The performance of the proposed technique can suppress the self-interference and mutual-interference signals by using the pre-known interferences which are affected by signal leakage and mutual coupling between antennas. The pre-known interferences employs to design modified hybrid coupler combined with phase shifters. Simulation results illustrate that the proposed system outperforms the system with interference. This implies the success of using the proposed concept for FDSC MIMO system. In addition, the measurement results indicate that the self-interference and mutual-interference reductions are good enough to successfully transmit and receive on the same frequency at the same time in practice. As a result, the proposed approach can achieve twice the throughput of the conventional system.

CHAPTER V

IMPLEMENTATION OF FDSC 2×2 MIMO SYSTEM

5.1 Introduction

In a real situation, the proposed FDSC 2×2 MIMO system has the problem of interference signals which is larger amplified because of the more number of antennas on the both transmitter and receiver. The interference signals are named as self-interference and mutual-interference signals. Therefore, this thesis presents two techniques of interference cancellation for FDSC 2×2 MIMO system, which is an analog cancellation and digital cancellation. The analog cancellation is already discussed in the Chapter 3 and 4. A test kit of two nodes was developed under Software-Defined Radio (SDR) technology. The test kit utilizes a Universal Software Radio Peripheral (USRP) as it provides high speed ADCs, DACs, FPGA and USB interface. Section 5.1 is an introduction of the chapter. Section 5.2 discusses the Software-Defined Radio (SDR) which utilized as a test kit. Section 5.3 proposes the digital cancellation part which utilized by the Space Time Block Code (STBC). Experimental results of analog and digital cancellations are proposed in Section 5.4. Finally, the chapter is concluded in Section 5.5.

5.2 Software-defined radio

Software-Defined Radio (SDR) is a radio communication system where components that have been typically implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer. SDR is a wireless device that typically consists of a configurable RF front end with a Field Programmable Gate Arrays (FPGAs). The ideal receiver scheme attaches an analog-to-digital converter to an antenna. The digital signal processor would be read the converter and then its software transforms the steam of data from the converter to any other form the application requires. An ideal transmitter would be similar the receiver. A digital signal processor generates a stream of data. These data would be sent to a digital-to-analog converter connected to a radio antenna in order to convert digital data into an analog signal which is amplified by RF hardware.

5.2.1 GNU radio companion

In this experiment, the proposed FDSC 2×2 MIMO system is developed by utilizing the Universal Software Radio Peripheral USRP family of boards with GNU Radio companion (GRC). GNU Radio is an open-source software that can be implemented on various hardware platforms such as USRP. GNU Radio provides an ideal SDR platform for developing wireless protocols. The signal processing blocks of GRC are primarily written using Python programming language, while performance/critical signal processing blocks are implemented in C++. GRC is the software development toolkit for building any kind of real-time signal processing applications.

5.2.2 Equipment list

For this thesis, the USRP B210 (board only) includes a Spartan

XC6SLX150 FPGA, Analog Devices AD9361 RFIC and USB 3.0 connectivity which equipped in the test kit. The USRP is manufactured by Ettus Research.

The USRP B210 provides a fully integrated, single-board, which can work with radio frequencies between 70 MHz - 6 GHz. Designed for low-cost experimentation, it combines the AD9361 RFIC, Spartan6 FPGA and USB3.0 connectivity (Ettus, (2015)). Figure 5.1 shows a USRP B210 module. The USRP B210 has the features as follows

- MIMO (2TX and 2RX), Half-duplex or Full-duplex
- Xilinx Spartan 6 XC6SLX150 FPGA
- Up to 56 MHz of instantaneous bandwidth in 1×1
- Up to 30.72 MHz of instantaneous bandwidth in 2×2
- Sample rate 61.44 MS/s, 12 bits ADC/DAC
- SuperSpeed USB 3.0 connectivity
- $\pm$2.0 ppm frequency accuracy reference.

In this work, a VERT2450 antenna is shown in Figure 5.2. The VERT2450 antenna has the features as follows

- Omni-directional vertical antenna
- Support dual band: 2.4 to 2.48 GHz and 4.9 to 5.9 GHz
- Provides 3 dBi Gain

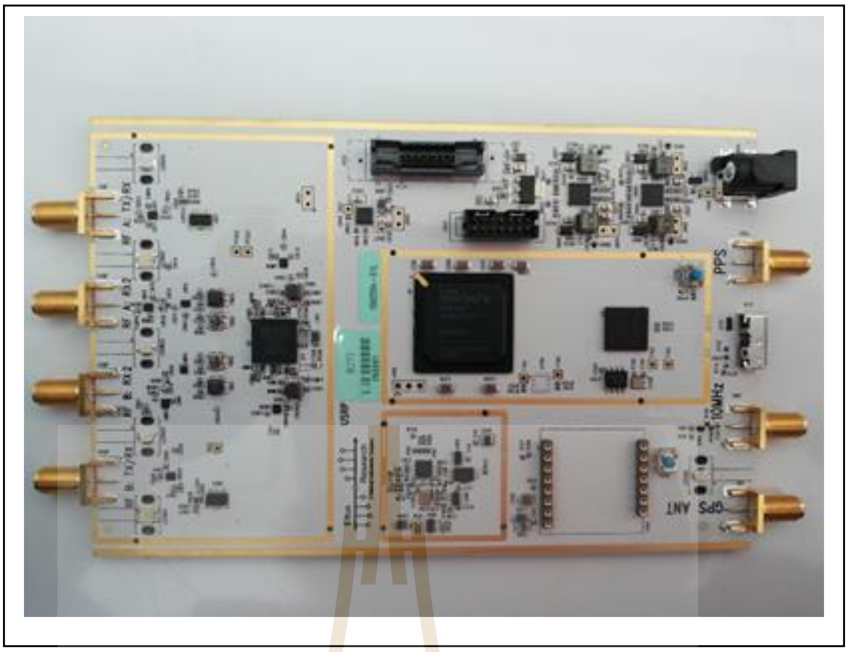

Figure 5.1 USRP B210 board.

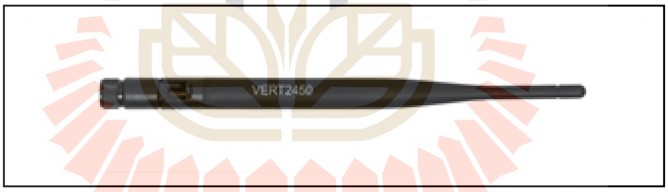

Figure 5.2 VERT2450 antenna.

5.3 Design of digital cancellation

This thesis presents the concept of FDSC communication for MIMO system which allows both sides of communications to transmit and receive at the same time on the same frequency. The main problem of this concept is the self-interference and mutual-interference signals. As shown in Figure 5.3, this thesis proposes both analog and digital cancellations in order to eliminate interference signals. The analog cancellation is already discussed in the Chapters 3 and 4. In these chapters, Space Time Block Code (STBC) technique for FDSC MIMO system is proposed to design digital cancellation part by estimation of channel. The simulation of transmitting and receiving for FDSC MIMO system uses the Simulink blocks in GRC. For the programming, the USRP B210 hardware is developed by Ettus Research which implemented over a GNU Radio companion (GRC) version 3.7.4 by building GNU Radio flow graphs.

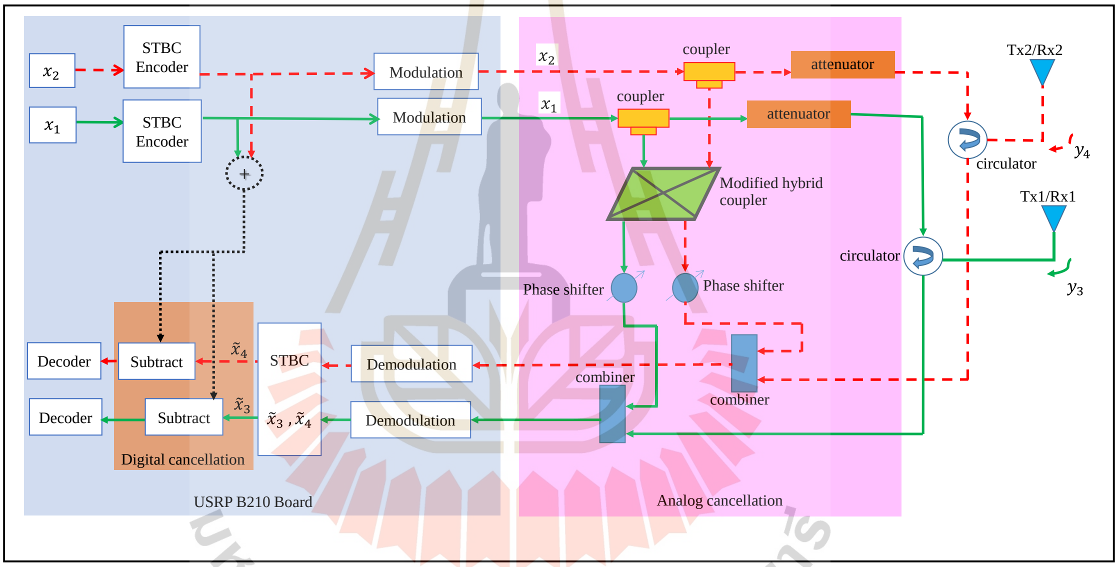

Figure 5.3 Diagram of analog and digital cancellations.

5.3.1 MIMO Space Time Block Code

Alamouti system is one of the first space times coding schemes developed for the MIMO systems. In this thesis, MIMO system employs two transmit antennas and two receive antennas. From Table 5.1 and the equations that follow, it can be seen that the encoding as well as channel estimation is identical to the STBC scheme

Table 5.1 2×2 Alamouti STBC

Time	Transmitter 1	Transmitter 2
t	x_3	x_4
t+T	$-x_4^*$	x_3^*

discussed in (Perisoara L., (2012); Santumon S.D., and Sujatha B.R., (2012); Pathak P. et al., (2014)).

Table 5.1 shows the principle of 2×2 Alamouti STBC. At time t, x_3 and x_4 are transmitted by transmitter 1 and 2 of the node 2, x_1 and x_2 are transmitted by transmitter 1 and 2 of the node 1, and after that at time (t+T) their conjugates are transmitted. Thus, the received signals $y_{13}, y_{14}, y_{23}, y_{24}$ from two receive antennas can be written as follow:

The first-time slot received data

$$y_{13} = h_{33}x_3 + h_{34}x_4 + h_{SI_{11}}x_1 + h_{MI_{12}}x_2 + n_{33}, \tag{5.1}$$

$$y_{14} = h_{43}x_3 + h_{44}x_4 + h_{SI_{22}}x_2 + h_{MI_{21}}x_1 + n_{34}, \tag{5.2}$$

The second-time slot received data

$$y_{23} = -h_{33}x_4^* + h_{34}x_3^* - h_{SI_{11}}x_2^* + h_{MI_{12}}x_1^* + n_{43}, \tag{5.3}$$

$$y_{24} = -h_{43}x_4^* + h_{44}x_3^* + h_{SI_{22}}x_1^* - h_{MI_{21}}x_2^* + n_{44}, \tag{5.4}$$

where y_{ij} is the received signals at the i^{th} time slot and the j^{th} antenna. The interference signals of transmitter 1 and 2 are the combination of signal leakage from circulator, the reflection of signal from an antenna and the effect of the neighboring antennas. The interference signals from the first-time and second-time slots are considered by the received data $(y_{13}+y_{23})$ and $(y_{14}+y_{24})$ respectively. y_1 and y_2 can be written as

$$y_1 = h_{SI_{11}}x_1 + h_{MI_{12}}x_2 - h_{SI_{11}}x_2^* + h_{MI_{12}}x_1^*, \tag{5.5}$$

$$y_2 = h_{SI_{22}}x_2 + h_{MI_{21}}x_1 + h_{SI_{22}}x_1^* - h_{MI_{21}}x_2^*, \tag{5.6}$$

where h_{SI} is the self-interference channels that combine the signal leakage channel h_L and the reflected antenna channel h_R.

Therefore, two combined signals are sent to receiver which the combined symbols $\widetilde{x_3}$ and $\widetilde{x_4}$ can be written as

$$\widetilde{x_3} = h_{33}^*y_{13} + h_{34}y_{23}^* + h_{43}^*y_{14} + h_{44}y_{24}^* + h_{SI_{11}}^*y_{13} + h_{MI_{12}}^*y_{13} - h_{SI_{11}}y_{23}^* + h_{MI_{12}}y_{23}^*, \tag{5.7}$$

$$\widetilde{x_4} = h_{34}^*y_{13} - h_{33}y_{23}^* + h_{44}^*y_{14} - h_{43}y_{24}^* + h_{SI_{22}}^*y_{14} + h_{MI_{21}}^*y_{14} + h_{SI_{22}}y_{24}^* - h_{MI_{21}}y_{24}^*, \tag{5.8}$$

where $\widetilde{x_3}$ and $\widetilde{x_4}$ are the estimated symbols that combines the received symbols and the interference symbols. The proposed digital cancellation can estimate interference after performing demodulation. It utilizes the correlation of original transmitting symbols (x_1, x_2) to reduce the interference symbols out of the estimated symbols $(\widetilde{x_3}, \widetilde{x_4})$.

This section designs flow graph for FDSC 2×2 MIMO system by using GNU Radio Companion (GRC) programming. Figure 5.4 shows the BER measurement of a test kit at 1^{st} and 2^{nd} nodes. The two USRP B210s are employed to transmitting and receiving at the 1^{st} and 2^{nd} nodes. All USRPs are connected to a laptop for signal processing and recording. The 1^{st} and 2^{nd} nodes transmits and receives simultaneously in the same time and on the same frequency which have a carrier frequency 2.45 GHz. Figure 5.5 presents a block diagram of the transmitting and receiving at 1^{st} and 2^{nd} nodes which transmit the bit symbols to each receiving nodes. The signal sources generate the digital data $(x_1 \quad x_2)^T$ which has the setup parameters as follows: data vector is to define digital data by utilizing STBC technique for MIMO system. Then, the signal is transmitted to an encoder which encoded by "Packet encoder". In this block, the signal is wrapped into a packet which provides a payload length with header, access code, and preamble. The setup parameters of this block are sample/symbol of 2 and bits/symbol of 1. Afterwards, the signals are modulated by the "Differential Binary Phase Shift Keying (DBPSK)" modulation. The setup parameters of this block are an excess bandwidth is 0.35 and Gray code is enabled. Then, the signals are transmitted to a "UHD USRP Sink" where USRP Hardware Driver (UHD) is a block available within the GNU Radio. This block acts as an interface to the USRP hardware. The transmitted gain in GRC is 40 dB. The received signal is conveyed to be a "UHD USRP Source". These UHD USRP block has the setup of parameters as follows: clock rate of 30.72 MHz for 2×2 MIMO system and center frequency of 2.45 GHz.

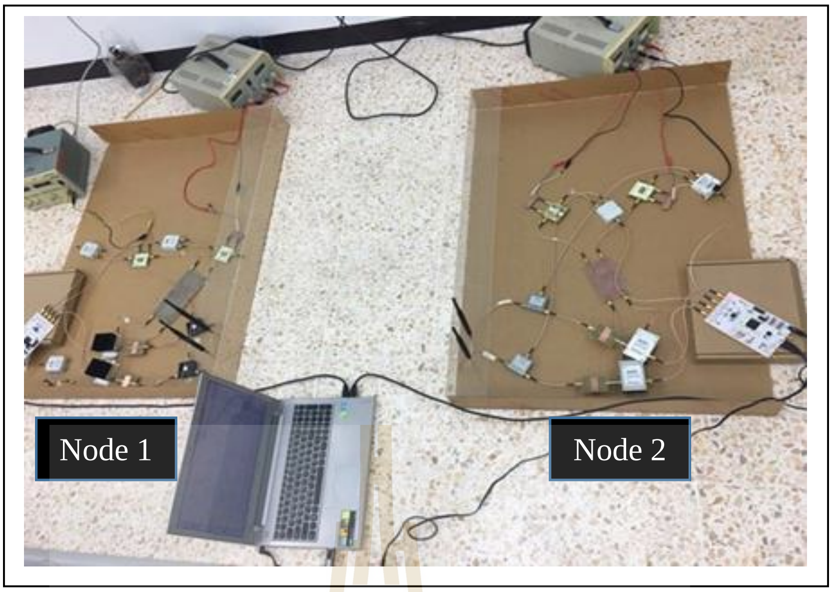

Figure 5.4 Two nodes of transmitting and receiving by using USRP B210.

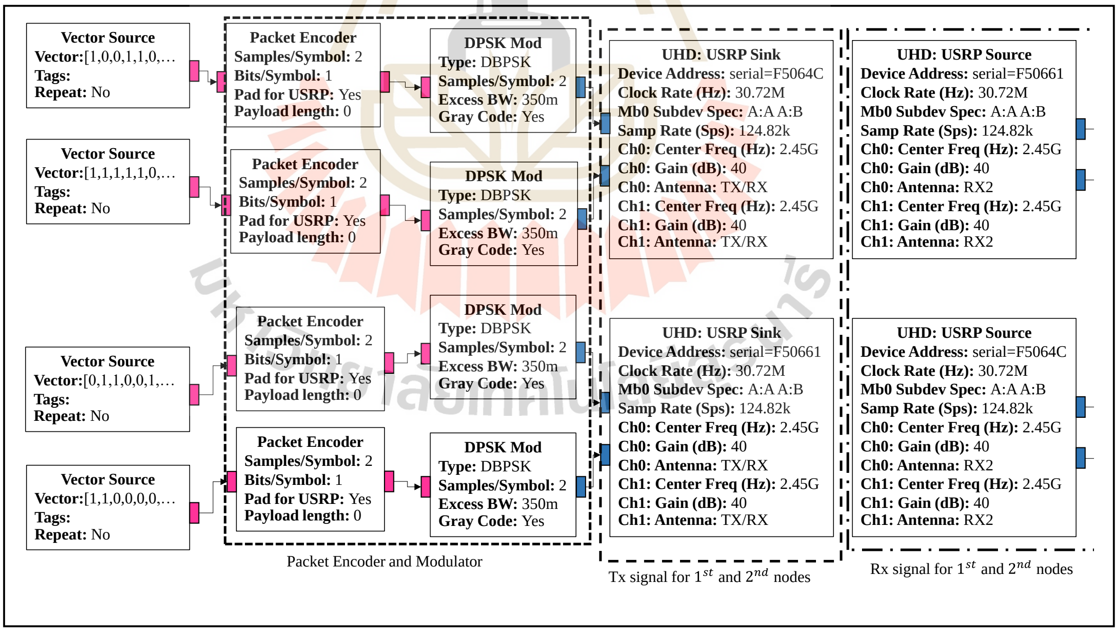

Figure 5.5 Programming block diagram of transmitting and receiving at the 1^{st} and the 2^{nd} nodes.

In finding channel, the first step defines the transmitted signal of the 1^{st} and the 2^{nd} antennas. The transmitted signal of the 1^{st} antenna is defined digital data of [1,1] and the transmitted signal of the 2^{nd} antenna is defined digital data of [0,0]. The first step is saved files of channel which is illustrated in Figure 5.6. The first step can be written as

$$y_1 = h_{11}x_1 + h_{12}(0) + n, \tag{5.9}$$

$$y_2 = h_{21}x_1 + h_{22}(0) + n. \tag{5.10}$$

The second step defines the transmitted signal of the 1^{st} and the 2^{nd} antennas. The transmitted signal of the 1^{st} antenna is defined digital data of [0,0] and the transmitted signal of the 2^{nd} antenna is defined digital data of [1,1]. The second step is to save the values of the channel which is illustrated in Figure 5.7. The second step can be written as

$$y_1 = h_{11}(0) + h_{12}x_2 + n, \tag{5.11}$$

$$y_2 = h_{21}(0) + h_{22}x_2 + n. \tag{5.12}$$

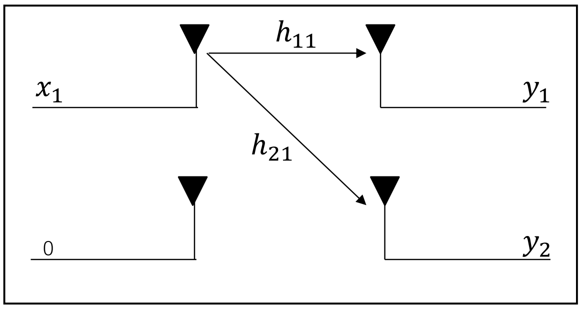

Figure 5.6 Illustration of finding channel at first antenna for MIMO system.

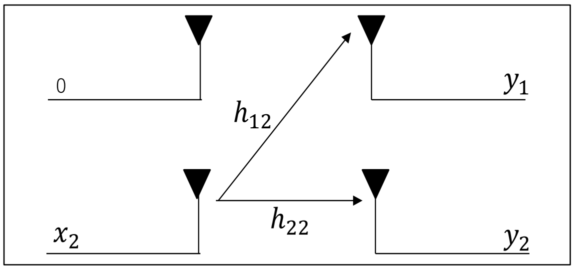

Figure 5.7 illustration of finding channel at second antenna for MIMO system.

In the steps of finding channel, the channel is saved at "File Sink" which is shown as Figure 5.8. The saved channel files are used for the proposed STBC technique. The STBC technique is described in equations (5.1), (5.2), (5.3) and (5.4). Figure 5.9 shows block diagram of the calculating for the estimated signal. The saved files are loaded by "File Source". The received signal and channel can be designed diagram as follows with the equation of STBC. Then, the estimated signal is saved at "File Sink".

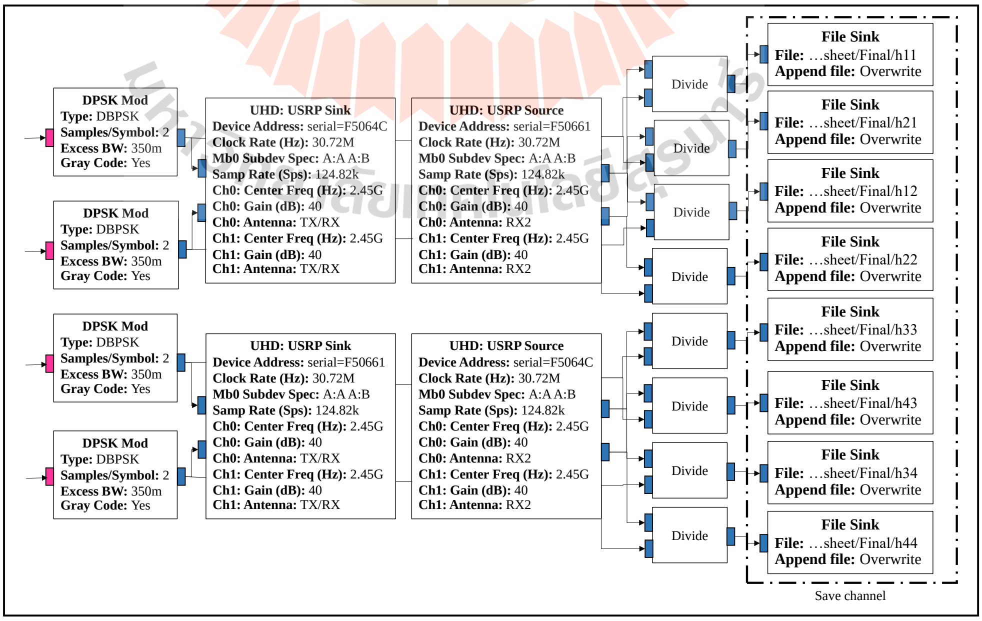

Figure 5.8 Programming block diagram of finding channel for MIMO system.

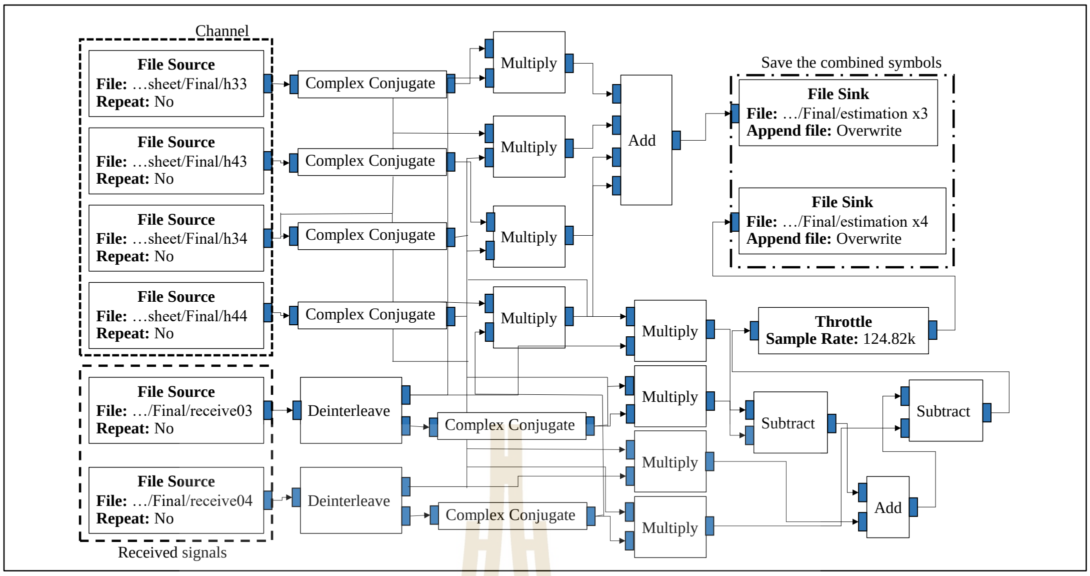

Figure 5.9 Programming block diagram of the STBC technique.

Figure 5.10 shows block diagram of the estimated signal. The saved files are loaded by “File Source”. The self-interference and mutual-interference channels are used to calculate the combination of interference channels and the desired signals. Then, the estimated signal is saved by “File Sink”. The calculation is described in the equations (5.5) and (5.6). Figure 5.11 shows block diagram of the digital cancellation. The received signal is demodulated using “DBPSK Demodulation”. The setup parameters of this block are as follows: as excess bandwidth is 0.35, frequency loop bandwidth is 0.0628 radians per sample, phase recovery loop bandwidth is 0.0628 radians per sample, timing recovery loop bandwidth in 0.0628 radians per sample and Gray code is enabled. This stage is used to estimate residual self-interference and mutual-interference signals after analog cancellation. Digital cancellation part eliminates interference after analog-to-digital converter (ADC). It uses the digital original transmit signal to correlate with the digital received signal. If correlation occurs, the origin signal will be subtracted from the received signal. Then the desired signal is saved by “File Sink”. Then, a demodulated signal is decoded by “Packet Decoder”. Finally, the decoded signal is used to collect a BER as shown in Figure 5.12.

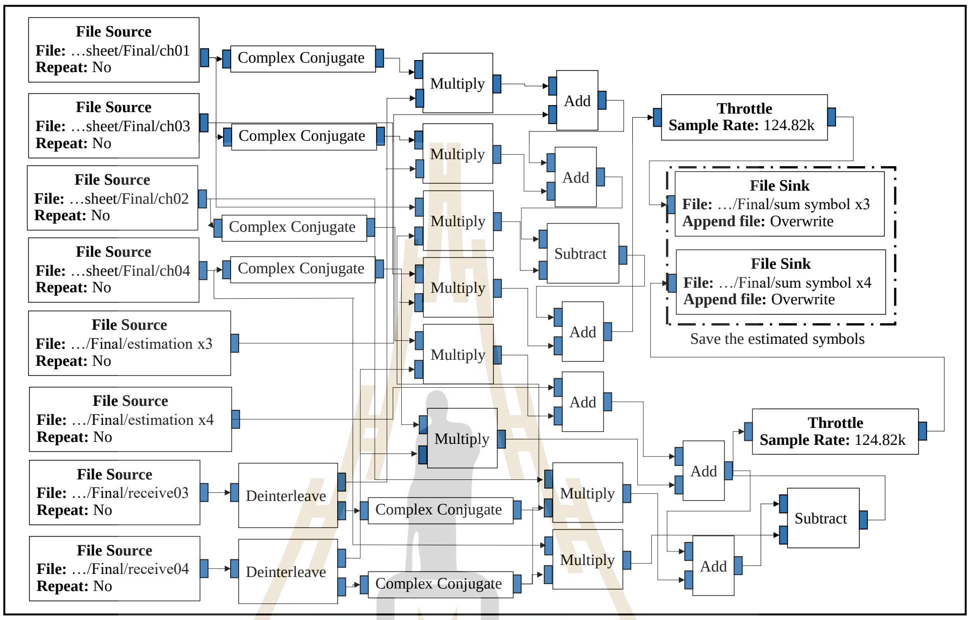

Figure 5.10 Programming block diagram of the estimated signal.

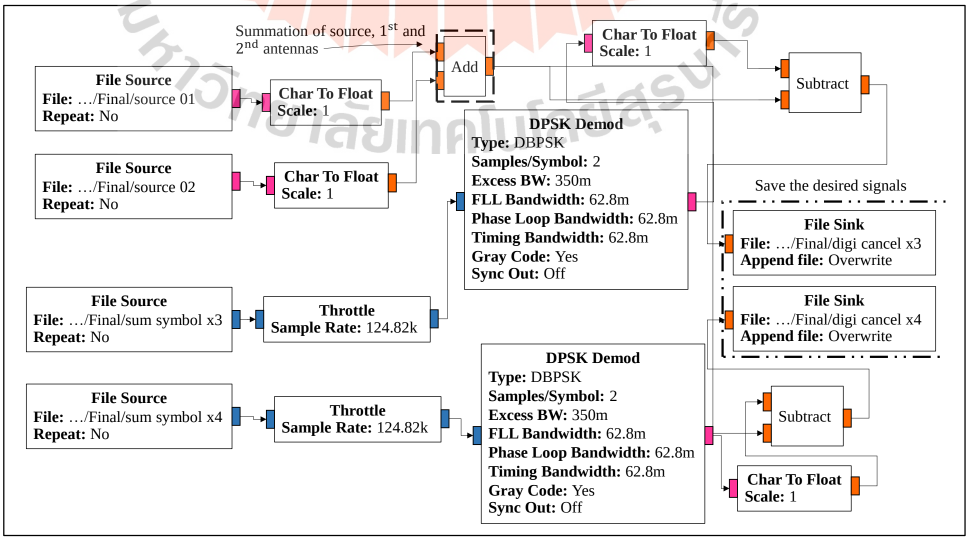

Figure 5.11 Programming block of digital cancellation part.

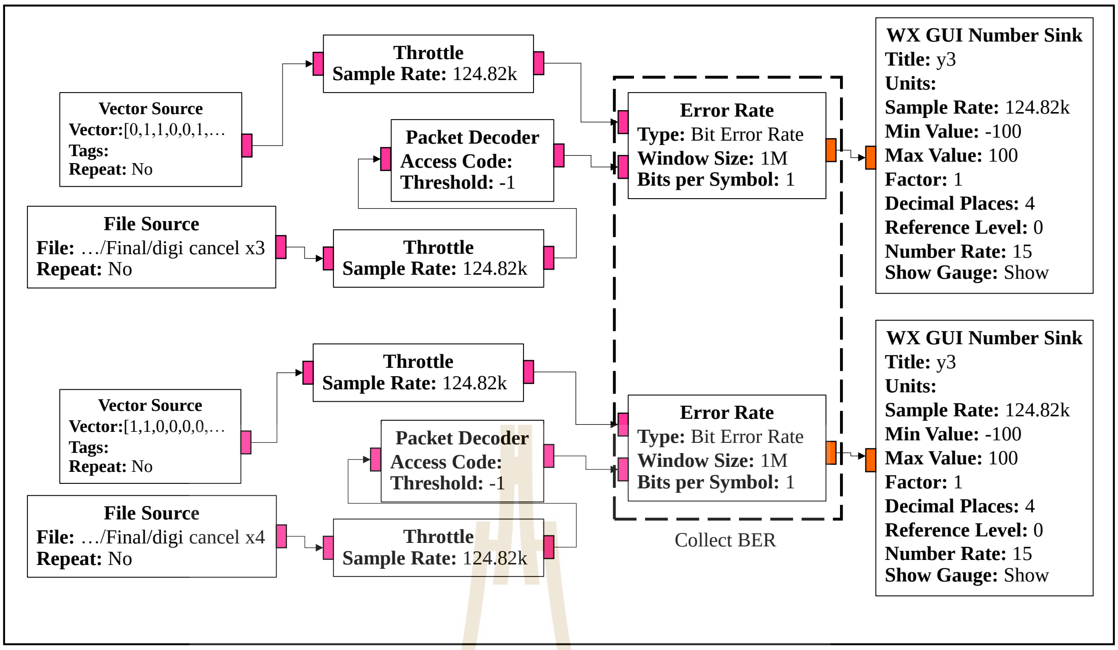

Figure 5.12 Programming block diagram of transmitting and receiving for experimental BER.

5.4 Analog and digital cancellations

The full operation of FDSC 2 × 2 MIMO system is demonstrated. The system allows simultaneous transmission and reception for both sides of communications. Definitely, both analog and digital cancellation have to be applied. Figure 5.13 shows the implementation of both analog and digital cancellations for FDSC 2 × 2 MIMO system. This thesis uses USRP B210 boards and Simulink blocks in GRC programming. The signal source generates a vector data source which is transmitted to BPSK digital modulation. The STBC technique is applied. Two different data streams are generated in order to transmit this data through USRP UHD block to receiver. In this experiment, the data is sent to decoder block in order to check error rate. The error rate is computed by this block in GRC as shown in Figure 5.12. The measurement results are presented in a histogram of BER. The measured BER utilizes USRPs which is relatively sensitive with noise. Thus, the major portion of measured BER is the excellent case as 0.0 or the worst case as 0.5. Then BER=0.0 means that there is no bit error at all. BER=0.5 means that bit error turns out be a half of transmitted bits, e.g. bit error is 500,000 when transmitting 1,000,000 bits. Table 5.2 shows BER vs. distance for FDSC 2×2 MIMO system. As seen in all three cases, the first case is a conventional 2 × 2 MIMO system on the one way. The second case is the proposed FDSC 2 × 2 MIMO system that both analog and digital cancellation are applied. The last case is FDSC 2 × 2 MIMO system without any cancellations. The proposed technique can improve the BER performance better than the system without any cancellations for farther distances. The FDSC 2 × 2 MIMO system without any cancellations provides the maximum error rate. It means the proposed technique can eliminate both self-interference and mutual-interference signals.

Figure 5.14 shows the measured throughput vs. distance of various 2×2 MIMO schemes. Then, the system throughput can be calculated as follow $Throughput\ (bps) = 1 - BER$. There are three schemes to be considered here. The first scheme is a conventional 2×2 MIMO system. This is one way communication which cannot transmit and receive data at the same time. The second scheme is the proposed FDSC 2×2 MIMO system in which both analog and digital cancellations are applied to this scheme. The last scheme is FDSC 2×2 MIMO system without any cancellations. This scheme is used for benchmarking which is the worst-case scenario for FDSC system. As seen in Figure 5.14, the system throughput decreases for farther distances. When comparing between three schemes, the proposed FDSC 2 × 2 MIMO system offers the highest throughput over the others and the FDSC system without any cancellations provides the lowest throughput. It means that the proposed cancellations can successfully eliminate both self-interference and mutual-interference. Moreover, the obtained results have indicated that FDSC 2 × 2 MIMO systems provide nearly double throughput compared to a conventional system.

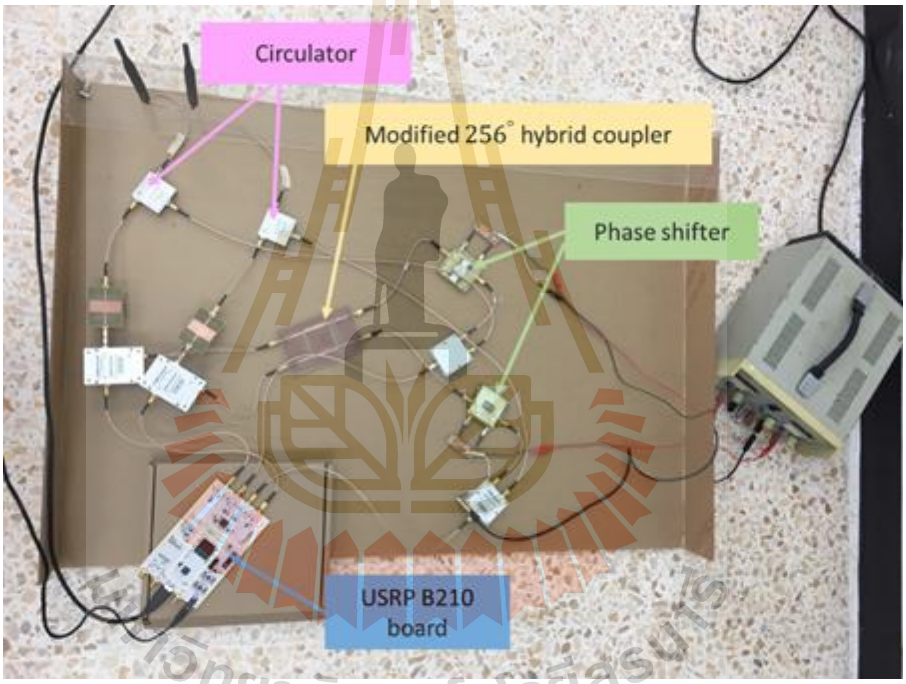

Figure 5.13 Implementation of both analog and digital cancellations for FDSC 2 × 2 MIMO system.

Table 5.2 The measured BER vs. distance of FDSC 2 × 2 MIMO system.

Distance (cm.)	Bit Error Rate		
	2 × 2 MIMO, one way.	FDSC 2 × 2 MIMO, analog and digital cancellations.	FDSC 2 × 2 MIMO, without any cancellations.
35	0.2267	0.2494	0.6688
50	0.2316	0.2493	0.7409
90	0.2449	0.2513	0.7489

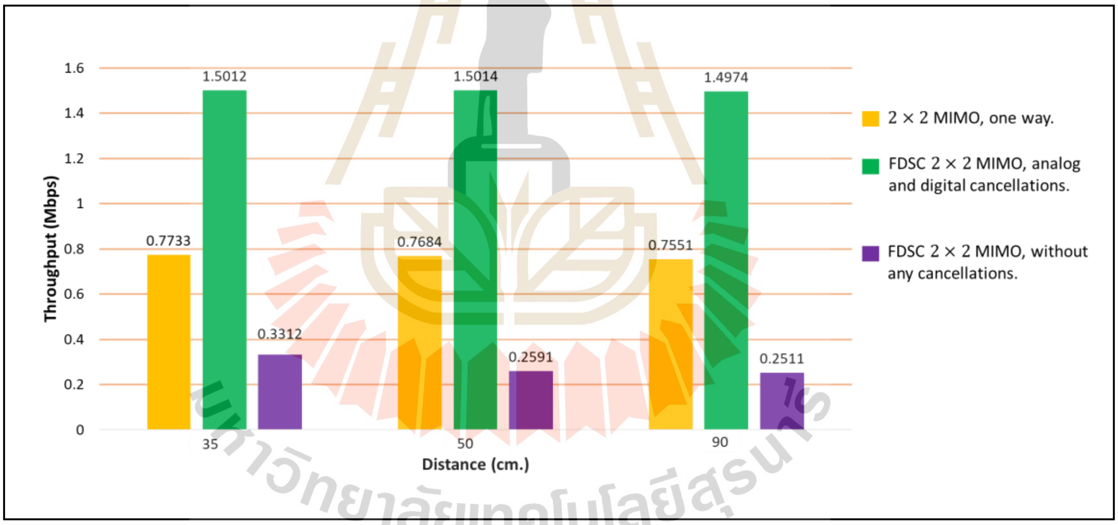

Figure 5.14 The measured throughput vs. distance of various FDSC 2 × 2 MIMO system.

5.5 Chapter summary

In this chapter, the proposed analog and digital cancellations have been analyzed under real indoor environment. The SDR is employed as a test kit. The measured results have presented that the proposed FDSC 2×2 MIMO system offers the optimum throughput over the others. In addition, it can enhance the system performance by reducing BER in comparison to the case without cancellation and by providing double throughput over the conventional system.

CHAPTER VI

THESIS CONCLUSION

6.1 Conclusion

A wireless research activity is already considering many technologies for a future wireless systems. High-speed data and low-latency demands will be the theme for the future fifth generation (5G) environment. The concept of full-duplex (FD) communications are the potential and promising technology for 5G of wireless communication systems as well as the multiple-input multiple-output (MIMO) systems. Full duplex data transmission means that data can be transmitted in both directions on the same frequency at the same time. Thus, the FD wireless communication approaches to increase the data rates, high spectral efficiency, double throughput, and larger network capacity. The challenge of FD system is the strong interference signals. Many techniques are proposed to eliminate self-interference signal ((Bharadia, (2014); Zhang Z., et al., (2015); Choi J. I., et al., (2010); Liempd V., et al., (2014)). The Full-Duplex Single-Channel (FDSC) MIMO system is one of the most interesting technologies for 5G wireless communications. This system can be transmit and receive simultaneously within a single antenna. Moreover, the main problem of FDSC MIMO system is the strong interference signals which consist of self-interference and mutual-interference signals. In (Lioliou P., et al., (2010); Darsena D., et al., (2015)), authors have proposed the methods for cancelling only self-interference which ignore the real power.

The first objective of this thesis was to design the FDSC 2×2 MIMO system which is the transmitting and receiving simultaneously at the same time and on the same frequency. The main challenge is presented in the implementation of FDSC 2×2 MIMO system which is the high power of self-interference and mutual-interference signals. The difference between self-interference and mutual-interference signals are that the transmitted signal leakage to the received signal is named self-interference signal. In other hand, the interference signal happening between antenna elements is named mutual-interference signal. This thesis mainly focuses on the analog cancellation and digital cancellation techniques. The design of analog cancellation utilizes the combination of modified hybrid coupler and phase shifters, so called reference signal. The modified hybrid couple is proposed to differentiate phase between self-interference and mutual-interference signals. The advantage of the proposed method is the amplitude and phase of self-interference and mutual-interference signals which can be known by calculating from only one measurement. In this cancellation part, the value of reference signal need to equal the combination of self-interference and mutual-interference signals. In the design of digital cancellation part, this thesis presents Space-Time Block Coding (STBC) technique by channel estimation for the MIMO systems. The proposed digital cancellation utilizes the correlation of original transmitted signals to eliminate the interference signals by subtracting the known interference signals. The design FDSC 2×2 MIMO system is operated under SDR technology by programming the Universal Software Radio Peripheral (USRP).

For the experiment, this thesis has shown the design and construction of proposed FDSC 2×2 MIMO system. The method can suppress the self-interference and mutual-interference signals by using both analog and digital cancellation techniques. The measured results reveal the success of interference cancellation by using the proposed technique. The proposed technique is not only to suppress the interference but also to improve the system performance capacity. The proposed system can provide double throughputs of the conventional system.

6.2 Future work

For the future studies, the full-duplex MIMO system should be designed to fit the requirement of future 5G communications. Also, it is interesting to find solutions for more antennas which the developed techniques for cancelling self-interference and mutual-interference have to be more efficient and less complex.

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APPENDIX A

PUBLICATIONS

List of Publications

National Conference Paper

Meerasri P., Uthansakul P. and Uthansakul M., (2013). **การลดทอนสัญญาณแทรกสอดในตัวเองของระบบไมโมเมื่อใช้กับการสื่อสารสองทางเต็มอัตรา.** ECTI-Conference on Application Research and Development 2013 (ECTI-CARD 2013). May 2013, no.1132, 5 pages.

International Conference Paper

Meerasri P., Uthansakul P. and Uthansakul M., (2013). **Self-Interference Suppression for Full-Duplex Single-Channel MIMO System**. 2013 IEEE 2nd Asia-Pacific Conference on Antennas and Propagation (APCAP), 5-7 August 2013, pp 1-2, 2 pages.

Meerasri P., Uthansakul P. and Uthansakul M., (2013). **Self-Interference Suppression Based Mutual Coupling for Full-Duplex Single-Channel MIMO Systems**. 2013 5th Thailand-Japan MicroWave (TJMW), 2-4 December 2013, pp 1-2, 2 pages.

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International Journal Paper

Meerasri P., Uthansakul P. and Uthansakul M., (2014). **Self-Interference Cancellation Based Mutual Coupling Model for Full-Duplex Single-Channel MIMO Systems**. International Journal of Antennas and Propagation, Volume 2014, Article ID 405487, 10 pages. (ISI Impact factor 0.827)

Meerasri P., Uthansakul P. and Widjaja D., (2017). **Self-Interference Cancellation Based Mutual Coupling Model for Full-Duplex Single-Channel MIMO Systems**. Suranaree Journal of Scienece and Technology, 10 pages.

การลดทอนสัญญาณแทรกสอดในตัวเองของระบบไมโมเมื่อใช้กับการสื่อสารสองทางเต็มอัตรา

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บทคัดย่อ

ในทางปฏิบัติการสื่อสารสองทางเต็มอัตราสามารถส่งและรับสัญญาณบนความถี่เดียวกันเกิดขึ้นในเวลาเดียวกัน ทำให้เกิดผลของสัญญาณแทรกสอดในตัวเองซึ่งเป็นสาเหตุให้สมรรถนะความจุของช่องสัญญาณลดลง การสื่อสารสองทางเต็มอัตรามีผลให้สัญญาณแทรกสอดสูงเพราะระบบมัลติเพิลอินพุท-มัลติเพิลเอาท์พุทใช้สายอากาศภาคส่งและสายอากาศภาครับหลายต้น ในบทความนี้เราเสนอเทคนิคใหม่สำหรับการลดสัญญาณแทรกสอดในตัวเองในการสื่อสารสองทางเต็มอัตราของระบบไมโมโดยชดเชยช่องสัญญาณ เพื่อจะทำการลดทอนสัญญาณแทรกสอดที่เกิดจากภายในสายอากาศต้นนั้น และสัญญาณแทรกสอดจากภาคส่งอื่นๆ ซึ่งวิธีการที่ได้เสนอมานี้สามารถลดสัญญาณแทรกสอดลงได้และทำให้สมรรถนะความจุของช่องสัญญาณดีขึ้น

Abstract

Practically, a full-duplex system can transmit and receive simultaneously at the same frequency bands. However, a critical issue involved in the full-duplex operation is the resulting of self-interference which caused the degradation of the channel capacity performance. The self-interference of full-duplex system using multiple-input multiple-output technique is considerably high because this technique uses multiple transmit and receive antennas at the same frequency bands. In this paper, we propose a novel technique for self-interference suppression in full-duplex multiple-input multiple-output systems by compensating the interference channel with the estimated value. By using the proposed scheme, the potentially self-interference from transmit signal and potentially interference from other transmitters can be reduced and then the channel capacity is improved.

คำสำคัญ

ระบบไมโม, สมรรถนะความจุช่องสัญญาณ, การสื่อสารสองทางเต็มอัตรา, สัญญาณแทรกสอดในตัวเอง

1. บทนำ

เทคโนโลยีไมโมเป็นระบบที่ได้รับความนิยมมากที่สุดในปัจจุบันนี้ เนื่องจากความสามารถในการเพิ่มความจุช่องสัญญาณ โดยระบบไมโมใช้สายอากาศภาคส่งและสายอากาศภาครับหลายต้น อย่างไรก็ตามเทคโนโลยีไมโมนั้นจะประกอบด้วยสายอากาศสำหรับส่งและรับหลายสายอากาศ ทำหน้าที่ส่งสัญญาณวิทยุความถี่สูงออกไปที่ความถี่เดียวกันในเวลาเดียวกัน ซึ่งทำให้เกิดสัญญาณแทรกสอดสูงระหว่างสายอากาศแต่ละต้น

นอกจากนี้การสื่อสารสองทางเต็มอัตราเป็นระบบที่มีความน่าสนใจเพราะมีการรับข้อมูลและส่งข้อมูลในเวลาเดียวกันบนความถี่เดียวกัน อย่างไรก็ตามการสื่อสารสองทางเต็มอัตราต้องการกำจัดสัญญาณแทรกสอดในตัวเองสาเหตุจากวิธีดำเนินการการสื่อสารสองทางแบบเต็มอัตรา ซึ่งในบทความอื่นได้เสนอ zero-forcing ของสัญญาณแทรกสอดในตัวเองและ minimum mean square error สำหรับกำจัดสัญญาณแทรกสอดในตัวเองที่โหนดการส่งผ่าน (Relaying) เป็นผลให้การตัดสัญญาณแทรกสอดและการกำจัดสัญญาณแทรกสอดในตัวเองสำหรับส่งผ่านการสื่อสารสองทางเต็มอัตรา [1-4]

ในบทความนี้เราเลือกเทคนิคสำหรับการลดทอนสัญญาณแทรกสอดในตัวเองของระบบไมโมเมื่อใช้กับการสื่อสารสองทางเต็มอัตราที่เกิดจากสองสาเหตุ โดยเราใช้การชดเชยช่องสัญญาณเพื่อลดทอนสัญญาณแทรกสอดในตัวเองและลดสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่น ดังนั้นเราจึงพิจารณาโดยการเปรียบเทียบระบบตอนที่ยังไม่มีการลดทอนสัญญาณแทรกสอดในตัวเองและตอนที่ระบบมีการลดทอน

สัญญาณแทรกสอดในตัวเองแล้ว ซึ่งผลที่ได้แสดงในอัลกอลิทึมที่นำเสนอนั้นไม่เพียงแต่ลดทอนสัญญาณแทรกสอดแต่ยังปรับปรุงสมรรถนะความจุของช่องสัญญาณให้ดีขึ้น

2. ที่มาและแรงจูงใจของปัญหา

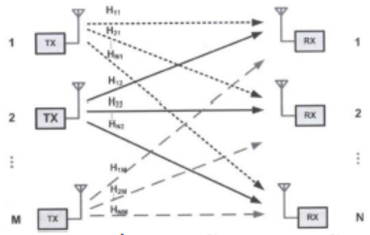
เนื่องจากการสื่อสารสองทางเต็มอัตราเป็นระบบที่มีความน่าสนใจเพราะมีการส่งข้อมูลและการรับข้อมูลในเวลาเดียวกันบนความถี่เดียวกัน แต่สำหรับเทคโนโลยีไมโมแล้วถ้านำมาใช้งานนั้นเนื่องจากมีจำนวนสายอากาศภาคส่งและสายอากาศภาครับหลายต้น ซึ่งทำให้เกิดสัญญาณแทรกสอดสูง ในบทความนี้เราจึงได้นำเสนอวิธีในการลดทอนสัญญาณแทรกสอดที่เกิดจากสองสาเหตุโดยการชดเชยช่องสัญญาณ เพื่อลดสัญญาณแทรกสอดในตัวเองและสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่น ดังนั้นเราจึงเปรียบเทียบระบบตอนที่ยังไม่มีการลดทอนสัญญาณแทรกสอดและตอนที่มีการลดทอนสัญญาณแทรกสอดเพื่อเปรียบเทียบดูสมรรถนะความจุของช่องสัญญาณ

3. งานและทฤษฎีที่เกี่ยวข้อง

3.1 แบบจำลองระบบไมโม

พิจารณาช่องสัญญาณระบบไมโมที่เป็นการใช้สายอากาศหลายต้นสำหรับส่งข้อมูลและใช้สายอากาศหลายต้นสำหรับการรับข้อมูลทำให้เกิดทิศทางของสัญญาณที่เดินทางในหลายทิศทาง เพราะสัญญาณจากสายอากาศต้นแรกของภาคส่งจะเดินทางไปยังสายอากาศของภาครับทุกต้น และสายอากาศที่สองของภาคส่งก็จะเดินทางไปยังสายอากาศของภาครับทุกต้นส่งออกอากาศที่ความถี่เดียวกัน ซึ่งเราพิจารณาถึงระบบที่มีการใช้สายอากาศแถวลำดับที่มีสายอากาศที่ภาคส่ง M_T ต้นและสายอากาศที่ภาครับ N_R ต้นดังแสดงในรูปที่ 1 แสดงความสัมพันธ์แบบเชิงเส้นของสัญญาณที่ได้รับที่สายอากาศภาครับและสัญญาณที่ส่งออกที่สายอากาศภาคส่งสามารถเขียนให้อยู่ในรูปเวคเตอร์ได้ดังนี้

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n}, \qquad (1)$$



รูปที่ 1 ระบบไมโมที่ประกอบด้วยสายอากาศด้านส่ง M_T ต้น และสายอากาศด้านรับ N_R ต้น

โดยที่ y คือเวคเตอร์สัญญาณที่ภาครับขนาด $N_R \times 1$, X คือเวคเตอร์สัญญาณที่ภาคส่งขนาด $M_T \times 1$, **H** คือเวคเตอร์นอร์มอลไลซ์ของช่องสัญญาณที่มีขนาด $N_R \times M_T$, **n** คือ เวคเตอร์สัญญาณรบกวนที่มีขนาด $N_R \times 1$

3.2 ความจุของช่องสัญญาณในระบบไมโม

ความจุของช่องสัญญาณ ซึ่งจะให้อัตราการส่งข้อมูลสูงสุดภายใต้ช่องสัญญาณที่มีความน่าจะเป็นในการเกิดความผิดพลาดน้อย ความจุช่องสัญญาณเทียบกับปริมาณที่สูญเสียอธิบายโดยอัตราเร็วการส่งข้อมูลในหน่วย bps/Hz เขียนในรูปแบบสมการได้ดังนี้

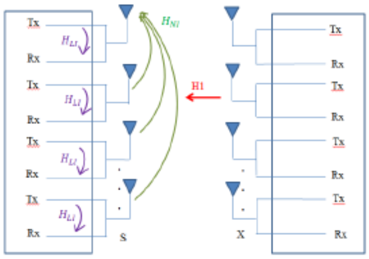
$$C = \log_2 \det\left(\mathbf{I}_{N_R} + \frac{\mathrm{P_T}}{\mathrm{N_T}}\mathbf{HH}^{\mathrm{H}}\right) \qquad (2)$$

โดยที่ $\mathbf{I}_{N_R}$ คือเมตริกซ์เอกลักษณ์ขนาด $N_R \times N_R$, P_T คือกำลังส่งทั้งหมด

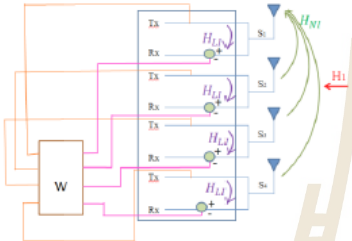
4. รายละเอียดการพัฒนา

4.1 ภาพรวมของระบบ

ในส่วนนี้เราได้อธิบายการออกแบบสัญญาณและการออกแบบระบบในรูปที่ 2 ซึ่งประกอบด้วยสายอากาศภาคส่งและสายอากาศภาครับ เราดำเนินการโดยการออกแบบระบบบนแถบความถี่แคบที่สายอากาศภาคส่งและสายอากาศภาครับโดยมีสายอากาศ s และ x ต้นตามลำดับ ให้ H_1 แทนช่องสัญญาณภาคส่ง-ภาครับขนาด X x S เราสมมุติให้เมตริกซ์ของสัญญาณแทรกสอดในตัวเองและสัญญาณแทรกสอดที่เกิดจากสายอากาศ อากาศต้นอื่นขนาด S x S แทนด้วย H_{LI} และ H_{NI} ตามลำดับ



รูปที่ 2 การออกแบบระบบสำหรับสัญญาณแทรกสอดในตัวเองของระบบไมโม



รูปที่ 3 การออกแบบระบบสำหรับลดทอนสัญญาณแทรกสอดในตัวเองของระบบไมโม

4.2 การออกแบบและพัฒนาระบบ

จากนั้นเราได้ดำเนินการออกแบบระบบเพื่อลดทอนสัญญาณแทรกสอดในตัวเองและสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่นดังรูปที่ 3 โดยเขียนในรูปสมการที่สัญญาณแทรกสอดได้ดังนี้

$$\mathbf{H_I S = H_{LI} S + H_{NI} S}, \qquad (3)$$

ซึ่ง S คือสัญญาณภาคส่งขนาด Sx1 และ H_{LI} คือเมตริกซ์ทะแยงซึ่งแทนช่องสัญญาณแทรกสอดในตัวเอง H_{NI} คือเมตริกซ์สมมาตรซึ่งแทนช่องสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่นจากนั้นเราได้มีการกำจัดสัญญาณแทรกสอดในตัวเองและสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่นได้รูปสมการดังนี้

$$\mathbf{WS = T_x S + GS}, \qquad (4)$$

ซึ่ง T_x คือ เมตริกซ์สมมาตรซึ่งแทนการลดสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่นขนาด SxS และการลดสัญญาณแทรกสอดในตัวเองแทนด้วย G คือเมตริกซ์ทะแยงขนาด SxS หลังจากแทนสมการ (3),(4) สามารถเขียนสมการของสัญญาณภาครับได้ดังนี้

$$\mathbf{Y = H_1 X + H_I S - WS + N}, \qquad (5)$$

4.3 ข้อจำกัดของระบบ

4.3.1วิธีการกำจัดสัญญาณแทรกสอด

4.3.1.1สิ่งที่ได้จากการสมมุติให้เครื่องส่งข้อมูลสามารถรู้ข้อมูลข่าวสารของช่องสัญญาณได้อย่างสมบูรณ์ (Channel State Information, CSI)

บทความนี้ที่ได้เสนอมานั้นขึ้นอยู่กับการสมมุติให้การกำจัดสัญญาณแทรกสอดนั้นเป็นไปได้แบบสมบูรณ์แบบโดยรู้ช่องสัญญาณ H_1, H_{LI}และ H_{NI}ซึ่งในขั้นต้นเรามีการประมาณค่าช่องสัญญาณแทรกสอด H_{LI}และ H_{NI} ในแต่ละช่องสัญญาณจากภาคส่งถึงภาครับโดยการประมาณค่า [5-6] ซึ่งนำมาใช้ในการออกแบบสายกาศภาคส่งและภาครับ

4.3.2ผลกระทบของการประมาณช่องสัญญาณผิดพลาด

จากที่ได้กล่าวมานั้นบทความที่ได้นำเสนอต้องรู้ช่องสัญญาณ H_1, H_{LI}และ H_{NI}การประมาณค่าผิดพลาดของ H_{LI}และ H_{NI}ที่สูงนั้นสามารถทำให้เกิดปัญหาความเสถียรภาพ ดังนั้นเราสามารถประมาณช่องสัญญาณผิดพลาดให้มีความเสถียรภาพได้ดังนี้

$$\sigma_{max}(\widehat{\mathbf{H_I}} + \Delta\mathbf{H_I}) < 1, \qquad (6)$$

เราสมมุติให้ $\widehat{H_I}$ แทนการประมาณช่องสัญญาณ H_Iและ $\Delta \mathbf{H_I}$ แทนการประมาณช่องสัญญาณผิดพลาด

เราพิจารณาระบบไมโมโดยที่สมการความจุของช่องสัญญาณสามารถแสดงได้ดังสมการที่ (7) [2, 7] จากสมการนี้เป็นการแสดงค่าเฉลี่ยของความจุของช่องสัญญาณในหน่วย bps/Hz โดยสมมุติกำลังสัญญาณที่ภาคส่ง

$(E\{\boldsymbol{x}\boldsymbol{x}^H\} = \frac{\mathrm{P_0}}{\mathrm{N_S}}\mathbf{I}_{N_S})$ นำข้อมูลจากการออกแบบสัญญาณมาเขียนเป็นสมการได้ดังนี้

$$\mathrm{I(y;x)} = log_2\det[\mathbf{I_{M_D}} + \frac{P_0}{N_S}\mathbf{H_1H_1^{\mathit{H}}} \times (\sigma_r^2\mathbf{H_1'H_1'^{\mathit{H}}} + \sigma^2\mathbf{I_{M_D}})], \quad (7)$$

เราสมมุติให้ P_0 คือกำลังส่งทั้งหมด, N_Sคือกำลังของสัญญาณแทรกสอด

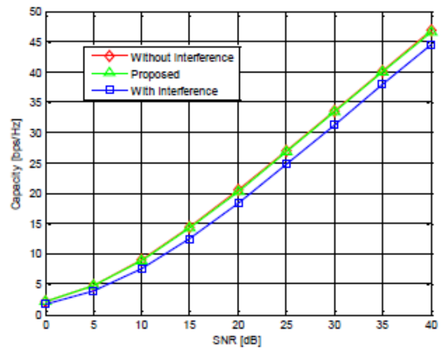
5. การทดสอบการใช้งาน

5.1 ผลการทดสอบและการวิจารณ์ผล

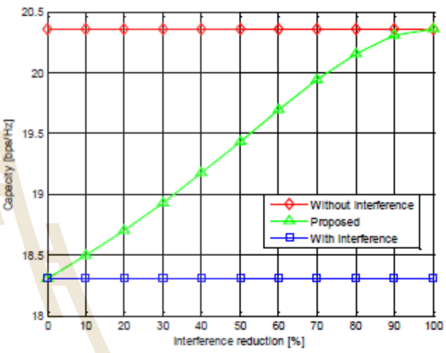
บทความนี้เราได้เสนอผลการออกแบบการกำจัดสัญญาณแทรกสอดในตัวเองและสัญญาณแทรกสอดที่เกิดจากสายอากาศต้นอื่นเปรียบเทียบกับตอนที่มีการลดสัญญาณแทรกสอดและตอนที่มีสัญญาณแทรกสอดแต่ยังไม่ได้มีการกำจัดสัญญาณแทรกสอด

ผลจำลองนี้เราสามารถอธิบายได้ว่าสายอากาศภาครับมี 4 ต้น และสายอากาศภาคส่งมี 4ต้น เราให้ S = X = 4 จากนั้นเราสมมุติเหตุการณ์ว่าช่องสัญญาณเป็น Rayleigh channel ด้วยเหตุนี้ช่องสัญญาณ $\mathrm{H_I}$ จึงมีการกระจายตัวแบบอิสระที่เหมือนกัน (identically independent distributed; i.i.d.) ด้วยกระบวนการแบบ complex normal distribution ที่มีค่าเฉลี่ยเป็นศูนย์ และค่าความแปรปรวนเป็นหนึ่ง สำหรับสัญญาณแทรกสอด $\mathrm{H_{LI}}$และ $\mathrm{H_{NI}}$ เราพิจารณาช่องสัญญาณเป็น Rayleigh channel มีการกระจายตัวแบบอิสระที่เหมือนกัน (identically independent distributed; i.i.d.) ด้วยกระบวนการแบบ Complex Gaussian ที่มีค่าเฉลี่ยเป็นศูนย์ และค่าความแปรปรวนเป็นหนึ่ง จากนั้นเราสมมุติให้สัญญาณรบกวนมีส่วนเบี่ยงเบนมาตรฐาน σ^2ในการออกแบบโดยใช้โปรแกรม MATLAB

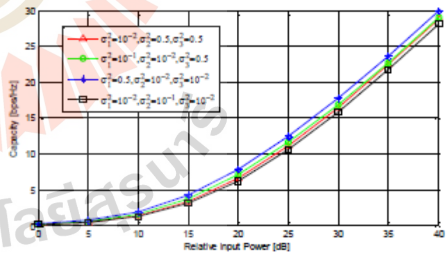
จากรูปที่ 4 เป็นการแสดงผลของความจุช่องสัญญาณสำหรับการลดสัญญาณแทรกสอดที่ *80%* จะเห็นว่าที่ความจุช่องสัญญาณ 15 bps/Hz ค่า *SNR* ของระบบที่มีการชดเชยช่องสัญญาณเพื่อลดสัญญาณแทรกสอด (ระบบที่ได้เสนอ)



รูปที่ 4 แสดงการเปรียบเทียบความจุช่องสัญญาณสำหรับการลดสัญญาณแทรกสอดที่ *80%*



รูปที่ 5 แสดงการเปรียบเทียบความจุช่องสัญญาณ ณ จุดทดสอบที่ค่า SNR = 20dB



รูปที่ 6 แสดงผลกระทบของการประมาณช่องสัญญาณผิดพลาดในอัลกอลิทึมที่ได้เสนอ

มีประสิทธิภาพที่ดีกว่าระบบที่มีสัญญาณแทรกสอดแต่ยังไม่ได้ทำการลดสัญญาณแทรกสอดประมาณ 3 dB

จากรูปที่ *5* เป็นการแสดงผลของความจุช่องสัญญาณ ณ จุดทดสอบที่มีเปอร์เซ็นต์การลดสัญญาณแทรกสอดต่างๆ ที่ค่า

SNR = *20dB* จะเห็นว่าสมรรถนะของความจุช่องสัญญาณทั้งระบบที่ไม่มีสัญญาณแทรกสอดและระบบที่มีสัญญาณแทรกสอดแต่ยังไม่ได้ลดสัญญาณแทรกสอดนั้นมีประสิทธิภาพความจุช่องสัญญาณคงที่ ส่วนสมรรถนะความจุช่องสัญญาณเมื่อระบบมีการชดเชยช่องสัญญาณเพื่อลดสัญญาณแทรกสอดนั้นประสิทธิภาพของระบบดีขึ้น

จากรูปที่ 6 เป็นการแสดงผลของความจุช่องสัญญาณเมื่อเกิดผลกระทบจากการประมาณช่องสัญญาณผิดพลาดเราจะพิจารณาประสิทธิภาพของวิธีการลดสัญญาณแทรกสอดที่ได้เสนอนั้นมีการประมาณช่องสัญญาณสำหรับ H_1, H_{LI} และ H_{NI} ผิดพลาดคือมีการออกแบบให้ ΔH_1 ด้วยกระบวนการแบบ complex normal distribution ที่มีค่าเฉลี่ยเป็นศูนย์ และส่วนเบี่ยงเบน σ_1^2, ΔH_{LI} ด้วยกระบวนการแบบ complex normal distribution ที่มีค่าเฉลี่ยเป็นศูนย์ และส่วนเบี่ยงเบน σ_2^2, และ ΔH_{NI} ด้วยกระบวนการแบบ complex normal distribution ที่มีค่าเฉลี่ยเป็นศูนย์ และส่วนเบี่ยงเบน σ_3^2 ตามลำดับ ซึ่งการประมาณช่องสัญญาณผิดพลาดของ H_{LI} และ H_{NI} ที่ส่วนเบี่ยงเบนมาตรฐานมากกว่า 1% ประสิทธิภาพของระบบดีกว่าการประมาณช่องสัญญาณผิดพลาดของ H_1 ซึ่งไม่มีผลต่อประสิทธิภาพของระบบ

6. บทสรุป

บทความนี้ได้เสนอวิธีการลดสัญญาณแทรกสอดในตัวเองของระบบไมโมเมื่อใช้กับการสื่อสารสองทางเต็มอัตรา ซึ่งอัลกอลิทึมที่เราได้เสนอนั้นสามารถนำมาประยุกต์ใช้ในการออกแบบระบบให้ดีขึ้น และผลการจำลองระบบที่ได้เสนอนั้นให้ผลประสิทธิภาพความจุของช่องสัญญาณดีกว่าระบบที่ยังไม่มีการลดสัญญาณแทรกสอด

6.1 แนวทางพัฒนาต่อ

ในการลดทอนสัญญาณแทรกสอดในตัวเองของระบบไมโมเมื่อใช้กับการสื่อสารสองทางเต็มอัตราเพื่อนำไปสู่ประสิทธิภาพการกำจัดสัญญาณแทรกสอดที่ดีขึ้น เราจะนำไปทดสอบกับอุปกรณ์จริง

7. กิตติกรรมประกาศ

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Self-Interference Suppression for Full-Duplex Single-Channel MIMO System

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***Abstract*— The challenge of a full-duplex single-channel system is that it can transmit and receive simultaneously at the same time and on the same frequency band. However, a critical issue involved in such an operation is the resulting self-interference. Moreover, for MIMO system, the full-duplex single-channel system is subject to the very strong self-interference signals due to multiple transmitting and receiving antennas. In this paper, a novel technique for self-interference suppression in full-duplex single-channel MIMO system is proposed. The interference can be minimized by using a pre-known interference that is the transmitting signal. The results indicate that the channel capacity and BER performance of using the proposed technique can significantly suppress the self-interference.**

***Keywords*— MIMO, channel capacity, full-duplex, self-interference**

I. Introduction

Nowadays, Multiple-Input Multiple-Output (MIMO) systems are the promising technique for the next-generation of wireless communication systems as MIMO systems can provide a wide coverage area, a high spectral efficiency, and an increased system capacity. The MIMO systems use multiple transmitting and receiving antennas on the same frequency which causes a strong interference signal.

Furthermore, the full-duplex single-channel MIMO system is an interesting technology for future wireless communications because it can offer double throughput than any conventional system. This is because the system is able to receive and transmit simultaneously within a single channel. In literature, this problem has been addressed on the specific configuration of MIMO relay nodes. At relaying node, the self-interference cancellation and suppression is presented in [1]-[3]. However, there is no technique proposed for source or destination. In this light, the authors propose the new technique to suppress the self-interference for full-duplex single-channel MIMO systems.

In this paper, the suppression technique to reduce the self-interference is performed by subtracting the interference signals with the transmitting signals that is suitably tuned according to the interactive between multiple antennas. This is because the self-interference signals do not depend on the environments. Then, the proposed technique can be considered as the pre-tuned process from the manufacturers.

The paper presents the comparison between the full-duplex single channel system with and without the proposed technique. The channel capacity and BER performance are the key performances used to indicate the merit of proposed technique. The results show that the proposed technique is not only to suppress the interference but also to improve the system performances, both capacity and BER.

II. System Model and Problem Formulation

In this section, the implemented system is designed to formulate the self-interference model. These self-interference signals are caused by multiple antennas. The model of full-duplex single-channel MIMO system is illustrated in Fig. 1. As shown in Fig. 1, the self-interference $\boldsymbol{H_I}$ can be written as

$$\boldsymbol{H_I s} = \boldsymbol{H_{LI} s} + \boldsymbol{H_{NI} s}, \quad (1)$$

where $\boldsymbol{s} \in C^{s\times 1}$ is the transmitted signal, $\boldsymbol{H_{LI}} \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals, and $\boldsymbol{H_{NI}} \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas.

Next, the proposed method to suppress the interference signals is performed by compensating the channels from self-interference signals and mutual-interference signals caused the other antennas. The compensation matrix, $\boldsymbol{W}$, is given by

$$\boldsymbol{Ws} = \boldsymbol{T_x s} + \boldsymbol{Gs}, \quad (2)$$

where $\boldsymbol{T_x} \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas, $\boldsymbol{G} \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals.

Then, the received signal at the destination with the proposed compensation matrix for the interference suppression can be rewritten as

$$\boldsymbol{y} = \boldsymbol{H_1 x} + \boldsymbol{H_I s} - \boldsymbol{Ws} + \boldsymbol{N}, \quad (3)$$

where $\boldsymbol{N} \sim CN(0, \sigma_d^2 \boldsymbol{I_s})$ is the AWGN contribution at the destination.

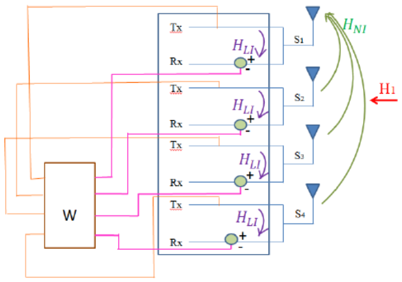

Fig. 1 Model of full-duplex single-channel 4x4 MIMO system

III. Results and Discussion

A. Channel Capacity

The channel capacity for our 4x4 MIMO system can be given by (4) [2],[4]. This capacity denotes the average of channel capacity in bps/Hz. Also, we assume an uniform transmitting power for each antenna $\left(E\{\boldsymbol{x}\boldsymbol{x}^H\} = \frac{P_0}{N_s}\boldsymbol{I}_x\right)$.

$$C = log_2 \det\left[\boldsymbol{I}_s + \frac{P_0}{N_s}\boldsymbol{H}_1\boldsymbol{H}_1^H \times (\sigma_l^2\boldsymbol{H}_l'\boldsymbol{H}_l'^H + \sigma_d^2\boldsymbol{I}_s)^{-1}\right]. \quad (4)$$

Fig. 2 shows the channel capacity versus SNR for 80% interference reduction. It can be noticed that the proposed technique lies between with and without the interference suppression. Fig. 3 shows the relation between capacity and the percentage of interference reduction. It is observed that the reduction is required only 80% to offer the capacity close to the system without any interference.

B. BER performance

In this paper, the zero forcing technique is adopted to decode the data. Fig. 4 shows BER performance for QPSK modulation and ZF receiver. It is clear that for Eb/No less than 15 dB the proposed technique can provide the similar BER to the system without interference. However, for Eb/No more than 15 dB it significantly improves the BER performance.

Acknowledgment

Financial support from the Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program (Grant No. PHD/0076/2554).

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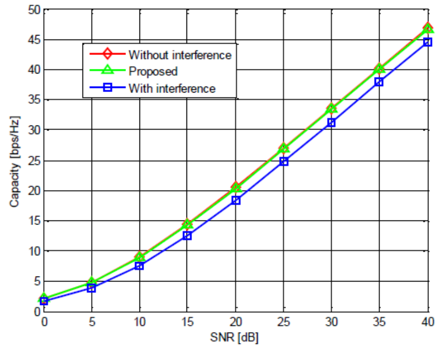

Fig. 2 Channel capacity versus SNR for 80% interference reduction.

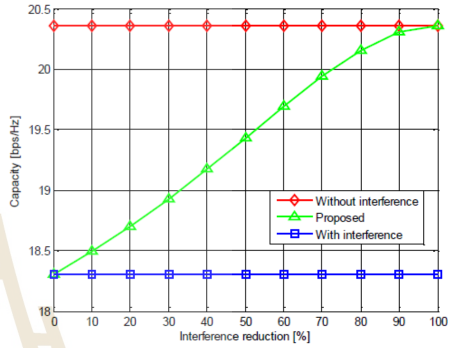

Fig.3 Relation between channel capacity and interference reduction for SNR = 20dB.

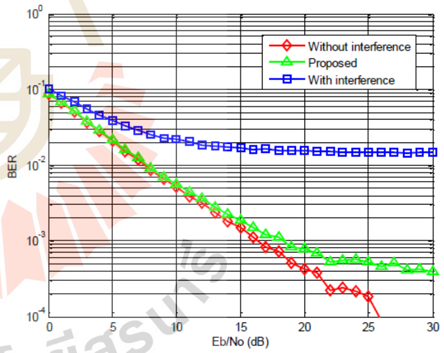

Fig.4 BER performance for QPSK modulation, ZF receiver and 80% interference reduction.

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Self-Interference Suppression Based Mutual Coupling Model for Full-Duplex Single-Channel MIMO Systems

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***Abstract*— The challenge of a full-duplex single-channel system is that it can transmit and receive simultaneously at the same time and on the same frequency band. However, a critical issue involved in such an operation is the resulting self-interference. Moreover, for MIMO system, the full-duplex single-channel system is subject to the very strong self-interference signals due to multiple transmitting and receiving antennas. From literatures on RF interference cancellation, there has not been any suitable technique to deal with a single antenna. In this paper investigates the effect of antenna mutual coupling involving the unconventional concepts of transmitting and receiving mutual impedances on the MIMO channel capacity. The novel technique for self-interference suppression in full-duplex single-channel MIMO system is proposed. The interference can be minimized by using a pre-known interference that is the transmitting signal. The results indicate that mutual coupling reduces the correlation between the antennas and the channel capacity performance of using the proposed technique can significantly suppress the self-interference.**

***Keywords*— MIMO, channel capacity, full-duplex, self-interference, mutual coupling**

I. Introduction

Furthermore, the MIMO systems use multiple transmitting and receiving antennas on the same frequency which causes a strong interference signal. The full-duplex single-channel MIMO system is an interesting technology for future wireless communications because it can offer double throughput than any conventional system. This is because the system is able to receive and transmit simultaneously within a single channel. In literature, this problem has been addressed on the specific configuration of MIMO relay nodes. At relaying node, the self-interference cancellation and suppression is presented in [1]-[3]. However, there is no technique proposed for source or destination. In this light, the authors propose the new technique to suppress the self-interference for full-duplex single-channel MIMO systems.

In this paper, we will investigate the effect of antenna mutual coupling (MC) on the full-duplex single channel MIMO system transmission accompanied by power allocation strategy in a MIMO system, especially when antenna separation is small in the transmitting and receiving arrays. We use the new concept of transmitting and receiving mutual impedances [4] to incorporate the antenna MC effect into the correlated channel model. This model is applied to work out the suppression technique to reduce the self-interference is performed by subtracting the interference signals with the transmitting signals that is suitably tuned according to the interactive between multiple antennas. This is because the self-interference signals do not depend on the environments. Then, the proposed technique can be considered as the pre-tuned process from the manufacturers. The paper presents the comparison between the MC full-duplex single channel system with and without the proposed technique. The channel capacity performance is the key performances used to indicate the merit of proposed technique. The results show that the proposed technique is not only to suppress the interference but also to improve the system performance capacity.

II. System Model

A. Mutual Coupling Effects on MIMO

In general, mutual coupling can be characterized by numerical modelling techniques [5]. However for dipoles, we can use analytical mutual coupling into the MIMO system model. The coupling matrix of transmitting antenna array $\boldsymbol{C_T}$ can be written using fundamental electromagnetic and circuit theory. $\boldsymbol{C_T}$ has the meaning of transfer function matrix for the transmitting array and is given as

$$\boldsymbol{C_T} = (Z_A + Z_T)(\boldsymbol{Z} + Z_T\boldsymbol{I}_{N_T})^{-1} \qquad (1)$$

Where Z_A is the element's impedance in isolation. The element Z_{mn} of matrix $\boldsymbol{Z}$ is defined by using the EMF method. Also the coupling matrix of receiving antenna array $\boldsymbol{C_R}$ can be determined in a similar manner. $\boldsymbol{C_R}$ has the meaning of transfer function matrix for the receiving array and is given as

$$\boldsymbol{C_R} = (Z_A + Z_T)(\boldsymbol{Z} + Z_T\boldsymbol{I}_{N_R})^{-1} \qquad (2)$$

III. Proposed Self-Interference Cancellation

In this section, the implemented system is designed to formulate the self-interference and the MIMO with mutual coupling effect model. These self-interference signals are caused by multiple antennas. The model of full-duplex single-channel MIMO system is illustrated in Fig. 1. As shown in Fig. 1, the proposed method to suppress the interference signals is performed by compensating the channels from self-interference signals and mutual-interference signals caused the other antennas. The compensation matrix, $\boldsymbol{W}$, is given by

$$\boldsymbol{Ws} = \boldsymbol{T}_x \boldsymbol{C}_T \boldsymbol{s} + \boldsymbol{Gs}, \quad (3)$$

where $\boldsymbol{T}_x \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas, $\boldsymbol{G} \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals.

Then, the received signal at the destination with the proposed compensation matrix for the interference suppression can be rewritten as

$$\boldsymbol{y} = \boldsymbol{H}_{mc}\boldsymbol{x} + \boldsymbol{H}_{mc_I}\boldsymbol{s} - \boldsymbol{Ws} + \boldsymbol{N}, \quad (4)$$

where $\boldsymbol{N} \sim CN(0, \sigma_d^2 \boldsymbol{I}_s)$ is the AWGN contribution at the destination.

IV. Results And Discussion

A. Channel Capacity

In order to investigate the effect of mutual coupling on MIMO capacity, in this section the channel capacity for our 4x4 MIMO system can be given by (5) [2]. This capacity denotes the average of channel capacity in bps/Hz. Also, we assume an uniform transmitting power for each antenna $\left(E\{\boldsymbol{xx}^H\} = \frac{P_0}{N_s}\boldsymbol{I}_x\right)$.

$$C = \log_2 \det\Big[\boldsymbol{I}_s + \frac{P_0}{N_s}\boldsymbol{H}_{mc}\boldsymbol{H}_{mc}^H \times \left(\sigma_I^2 \boldsymbol{H}'_{mc_I}\boldsymbol{H}'^H_{mc_I} + \sigma_d^2 \boldsymbol{I}_s\right)^{-1}\Big], \quad (5)$$

We assume P_0 is the maximum available power at the source, N_s is the power of the self-interference signals.

Fig. 2 shows the channel capacity versus SNR for 80% interference reduction when the MIMO system is affected mutual coupling. It can be noticed that the proposed technique lies between with and without the interference suppression. The channel capacity of the proposed system is about 0.70 bps/Hz (at SNR=20dB) higher than the system with self-interference and the system with mutual coupling. In Fig. 3, the relation between capacity and the percentage of interference reduction is presented. It can be noticed that the channel capacity of the proposed system requires only 90% interference reduction to achieve the capacity close to the system without any interference.

Acknowledgment

Financial support from the Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program (Grant No. PHD/0076/2554).

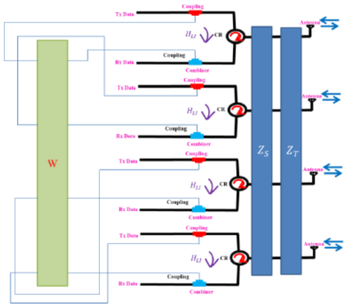

Fig.1 Proposed self-interference cancellation for full-duplex single-channel 4x4 MIMO system based on mutual coupling model

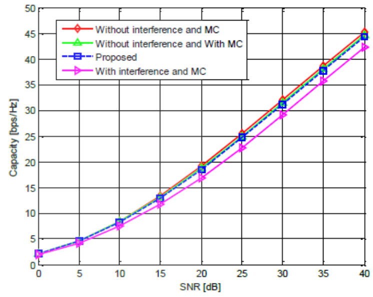

Fig. 2 Channel capacity versus SNR for 80% interference reduction

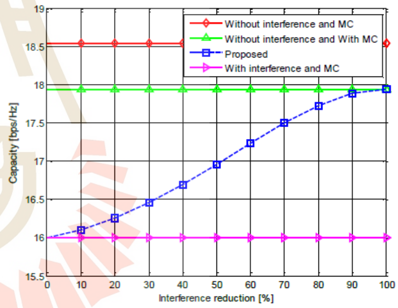

Fig.3 Relation between channel capacity and interference reduction for SNR=20dB

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Performance of Self and Mutual Interference Cancellation for FDSC MIMO Systems

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Abstract— **The benefit of a Full-Duplex Single-Channel (FDSC) system is the double throughput because it can transmit and receive simultaneously at the same time and on the same frequency. However, the expense of FDSC system is on the very strong self-interference signals due to the leakage of transmitting signals that interfere the receiving signals. Moreover, for MIMO systems, the problem of interferences is severely considered due to multiple transmitting and receiving antennas. So far in literatures, there have not been any suitable techniques presented to reduce the self and mutual interferences for FDSC MIMO systems. This paper present the performance of self and mutual interference cancellation by utilizing the mutual coupling model. The interferences can be eliminated by using pre-known interferences that are the mutual coupling signals. The results indicate that the channel capacity performance of the proposed technique can significantly be improved due to the reduction of the interference power. The measurement results indicate that the proposed FDSC MIMO system can suppress the self and mutual interferences signals with the reduction of 29.84 dBm received power.**

Keywords— **MIMO, channel capacity, full-duplex, self-interference, mutual coupling**

I. Introduction

Multiple-Input Multiple-Output (MIMO) system is the promising technology for the next-generation of wireless communication systems as MIMO system can provide a wide coverage area, a high spectral efficiency, and an increased system capacity. The MIMO system employs the multiple antennas to transmit signals on the same frequency which they cause the strong interference signals at the receiving antennas on the same side. These interferences are more pronounced when operating the FDSC MIMO system.

The FDSC system is one of the most interesting technology for future wireless communications because it can offer double throughput from any conventional system without paying any expenses of spectrum. This is because the system is able to receive and transmit simultaneously within a single channel. In literature, the problem of full-duplex interference has been addressed on the specific configuration of MIMO relay nodes. The self-interference cancellation (SIC) is introduced to use at only relaying node [1-3].

In this paper, we will investigate the effect of antenna mutual coupling (MC) on the FDSC MIMO system with the aims of self-interference eliminations. Based on the mutual coupling model, the signals with self-interference can be pre-known. As a result, it is possible to eliminate all self-interference signals by subtracting with pre-known signals. The concept of transmitting and receiving mutual impedances is employed to incorporate the antenna MC effect into the correlated channel model [4]. This model is applied to work out the cancellation technique to reduce the self-interference performed by subtracting the interference signals with the transmitting signals that is suitably tuned according to the interaction between multiple antennas. This is because the self-interference signals do not depend on the environments. Then, the proposed technique can be done on the manufacturing process and the MIMO system employs transmit and receive filters that suppress the strongest modes of the self-interference channel. Hence, the proposed design of the receive and transmit filters aims at maximizing the signal to interference ratio (SIR) at the transmit and receive side. The paper presents the comparison between the mutual coupling FDSC MIMO system with and without the proposed technique. The channel capacity performance is the key performances used to indicate the merit of proposed technique. The results show that the proposed technique is not only to suppress the interference but also to improve the system performance capacity.

II. System Model

A. MIMO Model

This section details the capacity formula of MIMO systems is briefly given. We assume an independent and identically distributed (i.i.d.) Rayleigh flat-fading channel in rich scattering environments, and the channel is unknown at the transmitter and perfectly known at the receiver. Let the number of transmit and receiving antennas be N_T and M_R, respectively. We denote this MIMO communication link as (N_T, M_R). The $M_R \times 1$ receive signal vector **y** can be written as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}, \tag{1}$$

where $\boldsymbol{H}$ is $M_R \times N_T$ channel matrix with the entry $h_{i,j}$ describing the channel gain between the j^{th} transmitting antenna and the i^{th} receiving antenna, $\boldsymbol{x}$ is the transmitted signal to the left with independent symbols. There is an arbitrary number of physical paths between the transmitter and the receiver [5]; the i^{th} path has an attenuation of a_i, makes an angle of $\emptyset_{ti}(\Omega_{ti} \coloneqq cos\emptyset_{ti})$ with the transmit antenna array and an angle of $\emptyset_{ri}(\Omega_{ri} \coloneqq cos\emptyset_{ri})$ with the receive antenna array. The channel matrix $\boldsymbol{H}$ can be written as:

$$\boldsymbol{H} = \sum_i a_i^b \, \boldsymbol{e_r}(\Omega_{ri})\boldsymbol{e_t}(\Omega_{ti})^* \quad (2)$$

Where

$$a_i^b \coloneqq a_i\sqrt{N_T M_R} exp\left(-\frac{j2\pi d^{(i)}}{\lambda_c}\right) \quad (3)$$

$$\boldsymbol{e_r}(\Omega) \coloneqq \frac{1}{\sqrt{M_R}}\begin{bmatrix} 1 \\ \exp(-j2\pi\Delta_r\Omega) \\ \vdots \\ \exp(-j2\pi(M_R-1)\Delta_r\Omega) \end{bmatrix} \quad (4)$$

$$\boldsymbol{e_t}(\Omega) \coloneqq \frac{1}{\sqrt{N_T}}\begin{bmatrix} 1 \\ \exp(-j2\pi\Delta_t\Omega) \\ \vdots \\ \exp(-j2\pi(N_T-1)\Delta_t\Omega) \end{bmatrix} \quad (5)$$

Also, $d^{(i)}$ is distance between transmit and receive antennas along path i. The vector $\boldsymbol{e_r}(\Omega)$ and $\boldsymbol{e_t}(\Omega)$ are, respectively, the transmitted and received unit spatial signatures along the direction Ω.

B. Mutual Coupling Effects on MIMO

In this section, in order to support parallel signal transmission in a MIMO system, the antennas at transmitter and receiver have to be properly coupled to the modes offered by the wireless communication channel. Hence, the array elements location (including spacing and orientation) with respect to the scatterers is of paramount importance in the operation of the MIMO system. The interactions between the entire set of antennas and scatterers are initially described by the impedance matrix $\boldsymbol{Z}$ [6]. For dipoles, however, the mutual impedance can easily be calculated using classical Induced Electromagnetic Force (EMF) method [7].

In general, mutual coupling can be characterized by numerical modelling techniques [7]. However for dipoles, we can use analytical MC into the MIMO system model. The coupling matrix of transmitting antenna array $\boldsymbol{C_T}$ can be written using fundamental electromagnetic and circuit theory [7]. $\boldsymbol{C_T}$ has the meaning of transfer function matrix for the transmitting array and is given as

$$\boldsymbol{C_T} = (Z_A + Z_T)(\boldsymbol{Z} + Z_T\boldsymbol{I}_{N_T})^{-1} \quad (6)$$

where Z_A is the element's impedance in isolation. The element Z_{mn} of matrix $\boldsymbol{Z}$ is defined by using the EMF method [6]. Also the coupling matrix of receiving antenna array $\boldsymbol{C_R}$ can be determined in a similar manner. $\boldsymbol{C_R}$ has the meaning of transfer function matrix for the receiving array and is given as

$$\boldsymbol{C_R} = (Z_A + Z_T)(\boldsymbol{Z} + Z_T\boldsymbol{I}_{M_R})^{-1} \quad (7)$$

III. Proposed self-interference cancellation

In this section, we would like to form a criterion function for jointly calculating the optimal receive and transmit cancellation filters, $\boldsymbol{G_r}$ and $\boldsymbol{G_t}$ respectively. For instance, we could either choose to maximize the signal to interference ratio (SIR) at the input or maximize the SIR at the output. First we begin by designing the receive cancellation matrix, $\boldsymbol{G_r}$ and neglecting for the transmit cancellation matrix $\boldsymbol{G_t}$. Our goal is to reduce the power of the self-interference signal and at the same time improve the useful signal power received.

Hence, we aim at maximizing the SIR at the input

$$\max_{\boldsymbol{G_t}} \frac{\|\boldsymbol{G_t H_{mc}}\|^2}{\left\|\boldsymbol{G_t H_{mc_I}}\right\|^2} \quad (8)$$

or equivalently

$$\max_{\boldsymbol{G_t}} \frac{Tr\{\boldsymbol{G_t H_{mc} H_{mc}^H G_t^H}\}}{Tr\{\boldsymbol{G_t H_{mc_I} H_{mc_I}^H G_t^H}\}} \quad (9)$$

If we assume that the matrix $\boldsymbol{H_{mc_I} H_{mc_I}^H}$ is invertible, then the solution to (9) is obtained by solving the generalized eigenvalue problem. Therefore, the optimal receive cancellation matrix can be expressed as

$$\boldsymbol{G_{t,opt}} = \boldsymbol{U}^H\left(\boldsymbol{H_{mc_I} H_{mc_I}^H}\right)^{-1/2} \quad (10)$$

The columns of $\boldsymbol{U}$ are the corresponding eigenvectors of the matrix $\left(\boldsymbol{H_{mc_I} H_{mc_I}^H}\right)^{-1/2}\boldsymbol{H_{mc} H_{mc}^H}\left(\boldsymbol{H_{mc_I} H_{mc_I}^H}\right)^{-1/2}$.

After deriving the receive cancellation filter $\boldsymbol{G_{t,opt}}$, we proceed with the design of the transmit cancellation matrix $\boldsymbol{G_t}$. In this second step, we aim at maximizing the ratio between the power of the useful signal at the output to the remaining self-interference power. In other words, we maximize the SIR at the transmit side. The remaining self-interference can be expressed as

$$\widetilde{\boldsymbol{H}}_{mc_I} = \boldsymbol{G_{t,opt} H_{mc_I}} \quad (11)$$

We can now formulate the SIR maximization problem at the output

$$\max_{\boldsymbol{G_r}} \frac{\|\boldsymbol{H_{mc} G_r}\|^2}{\left\|\widetilde{\boldsymbol{H}}_{mc_I}\boldsymbol{G_r}\right\|^2} \quad (12)$$

or equivalently

$$\max_{\boldsymbol{G_r}} \frac{Tr\{\boldsymbol{H_{mc} G_r G_r^H H_{mc}^H}\}}{Tr\{\widetilde{\boldsymbol{H}}_{mc_I}\boldsymbol{G_r G_r^H}\widetilde{\boldsymbol{H}}_{mc_I}^H\}} \quad (13)$$

Similarly to (10) the optimal transmit cancellation matrix is obtained by

$$\boldsymbol{G_{r,opt}} = \left(\widetilde{\boldsymbol{H}}_{mc_I}^H \widetilde{\boldsymbol{H}}_{mc_I}\right)^{-1/2}\overline{\boldsymbol{U}} \quad (14)$$

The matrix $\overline{\boldsymbol{U}}$ is obtained by the eigenvalue decomposition of the matrix $\left(\widetilde{\boldsymbol{H}}_{mc_I}^H \widetilde{\boldsymbol{H}}_{mc_I}\right)^{-1/2}\boldsymbol{H_{mc}^H H_{mc}}\left(\widetilde{\boldsymbol{H}}_{mc_I}^H \widetilde{\boldsymbol{H}}_{mc_I}\right)^{-1/2}$ and its columns are the corresponding eigenvectors.

The proposed system is designed to formulate the self-interference based on MC model. These self-interference signals are caused by multiple antennas. The proposed system for FDSC MIMO system is illustrated in Fig. 1. In this study antenna array with four elements an antenna spacing of one half of a wave length $\left(\lambda/_2\right)$ is assumed. As shown in Fig. 1, the self-interference based on mutual coupling H_{mc_I} can be written as

$$H_{mc_I}s = H_{LI}s + H_{NI}C_R s, \tag{15}$$

where $s \in C^{s\times 1}$ is the transmitted signal to the right, $H_{LI} \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals, and $H_{NI} \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas.

Next, the proposed method to suppress the interference signals is performed as shown in Fig.1. The transmitted signals are coupled to matrix W in order to perform the negative self-interference and mutual-interference signals as closely as possible. Inside matrix W, the attenuation and phase shifter are employed to adjust the pre-known signals for compensating the self-interference signals and mutual-interference signals. The compensation matrix, W, is given by

$$Ws = T_x C_T s + Gs, \tag{16}$$

where $T_x \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas, $G \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals.

Then, the received signal at the destination with the proposed compensation matrix for the interference cancellation can be rewritten as

$$y = G_{r,opt}H_{mc}G_{t,opt}x + G_{r,opt}H_{mc_I}G_{t,opt}s$$
$$-G_{r,opt}WG_{t,opt}s + N, \tag{17}$$

where $N \sim CN(0, \sigma_d^2 I_s)$ is the AWGN contribution at the destination

IV. Results and Discussion

A. Channel Capacity

In order to investigate the effect of MC on MIMO capacity, in this section the channel capacity for our 4x4 MIMO system can be given by (18) [2]. This capacity denotes the average of channel capacity in bps/Hz. Also, we assume the uniform transmitting power for each antenna $\left(E\{xx^H\} = \frac{P_0}{N_s} I_x\right)$.

$$C = log_2 \det [I_s + \tfrac{P_0}{N_s} G_{r,opt}H_{mc}H_{mc}^H G_{t,opt}$$
$$\times \left(\sigma_I^2 G_{r,opt}H'_{mc_I}H'^H_{mc_I}G_{t,opt} + \sigma_d^2 I_s\right)^{-1}], \tag{18}$$

We assume P_0 is the maximum available power at the source, N_s is the power of the self-interference signals.

The performance of channel capacity is presented by considering three cases. The first case is that there is no either self-interference or mutual coupling effect (called as without interference and MC) in the system. The second case is the case that the system uses the self-interference cancellation and there is a mutual coupling effect in the systems (called as proposed). For the last case, the system experiences both interference and mutual coupling effect but no any cancellation technique is applied (called as with interference and MC).

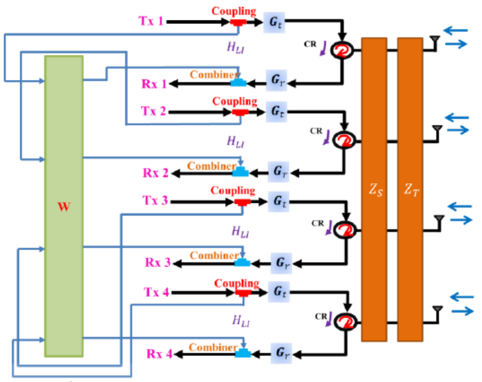

Fig. 1 Proposed self-interference cancellation for FDSC 4x4 MIMO system based on mutual coupling model

The simulation produced by MATLAB programming can be described as follows. The source and the destination are equipped with four transmitting and four receiving antennas, i.e. $s = x = 4$. We assume that the source-destination channels experience Rayleigh fading. Hence, the new channel matrix H_{mc} is an independent matrix containing independent identically distributed (i.i.d) entries which the random distribution is explained by $CN(0,1)$. For the self-interference channels, they also experience Rayleigh fading. Hence, the self-interference channel matrices H_{LI}, and H_{NI} are independent matrices containing independent identically distributed (i.i.d) entries distributed as $CN(0,1)$. For simplicity, we assume that the noise variance is equal on each antenna, σ^2.

Fig. 2, the relation between capacity and the percentage of interference reduction is presented. It is obvious that self-interference cancellation improves the system performance. For the optimal receive and transmit cancellation filters by choosing maximize the SIR at the transmitter and receiver. It can be noticed that the channel capacity of the proposed system requires only 90% interference reduction to achieve the capacity close to the system without any interference.

B. Mutual-Interference Reduction

In the previous section, the reduction of self-interference power is observed. However, in MIMO system, there are other interference signals called as mutual-interference signals. The proposed work also considers the reduction of mutual-interference as well. By using the same measurement as previous section but increasing all sets for 4x4 MIMO operation, the mutual-interference power can be observed. The operating frequency band is on 2.45GHz for all transmitting antennas. The attenuations and phase shifters are employed to perform the suitable matrix W which is

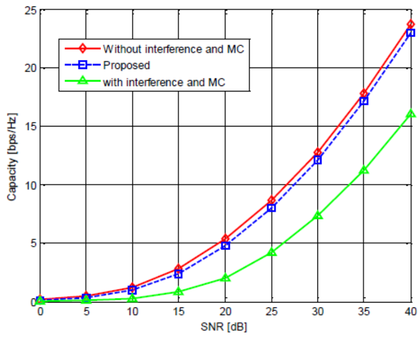

Fig. 2 Relation between channel capacity and interference reduction for 4x4 MIMO

illustrated in Fig.1. The power inputs of Tx1, Tx2, Tx3 and Tx4 are equal. TABLE I shows the measured powers from Rx1 output. In Fig.3 (a), the self-interference and mutual-interference signals before SIC, there are equal powers for Tx1, Tx2, Tx3 and Tx4 but there is no matrix ***W*** in the system. In the proposed technique, the matrix ***W*** is performed to suppress both self-interference and mutual-interference signals. In this measurement, there is no signal coming from the other side. Hence, Rx1 should not receive any power if matrix ***W*** works very well. In our measurement, it can be noticed that the received power of the proposed method is the least. The self-interference and mutual-interference signals can be reduced by adjusting the suitable voltage control for phase shifter. Actually, there are four phase shifters related to this curve and all are needed to be properly adjusted at the same time. To explain the mechanism of phase adjustment, only one voltage control has been presented after SIC in Fig.3 (b). It can be clearly seen that the right voltage offers the maximum reduction of interference signals. At control voltage 4-5 V, the received power of self-interference and mutual-interference signals is reduced by 29.84 dBm.

V. Conclusions

In this paper, we proposed the method of self and mutual interference cancellation for FDSC MIMO system based on mutual coupling model. The performance of proposed technique can suppress the interference signals by using the pre-known interferences which are affected by MC between antennas. Simulation results illustrate that the proposed system outperforms the system with interference and the proposed algorithm suppresses the interference signal by applying receive and transmit filters. This implies the success of using the proposed concept for FDSC MIMO system. In addition, the measurement results indicate that the self and mutual interference reduction is good enough to successfully transmit and receive on the same frequency at the same time in practice.

Acknowledgment

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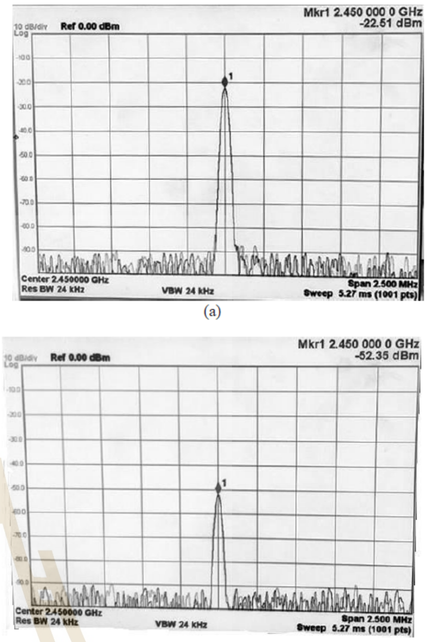
TABLE I

Cancellation of a 2.45 GHz Self-Interference Using Attenuations and Phase Shifters

	before SIC	after SIC
4 antennas	-22.51 dBm	-52.35dBm



(b)

Fig.3. Measured spectrum of self-interference signal (a) without cancellation (b) with cancellation.

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Research Article

Self-Interference Cancellation-Based Mutual-Coupling Model for Full-Duplex Single-Channel MIMO Systems

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The challenge of a full-duplex single-channel system is the method to transmit and receive signals simultaneously at the same time and on the same frequency. Consequently, a critical issue involved in such an operation is the resulting self-interference. Moreover, for MIMO system, the full-duplex single-channel system is subjected to the very strong self-interference signals due to multiple transmitting and receiving antennas. So far in the pieces of literature, there have not been any suitable techniques presented to reduce the self-interference for full-duplex single-channel MIMO systems. This paper initially proposes the method to cancel the self-interference by utilizing the mutual-coupling model for self-interference cancellation. The interference can be eliminated by using a preknown interference, that is, the mutual-coupling signals. The results indicate that the channel capacity performance of the proposed technique can significantly be improved due to the reduction of the self-interference power. The measurement results indicate that the proposed MIMO system can suppress the self-interference and mutual-interference signals with the reduction of 31 dB received power.

1. Introduction

Nowadays, multiple-input multiple-output (MIMO) system is the promising technology for the next generation of wireless communication systems as MIMO system can provide a wide coverage area, a high spectral efficiency, and an increased system capacity. The MIMO system employs the multiple antennas to transmit signals on the same frequency which cause the strong interference signals at the receiving antennas on the same side. These interferences are more pronounced when operating the full-duplex single-channel MIMO system.

The full-duplex single-channel system is one of the most interesting technologies for future wireless communications because it can offer double throughput from any conventional system without paying any expenses of spectrum. This is because the system is able to receive and transmit simultaneously within a single channel. In the literature, the problem of full-duplex interference has been addressed on the specific configuration of MIMO relay nodes. The self-interference cancellation is introduced to be used at only relaying node [1–3]. So far there have not been any techniques proposed for source or destination. In this light, the authors propose the new technique to suppress the self-interference for full-duplex single-channel MIMO systems. From the literature on RF interference cancellation, the work in [4–9] presents a full-duplex wireless system that can transmit and receive signals at the same time and on the same frequency band since it requires at least two antennas having one for transmitter (Tx) and one for receiver (Rx). The key challenge in realizing such a system lies in addressing the self-interference generated by the Tx antenna at the Rx antenna. For example, one can implement the above self-interference cancellation idea completely in analog domain using noise cancellation circuits reported by Radunovic et al. [5]. But the practical noise cancellation circuits can only handle a dynamic range of at most ~30 dB. Another technique in [6] employs the antenna cancellation by using three antennas to create a beam forming null. This method cancels the self-interference at the receiver antenna by using antenna placement as an additional cancellation technique or antenna cancellation. The antenna cancellation requires two asymmetrically placed transmitting antennas and one receiving antenna. This three-antenna system can remove ~60 dB reduction of self-interference power for a802.15.4 system. Although it looks promising, the antenna cancellation-based designs have two major limitations. The first is that they require three antennas having two transmitting antennas and one receiving antenna, which are very sensitive to the relative location of antennas and any material around them. It is a fact that the full-duplex system can have double throughput, but with three antennas a MIMO system can have triple throughput. Hence, the use of multiple antennas for only full-duplex purpose is not worth. The second limitation is a bandwidth constraint, a theoretical limit which prevents supporting wideband signal such as WiFi.

The MIMO techniques for wireless communications have been studied extensively over the past decade as a means of achieving significant capacity gains needed for supporting high-rate wireless broadband applications [10]. A critical factor in the design and analysis of MIMO systems is the theoretical models which are used for representing the MIMO transceiver as well as the wireless fading channel. So far in the literature, the factor on realistic channel configuration has gained a lot of attention such as spatial correlation (see, e.g., [11, 12] and many others). One issue which has received less attention in comparison is that of mutual coupling [10, 13–15], which occurs due to electromagnetic interactions between the antennas in both transmitter and receiver. This effect, as well as spatial correlation, is particularly significant for applications with compact antennas, such as cellular mobile, in which the available space for placing the antennas is highly restrictive.

In this paper, we will investigate the effect of antenna mutual coupling (MC) on the full-duplex single-channel MIMO system with the aim of self-interference eliminations. Based on the mutual-coupling model, the signals with self-interference can be preknown. As a result, it is possible to eliminate all self-interference signals by subtracting from preknown signals. The concept of transmitting and receiving mutual impedances is employed to incorporate the antenna MC effect into the correlated channel model [16]. This model is applied to work out the suppression technique to reduce the self-interference performed by subtracting the interference signals from the transmitting signals that are suitably tuned according to the interaction between multiple antennas. This is because the self-interference signals do not depend on the environments. Then, the proposed technique can be done on the manufacturing process. The paper presents the comparison between the MC full-duplex single-channel systems with and without the proposed technique. The channel capacity performance is the key performance used to indicate the merit of proposed technique. The results show that the proposed technique is not only to suppress the interference but also to improve the system performance capacity.

2. Problem Formulation

This paper focuses on the full-duplex wireless communications operating on the same frequency and at the same time. The simultaneous transmitting and receiving signals can be achieved via the cancellation of the self-interference signal. However, the problem is that the self-interference is billions of times stronger (60–90 dB) than a received signal; for example, for WiFi the self-interference would be nearly up to 80 dB stronger. Hence, the main key success is to eliminate the self-interference as much as possible. In this section, the overview of full-duplex system is presented in order to be the basic knowledge before getting to the main problem of this work. Next, the survey of RF interference cancellation techniques is detailed.

2.1. Full-Duplex Wireless Communication. Currently, full-duplex wireless systems achieve the isolation required between the two directions of communication using independence in either time or frequency. Accordingly, these duplexings are called time division duplexing (TDD) and frequency division duplexing (FDD). The TDD system is the system that divides the access of each node in time. TDD is also commonly known as half-duplexing. Other full-duplex wireless systems separate the Tx and Rx functions in the frequency domain, the so-called FDD, and may operate using two different carrier frequencies for carrying transmissions. In this case, nodes 1 and 2 can send data to each other at the same time, although using two different frequencies. The use of different frequencies prevents the two signals from interfering with each other, even though the two transmissions occur at the same time. Time division duplexing exacerbates the inconsistency in the channel views across nodes. Since only one node among a pair of communicating nodes can transmit at a given time, the wireless channel around the transmitting node may look occupied, while the wireless channel around the receiving node may look unoccupied. Such inconsistencies are the root cause of many of the problems with time division duplexing wireless networks, such as packet losses due to hidden terminal effects. On the other hand, frequency division duplexing requires a wireless node to use twice the frequency bandwidth for sending and receiving signals of a given bandwidth. In some cases, this is expensive and infeasible. The key challenge in implementing a full-duplex wireless system, where a device can simultaneously transmit and receive signals over-the-air at the same time and in the same frequency band, is the large power differential between the self-interference from a node's own transmission and the signal of interest coming from a distant source.

2.2. Single-Channel Full-Duplex Wireless Communications. A basic perception of wireless communication is that a radio cannot transmit and receive on the same frequency and at the same time. As wireless signals attenuate quickly over distance, the signal from a local transmitting antenna is hundreds of thousands of times stronger than transmissions from other nodes. Figure 1 shows an example where nodes 1 and 2 are trying to send data to each other simultaneously using the same frequency. Node 1 own transmission is much stronger at its receiving antenna, compared to the signal it receives from node 2. With such strong self-interference, the receiver

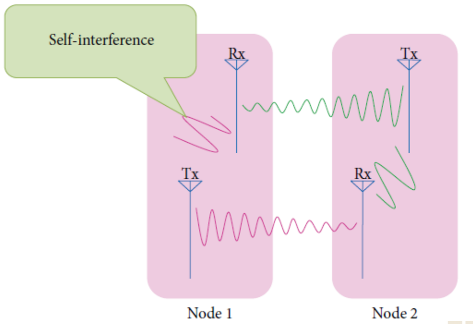

FIGURE 1: Self-interference in the single-channel full-duplex wireless communications using one transmitting antenna and one receiving antenna.

of node 1 is unable to decode any signals that node 2 is trying to send to node 1. This example shows that the biggest challenge in designing single-channel full-duplex wireless communications is to eliminate the self-interference signal from the receiver of the wireless node. In theory, this problem should be easy to solve. For a system with antennas each for transmitting and receiving, since the system knows the signal of transmitting antenna, it can subtract this from the signal of receiving antenna and decode the remainder.

2.3. Self-Interference Cancellation. The work in [17] proposed the design of full-duplex system that requires only one antenna using circulator to share the same antenna for transmitting and receiving paths as shown in Figure 2. The self-interference cancellation (SIC) uses the knowledge of transmission to cancel self-interference in the RF signal before it is digitized. In an ideal analog cancellation scenario, the amplitudes from the two paths would be perfectly matched at the receiver and phase of the two signals would differ by exact π. To cancel self-interference, the best performing prior design is obtained. The authors gain the inverse of the transmitted signal using a phase shifter with attenuator. The attenuator and phase shifter allow a modulator to control the angle and amplitude of a feed signal.

3. System Model

3.1. MIMO Model. In this section, the capacity formula of MIMO systems is briefly given. We assume an independent and identically distributed (i.i.d.) Rayleigh flat-fading channel in rich scattering environments, and the channel is unknown at the transmitter and perfectly known at the receiver. The basic MIMO structure is depicted in Figure 3. Let the number of transmitting and receiving antennas be N_T and M_R, respectively. We denote this MIMO communication link as (N_T, M_R). The $M_R \times 1$ received signal vector $\mathbf{y}$ can be written as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

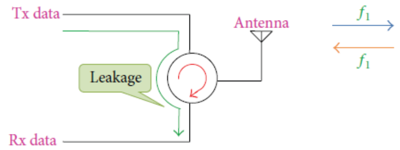

FIGURE 2: Self-interference in the single-channel full-duplex single-antenna wireless communications.

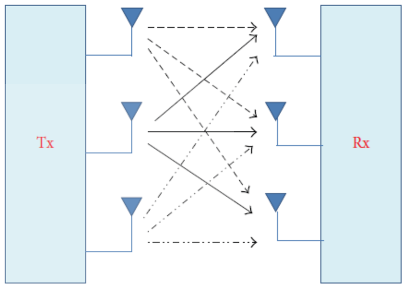

FIGURE 3: Basic structure of MIMO system.

with this notation channel output sequence that can be written in matrix form as

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{M_R} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & & h_{1N_T} \\ h_{21} & h_{22} & \cdots & h_{2N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_R1} & h_{M_R2} & \cdots & h_{M_RN_T} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N_T} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{M_R} \end{bmatrix}, \tag{2}$$

where $\mathbf{H}$ is $M_R \times N_T$ channel matrix with the entry $h_{i,j}$ describing the channel gain between the jth transmitting antenna and the ith receiving antenna, $\mathbf{x}$ is $N_T \times 1$ transmitted signal vector with independent symbols, and $\mathbf{n}$ is $M_R \times 1$ additive white Gaussian noise (AWGN) vector.

The AWGN vector $\mathbf{n}$ satisfies $E\{\mathbf{n}\mathbf{n}^H\} = \mathbf{I}_{M_R}$ in which $\mathbf{n}^H$ denotes the conjugate transpose of $\mathbf{n}$ and $\mathbf{I}_{M_R}$ denotes $M_R \times M_R$ identity matrix.

As the channel is unknown at the transmitter, equal power is allocated to each of the transmitting antennas. Then the MIMO capacity in bits per second per Hertz (bps/Hz) is derived as

$$C = \log_2 \det\left(\mathbf{I}_{M_R} + \frac{\rho}{N_T}\mathbf{H}\mathbf{H}^H\right), \tag{3}$$

where ρ is the average received signal to noise ratio (SNR). $\mathbf{H}$ is normalized channel matrix [18].

3.2. Mutual-Coupling Effects on MIMO. In this section, in order to support parallel signal transmission in a MIMO system, the antennas at transmitter and receiver have to be properly coupled to the modes offered by the wireless communication channel. Hence, in Figure 4, the array elements

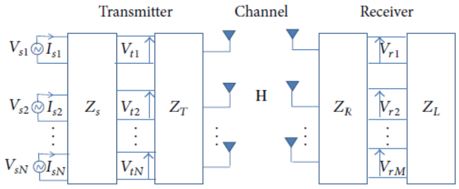

FIGURE 4: An $M_R \times N_T$ MIMO system based on mutual-coupling model.

location (including spacing and orientation) with respect to the scatterers is of paramount importance in the operation of the MIMO system. The interactions between the entire set of antennas and scatterers are initially described by the impedance matrix $\mathbf{Z}$. For dipoles, however, the mutual impedance can easily be calculated using classical induced electromagnetic force (EMF) method [19]. The value of the mutual impedance between the mth and nth dipoles Z_{mn} is given by [20]

$$Z_{mn} = \begin{cases} 30\left[0.5772 + \ln\left(\beta d_{\text{lam}}\right) - C_i\left(\beta d_{\text{lam}}\right)\right] \\ \quad + j\left[30 S_i\left(\beta d_{\text{lam}}\right)\right] & m = n, \\ 30\left[2C_i\left(u_0\right) - C_i\left(u_1\right) - C_i\left(u_2\right)\right] \\ \quad - j\left[30\left(2S_i\left(u_0\right) - S_i\left(u_1\right) - S_i\left(u_2\right)\right)\right] & m \neq n, \end{cases} \tag{4}$$

where $\beta = 2\pi/d_{\text{lam}}$ is the wave number, $d_{\text{lam}}/2$ is the dipole length, and the constants are given by [20]

$$\begin{aligned} u_0 &= \beta d_h, \\ u_1 &= \beta\left(\sqrt{d_h^2 + \left(d_{\text{lam}}/2\right)^2} + \left(d_{\text{lam}}/2\right)\right), \\ u_2 &= \beta\left(\sqrt{d_h^2 + \left(d_{\text{lam}}/2\right)^2} - \left(d_{\text{lam}}/2\right)\right), \end{aligned} \tag{5}$$

where d_h is the horizontal distance between the two dipole antennas and $C_i(u)$ and $S_i(u)$ are the cosine and sine integrals, respectively:

$$C_i(u) = \int_{\infty}^{u} \frac{\cos(x)}{x} dx, \qquad S_i(u) = \int_{0}^{u} \frac{\sin(x)}{x} dx. \tag{6}$$

It has to be noted that, while calculating Z_{mn}, we assume that the nth dipole is excited with current, while all the remaining dipoles are open circuited.

In general, mutual coupling can be characterized by numerical modelling techniques [19]. However, for dipoles, we can use analytical mutual coupling into the MIMO system model. The coupling matrix of transmitting antenna array $\mathbf{C}_T$ can be written using fundamental electromagnetic and circuit theory [19]. $\mathbf{C}_T$ has the meaning of transfer function matrix for the transmitting array and is given as

$$\mathbf{C}_T = \left(Z_A + Z_T\right)\left(\mathbf{Z} + Z_T \mathbf{I}_{N_T}\right)^{-1}, \tag{7}$$

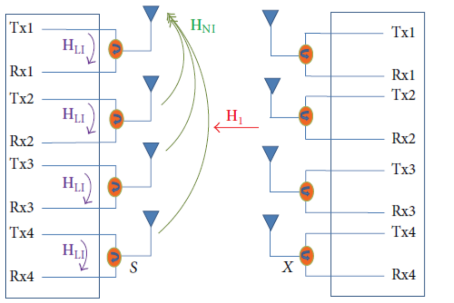

FIGURE 5: Model of full-duplex single-channel 4 × 4 MIMO system.

where Z_A is the element's impedance in isolation. The element Z_{mn} of matrix $\mathbf{Z}$ is defined by using the EMF method as described in (4). Also the coupling matrix of receiving antenna array $\mathbf{C}_R$ can be determined in a similar manner. $\mathbf{C}_R$ has the meaning of transfer function matrix for the receiving array and is given as

$$\mathbf{C}_R = \left(Z_A + Z_T\right)\left(\mathbf{Z} + Z_T \mathbf{I}_{M_R}\right)^{-1}. \tag{8}$$

4. Proposed Self-Interference Cancellation

In this section, we consider a generic MIMO radio unit equipped with M_R RF receivers antennas and N_T RF signal generators/transmitters. Among all generators, there are $N_s = N_T - M_R$ primary generators and M_R auxiliary generators. The primary generators are used to transmit up to N_S independent streams of data. The auxiliary streams of data are used to generate RF waveforms for SIC at the RF frontend of the receivers on the same frequency. See Figure 5.

Furthermore, we index the receiver by $k = 1, \ldots, M_R$ and the transmitter by $k = M_R + 1, \ldots, N_T$. Then, for each transmitted data packet subject to linear modulation, a RF signal stream transmitted from the kth generator ideally can be expressed by $\widetilde{x_k}(t) = \text{Re}\{x_k(t)\exp(j2\pi f_c t)\}$, where f_c is the carrier frequency and

$$x_k(t) = \sum_{i=1}^{I} g_k^{(i)}(t) * \sum_{n=-L}^{N-1} s_n^{(i)} p(t - nT), \tag{9}$$

where $x_k(t)$ is the complex baseband form (also called I/Q waveform) of $\widetilde{x_k}(t)$. Here, $g_k^{(i)}(t)$ is the complex impulse response of the kth transmission for data stream i (of total I streams), $s_n^{(i)}$ is the complex symbol sequence for data stream i, $N + L$ is the number of complex symbols per stream (including the L prefixed symbols as used in OFDM system), and $p(t)$ is the fundamental pulse waveform used for linear pulse modulation, which has the double-sided bandwidth W and the effective duration T. For high spectral efficiency, it is typical that T is equal to or only slightly larger than $1/W$. The operator $*$ denotes convolution.

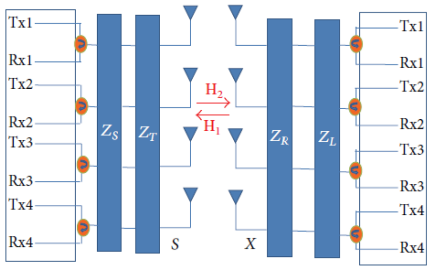

FIGURE 6: 4 × 4 MIMO system with mutual-coupling model.

The RF self-interference received by the by the lth receiver is $\tilde{y}_l(t) = \mathrm{Re}\{y_l(t)\exp(j2\pi f_c t)\}$, where $l = 1, \ldots, M_R$, and $y_l(t) = \sum_{k=1}^{N_T} h_{\mathrm{mc}_{l,k}}(t) * x_k(t) = \sum_{i=1}^{I}([\sum_{k=1}^{N_T} h_{\mathrm{mc}_{l,k}}(t) * g_k^{(i)}(t)] * \sum_{n=0}^{N-1} s_n^{(i)} t(t - nT))$ is the I/Q waveform of $\tilde{y}_l(t)$. In Figure 6, when the mutual coupling is presented, $h_{l,k}(t)$ is the complex baseband channel impulse response from the kth generator to the lth receiver on the same radio. Hence, the channel matrix $h_{l,k}(t)$ obtained from the case that this effect is absent has to be pre- and postmultiplied by coupling matrices C_R and C_T. As a result, the new channel matrix is given by $\mathrm{H}_{\mathrm{mc}} = \mathrm{C}_R \mathrm{H} \mathrm{C}_T$. To cancel the RF self-interference $\tilde{y}_l(t)$ for all l and t, it is necessary to find $g_k^{(i)}(t)$ for all k and i such that $y_l(t) = 0$ for all l or equivalently $\sum_{k=1}^{N_T} h_{\mathrm{mc}_{l,k}}(t) * g_k^{(i)}(t) = 0$ for all l and i. The matrix form of this condition is

$$\begin{bmatrix} h_{\mathrm{mc}_{1,1}}(t) & \cdots & h_{\mathrm{mc}_{1,N_T}}(t) \\ \cdots & \cdots & \cdots \\ h_{\mathrm{mc}_{M_R,1}}(t) & \cdots & h_{\mathrm{mc}_{M_R,N_T}}(t) \end{bmatrix} * \begin{bmatrix} g_1^{(i)}(t) \\ \cdots \\ g_{N_T}^{(i)}(t) \end{bmatrix} = 0 \qquad (10)$$

or equivalently in more compact form:

$$\mathrm{H}_{\mathrm{mc}}(t) * \mathrm{g}^{(i)}(t) = 0. \qquad (11)$$

Although given in baseband, (11) ensures SIC even at the RF frontend. Also note that when all elements in a row of $\mathrm{H}_{\mathrm{mc}}(t)$ are corrupted by a common scalar due to receiver phase noise, the solution $\mathrm{g}^{(i)}(t)$ to (11) is not affected.

To find the solution to (10), we need to apply a known notion of vector space in the field of functions of time. The rank $r_{\mathrm{H}(t)}$ of the matrix $\mathrm{H}_{\mathrm{mc}}(t)$ that are convolutely independent. It follows that $r_{\mathrm{H}(t)} \le \min\{M_R, N_T\} = M_R$. The dimension of the solution space of (10), which is also called the dimension of the (right) null space of $\mathrm{H}_{\mathrm{mc}}(t)$, is the number of convolutely independent solutions to (10), which is $d_{\mathrm{null}} = N_T - r_{\mathrm{H}(t)} \ge N_s$. If $d_{\mathrm{null}} = N_s$, we call it a typical case (very likely in practice), or otherwise, if $d_{\mathrm{null}} > N_s$, we call it atypical case (not very likely in practice). The number I of the data streams in (9) must be no larger than d_{null}.

In general, for $M_R \ge 1$ and $N_s \ge 1$, the ith in a set of N_s convolutely independent solutions to (12) can be written as

$$\mathrm{g}^{(i)}(t) = \begin{bmatrix} \bar{\mathrm{g}}^{(i)}(t) \\ \mathbf{0}_{i-1,1} \\ g_0^{(i)}(t) \\ \mathbf{0}_{I-1,1} \end{bmatrix}, \qquad (12)$$

where $\mathbf{0}_{m,1}$ is the $m \times 1$ zero vector and $\bar{\mathrm{g}}^{(i)}(t)$ and $g_0^{(i)}(t)$ are a solution to $\mathrm{A}(t) * \bar{\mathrm{g}}^{(i)}(t) + \mathrm{b}_i(t) * g_0^{(i)}(t) = 0$, where $\mathrm{A}(t)$ is a square matrix equal to $\mathrm{H}_{\mathrm{mc}}(t)$ without its last N_s columns and $\mathrm{b}_i(t)$ is the $(M_R + i)$th column of $\mathrm{H}_{\mathrm{mc}}(t)$. Furthermore, we can choose the solution

$$\bar{\mathrm{g}}^{(i)}(t) = -\mathrm{adj}\{\mathrm{A}(t)\} * \mathrm{b}_i(t), \qquad (13)$$

and $g_0^{(i)}(t) = \det\{\mathrm{A}(t)\}$. Both the adjoint $\mathrm{adj}\{\mathrm{A}(t)\}$and the determinant $\det\{\mathrm{A}(t)\}$ can be obtained analytically in the same way as those of a matrix of numbers as shown in [21] except that all multiplications should be substituted by convolutions. It is important to note that expression (13) does not involve any division but only convolutions and sums.

The solutions shown in (12) are valid for arbitrary $\mathrm{H}_{\mathrm{mc}}(t)$ as long as $\det\{\mathrm{A}(t)\} \ne 0$. This condition can be met if $h_{k,k}(t)$ for $k = 1, \ldots, M_R$ have the largest norms among $h_{l,k}(t)$ for all l and k. To ensure that, we can either place the M_R auxiliary transmitting antennas close enough to the M_R receiving antennas or directly couple the M_R auxiliary generators to the M_R receivers at the RF frontend.

In this section, the proposed system is designed to formulate the self-interference based on mutual-coupling model. These self-interference signals are caused by multiple antennas. The proposed system for full-duplex single-channel MIMO system is illustrated in Figure 7. As shown in Figure 7, the self-interference based on mutual-coupling $\mathrm{H}_{\mathrm{mc}_I}$ can be written as

$$\mathrm{H}_{\mathrm{mc}_I}\mathrm{s} = \mathrm{H}_{\mathrm{LI}}\mathrm{s} + \mathrm{H}_{\mathrm{NI}}\mathrm{C}_R\mathrm{s}, \qquad (14)$$

where $\mathrm{s} \in C^{s\times 1}$ is the transmitted signal, $\mathrm{H}_{\mathrm{LI}} \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals, and $\mathrm{H}_{\mathrm{NI}} \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas.

Next, the proposed method to suppress the interference signals is performed as shown in Figure 7. The transmitted signals are coupled to matrix W in order to perform the negative self-interference and mutual-interference signals as closely as possible. Inside matrix W, the attenuation and phase shifter are employed to adjust the preknown signals for compensating the self-interference signals and mutual-interference signals. The compensation matrix, W, is given by

$$\mathrm{W}\mathrm{s} = \mathrm{T}_x\mathrm{C}_T\mathrm{s} + \mathrm{G}\mathrm{s}, \qquad (15)$$

where $\mathrm{T}_x \in C^{s\times s}$ is a symmetric matrix that represents the mutual-interference signals caused by the other antennas,

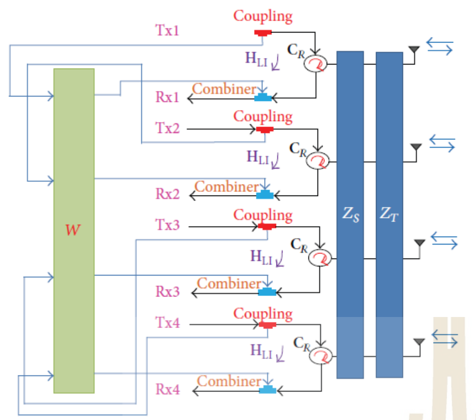

FIGURE 7: Proposed self-interference cancellation for full-duplex single-channel 4 × 4 MIMO system based on mutual-coupling model.

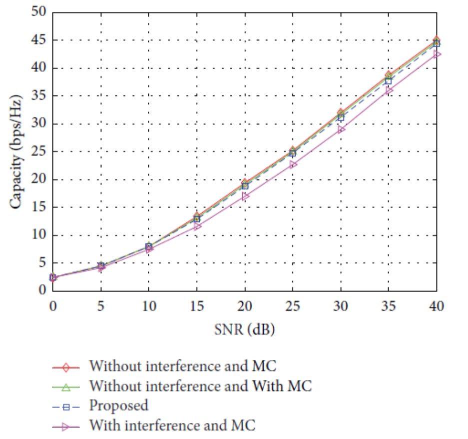

FIGURE 8: Channel capacity versus SNR for 80% interference reduction.

$\mathbf{G} \in C^{s\times s}$ is a diagonal matrix that represents the self-interference signals.

Then, the received signal at the destination with the proposed compensation matrix for the interference suppression can be rewritten as

$$\mathbf{y} = \mathbf{H}_{\mathrm{mc}}\mathbf{x} + \mathbf{H}_{\mathrm{mc}_I}\mathbf{s} - \mathbf{W}\mathbf{s} + \mathbf{N}, \quad (16)$$

where $\mathbf{N} \sim \mathrm{CN}(0, \sigma_d^2 \mathbf{I}_s)$ is the AWGN contribution at the destination.

5. Results and Discussion

5.1. Channel Capacity. In order to investigate the effect of mutual coupling on MIMO capacity, in this section the channel capacity for our 4 × 4 MIMO system can be given by (17) [2]. This capacity denotes the average of channel capacity in bps/Hz. Also, we assume the uniform transmitting power for each antenna ($E\{\mathbf{x}\mathbf{x}^H\} = (P_0/N_s)\mathbf{I}_x$). Consider

$$C = \log_2 \det\left[\mathbf{I}_s + \frac{P_0}{N_s}\mathbf{H}_{\mathrm{mc}}\mathbf{H}_{\mathrm{mc}}^H \times \left(\sigma_I^2 \mathbf{H}'_{\mathrm{mc}_I}\mathbf{H}'^H_{\mathrm{mc}_I} + \sigma_d^2 \mathbf{I}_s\right)^{-1}\right]. \quad (17)$$

We assume that P_0 is the maximum available power at the source and N_s is the power of the self-interference signals.

The performance of channel capacity is presented by considering four cases. The first case is that there is neither self-interference nor mutual-coupling effect (called without interference and MC) in the system. In the second case, there is no interference but including mutual-coupling effect (called without interference and with MC). The third case is the case that the system uses the self-interference cancellation and there is a mutual-coupling effect in the systems (called proposed). For the last case, the system experiences both interference and mutual-coupling effect but no any cancellation technique is applied (called with interference and MC).

The simulation produced by MATLAB programming can be described as follows. The source and the destination are equipped with four transmitting and four receiving antennas; that is, $s = x = 4$. We assume that the source-destination channels experience Rayleigh fading. Hence, the new channel matrix $\mathbf{H}_{\mathrm{mc}}$ is an independent matrix containing independent identically distributed (i.i.d.) entries in which the random distribution is explained by $\mathrm{CN}(0, 1)$. For the self-interference channels, they also experience Rayleigh fading. Hence, the self-interference channel matrices $\mathbf{H}_{\mathrm{LI}}$ and $\mathbf{H}_{\mathrm{NI}}$ are independent matrices containing independent identically distributed (i.i.d.) entries distributed as $\mathrm{CN}(0, 1)$. For simplicity, we assume that the noise variances are equal in each antenna, σ^2.

Figure 8 shows the channel capacity versus SNR for 80% interference reduction when the MIMO system is affected by mutual coupling. It can be noticed that the proposed technique lies between with and without the interference suppression. The channel capacity of the proposed system is about 0.70 bps/Hz (at SNR = 20 dB) higher than the system with self-interference and the system with mutual coupling. In Figure 9, the relation between capacity and the percentage of interference reduction is presented. It can be noticed that the channel capacity of the proposed system requires only 90% interference reduction to achieve the capacity close to the system without any interference.

5.2. Self-Interference Reduction. The work in [6, 8, 17, 22–25] shows that a single-channel full-duplex system can be worked by using the method of self-interference cancellation. Two key techniques are RF interference cancellation (RFIC) and

FIGURE 9: Relation between channel capacity and interference reduction for SNR = 20 dB.

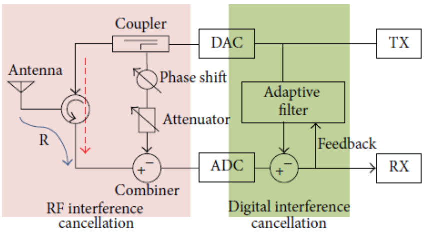

FIGURE 10: Block diagram of the proposed system in practice.

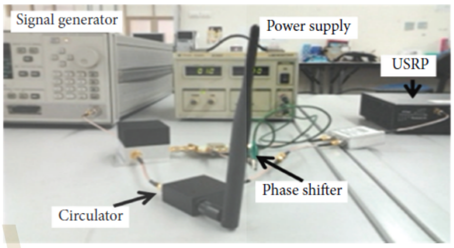

FIGURE 11: Photograph of experimental scenario.

digital interference cancellation (DIC) which utilize the signals from both the transmitting and receiving paths. Figure 10 presents the signal diagram of self-interference cancellation consisting of both RFIC and DIC. RFIC uses the knowledge of transmitting signals to cancel the self-interference in the RF signal before it is digitized. For analog cancellation, the amplitudes from two paths have to be perfectly matched at the receiver. Then, the phase of the two signals would be ideally differed by the exact π. To cancel self-interference, the best performing prior design is obtained. The authors gain the inverse of the transmitted signal using phase shifter and attenuator, dynamically adjusting the attenuation and phase of the inverse signal to match the self-interference leaking from circulator. After combining both inverse and leak signals, the received signal can be passed through the processing unit with the minimum effect of self-interference.

In measurement, the operating frequency band is on 2.45 GHz in order to match with a practical wireless channel as IEEE 802.11. The measurement has been performed to investigate the concept of a single-channel full-duplex wireless system. The results show that the system can reduce the self-interference about −75 dB. This reduction is good enough to investigate the concept of a single-channel full-duplex wireless system. The results show that the system can reduce the self-interference about −75 dB. This reduction is good enough to transmit and receive on the same frequency at the same time. However, we have proposed the self-interference suppression for MIMO system in which the self-interference signals are caused by mutual coupling. The proposed suppression technique can also be applied to the MIMO system by separating the multiple antennas into individual measurement. In this paper, the RFIC is performed according to the diagram shown in Figure 10. Then the DIC is performed inside USRP (Universal Software Radio Peripheral) processors.

The Universal Software Radio Peripheral (USRP) is a platform developed by Ettus Research LLC. Inside the USRP, there are two main components. The first component is a mother board containing an Altera Cyclone EP1C12 Field Programmable Gate Array (FPGA). It has 4 ADCs with 12 bits per sample and 4 DACs with 14 bits per sample. The second component is a daughter board that all working processes are in a field of RF-Front End. This paper employs XCVR2450 daughter board which responses to radio frequency in dual band, both 2.4 GHz and 5.9 GHz. All components are assembled in one USRP box using 3 A-6 V power supply. USRP is connected to the host PC via USB 2.0 (Universal Serial Bus 2.0).

The digital interference cancellation technique in our design employs a finite impulse response (FIR) filter to cancel the remainder of the self-interference signals after RF interference cancellation. The transmitted digital samples are passed through the FIR filter to create digital interference cancellation samples which are subtracted from the received samples to further clean interference from the received signal.

Figure 11 shows the photograph of the experimental scenario for measuring the self-interference signal. The block diagram of each antenna with both RFIC and DIC is shown in Figure 10.

Figure 12 shows the measured spectrum of self-interference signal. In Figure 12(a), the spectrum of the self-interference leakage without any cancellation is noticeably high. In Figure 12(b), the measured spectrum of self-interference signal with RF interference cancellation is reduced by 58 dB. In Figure 12(c), the measured spectrum of

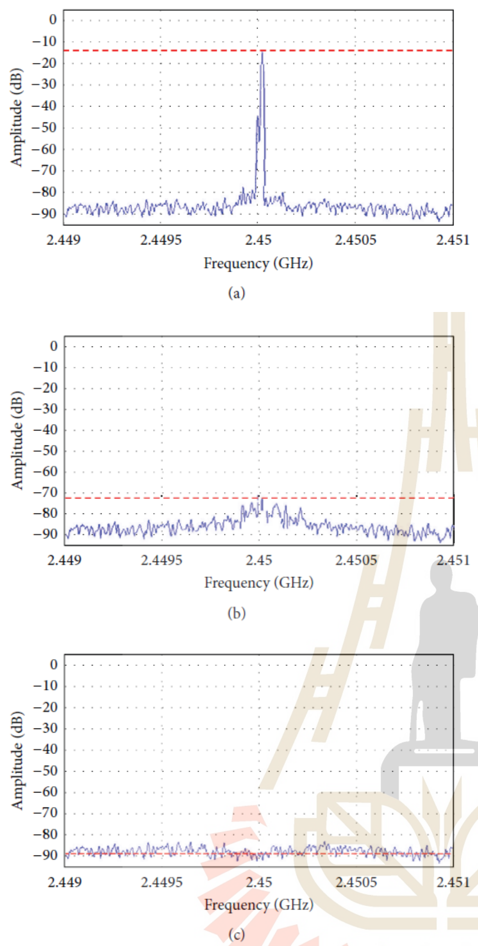

FIGURE 12: Measured spectrum of the self-interference signal (a) without any cancellations, (b) with RF interference cancellation but without digital interference cancellation, and (c) with both RF and digital interference cancellations.

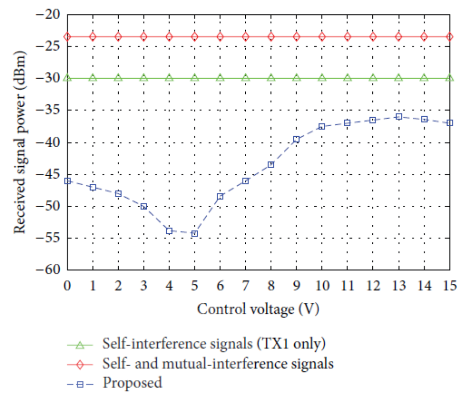

FIGURE 13: The received signal power of interference signals at Rx1.

self-interference signals with both RF and digital cancellations is very low and close to the noise floor level with the reduction of 75 dB. At this stage, the self-interference signal is low enough to provide a little impact on the desirably received signals. It means that the full-duplex system can be operated on the same channel at the same time because the self-interference is treated to be a noise for both forward and reserve links. Consequently, the throughput can be doubled by using our proposed method.

5.3. Mutual-Interference Reduction. In the previous section, the reduction of self-interference power is observed. However, in MIMO system, there are other interference signals called mutual-interference signals. The proposed work also considers the reduction of mutual interference as well. By using the same measurement as previous section but increasing all sets for 4×4 MIMO operation, the mutual-interference power can be observed. The operating frequency band is on 2.45 GHz for all transmitting antennas. The attenuations and phase shifters are employed to perform the suitable matrix **W** which is illustrated in Figure 7. The power inputs of Tx1, Tx2, Tx3, and Tx4 are equal. Figure 13 shows the measured powers from Rx1 output. There are three curves presented in Figure 13. The first curve is named as self-interference signals because the signal is sent by only Tx1 while there is no input power for Tx2, Tx3, and Tx4. This is the same situation as in the previous section except that it might be the effect of mutual coupling from the neighbour antenna. For the second curve named as self- and mutual-interference signals, there are equal powers for Tx1, Tx2, Tx3, and Tx4, but there is no matrix **W** in the system. It can be observed that the total power of this curve is higher than the first curve. In the third curve named as proposed, the matrix **W** is performed to suppress both self-interference and mutual-interference signals. In this measurement, there is no signal coming from the other side. Hence, Rx1 should not receive any power if matrix *W* works very well. In our measurement, it can be noticed that the received power of the proposed method is the least. The self-interference and mutual-interference signals can be reduced by adjusting the suitable voltage control for phase shifter. Actually, there are four phase shifters related to this curve and all are needed to be properly adjusted at the same time. To explain the mechanism of phase adjustment, only one voltage control has been presented in Figure 13. It can be clearly seen that the right voltage offers the maximum reduction of interference signals. At control voltage 4-5 V,

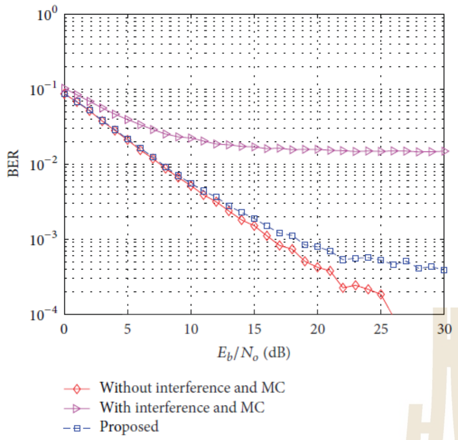

FIGURE 14: BER performance for 4 × 4 MIMO system.

the received power of self-interference and mutual-interference signals is reduced by 31 dB.

5.4. Performance of Proposed MIMO System. After getting the suitable matrix W, the other side of communication sends the data signal through the wireless 4×4 channel. It is a fact that the channel capacity is a theoretical quantity which cannot be directly measured. In practice, throughput and bit error rate (BER) are two indicators to judge the merit of system. In this paper, BER can be obtained by using the zero forcing technique to decode the data. All signals are sent with QPSK modulation. Figure 14 shows BER performance for 4 × 4 MIMO system. It is clearly seen that the proposed technique can provide a similar BER to the system without interference when Eb/No is less than 15 dB. Even though Eb/No is more than 15 dB, the proposed system still significantly improves the BER performance in comparison with the system with interference.

Note that even the BER of proposed system is nearly the same as that of the system without interference but the throughput of proposed system is a double of that of normal full-duplex system. This is because the proposed MIMO system can transmit and receive at the same time and on the same frequency.

6. Conclusions

In this paper, we proposed the method of self-interference cancellation for full-duplex single-channel MIMO system based on mutual-coupling model. The performance of proposed technique can suppress the self-interference signals by using the preknown interferences which are affected by mutual coupling between antennas. Simulation results illustrate that the proposed system outperforms the system with interference. This implies the success of using the proposed concept for full-duplex single-channel MIMO system. In addition, the measurement results indicate that the self-interference and mutual-interference reductions are good enough to successfully transmit and receive on the same frequency at the same time in practice. As a result, the proposed throughput can be actually twice the conventional system.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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DESIGN OF RF CANCELLATION FOR 5G FULL-DUPLEX MIMO SYSTEMS

Running head : Design of RF Cancellation for 5G Full-Duplex MIMO Systems

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Abstract

The imagination of our future is the better quality of service, higher data rates, and decreased latency, which is an important focus of the fifth generation (5G) technologies. Thus, the prime concept of full-duplex single-channel (FDSC) for MIMO system can provide double throughput and higher spectral efficiency. The design and simulation results of the FDSC communication for MIMO systems are the methods to transmit and receive at the same time on the same frequency. The main challenge of full-duplex communication systems are the resulting self-interference and mutual-interference signals. In this paper, we propose a novel technique for the interference cancellation using pre-defined RF circuit network in the analog cancellation part. Our simulation results show that the proposed technique can improve the performance of transmitting and receiving systems depending on the decrease of interference powers.

Keywords: MIMO systems, self-interference, mutual-interference, full-duplex communication

Introduction

In the near future, the concept of full duplex (FD) communications are the potential and promising technology for the fifth generation of wireless communication systems as well as the multiple-input multiple-output (MIMO) systems (Albreem M . A. M., et al., 2015; Gupta 2015; Zhang X., et al., 2015). It has been accepted as the key idea of the designed 5G technology in order to increase demand for higher data rate, more users, real-time. Thus, the FD wireless communication approaches to increase the data rates, high spectral efficiency, double throughput, and larger network capacity. Moreover, the FD wireless transmission is typically implemented using both time division multiplexing (TDD) and frequency division multiplexing (FDD). The simultaneous transmitting and receiving operate at the same time and on the same frequency band (Zhang Z., et al., 2016; Alves H., et al., 2015), so called the full-duplex single-channel (FDSC). The challenge of this concept is the strong interference signals generated from transmitter to receiver at the same side. The interference signal is happened that the signal leakage between transmitting and receiving at the same antenna, so called as self-interference signal. The literatures propose many techniques in order to suppress self-interference. The RF interference cancellations are proposed in the literatures (Bharadia, 2014; Zhang Z., et al., 2015; Choi J. I., et al., 2010; Liempd V., et al., 2014). In (Bharadia, 2014), authors have cancelled the self-interference by using RF cancellation circuit, whose complexity scales linearly with the number of antennas and this complexity is close to the optimum as possible. In (Choi J. I., et al., 2010), this literature presents using antenna cancellation technique which use two transmitting and one receiving antenna. For a wavelength λ, the two transmit antennas are placed at distances d and $d + \frac{\lambda}{2}$ from the receive antenna. Offsetting the two transmitters by half a wavelength causes their signals to add destructively and cancel one another.

The FDSC MIMO system is one of the most interesting technologies for 5G wireless communications. This is because the system is able to transmit and receive simultaneously within a single channel. Moreover, the problem of interference signals are happened due to multiple transmitting and receiving antennas. The interference signals are happened between antennas both the transmitting and receiving, so called as mutual-interference. This problem is not considered by all techniques in the literatures. The interference signals are the combination of both self-interference and mutual-interference signals. The past technique considers only self-interference. The analog cancellation is proposed using the elimination of self-interference signal. The main key of interference cancellation are amplifier and phase shifter techniques. The many works in literatures neglect the real power (Lioliou P., et al., 2010; Suraweera H. A., et al., 2013; Sung Y., et al., 2012; Darsena D., et al., 2015).

In this paper, the design of RF cancellation for 5G FDSC 2 × 2 MIMO system has been presented. The design of analog cancellation is pre-known as the interference signals. This design uses the combination of a modified hybrid coupler and phase shifter. The modified hybrid coupler is designed from different phase between mutual-interference and self-interference. As a result, it is that the success of interference signal cancellation by using the novel technique is proposed. The results show that the proposed technique is not only to suppress the interference but also to improve the system performance capacity.

Problem Formulation

In this section, the authors explain the basic challenges in building a full-duplex radio. However, the authors consider the full-duplex wireless communication operating on the same frequency and at the same time. The proposed FDSC MIMO system can transmit and receive simultaneously, which the self-interference and mutual-interference signals are the main problem of communication. Hence, the main key success is to eliminate the self-interference and mutual-interference signals as much as possible.

A. Full-Duplex Single-Channel MIMO Systems

As shown in Figure 1, our design is a single channel 2 × 2 MIMO systems (i.e. the MIMO system employs the multiple antennas to transmit and receive on the same frequency and the same time). Each antenna is connected with circulator (CR) to transmit and receive signals simultaneously. However, the imperfection of circulator allows the transmitting signal leak into the receiving path, so called self-interference. A single antenna is connected to a circulator at 2^{nd} port, which provides limited isolation between 1^{st} port and 3^{rd} port as shown in Figure 1. The transmitted signal is fed through 1^{st} port, which routes it to the antenna connected to 2^{nd} port while the received signal from the antenna is passed to 3^{rd}port through 2^{nd} port. A circulator cannot isolate the 1^{st} port and 3^{rd} port completely. So, the transmitted signal leaks (self-interference) from 1^{st} port to 3^{rd} port and cause interference to the received signal.

The problem of MIMO system is the effect of mutual coupling. The mutual coupling describes energy absorbed by one antenna's receiver when another nearby antenna is operating. The mutual coupling (Shi H., et al., 2012) is typically undesirable because energy that should be radiated away is absorbed by a nearby antenna. Similarly, energy that could have been captured by one antenna is instead absorbed by a nearby antenna. Hence, mutual coupling reduces the antenna efficiency and performances of antennas in both transmit and receive mode. The problem of mutual coupling is called as mutual-interference shown in Figure 1. Furthermore, the problem of mutual-interference cannot neglect because the power of mutual-interference is stronger than self-interference. Thus, the main challenge of 2×2 FDSC MIMO system is to cancel both self-interference and mutual-interference signals.

B. System Model

In this section, the theoretical model of MIMO system is proposed with m transmitting antennas and n receiving antennas. Let x be the desired signal, H is the channel between transmitting and receiving antennas. The received signal, y can be written as

$$y = H * x + n \tag{1}$$

where $(*)$ denotes the convolution operator. The FDSC system uses a single antenna for transmitting and receiving paths. The proposed system has the strong self-interference and mutual-interference signals at the receiving antenna. The received signal can be written as

$$y = H * x + H_I * s + n \tag{2}$$

where H_I is the interference channel for both self-interference and mutual-interference. s is the transmitted signal. The interference channels are the combination of both self-interference and mutual-interference channels, H_I is given by

$$H_I * s = H_{SI} * s + H_{MI} * s \tag{3}$$

where H_{SI} denotes the self-interference channel. H_{MI} denotes the mutual-interference channel. The interference signal can be estimated by subtracting with the known transmitted signal which the defined channel is shown by $\widetilde{H_I}$. The received signal after the estimation of interference channel, $\tilde{y} = \widetilde{H_I} * s$, can be written as

$$y - \tilde{y} = H * x + H_I * s - \widetilde{H_I} * s + n \tag{4}$$

The challenges of FDSC communication for MIMO systems are to cancel the power levels of self-interference and mutual-interference at the receiving antennas. Therefore we proposed to design the interference cancellation technique. We design the analog cancellation part.

Design for Interference cancellation

In this section we describe the design of analog cancellation technique. Our design is a single antenna system (i.e. the same antenna is used to simultaneously transmit and receive at the same time and on the same frequency). The novelty of our work lies in the design and implement of the RF cancellation, as well as their performance.

A. Modified hybrid coupler

This section describes the design of 90° hybrid coupler, which inputting signal of each input ports are sent to each output ports. The 90° hybrid coupler have phase shifts and amplitude balance. The 90° hybrid coupler is called branch line couplers by using transmission lines. In (Nachouane H., et al., 2014; Zhou C., et al., 2014) the design of microstrip transmission lines, the signal at output ports are attenuated three decibels and a 90° phase of the each lines. The each transmission lines have length depend on the center frequency. Hence, this paper presents to design FDSC communication for 2×2 MIMO systems as shown in Figure 2. We design modified hybrid coupler by designing the green lines denote first antenna and the red lines denote second antenna that the $3^{rd}$and 4^{th} ports are represented the input of modified hybrid coupler and the 5^{th} and 6^{th} ports are represented the output of modified hybrid coupler. In the first antenna, the 3^{rd} port is the reference signal for self-interference and the 4^{th} port is the reference signal for mutual-interference that it is the effect of mutual-interference signal of the first antenna. In the second antenna, the 4^{th} port is the reference signal for self-interference signal and the 3^{rd} port is the reference signal for mutual-interference that it is the effect of mutual-interference signal of the second antenna. So, we can find coefficient of modified hybrid coupler and phase of modified hybrid coupler. The modified hybrid coupler is proposed to difference phase between self-interference and mutual-interference signals, as described in the following.

B. Design of analog cancellation

The novel technique is described on design and implementation of analog cancellation. As we know that the advantages of this communication systems are the amplitude and phase of self-interference and mutual-interference signals from the measurement results. It can be designed and developed the system in order to reduce the power levels of interference signals. The design of the circuit considers phase and amplitude of signals using analog cancellation technique for the circulator leakage and mutual coupling between antennas. To cancel interference signals, it includes the attenuators, modified hybrid coupler and phase shifters.

Thus, we propose technique to cancel the self-interference and mutual-interference signals by using modified hybrid coupler and phase shifter as shown in Figure 2. The green lines is the signals at the first antenna and the red lines is the signals at the second antenna. The signals of the 1^{st} port can be written as

$$x_1^i = A_1 e^{-j(\omega t + \emptyset_1)} \tag{5}$$

where A_1 is amplitude of the 1^{st} port and $\emptyset_1$ is phase of the 1^{st} port at the i^{th} antenna. The signals of 2^{nd} port is denoted by $x_2^i = A_2 e^{-j(\omega t + \emptyset_2)}$. When the x_1^i signal is transmitted to coupler, which is separated into two ways. The principal power of x_1^i signal goes through the antenna and the residual in the 3^{rd} port is the input of modified hybrid coupler. From the diagram of the first antenna, the signal in the 3^{rd} port is the reference signal for self-interference signal and the signal in the 4^{th} port is the reference for mutual-interference. Then, the combination of reference signals of self-interference and mutual-interference at the first antenna can be written as

$$x_{cm1}^i = \frac{1}{\sqrt{2}}\left(\alpha_{c_{11}}\alpha_{cm_1}A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{11}} + \emptyset_{cm_1}\right)} + \alpha_{c_{21}}\alpha_{cm_2}A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{21}} + \emptyset_{cm_2}\right)}\right) \tag{6}$$

where $\alpha_{c_{11}}$ *and* $\alpha_{c_{21}}$ denote the attenuation coefficients of the 3^{rd} and 4^{th} ports respectively, $\emptyset_{c_{11}}$ and $\emptyset_{c_{21}}$ denote the phases of the 3^{rd} and 4^{th} ports respectively, α_{cm_1} *and* α_{cm_2} denote the attenuation coefficients of the received signals at the first and second antennas respectively, $\emptyset_{cm_1}$ *and* $\emptyset_{cm_2}$ denote the phases of the received signals at the first and second antennas, respectively. The signal of 7^{th} port is transmitted into circulator. The signal leakage is happened because imperfection of circulator. This leakage is named as self-interference signal, which can be written as

$$x_{L1}^i = (1 - \alpha_{c_{11}})\alpha_L A_1 e^{-j\left(\omega t + \emptyset_1 + \emptyset_{c_{12}} + \emptyset_L\right)} + (1 - \alpha_{c_{21}})\alpha_t \alpha_{mc} \alpha_t A_2 e^{-j\left(\omega t + \emptyset_2 + \emptyset_{c_{22}} + \emptyset_t + \emptyset_{mc} + \emptyset_t\right)} \tag{7}$$

where α_L and $\emptyset_L$ denote the attenuation coefficient and phase of the signal leakage from circulator respectively. α_t and $\emptyset_t$ denote the attenuation coefficient and phase of the coaxial cable respectively. α_{mc} and $\emptyset_{mc}$ denote the attenuation coefficient and phase of the mutual-interference signals, respectively. The main concept of analog interference cancellation is the suitable design of modified hybrid coupler and phase shifters by phase of 5^{th} port and the phase of 9^{th} port differ π. The amplitude of both signals should be approximately the same level. As shown in (8), the received signal R_{11}^i must be equal the desired receiving signaly_3^i. The interference signals are perfectly suppressed, $x_{cm1}^i = -x_{L1}^i$ can be written as

$$R_{11}^i = y_3^i + x_{cm1}^i + x_{L1}^i \tag{8}$$

So, the attenuation coefficients and phase shifts are matched, $x_{cm1}^i = x_{L1}^i$ can be rewritten as

$$(1-\alpha_{c_{11}})\alpha_L A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{12}}+\emptyset_L)} = -\frac{1}{\sqrt{2}}\alpha_{c_{11}}\alpha_{cm_1}A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{11}}+\emptyset_{cm_1})} \tag{9}$$

and

$$(1-\alpha_{c_{21}})\alpha_t\alpha_{mc}\alpha_t A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{22}}+\emptyset_t+\emptyset_{mc}+\emptyset_t)} = -\frac{1}{\sqrt{2}}\alpha_{c_{21}}\alpha_{cm_2}A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{21}}+\emptyset_{cm_2})} \tag{10}$$

Therefore, the self-interference and mutual-interference cancellations are that the design the modified hybrid coupler based on (9) and (10).

When considering the second antenna, the principal power of x_2^i signal goes through the antenna and the residual in the 4^{th} port is the input of modified hybrid coupler. From the diagram of the second antenna, the signals in the 4^{th} and 3^{rd} ports are the reference signals for self-interference and mutual-interference, respectively. The combination of reference signals of self-interference and mutual-interference at the second antenna (x_{cm2}^i) are same as that of the reference signals at the first antenna (x_{cm1}^i) as defined in (6).

Next, the signal leakage of circulator at the 8^{th} port can be written as

$$x_{L2}^i = (1-\alpha_{c_{21}})\alpha_L A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{22}}+\emptyset_L)} + (1-\alpha_{c_{11}})\alpha_t\alpha_{mc}\alpha_t A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{12}}+\emptyset_t+\emptyset_{mc}+\emptyset_t)} \tag{11}$$

As shown in (12), the received signal R_{12}^i must be equal the desired receiving signal y_4^i. The interference signals are perfectly suppressed, $x_{cm2}^i = -x_{L2}^i$ can be written as

$$R_{12}^i = y_4^i + x_{cm2}^i + x_{L2}^i \tag{12}$$

So, the attenuation coefficients and phase shifts are matched, $x_{cm2}^{i} = x_{L2}^{i}$ can be rewritten as

$$(1-\alpha_{c_{21}})\alpha_L A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{22}}+\emptyset_L)} = -\frac{1}{\sqrt{2}}\alpha_{c_{21}}\alpha_{cm_2} A_2 e^{-j(\omega t+\emptyset_2+\emptyset_{c_{21}}+\emptyset_{cm_2})} \quad (13)$$

and

$$(1-\alpha_{c_{11}})\alpha_t\alpha_{mc}\alpha_t A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{12}}+\emptyset_t+\emptyset_{mc}+\emptyset_t)} = -\frac{1}{\sqrt{2}}\alpha_{c_{11}}\alpha_{cm_1} A_1 e^{-j(\omega t+\emptyset_1+\emptyset_{c_{11}}+\emptyset_{cm_1})} \quad (14)$$

Finally, this proposed method is that the amplitude and phase of self-interference and mutual-interference signals can be calculated from only measurement. Figure 3 shows the measurement of FDSC 2 × 2 MIMO system by using analog cancellation technique. For the measured self-interference signal, the 1^{st} port of the network analyzer connects with the power splitter. The signal is sent from 1^{st} to 3^{rd} ports of circulator. For the measured mutual-interference signal, the one antenna receives a signal from another antenna. The modified hybrid coupler and phase shifter are the reference signals which are designed to reduce the power levels of interference signals. Thus, the values of amplitude and phase of interference signals will not be changed because all positions are determined. Hence, the proposed circuit can cancel interferences very well.

Results and Discussion

A. Channel Capacity

In this section, the interference channels are pre-known from the signal leakage and the effect between antennas (mutual coupling). This is the average of capacity in bits per second per Hertz (bps/Hz). Hence, the uniform transmitting power is assumed for each antenna, $\left(E\{\boldsymbol{x}\boldsymbol{x}^H\} = \frac{P_o}{N_s}\boldsymbol{I}_x\right)$. The capacity of FDSC 2 × 2 MIMO system can be written by (15)

$$C = \log_2 det[\boldsymbol{I} + \frac{P_o}{N_s}\boldsymbol{H}_I\boldsymbol{H}_I^H \times \left(\boldsymbol{\sigma}_I^2\boldsymbol{H}_I'\boldsymbol{H}_I'^H + \boldsymbol{\sigma}_d^2\boldsymbol{I}\right)^{-1}] \quad (15)$$

where P_o denotes the maximum received power, N_s denotes the power of interference signals. Figure 4 shows the performance of capacity by considering three cases. In first case, there is no the self-interference and mutual-interference signals in the system, so called as without interference. The second case is that the analog cancellation is proposed on the FDSC 2 × 2 MIMO system (by using modified hybrid coupler and phase shifters technique) for self-interference and mutual-interference signals. In last case, we have not used any cancellation technique to eliminate the self-interference and mutual-interference signals so there will be interference.

The simulation of MATLAB programming can be described as follows. The source and destination are assigned with two transmitting and two receiving antennas; $x = s = 2$. The interference channel H_I is the combination of both self-interference as well as mutual-interference channels, H_{SI} and H_{MI}. Figure 4 shows the channel capacity versus SNR with the FDSC 2 × 2 MIMO system. As seen in Figure 4, the proposed technique lies between with and without the interference cancellation. The capacity of the proposed technique is about 3.907 bps/Hz (at SNR = 20 dB) higher than the system with interference signals.

B. Performance of FDSC 2 × 2 MIMO system

In this paper, the design digital cancellation employs Space Time Block Coding (STBC) technique to eliminate the residue of the self-interference and mutual-interference signal after analog cancellation with the known transmitted signals. All signals are sent to decoder in order to check error rate. As shown in Table 1, when the distance between transmitter and receiver is 35 cm. then the conventional one way 2 × 2 MIMO gives BER of 0.2267. Whereas the proposed 2 × 2 MIMO system (full-duplex) gives BER of 0.2494 by using the self-interference and mutual-interference cancellation techniques. In last case, we have not used any cancellation techniques for 2 × 2 MIMO system (full-duplex) so it increases the error rate and it comes out to be BER of 0.6688. Thus, the self-interference and mutual-interference signals have not happened with the conventional one way 2 × 2 MIMO system so it has lower bit error. Experiment result shows that the proposed technique can improve the BER performance better than the system without any cancellations for farther distances. The FDSC 2 × 2 MIMO system without any cancellations provides the maximum error rate. It means that the proposed technique can eliminate both self-interference and mutual-interference signals and improves the performance of the system by decreasing the BER.

Conclusion

Analog cancellation technique is proposed using modified hybrid coupler and phase shifters. In this paper, we design the model of FDSC 2 × 2 MIMO system. We proposed the method of analog cancellation for the self-interference and mutual-interference cancellations. The performance of proposed technique can cancel the interference signals using pre-known interference signals which are affected by signal leakage and mutual coupling between antennas. Simulation results show that the self-interference and mutual-interference are eliminated with proposed analog cancellation. It can be achieved in FDSC 2 × 2 MIMO system which can illustrate with the more capacity.

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Table 1. The measured BER versus distance for FDSC 2 × 2 MIMO system.

Distance (cm.)	Bit Error Rate		
	2 × 2 MIMO, one way.	FDSC 2 × 2 MIMO, analog and digital cancellations.	FDSC 2 × 2 MIMO, without any cancellations.
35	0.2267	0.2494	0.6688
50	0.2316	0.2493	0.7409
90	0.2449	0.2513	0.7489

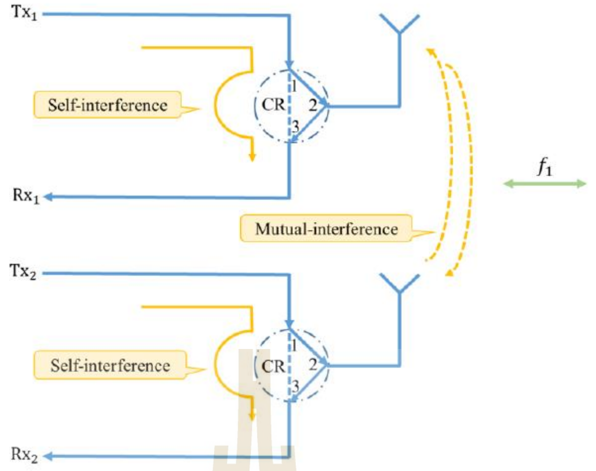

Figure 1. **The 2 × 2 FDSC MIMO system with both self-interference and mutual-interference signals.**

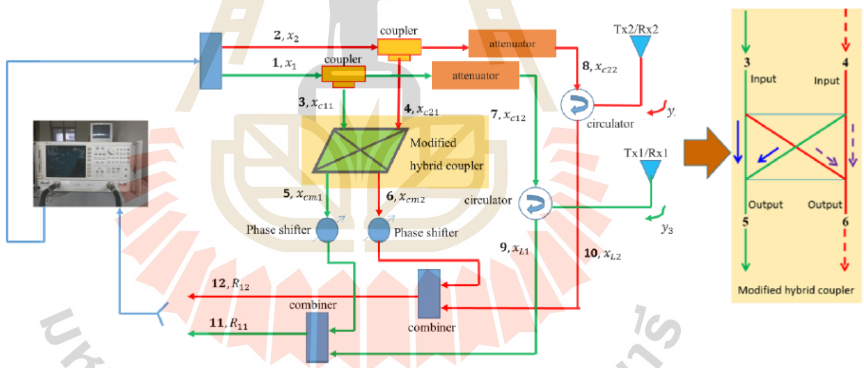

Figure 2. **The block diagram of analog interference cancellation part.**

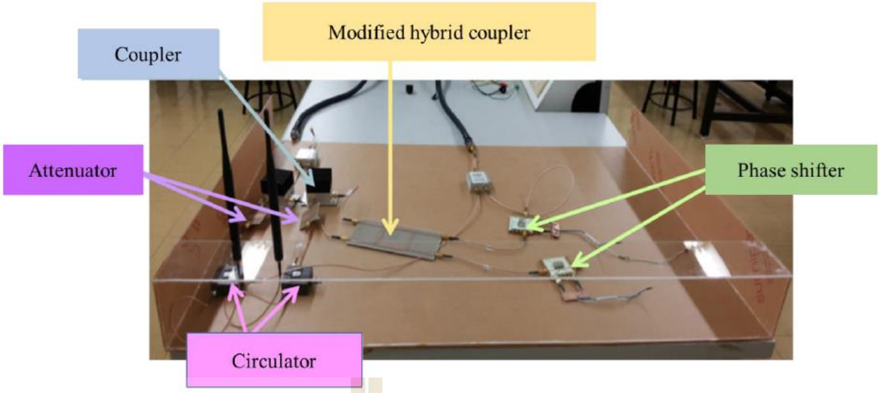

Figure 3. The measurement of FDSC 2 × 2 MIMO systems on the analog cancellation technique.

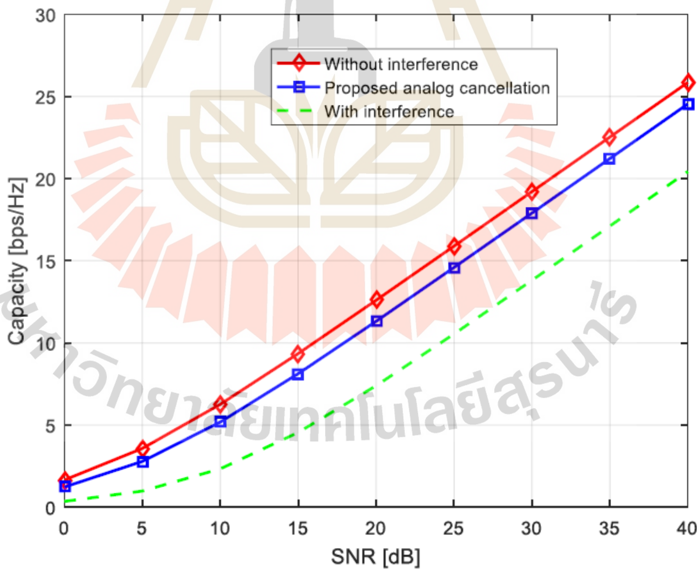

Figure 4. Capacity versus SNR for 2 × 2 MIMO system.

BIOGRAPHY

Miss Pawinee Meerasri was born in Suphanburi, Thailand, in 1990. She graduated with the Bachelor degree of Engineering in Telecommunication Engineering in 2011 from Suranaree University of Technology, Nakorn Ratchasima, Thailand. Then, she is currently pursuing her Ph.D program in Telecommunication Engineering, School of Telecommunication Engineering, Suranaree University of Technology. Her research interests are 5G mobile, wireless communication and its application.