DOA-ASSISTED ORTHOGONAL BEAMFORMING WITHOUT FEEDBACK INFORMATION

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ปาลีรัตน์ วงจำปา : การก่อรูปลำคลื่นแบบตั้งฉากโดยอาศัยทิศทางการมาถึงของสัญญาณซึ่งปราศจากข้อมูลย้อนกลับ (DOA-ASSISTED ORTHOGONAL BEAMFORMING WITHOUT FEEDBACK INFORMATION) อาจารย์ที่ปรึกษา : รองศาสตราจารย์ ดร.มนต์ทิพย์ภา อุทารสกุล, 134 หน้า

มาตรฐานของระบบการสื่อสารไร้สายได้ถูกพัฒนาจากการสื่อสารแบบผู้ใช้งานเดียวไปสู่การสื่อสารแบบหลายผู้ใช้งาน เพื่อให้ผู้ใช้งานมีการส่งข้อมูลที่ดีขึ้น ลดการใช้พลังงานและครอบคลุมพื้นที่ที่กว้างขึ้น การสื่อสารแบบหลายผู้ใช้งานเป็นการส่งข้อมูลจากสถานีฐานไปยังผู้ใช้งานหลายๆ ผู้ใช้งานพร้อมกันอย่างเป็นอิสระต่อกันที่เวลาและความถี่เดียวกัน ที่ผ่านมาได้มีการนำเทคโนโลยีสายอากาศหลายต้นมาช่วยพัฒนาระบบการสื่อสารไร้สายให้มีประสิทธิภาพยิ่งขึ้น โดยส่วนใหญ่แล้วจะต้องมีการป้อนกลับของช่องสัญญาณหรือข้อมูลย้อนกลับจากผู้ใช้งานไปยังสถานีฐาน ซึ่งเป็นกระบวนการที่มีความซับซ้อนและยุ่งยากในการประมวลผล และสิ้นเปลือง อีกทั้งช่องสัญญาณมีการเปลี่ยนแปลงตลอดเวลาอาจทำให้สัญญาณย้อนกลับเกิดความผิดเพี้ยนไปได้ ดังนั้นจึงเกิดแนวคิดที่จะปรับปรุงประสิทธิภาพการก่อรูปลำคลื่นที่เหมาะสมกับการนำไปใช้ในระบบการสื่อสารหลายผู้ใช้และไม่มีการป้อนข้อมูลหรือช่องสัญญาณย้อนกลับ ซึ่งเรียกว่าการก่อรูปลำคลื่นแบบตั้งฉาก โดยจะสามารถก่อรูปลำคลื่นหลักไปยังผู้ใช้งานได้หลายผู้ใช้งานพร้อมกันและที่ความถี่เดียวกัน โดยส่วนที่เป็นพูข้างจะต้องไม่รบกวนผู้ใช้งานคนอื่นๆ วิธีการนี้อาศัยการประมาณทิศทางการมาถึงของสัญญาณของแต่ละผู้ใช้งาน เพื่อช่วยทำให้การก่อรูปลำคลื่นมีลักษณะตั้งฉากซึ่งกันและกัน กล่าวคือลำคลื่นหลักจะหันไปยังทิศทางของผู้ใช้งานแต่ละคนโดยเฉพาะและจะต้องไม่รบกวนผู้ใช้ในทิศทางอื่นๆ วิทยานิพนธ์ฉบับนี้ยังได้นำเสนอการจำลองแบบและออกแบบสร้างระบบต้นแบบเพื่อทดสอบในสภาพแวดล้อมจริง ผลจากการจำลองแบบและผลการการทดสอบชุดอุปกรณ์ต้นแบบพบว่า การก่อรูปลำคลื่นแบบตั้งฉากให้ค่าอัตราส่วนสัญญาณต่อสัญญาณแทรกสอดและค่าวิสัยสามารถได้มากกว่าการก่อรูปลำคลื่นแบบดั้งเดิม และยังให้ค่าความผิดพลาดบิตต่ำกว่าการก่อรูปลำคลื่นแบบดั้งเดิม

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PALEERAT WONGCHAMPA : DOA-ASSISTED ORTHOGONAL
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MULTI-USER COMMUNICATIONS/ARRAY ANTENNAS/BEAMFORMING/
CO-CHANNEL INTERFERENCE/ NON FEEDBACK/ ORTHOGONAL BEAMS

Standards of wireless communication systems have been developed from single-user to multi-user communications so that users can gain a higher data transmission speed, a reduction of power consumption and a wider coverage. For the multi-user transmission, a base station transmits data to a number of users using the same frequency at the same time. So far, multiple antenna technology has been taken into account to upgrade the multi-user communication systems. However, most of them can be accomplished with the help of feedback information or channel in order to keep the accuracy of the received data. Consequently, the systems are relatively complicated and need high power consumption. Therefore, this thesis proposes an alternative beamforming for multi-user communications, so called orthogonal beamforming. A number of beams are formed in pre-defined directions at the same time, where all beams also use the same frequency. This orthogonal property helps the systems avoid interference in the direction of mainbeam. The proposed orthogonal beamforming also requires the estimation of direction of arrival (DOA) for users of interest because this work applies the DOA in order to adjust the weighting coefficients of array antennas. To validate the proposed concept, computer simulations and experiments in various scenarios are performed. The obtained simulation results reveal that the orthogonal beamforming provides higher Signal to Interference plus Noise Ratio (SINR) over conventional beamforming. In addition, a constructed prototype tested in real indoor environment reveals that the proposed orthogonal beamforming provides higher received signal strength and throughput but low packet error rate compared to conventional beamforming.

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มหาวิทยาลัยเทคโนโลยีสุรนารี

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SYMBOLS AND ABBREVIATIONS

AP = Access Point

BER = Bit Error Rate

BFM = Conventional BeamForMing

BS = Base Station

DOA = Direction of arrival

ESPRIT = Estimation of signal parameters via rotational invariance technique

LOS = Line of sight

LTE = Long term evolution

MIMO = Multiple input multiple output

MSS = Maximum segment size

MU-BFM = Multi-user with conventional beamforming

MU-MIMO = Multi-user with multiple input multiple output

MU-OBFM = Multi-user with orthogonal beamforming

MUSIC = Multiple signal classification

MVDL = Minimum variance distortionless look

NLOS = Non line of sight

OBFM = Orthogonal beamforming

PER = Packet error rate

PU^{2}RC = Per-user unitary rate control

RSSI = Received signal strength indicator

SYMBOLS AND ABBREVIATIONS (Continued)

RTT = Round trip time

SINR = Signal to interference plus noise ratio

SNR = Signal to noise ratio

SU-BFM = Single-user with conventional beamforming

SU-MIMO = Single-user with multiple input multiple output

TCP = Transmission control protocol

USRP = Universal software radio peripheral

ZF = Zero forcing

CHAPTER I

INTRODUCTION

1.1 Background and problems

Nowadays, wireless communication technologies play an important role in people's daily lives because people constantly exchange or consume information most of the time. This includes information file transmission, information search on Internet or chatting and sending massages. Accordingly, the number of wireless users have significantly increased from past to present and will be greatly multiplied in the near future. As a result, numerous wireless communication standards have been continually developed to respond to the increasing needs, including a higher speed of data transmission, a higher mobility, a higher reliability and a wider service coverage. These requirements cater multimedia data communications consisting of image data, audio data and other communication data, which all take the same limited frequency spectrum.

An increase in data transmission speed and supporting a large number of users are important keys which have driven research in wireless communication areas so far. The main focus is to develop wireless communication standards which include the standard of mobile wireless communications developed from the 1st through the 5th periods and so on (Afif Osseiran et al, 2014; Shanzhi Chen and Jian Zhao, 2014). At the beginning, people communicate to one another via only voice transmission. Later a multimedia data communications became available by enhancing the system capacity. This includes enhancing the effectiveness of data transmission and enabling information exchange, hence providing more comfortable daily lives. A recent development of mobile wireless communications is based on Long Term Evolution (LTE) technology which is one of the international standards from the Third Generation Partner Ship Project (3GPP) and is a further development of the Third Generation mobile telecommunications (3G). The main goal of LTE technology is to provide higher speed of data transmission and to reduce latency which enables users to perform video conference within a limited frequency spectrum (Amitava Ghosh et al, 2010 and Erik Dahlman, Stefan Parkvall, Johan Skold, 2011).

Wireless Local Area Network (WLAN) standard or IEEE802.11 (IEEE Standard 802.11, 1999) is a standard widely used in many areas. In its early stage, the effectiveness of WLAN performance was quite low and its service quality was not guaranteed. This resulted in having the development of IEEE802.11a which has a capability to transmit data at 54 Mbps but within a short distance. After that, IEEE802.11b and IEEE802.11g were developed to work together to support wider service areas and higher speed of data transmission. Then, IEEE802.11n which provides data transmission at a speed of 100 Mbps was developed. Ultimately, IEEE802.11ad, a new standard, is developed for a faster effectiveness of frequency transmission resulting in higher speed, longer distance and better penetration through obstacles (Richard Van Nee, Qualcomm Inc, 2011).

Worldwide Interoperability for Microwave Access (WIMAX) is a high-speed wireless broadband technology based on IEEE802.16 technology providing high-speed wireless communication service in suburbs which works well, even with obstacles

(Daan Pareit et al, 2012). The WIMAX enables users to expand Internet connection networks and to acquire higher speed of data transmission.

All aforementioned standards share the same objectives which aim to serve the increasing needs of users, enable higher speed of data transfer and provide wide coverage. At the beginning, all standards were designed to transmit data in point-to-point scheme, so called single-user communications. This can be pictured as a base station transmitting data to one user at a time. A transmission direction is straight without any obstacles so that data can be transferred in a long distance with high speed. However, in this case, the frequency spectrum cannot be efficiently used, hence the obtained channel capacity is relatively low. Later, IEEE802.11ac, IEEE802.11ad, IEEE802.16 and LTE-A release 12-15 have been developed for point-to-multipoint scheme, so called multi-user communications (Buon Kiong Lau et al, 2012 and Lingjia Liu et al, 2012). This enables users to have higher effectiveness of data transmission, to reduce energy consumption and to gain larger coverage. In multi-user communications a base station transmits data to a number of users at the same time and the same frequency. This increases an efficient use in frequency bandwidth and throughput compared with single-user communications. So far, there are a number of literatures which compare the performance between single-user and multi-user communications (Hieu Duy Nguyen, 2013; Liangbin Li, 2013 and Pei Xiao, Mathini Sellathurai, 2010). Such investigations have revealed that a data transmission in multi-user communication systems is of higher rate compared to single-user systems. However, multi-user transmission still experience signal interference when the same frequency is utilized at the same time. Therefore, several research studies have proposed the remedy for the mentioned signal impairment. The work presented in Emil

Björnson (2013) and Nikhil Gupta, Aditya K. Jagannatham (2014) proposed the utilization of multiple antenna technology for increasing data transmission speed and coverage area. This can be achieved because the increase in the number of antennas gives rise to degrees of freedom of the systems. Additionally, this is a less-complicated and low-cost technology to reduce signal interference from other users hence the system Signal-to-Interference plus Noise Ratio (SINR) increases (Peter J. Smith, 2014; Rafik Addaci, 2014 and Mohammad Hassan Shariat, 2013). Moreover, the work presented in Siyoung Choi (2014), Janne Ilvonen (2014) and Redha M. Radaydeh, Mohamed-Slim Alouini (2014) has shown that a multiple antenna technology is able to provide efficient utilization in a limited frequency spectrum.

From the literatures, the feedback methodology of multiple antenna technology can be divided into 2 types as follows: 1) Utilization of channel feedback, such as MIMO technology and Per-User Unitary Rate Control (PU^{2}RC). These techniques require identification of the current channel in which data will be transmitted through the channel and sent back to complete the round trip communications. 2) Utilization of information feedback, such as distributed beamforming technique and opportunistic beamforming. These techniques require feedback loops to pick up signals, to generate a reference signal and send it back to feedback procedures to be used for a weighted mean calculation. The mentioned channel and information feedback is a process to synchronize both transmitter and receiver so that they can communicate with the correct data. The advantages of the two-way feedback are that there are few errors in data transmission and also it can increase the effectiveness of data transmission. However, its processing procedures are complicated and consume energy. Significantly, if there is a high attenuation in the feedback channel, a reference signal may be incorrect. Also, the communication channel alters all the time. So, the channel estimation is difficult to be completely predicted.

As some drawbacks of aforementioned feedback transmission, a multi-user transmission without channel or information feedback has been proposed to reduce complicated procedures. The proposed concept is to utilize multiple antennas to provide maximum gain in the direction of the desired user while reducing attenuation in interference directions. However, this technique has limitation when applied to a multi-user transmission. As a number of users operate at the same time and the same frequency, signal can interfere one another, hence the system SINR and throughput are relatively low for multi-user communication systems. However, lots of null steering schemes proposed in literatures (Reeta Gaokar and Alice, 2011 and Maja Sarevska et al, 2008) cannot be applied to tackle the mentioned impairment. This is because they cannot handle multi-direction operation at the time and the same frequency. So, this paper proposes an alternative approach in beam formation when all beams operate at the same time and the same frequency in order to ease the mentioned interference signal. The proposed concept needs a help of Direction Of Arrival (DOA) estimation from some signal processing methods available in literatures. The systems can utilize these predicted knowledge to form a number of orthogonal beams in which all beams perform self-maximized gain in one direction and null steering to the rest pre-defined beams when all beams operate at the same frequency and the same time, so called an *orthogonal beamforming*.

1.2 Research objectives

The objectives of this research are as follows:

1.2.1 To propose an orthogonal beamforming technique for multi-user communications without feedback information. The orthogonal beamforming with the help of DOA estimation is proposed to avoid interference in the main beam direction as all beams are launched at the same time and the same frequency.

1.2.2 To design and construct a prototype of orthogonal beamformer in order to validate the proposed concept under real circumstances.

1.3 Scope of and limitation of the study

1.3.1 All simulation results have been performed by own developed MATLAB programming.

1.3.2 The performances of proposed orthogonal beamforming in multi-user communications are compared with the ones employing a conventional beamforming.

1.3.3 The proposed orthogonal beamforming needs a help of DOA estimation from some signal processing methods available in literatures.

1.3.4 The experimental results are based on static scenario and indoor environment.

1.4 Contributions

1.4.1 To obtain the concept for orthogonal beamforming without feedback information for multi-user communications.

1.4.2 The orthogonal beamforming can reduce interference from there users at the same time and the same frequency for multi-user communications.

1.4.3 To obtain a prototype of orthogonal beamformer, which can increase the performance of multi-user communications.

1.5 Thesis organization

The remainder of this thesis is organized as follows. The literature reviews are discussed in Chapter II. This chapter also presents the communication systems including the utilization of a multiple antenna technology in multi-user communications and the problem formulation of employing a conventional beamforming in multi-user communications.

Chapter III describes the background theory of array antennas including the conventional beamforming and DOA estimation algorithms. This knowledge is important to be a useful tool for designing the proposed orthogonal beamforming.

Chapter IV presents the proposed orthogonal beamforming. The aim of the orthogonal beamforming is to propose an alternative approach to perform a multiple-beam formation without any feedback procedure for multi-user communications in which all users operate at the same time and the same frequency.

Chapter V presents the simulation results to show the performance of proposed orthogonal beamforming in multi-user communications compared with a conventional beamforming. The impact of different parameters, such as the distance between users and base station, and also the transmitted power on the average SINR are also investigated.

In Chapter VI, the experimental setup including experimental results are presented and discussed. This chapter validates the proposed concept via testing a constructed prototype of proposed orthogonal beamformer under real circumstances.

Chapter VII provides the conclusions of the research work and suggestion for further study

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The details of this section introduce for the literature reviews relating to the objectives of this dissertation. This section begins with a brief concept of communication systems including wireless communication standards. Then, the multiple-antenna technology is applied in multi-user communications. Afterwards, this section presents the problem formulation of conventional BeamForMing (BFM) when applied to multi-user communications. The last section concludes this chapter.

2.2 Communication systems

All wireless communication standards have been continually developed to respond to the increasing needs such as a higher speed of data transmission, a higher mobility, a higher reliability and a wider service coverage. At the beginning, all standards were designed to transmit data for point-to-point scenarios as known as single-user communications. In this case, the direction of transmission is line of sight without any obstacles so that data can be transferred in a long distance with a high-speed. However, in this case, the frequency spectrum is not efficiently used, hence the obtained channel capacity is relatively low. Then, all new standards of wireless communications were developed for point-to-multipoint scenarios, so called multi-user communications, to improve a spectrum efficiency, reduce an energy consumption and gain a larger coverage (Buon Kiong, Lau et al, 2012 and Lingjia Liu et al, 2012). Here is some brief discussion regarding single-user and multi-user communication background where we can see advantages and disadvantages for these two distinguished communication systems.

2.2.1 Single-user communication systems

A single-user communication system is a point-to-point communications between a base station and user terminals. In this system, a base station transfers data to one user at a specific time or frequency as shown in Figure 2.1. Recently, a multiple antenna technology has been adopted for increasing the system gain and coverage, usually attached at the base station. In this case, if several users transmit data at different time but the same frequency, their data transmission rate is relatively low. Vice versa, if they utilize the same time slot but occupy different individual frequencies, user congestion occurs as they cannot efficiently utilize the frequency spectrum. Nonetheless, advantages of this kind of communication systems is that the systems are not complicated and interference signal having the same frequency is not pronounced. However, these advantages come with non-fascinating transmission speed and throughput.

2.2.2 Multi-user communication systems

With the rapid growth of a number of wireless communication users, lots of attempts have been push to allow several users to communicate to one another at the same time and the same frequency in order to increase data transmission speed, channel capacity and system throughput, so called multi-user communication systems. Figure 2.2 depicts the configuration of multi-user communication systems with a number of antenna elements employed at the base station. Not only the frequency spectrum can be efficiently utilized, but also the data transmission speed can be increased without the use of multiple antenna elements at the user side, hence the problem of distance-related correlations in array antennas can be avoided. From literatures, there have been lots of studies regarding the comparison of system effectiveness between single-user and multi-user communications (Hieu Duy Nguyen, 2013; Liangbin Li, 2013; Pei Xiao, Mathini Sellathurai, 2010; Stefan Schwarz, Robert W Heath, Markus Rupp, 2013 and Saurabh Dixit, Himanshu Katiyar, 2014). So far, multi-user communications have been applied to various wireless communication standards such as 4G/IMT-Advance, LTE-Advance, 802.16m/WIMAX, 802.11ac and 802.11ad. Nevertheless, the major problem of multi-user communications is that users become interference to themselves as they are operating at the same time and the same frequency.

2.3 Multiple-antenna technology in multi-user communications

So far, the wireless communication systems have been rapidly developed. The goal of wireless communications is to support an increasing number of users with a rapid transmission rate and also to extend a coverage area. From previous section, the literature investigations have revealed that the data transmission in multi-user communications is of higher rate compared with single-user communications. The standard of wireless communications has been developed from single user to multi-user which requires an information transmitting from base station to a number of users simultaneously and independently at the same time and the same frequency. However, the multi-user communications still have signal interference occurring when the same frequency is utilized at the same time. Therefore, lots of research studies have proposed the remedy to the mentioned impairment. The multiple-antenna technology is one of the method and regarded as a significant role in the development of the multi-user communications performance. Moreover, the multiple-antenna technology has been taken into account to upgrade the wireless communication systems. Many works have been proposed to enhance the performance of the multi-user communications. Accordingly, the literatures can be classified into 3 types regarding the beam formation for multi-user communications as shown in Figure 2.3.

This classification is based on the feedback from users or receivers. The first one is the utilization of channel feedback such as Multiple-Input Multiple-Output (MIMO) and Per-user Unitary Rate Control (PU^{2}RC). The second one is the utilization of information feedback such as Distributed Beamforming and Opportunistic Beamforming. The last classification is the method without channel or information feedback, so far known as BFM.

Focusing on multi-user communications, the most popular methods including a MIMO technology (B. N. Bharath and Chandra R. Murthy, 2013 and Vincent K. N. Lau et al, 2013), a PU^{2}RC (Sayed Ata Sattarzadeh, Ali Olfat, 2012 and 2014), a distributed beamforming (Eunsung Park et al, 2013 and Robert Heath et al, 2013) and an opportunistic beamforming (Ozgur Ozdemir, Murat Torlak, 2010) need some feedback channel or feedback information in order to meet the system requirements for having low bit error rate and high throughput. Figure 2.4 shows the procedure of feedback information or channel. The receiver or user obtains information of wireless channel (either perfect or imperfect) through some techniques such as training, feedback quantization and partial feedback etc. This channel information is then fed into a quantizer. Then, the receiver will return feedback bits to the transmitter on the reverse link. The transmitter or Access Point (AP) can use the received feedback bits to adapt the transmitted signal to the forward channel. However, this reflects a complicated processing to accomplish those tasks through an uncertain communication channel and also consumes lots of energy.

However, one technique avoiding the feedback information is a BFM technique employing the estimation of Direction Of Arrival (DOA). More detail for BFM is described in next section.

2.4 Problem formulation for conventional beamforming

As mentioned earlier, the conventional BeamForMing (BFM) does not require channel and information feedback. The beamforming or array signal processing is an action to create beam having maximum gain in a desired direction while providing a large attenuation in other directions which are usually the direction of interference signals. The beamforming systems normally consist of array antennas and signal processing units (Rivas, Shuguo Xie, 2010 and Klumperink et al 2012). The processing units are normally used to identify DOA of incoming signal and to point the main beam to the direction of desired signal. Lots of advantages obtained from having beam formation are such as an increased coverage area, a decrease of power consumption and an improved link quality/reliability (Nuteson et al, 2004 and Mack et al, 2004).

In general, the weighting coefficients for BFM can be simply calculated from the knowledge of user location. However, this BFM cannot be applied to multi-user communications as all users employing the same time slot and the same frequency become interference among themselves. Figure 2.5 represents a scenario for multi-user communications having 3 users operating at the same time and the same frequency. Also, Figure 2.6 shows beam patterns for the scenario displayed in Figure 2.5. As we can see, when user 1 is the user of interest, users 2 and 3 becomes interference as they are operating at the same frequency and time. According to this, Signal to Interference plus Noise Ratio (SINR) at user 1 is relatively high. Vice versa, user 1 also interferes users 2 and 3 as seen in Figure 2.5. Unfortunately, most of available null steering schemes cannot be applied for this scenario as nulls and main beams have to be produced in exactly the same directions. Recently, researcher have pursued the remedy of the mentioned problems e.g., MIMO technology or PU^{2}RC. However, these technologies needs feedback information between transmitter and receiver in order to obtain a lower Bit Error Rate (BER) and a higher throughput. However, this reflects a complicated processing to accomplish those tasks through an uncertain communication channel.

Therefore, the procedure without feedback is more interesting and simplifying. The without feedback does not require any feedback signal from the user and the reference signals among transmitting communications. So, the aim of this thesis is to propose an alternative approach to perform multi- beam formation without feedback procedure for multi-user communications in which all users operate at the same time and the same frequency. In this case, all beams are orthogonally formed in pre-defined directions, so called Orthogonal BeamForMing (OBFM) as shown in Figure 2.7. The proposed OBFM is into categorized the without feedback one comparing to Figure 2.3. The detail of proposed beamforming is shown in next section.

2.5 Chapter summary

This chapter has discussed literature reviews. Firstly, the introduction of various communication systems has been discussed. The advantages and disadvantages of these two communication systems have been described. Then, the multiple antenna technology has been taken into account to upgrade the wireless communication systems. The multiple antenna technology needs information or channel feedback from users such as MIMO technology, PU^{2}RC, distributed beamforming technique and opportunistic beamforming. However, the information or channel feedback procedures are relatively complicated and consume lots of energy via sending the feedback signal. Significantly, the feedback signal may be distorted as the communication channel is always unpredictable. However, one technique avoiding the feedback information is a BFM technique employing the estimation of DOA. However, the BFM cannot be applied to multi-user communications because the minor lobes from some other beams interfere the desired signal coming in the direction of main beam at the same time and the same frequency. According to this, the SINR and also throughput of the systems are low. According to the drawbacks of feedback transmission mentioned earlier, this thesis proposes an alternative beamforming for multi-user communications without feedback channel information.

CHAPTER III

BACKGROUND THEORY

3.1 Introduction

This chapter begins with the brief background of beam formation technology. This technology can be accomplished using array antennas and signal processing units. The signal processing units including weighting and summing play an important role to eliminate interference signals without any distortion to the desired signal. Afterwards, the effect of communication channel on beamforming performance will be discussed. Then, some popular Direction Of Arrival (DOA) estimation algorithms will be discussed as the information of signal direction is essential to the proposed beamforming for this thesis works. Finally, the last section concludes the chapter.

3.2 Beam formation

The beamforming or smart antenna technology is an array antenna technology capable of beam formation in which its main lobe is directed to one specific direction while turning nulls or sidelobes to other directions, usually the direction of interference signals. This technology gives rise to the performance of wireless communication systems in terms of signal quality and system capacity. In general, beamforming can reduce the effect of co-channel signal interference while retaining the maximum gain in the direction of desired signal. In addition, it can reduce the time delay spread of the systems when facing the scenario having multipath signals. Moreover, the benefits of beamforming include an increased coverage area, an optimized transmission, a lower power consumption and an increased spectral efficiency.

The beamforming systems normally consist of array antennas and signal processing units as shown in Figure 3.1. The processing units are normally used to identify DOA of incoming signal and adjust the received signal in order to point the main beam to the direction of the desired signal, so called weighting process. The weighting coefficients are calculated in the weighting process in order to give the maximum value of combined received signal at the system output. As can be seen in the figure, the utilization of array antennas has an impact on an overall system gain and a maximized Signal to Interference plus Noise Ratio (SINR). The array geometries mainly include uniform linear array, planar array and circular array. The most popular one is linear array antennas because of their simplicity, which consist of antenna elements uniformly placed along a straight line as shown in Figure 3.2.

In Figure 3.2, there are N antenna elements which are equally spaced next to each other, usually half-wavelength. Please note that a large array is out of scope for this thesis work, so the signal amplitudes at individual elements are considered to be equal. The spatial response of the array due to an incident plane wave from θ direction is modeled by the $N \times 1$ array steering vector $\boldsymbol{a(\theta)}$ as shown in (3.1). From Figure 3.2, a steering vector represents the relative phases between the antenna elements as follows

$$\boldsymbol{a(\theta)} = [1 \quad e^{-jkd\cos\theta} \quad e^{-j2kd\cos\theta} \quad \ldots \quad e^{-j(N-1)kd\cos\theta}]^T \tag{3.1}$$

where k is wave number with $k = 2\pi/\lambda$ and the N-antenna elements are equally spaced by d. Also, the angle represented by θ is the direction of signal arrival and $(\cdot)^T$ denotes transpose operation.

The principle of beam formation in receiving side can be explained with the use of N antenna elements which are linearly aligned as shown in Figure 3.3. For mobile communications, the base station usually employs N antenna elements collaborating with one another to perform beam formation. Let $\boldsymbol{y}$ is the received signal vector containing received signal at each antenna element $y_1, y_2, \ldots, y_n$ and $\boldsymbol{w}$ is weighting coefficient vector containing each weighting coefficient at individual antennas $w_1, w_2, \ldots, w_n$. The output signal from these antennas are mostly multiplied by a set of N weighting coefficients. Then, the output signal is finally obtained from the summation of all weighted signal as shown in the figure. The output signal y_{out} is therefore given by

$$y_{out} = \sum_{i=1}^{N} w_i^* y_i = \boldsymbol{w}^{\boldsymbol{H}} \boldsymbol{y} \tag{3.2}$$

where $\boldsymbol{y}$ is the N-length vector of received signals, $\boldsymbol{w}$ is the N-length vector of weighting coefficients and the superscript H represents the Hermitian of a vector (the conjugate transpose), i.e., $\boldsymbol{w}^{\boldsymbol{H}} = [w_1^*, w_2^*, \ldots, w_N^*] = [\boldsymbol{w}^{\boldsymbol{T}}]^*$. The weighting coefficients are very important for beam formation because they control the amplitudes and phases in individual antenna elements. Some appropriate weighting coefficients can provide maximum output response towards the desired direction while providing high attentions in undesired directions. As a result, the interference signal can be eliminated without any distortion to the desired signal.

To give some example, a set of weighting coefficients for *N*-linear array antennas when turning the main beam to 60 degrees is as follows.

$$\boldsymbol{w}^{\boldsymbol{H}} = \left[1^{*}, \left(e^{-j\pi/2}\right)^{*}, \left(e^{-j2\pi/2}\right)^{*}, \left(e^{-j3\pi/2}\right)^{*}, \left(e^{-j4\pi/2}\right)^{*}, \left(e^{-j5\pi/2}\right)^{*}, \ldots, \left(e^{-jN\pi/2}\right)^{*}\right]$$

Figures 3.4 and 3.5 shows radiation patterns of the beamformer employing the above weighting coefficients when employing a large and small number of antenna elements, respectively. Please note that 4 isotropic antenna elements are assumed for Figure 3.4 and 40 isotropic antenna elements are assumed for Figure 3.5. As we can see, beamforming gain increases for 10 times when employing 40 elements instead of 4 elements. Also, a narrower beamwidth is achieved when employing a larger number of antenna elements.

Next section discusses the effect of communication channel on beamforming response in which this information will reflect the true performance of beamforming in wireless communications.

3.3 Communications channel response

In analyzing the performance of beamforming systems, it is important to understand the relationship between the response of the array antennas and the communications channel. In wireless communication systems, the signal transmitted from users through the communication channel interacts with environment in a very complicated way to Base Station (BS), which includes reflections from large objects, diffraction of electromagnetic waves around objects, path loss and signal scattering. The result of these complex interactions is the presence of many signal components or multipath signals at the receiver. A simplified graphic of multipath environment with two users is shown in Figure 3.6. In this figure, each user transmits signal to the BS which is equipped with N linear array antennas. The received signal at BS is a sum of signal, interference and communication channel response which can be written as

$$\boldsymbol{y} = \sqrt{P}\boldsymbol{Hs}(\boldsymbol{t}) + \boldsymbol{n} \tag{3.3}$$

where $\boldsymbol{s(t)}$ is $M\times1$ signal vector containing the user data $s_1, s_2, \ldots, s_m$, when s_m is the data of m^{th} user. Let $\boldsymbol{y}$ is received signal matrix at BS, $\boldsymbol{n}$ is noise at antennas and P is transmitted power of each user. The $\boldsymbol{H}$ is channel coefficient vector.

The channel coefficient vector ($\boldsymbol{H}$) considers the scenario in which the users are surrounded by local scattering structures. A multipath environment with M users is assumed in Figure 3.6. This figure shows that each user transmits signal to BS including Line-Of-Sight (LOS) and multipath or Non-Line-Of-Sight (NLOS) signals. The LOS signals is a type of propagation that can transmit and receive data only where transmitting and receiving stations are in view of each other without any sort of an obstacle between them. The path loss is a loss in LOS which defined as an overall decrease in signal strength with distance between transmitter and receiver.

The LOS signal coming from m^{th} user (A_m) can be modelled using a simplified path loss as expressed in (3.4).

$$A_m = PK\left(\frac{d_0}{d_m}\right)^{\gamma} \tag{3.4}$$

where K is the unitless constant that depends on the antenna characteristics and free-space path loss up to distance d_0 which is the reference distance between user and BS

(H. Liu, Y. Zhang and J. Luo,2007), d_m is the distance between the m^{th} user and BS, and γ is a path-loss exponent with typical values ranging from 1.6 to 1.8 (D.Tse and P.Viswanath, 2005). Note that these values were chosen as we only consider indoor environment.

Furthermore, the other signal components have a different multipath environment which determines the amplitude($\alpha_{m,l}$), carrier phase shift ($\emptyset_{m,l}$), time delay$\left(\tau_{m,l}\right)$, DOA ($\theta_{m,l}$) and Doppler shift (f_D) of the l^{th} path component from the m^{th} user. In general, it is simpler to group the amplitude, phase shift and Doppler frequency in one expression as

$$A_{m,l}\,(t) = \alpha_{m,l}(t)e^{j(\emptyset_{m,l}(t)+2\pi f_D t cos\theta_{m,l})} \tag{3.5}$$

In addition, the channel model considers the DOA of each path so let $\boldsymbol{B}^{LOS}$ and $\boldsymbol{B_l}^{NLOS}$ be the steering vectors of LOS and NLOS signals, respectively. As considering linear array antennas in this research work, the steering vectors for both cases are given as

$$\boldsymbol{B}^{LOS} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \quad \cdots \quad \boldsymbol{a}(\theta_M)]_{N\times M} \tag{3.6}$$

$$\boldsymbol{B_l}^{NLOS} = [\boldsymbol{a}(\theta_{1,l}) \quad \boldsymbol{a}(\theta_{2,l}) \quad \cdots \quad \boldsymbol{a}(\theta_{M,l})]_{N\times M} \tag{3.7}$$

where $\boldsymbol{a}(\theta_m)$ and $\boldsymbol{a}\left(\theta_{m,l}\right)$ are the steering vector of LOS and NLOS respectively. Therefore, the channel coefficient vector between all M users and BS can be formulated as

$$\boldsymbol{H} = \quad \boldsymbol{B}^{LOS}\boldsymbol{A}^{LOS} + \textstyle\sum_{l=1}^{L}\boldsymbol{B}^{NLOS}\boldsymbol{A}_l^{NLOS} \tag{3.8}$$

where $\boldsymbol{A}^{LOS}$ is LOS signals vector, $\boldsymbol{A}^{NLOS}$ is th NLOS signals vector, $\boldsymbol{B}^{LOS}$ is the steering vector of LOS signal and $\boldsymbol{B}^{NLOS}$ is the steering vector of NLOS signal. The L is the number of multipath components. As mentioned above, this section presents the channel or medium of wireless communications which include LOS and NLOS signals. Next section will discuss DOA estimations for preparing the weighting coefficients to the desired user.

3.4 Direction of arrival estimation algorithms

According to the beam formation mentioned earlier, the beamforming systems normally consist of array antennas and signal processing units. The processing units are normally used to identify Direction Of Arrival (DOA) of incoming signals and to point the main beam to the direction of desired signal.

The DOA algorithms are used to estimate the direction of incoming signal impinging on the array antennas. This research work applies the DOA estimation in order to adjust the weighting coefficients of array antennas. There are lots of DOA estimation algorithms available in literatures e.g., delay-and-sum method, Capon's minimum variance method, subspace method with MUltiple SIgnal Classification (MUSIC) algorithm and subspace method with Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) algorithm (Xiaofei Zhang et al., 2009 and Feng-Gang Yan et al., 2014). The brief backgrounds of some DOA estimation algorithms are as follows.

3.4.1 Delay-and-sum method

A delay-and-sum method has been referred as the classical beamformer method as its simplicity. It can be achieved by a simple signal processing, where multiple received signals are phase-adjusted and added, and can be simply implemented both in analogue and digital manners. A target signal coming from a desired direction is not distorted by delay-and-sum beamforming. The width of the beam and the height of the sidelobes limit the effectiveness of this algorithm when signals arriving from multiple directions are present because the signals over a wide angular region contribute to the measured average power at each look direction. So, this technique has a poor resolution. Although it is possible to increase the resolution by adding more antenna elements.

3.4.2 Capon's minimum variance method

The Capon's minimum variance method is also known as the Minimum Variance Distortionless Look (MVDL). The MVDL is an attempt to overcome the poor resolution problem associated with the delay-and-sum method and it results a significant improvement. In this method, the output power is minimized with the constraint that the gain in the desired direction remains unity. The Capon's minimum variance method provides a better resolution when compared to the delay-and-sum method but the Capon's method suffers from many disadvantages. Capon's method fails if other signals that are correlated with the interest signal because the correlated components may be combined destructively in the process of minimizing the output power. Also, the Capon's method requires the computation of a matrix inverse which can be expensive for large arrays.

3.4.3 Multiple signal classification algorithm

Though the Capon's method are often successful and are widely used but this technique has some limitations in resolution. The MUltiple SIgnal Classification (MUSIC) algorithm proposed by Schmidt in 1979 is a high resolution multiple signal classification technique based on exploiting the eigenstructure of the input covariance matrix. The MUSIC is a signal parameter estimation algorithm which provides information about the number of incident signals and noise power. While the MUSIC algorithm provides very high resolution, it requires very precise and accurate array calibration. The MUSIC algorithm has been implemented and its performance has been experimentally verified (R. O. Schmidt and R.E. Frank, 1986).

The advantage of MUSIC is that no constraint on the geometry of the sensor array is required. The array pattern can be absolutely arbitrary as long as it is known or calibrated. Though performance advantages are substantial but it is achieved at a considerable cost in computation and storage. Up to now the MUSIC is the most popular and often cited work. It has been widely studied and new algorithms have been developed such as Weighted-MUSIC (D. Johnson, 1982) and Root-MUSIC (A.J. Barabell, 1983).

3.4.4 Estimation of signal parameters via rotational invariance technique algorithm

The Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) algorithm developed by Roy and Kailath in 1989. The ESPRIT dramatically reduces the computational and storage requirements of MUSIC and does not involve an exhaustive search through all possible steering vectors to estimate the

DOA. The ESPRIT achieves a reduction in computational complexity by imposing a constraint on the structure of an array. The ESPRIT has certain advantages over MUSIC algorithm such as it does not require knowledge of the array geometry and element characteristics and it is computationally much less complex.

So far, there are lots of literatures regarding the performance of DOA algorithms such as the DOA estimation under coherent signal conditions, the iterative Least-squares Projection Based CMA (ILSP-CMA) and the integrated approach to DOA estimation etc. (IA) (Janis Werner et al, 2015 and Xiurong Ma, Xuhao Dong, and Yufeng Xie, 2016)

3.4.5 Performance comparison

Direction Of Arrival (DOA) estimation plays a vital role in many applications. Beamforming is the most prominent technique to estimate DOA. This section shows performance comparison of some famous DOA estimation techniques. In Tassanee's thesis (2016), the thesis has presented the simulation for comparing the DOA estimation algorithms shown in Figure 3.7. The results have shown the use of 30 elements linearly spaced by half wavelength dealing with 7 uncorrelated sources (non-coherent signals) which are incident at the same time.

The results from Figure 3.7 shows that the delay and sum method and Capon's method cannot give accuracy in direction estimation. So, the MUSIC, Coherent and IA method have better angular resolution than delay and sum method and Capon's method.

Furthermore, the complexity of the DOA estimation algorithms is one of important parameters to evaluate the feasibility of algorithms. Table 3.1 shows the comparison in terms of resolution, complexity and general remarks (Nauman Anwar Baig and Mohammad Bilal Malik, 2013). Please note that resolution refers to the accuracy in determining the direction of the received signal in right direction. As the direction of incoming signal is one of key success factors for the proposed beamforming concept in this thesis work. Also, there are lots of literatures regarding some simple DOA estimation algorithms which provide the estimation error not higher than 2 degrees (Xiurong Ma, Xuhao Dong, and Yufeng Xie, 2016 and Bin Liao et al., 2012). So any new idea for the estimation is out of scope for this research work.

3.5 Chapter summary

This chapter has presented background theory related to the thesis work. The beamforming technique consists the array antennas and signal processing systems. The linear array is used for beamforming because it has excellent directivity and it can form the narrowest main lobe in a given direction. Moreover, the wireless communication systems have related to the response of the array and the multipath channel. The channel coefficient of each user transmitting signal to BS contains both LOS and multipath or NLOS signals. In addition, the DOA estimation is important for the beamforming technique. The signal processing systems of beamforming are normally used to identify DOA of an incoming signal and to point the main beam to the direction of the desired signal. The background theory of this chapter is necessary to obtain the system model of the proposed orthogonal beamforming (OBFM) which will be discussed in next chapter.

CHAPTER IV

PROPOSED ORTHOGONAL BEAMFORMING

4.1 Introduction

This chapter presents the proposed Orthogonal BeamForMing (OBFM). The system model of OBFM with the help of Direction Of Arrival (DOA) estimation is proposed to avoid interference in the main beam direction as all beams are launched at the same time and the same frequency. Moreover, the system is without feedback information. The effect from communication channel between base station and users including multipath, fading and path will be taken into account. According to this, the true performance of proposed beamforming concept can be shown.

4.2 System model

The proposed concept of Orthogonal BeamForMing (OBFM) in this thesis works is to introduce an alternative beamforming scheme which is able to perform multi-beam formation when all beams operate at the same frequency and the same time. Moreover, all produced beams are orthogonal to each other, hence one's nulls can be generated at the directions of others' main beams. This thesis works focus on the multi-user communications having the system model shown in Figure 4.1.

In this figure, there are desired signals coming from M users arriving the array antennas at the same time. Also, those M users are employing the same frequency. The M users are individually equipped with a single antenna element and the Base Station (BS) is equipped with N antenna elements which are linearly aligned. When all users transmit their signal to BS, the received signal vector at BS (before weighted) can be written as

$$\boldsymbol{y} = \sqrt{P}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{4.1}$$

where x is the $M\times 1$ signal vector containing user data $x_1, x_2, \ldots, x_m$, when x_m is the user data of the m^{th} user. Also, y is the received signal vector at each antenna element containing $y_1, y_2, \ldots, y_n$ and $\boldsymbol{w}$ is the weighting coefficients of each antenna element at BS. Let $\boldsymbol{y_{out}}$ is the received signals vector at BS after performing beam formation and P is the transmitted power of each user. The channel coefficient vector between all M users and BS employing N array antennas is given by

$$\boldsymbol{H} = \boldsymbol{B}^{LOS}\boldsymbol{A}^{LOS} + \sum_{l=1}^{L} \boldsymbol{B}_l^{NLOS}\boldsymbol{A}_l^{NLOS} \tag{4.2}$$

where $\boldsymbol{A}^{LOS}$ is Line-Of-Sight (LOS) signal vector, $\boldsymbol{A}^{NLOS}$ is Non-Line-Of-Sight (NLOS) signal vector, $\boldsymbol{B}^{LOS}$ is the steering vector of LOS signal and $\boldsymbol{B}^{NLOS}$ is the steering vector of NLOS signal.

Considering the scenario where users are surrounded by local scattering structures, a multipath environment with M users is assumed as depicted in Figure 4.2. This figure shows that each user transmits signal to BS including LOS and multipath or NLOS signals. These NLOS signals may occur in several directions as the antenna employed at mobile terminal is omni-directional.

The LOS signal coming from the m^{th} user (A_m^{LOS}) can be modelled using a simplified path loss as expressed in (4.3).

$$A_m^{LOS} = PK\left(\frac{d_0}{d_m}\right)^{\gamma} \tag{4.3}$$

where P is the transmitted power of users, K is the unitless constant that depends on the antenna characteristics and free-space path loss up to distance d_0 which is the reference distance between user and BS (H. Liu, Y. Zhang and J. Luo, 2007), d_m is the distance between the m^{th} user and BS, and γ is a path-loss exponent with typical values ranging from 1.6 to 1.8 (D.Tse and P.Viswanath, 2005). Note that these values were chosen as we only consider indoor environment.

The NLOS signals coming from the m^{th} user and the l^{th} path (${A_{m,l}}^{NLOS}$) can be modelled using a Rayleigh fading channel consideration as follows.

$${A_{m,l}}^{NLOS} = \alpha_{m,l} e^{j(\emptyset_{m,l}+2\pi f_D t \cos\theta_{m,l})} \tag{4.4}$$

where $\alpha_{m,l}$ is the real number describing the difference in amplitude of the l^{th} path component from the m^{th} user, $\emptyset_{m,l}$ is the random phase of each l^{th} path uniformly distributed over [0,2π], $\theta_{m,l}$ is the direction of arrival (DOA) for the l^{th} path and f_D stands for a Doppler frequency.

In addition, the channel model considers the DOA of each path so let $\boldsymbol{B}^{LOS}$ and ${\boldsymbol{B}_l}^{NLOS}$ are the steering vector of LOS and NLOS, respectively. As we only consider linear array antennas in this thesis works, the steering vector is given by

$$\boldsymbol{B}^{LOS} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \quad \cdots \quad \boldsymbol{a}(\theta_M)]_{N\times M} \tag{4.5}$$

$$\boldsymbol{B_l}^{NLOS} = [\boldsymbol{a}(\theta_{1,l}) \quad \boldsymbol{a}(\theta_{2,l}) \quad \cdots \quad \boldsymbol{a}(\theta_{M,l})]_{N\times M} \tag{4.6}$$

where,

$$\boldsymbol{a}(\theta_m) = (1 \quad e^{-jkdsin\theta_m} \quad \ldots \quad e^{-jkd(N-1)sin\theta_m})^T$$

and

$$\boldsymbol{a}(\theta_{m,l}) = (1 \quad e^{-jkdsin\theta_{m,l}} \quad \ldots \quad e^{-jkd(N-1)sin\theta_{m,l}})^T$$

where θ_m is DOA from LOS signal of the m^{th} user, $\theta_{m,l}$ is DOA from NLOS of the m^{th} user and the l^{th} path, k is wave number which equals $2\pi/\lambda$ and d is the distance between each user and BS.

Therefore, the channel coefficient vector given in (4.2) contains both LOS and NLOS signal. In this thesis works, the BS is equipped with linear array antennas for the purpose of beam formation. The beamforming technique or array signal processing is an action to create a beam having maximum gain in a desired direction while providing a large attenuation in other directions which are usually the direction of interference signals. The beamforming systems normally consist of array antennas and signal processing units. The processing units are normally used to identify DOA of incoming signals and to point the main beam to the direction of the desired signal.

The incident signal at each antenna element will be multiplied by the vector of each antenna element at BS in the DOA of each user. So, the received signals at BS after performing beam formation or output signal is

$$\boldsymbol{y}_{\boldsymbol{out}} = \boldsymbol{wy} \tag{4.7}$$

Then, substituting (4.1) back to (4.7) yields the $\boldsymbol{y}_{out}$ as

$$\boldsymbol{y}_{out} = \boldsymbol{w}\left(\sqrt{P}\boldsymbol{Hx} + \boldsymbol{n}\right) \tag{4.8}$$

Then,

$$\boldsymbol{y}_{out} = \sqrt{P}\boldsymbol{wHx} + \boldsymbol{n_s} \tag{4.9}$$

where $\boldsymbol{n_s} = \boldsymbol{wn}$. Then, substituting (4.2) back to (4.9) yields the $\boldsymbol{y}_{out}$ as

$$\boldsymbol{y}_{out} = \sqrt{P}\boldsymbol{w}(\boldsymbol{B}^{LOS}\boldsymbol{A}^{LOS} + \textstyle\sum_{l=1}^{L}\boldsymbol{B}_l^{NLOS}\boldsymbol{A}_l^{NLOS})\,\boldsymbol{x} + \boldsymbol{n_s} \tag{4.10}$$

The output signal ($\boldsymbol{y}_{out}$) at BS appeared in (4.10) has an information of each user. The proposed concept in this paper is to introduce an alternative beamforming scheme which is able to perform multi-beam formation when all beams operate at the same frequency and time. Moreover, all produced beams are orthogonal to each other, hence one's nulls can be generated at the directions of others' main beams. Users transmit data to the receiver but it is essential that the receiver should be able to receive every data completely and accurately in which the received signals are the same as the signal vector containing the user data matrix $\boldsymbol{x}$. The proposed concept is to find an appropriate weighting coefficients $\boldsymbol{w}$ to avoid interference in the main beam direction as all beams are launched at the same time and the same frequency.

From (4.9), the weighting coefficients $\boldsymbol{w}$ is multiplied by $\boldsymbol{H}$. If $\boldsymbol{w} = \boldsymbol{H}^{-1}$, the output signal will contain only information of each user plus noise. However in real environment, the changes in the physical environment occur all the time, knowing the exact channel ($\boldsymbol{H}$) is impossible. This makes the weighting coefficients $\boldsymbol{w}$ unstable.

From (4.10), the $\boldsymbol{B}^{LOS}$ is the steering vector in which we can utilize some available DOA estimation methods. Then, we can easily get rid of $\boldsymbol{B}^{LOS}$. The key element to accomplish the proposed OBFM is to find steering vectors according to incoming signal from users which can be expressed by (4.5). According to this, matrix $\boldsymbol{B}^{LOS}$ must be invertible as follows.

$$\boldsymbol{w} = (\boldsymbol{B}^{LOS})^{-1} \tag{4.11}$$

The equation (4.11) indicates that the steering matrix $\boldsymbol{B}^{LOS}$ must be non-singular matrix so that it can be invertible. However, if the system employs a higher number of antennas comparing to the number of users, the matrix $\boldsymbol{B}^{LOS}$ cannot be directly inversed. For this case, the Moore-Penrose preudoinverse can be helpful (J. C. A. Barata and M. S. Hussein, 2011). Then, the weighting coefficients (**$\boldsymbol{w}$)** is given by

$$\boldsymbol{w} = (\boldsymbol{B}^{\boldsymbol{LOS}})^{\dagger} = (\boldsymbol{B}^{\boldsymbol{LOS}})^{*}(\boldsymbol{B}^{\boldsymbol{LOS}}(\boldsymbol{B}^{\boldsymbol{LOS}})^{*})^{-\boldsymbol{1}} \tag{4.12}$$

where, $(\boldsymbol{B}^{\boldsymbol{LOS}})^{\dagger}$ denotes the Moore-Penrose pseudoinverse of $\boldsymbol{B}^{\boldsymbol{LOS}}$.

Furthermore, the SINR can be obtained by considering individual channel for each user as given by

$$\boldsymbol{H_m} = \boldsymbol{a}(\boldsymbol{\theta_m})A_{\boldsymbol{m}}^{\boldsymbol{LOS}} + \sum_{\boldsymbol{l=1}}^{\boldsymbol{L}} \boldsymbol{a}\left(\boldsymbol{\theta_{m,l}}\right)A_{m,l}^{NLOS} \tag{4.13}$$

where $\boldsymbol{H_m}$ is a communication channel for the m^{th} user. Then, the signal output of the m^{th} user is

$$y_{out,m} = \sqrt{P}\boldsymbol{w_m}\boldsymbol{H_m}x_m + \sum_{\boldsymbol{j\neq m}}^{\boldsymbol{M}} \sqrt{P}\boldsymbol{w_m}\boldsymbol{H_j}x_j + n_{s,m} \tag{4.14}$$

So, the SINR of the m^{st} user can be expressed as

$$SINR_m = \frac{P(\boldsymbol{w_m H_m})\boldsymbol{H_m}^{*}\boldsymbol{w_m}^{*}|x_i|^2}{\sum_{\boldsymbol{j \neq m}}^{\boldsymbol{M}} P(\boldsymbol{w_m H_j})\boldsymbol{H_j}^{*}\boldsymbol{w_m}^{*}\left|x_j\right|^2 + \left|n_{s,m}\right|^{\boldsymbol{2}}} \tag{4.15}$$

As we can see in (4.5), the $\boldsymbol{B}^{LOS}$ is a steering vector matrix which can be formed using the knowledge of directions (DOA) of incoming signal employing DOA estimation algorithms available in literatures e.g., MUSIC and ESPRIT. The evaluation of proposed concept in terms of beamforming performance and SINR is initially demonstrated via computer simulation in next chapter.

4.3 Chapter summary

This chapter has presented the concept and process of proposed OBFM for multi-user communications. The proposed concept consists of a set of array antennas and signal processing units. The system model has been designed for finding an appropriate weighting coefficients to avoid interference in the main beam direction as all beams are launched at the same time and the same frequency, so called OBFM. Moreover, the communication channel model including LOS and NLOS signals has been discussed to reflect the true performance of proposed OBFM which will be show in next chapter.

CHAPTER V

SIMULATION RESULTS

5.1 Introduction

The motivation of this research is the development of wireless communication systems from single-user to multi-user communications. Recently, two promising technologies are Multiple Input Multiple Output (MIMO) and conventional BeamForming (BFM) techniques. So, the first simulation goes to the performance comparison between MIMO and BFM for single-user and multi-user communications. Moreover, this chapter shows the performance of proposed Orthogonal BeamForMing (OBFM) in multi-user communications compared with a BFM. Then, the impact of different parameters, such as the distance between users and Base Station (BS), and also the transmitted power on the average Signal to Interference plus Noise Ratio (SINR) are also investigated. Afterwards, the system performance in terms of Bit Error Rate (BER) for the proposed OBFM and Zero Forcing (ZF) is revealed. Then, the parameters affecting the OBFM performance such as Direction Of Arrival (DOA) error, distance between users and mutual coupling between antenna elements will be presented. Finally, the last section concludes the chapter.

5.2 Multiple input multiple output vs. conventional beamforming

Wireless communications have been developed to respond to user's needs such as a higher data transmission rate, a higher capacity, a higher reliability and a wider service coverage. Therefore, all standards of wireless communications have been developed from single-user to multi-user communications. From literatures, lots of research articles have demonstrated the advantages of multi-user communication over signal-user systems in terms of data transmission rate (Hieu Duy Nguyen, 2013; Liangbin Li, 2013; Pei Xiao and Mathini Sellathurai, 2010). However, the multi-user communication is facing a problem of co-channel interference between cells. From literatures, lots of works have been proposed to tackle this impairment e.g. the utilization of array antennas or frequency reuse techniques. The works presented in (Emil Björnson, 2013; Peter J. Smith, 2014; Rafik Addaci, 2014 and Mohammad Hassan Shariat, 2013) have demonstrated an increase in channel capacity and coverage employing array antennas at base station. This is because they are able to provide high value of directivity. Nowadays, a lot of attentions have been paid to a multiple-antenna technology as it is low of cost and also not complicated. So far, the multiple-antenna technology has been usually reflected by Multiple-Input Multiple-Output (MIMO) or conventional BeamForming (BFM) BFM technologies. These two unique technologies have different advantages and disadvantages. The MIMO technology allows a number of users sending their information through a number of antenna elements at the same time. So the system capacity and throughput can be tremendously increased comparing to the system employing only single antenna element. However, the success of MIMO technology totally depends on the knowledge of communications channel which alters all the time. Moreover, the mentioned impairment is more pronounced for long distance communication due to some phenomena e.g. path loss, shadowing or multipath fading, which make the communication channel crucially unexpected. This degrades the system capacity and throughput. On the other hand, beamforming technology provides a higher stability for long distance communications as the system provides high directivity gain in the desired direction. For this system, a user conveys the same information into a number of antennas which are properly weighted to coherently adjust the signal phase in order to be constructively combined at destination. Unfortunately, the beamforming technology cannot provide a high rate of data transmission.

As mentioned above, the first simulation of this research studies the performance of MIMO and BFM. The MIMO and BFM technologies have different prominent points. So, this section shows the performance comparison between MIMO and conventional BFM for single-user and multi-user communications.

5.2.1. Single-user communications

Figure 5.1 shows Multiple-Input Multiple-Output (MIMO) and conventional BeamForming (BFM) schemes for single-user communications. In these schemes, a Access Point (AP) transfers data to one user at a specific time or frequency. The MIMO technique is an antenna technology in which multiple antennas are used at both transmitter and receiver. Figure 5.1(a) shows the Single-User with MIMO (SU-MIMO) scheme in which the AP is equipped with N antenna elements. Usually, those elements are linearly aligned. Furthermore, M is the number of antennas at a user terminal. The simulation was assumed that the number of transmitting antennas at AP and receiving antennas at user are the same (N=M). Then, another scheme applies BFM technique into single user communications, so called Single-User with BFM (SU-BFM) as shown in Figure 5.1(b). We consider the case of a single user with a single antenna element employed at the user. The number of antenna elements at the AP is higher than 1 ($N > 1$) which is linearly aligned.

For the simulation, we assume that all users are uniformly distributed and they adaptively select their data rates based on their average Signal to Noise Ratio (SNR). In addition, the system parameters referring to literatures (H. Jin, B. C. Jung, H. Y. Hwang, and D. K. Sung, 2011) and (IEEEStd802.11a, 1999) were adopted. Then, the average SNR at a user with distance *d* apart from AP can be expressed as

$$SNR = SNR_0 - 44.2 - (10 \times PLe)\log d \tag{5.1}$$

Where SNR_0 is the transmitted SNR for each antenna. The path loss at 1 meter is also set to 44.2 dB and *PLe* is the path loss exponent which is 4. Also, *d* is distance between user and AP.

In wireless communications, the users exploit high SNR as they are close to the AP. On the other hand, the SNR is degraded when users are moving away from AP. The performances in terms of data rate for SU-MIMO and SU-BFM when employing $N = 2$ and $N = 4$ through the computer simulation are shown in Figures 5.2 and 5.3 respectively. As a result, the SU-MIMO (solid line) provides a higher data rate comparing to SU-BFM (dash line) case when the system SNR is high. Conversely, at a low SNR, the results obtained from employing SU-BFM provide a higher data rate comparing to the cases of SU-MIMO. Figure 5.3 shows the similar simulation, but $N =$ 4 at AP. As expected, the SU-MIMO provides a better data rate than the SU-BFM case when the system experiences a high SNR. This is because the MIMO technique can increase the spectrum efficiency and improve data rate performance. On the other hand, the SU-BFM provides better performance in terms of data rate when staying in a low SNR situation. This is because BFM technique has a high directive gain. So, it works well for a long distance communication (low SNR). In addition, the feedback channel for MIMO is dramatically degraded when the users stay at long distance having low SNR.

5.2.2 Multi-user communications

Figure 5.4 shows MIMO and BFM schemes in multi-user communications . The systems independently transmit data from AP to a number of users at the same time and the same frequency . The MU- MIMO scheme is shown in Figure 5.4 (a). For this case, we consider a single antenna employed at each user. The number of transmitting antennas (N) at AP is equal to the number of receiving users ($N = M$). The MU-BFM scheme shown in Figure 5.4(b) can perform the beamforming and its main lobe can be directed to each user . In this case, the number of antenna at each user is 1. The number of users (M) and the number of transmitting antennas (N) are the same as the ones used for MU-MIMO scheme.

In the simulation results, the data rate and SNR for MU-MIMO vs. MU-BFM when the number of users M = 2 and M = 4 are shown in Figures 5.5 and 5.6 respectively. Please note that the data rate is considered per 1 user. As the results, the MU-MIMO provides a higher data rate than MU-BFM at high SNR. At the longer distance or low SNR, the MU-BFM outperforms MU-MIMO instead.

Then, the system throughput can be obtained by the following equation:

$$Throughput = \frac{\sum_{m=1}^{user} m \cdot P_{tr}^{m} \cdot [payload\ size]}{(1-P_{tr}^{sys})SlotTime + \sum_{m=1}^{user} P_{tr}^{m} T_{tr}^{m} + \sum_{m=2}^{N} P_{tr}^{m} T_{c}^{m}} \quad (5.2)$$

where m is the number of simultaneous transmitting users. The probability for m users is given for transmission in one time slot. Also, the probability represents the case having at least one user transmitting a signal in one time slot. In addition, T_{tr}^{m} is the time used to transmit m simultaneously transmitted frames including overhead and T_{c}^{m} is the time for the number of users higher than M simultaneously users transmitting a signal which is considered as a collision. Also, payload size is given for 1000 bytes.

Figures 5.7 and 5.8 show the average throughput for varying the number of users when the payload size is set to 1000 bytes and cell radius is set to 20 m and 45 m. At the distance of 20 m, SU-MIMO and MU –MIMO provide better average throughput than SU-BFM and MU–BFM. Howver, at distance of 45 m, SU-BFM and MU–BFM provide better average throughput than SU-MIMO and MU–MIMO.

Figures 5.9 and 5.10 show the average throughput for varying the payload size from 100 to 10000 bytes when there are 10 numbers of simultaneous transmitting users and cell radius is set to 20 m and 45 m. The results show that at distance 20 m SU-MIMO and MU-MIMO provide better average throughput than SU-BFM and MU-BFM. The result obtained at distance 45 m SU-BFM and MU–BFM provide better average throughput than SU-MIMO and MU–MIMO.

From the simulation results, the performance of wireless communications have been compared with the utilization of SU-MIMO, SU-BFM, MU-MIMO and MU-BFM schemes in terms of data rate with respect to SNR. The results have revealed that both SU-MIMO and MU-MIMO provide a higher data rate comparing to the case of SU-BFM and MU-BFM at high SNR. Instead, both SU-BFM and MU-BFM provide a higher data rate over the case of SU-MIMO and MU-MIMO at low SNR. In conclusion, the MIMO and BFM techniques have different benefits.

From the above results, the multi-user communications provide a higher performance over single-user communications. That is the motivation of developing all of wireless communications standards single-user to multi-user communications.

Therefore, this research has paid attentions to multi-user communication systems. Also, BFM is more interesting than MIMO as it does not require any channel feedback and also it has a less computational complexity when comparing to MIMO systems.

5.3 Performance comparison of proposed orthogonal beamforming and conventional beamforming

This section presents the simulation results in terms of radiation pattern of Orthogonal BeamForMing (OBFM) comparing to conventional BeamForMing (BFM) as their model has been defined in chapter IV. The performance of interest includes beam pattern and Signal to Interference plus Noise Ratio (SINR). The beam direction of interest is separated into 2 cases: 1) evenly separate 4 beams in 120-degrees sector and 2) randomly give the directions to all 4 beams. Note that 4 users are assumed to be operating at the same time and the same frequency. All simulation results are compared with the case of employing BFM, which only aims to have maximum gain at desired direction. In this simulation, the 4 omni-directional antennas equally spaced by $\lambda/2$ at 2.4 GHz and arranged in linear manner are assumed.

Case 1: signals are coming from 30, 60, 90 and 120 degrees. In this case, the direction of 4 beams are evenly separated by 30 degrees throughout a 120-degrees sector. In practical, these pre-defined angles can be calculated using DOA estimation algorithms available in literatures. Then, some own developed programing was created using Matlab according to the given parameters mentioned earlier. Firstly, the weighting coefficients was calculated using steering vector matrix according to those 4 pre-defined beams. Then, beam patterns and SINR were generated in computer to see the performance of proposed concept.

Figure 5.11 shows beam patterns employing BFM. As we can see, all 4 beams can be perfectly directed to pre-defined beams: 30, 60, 90 and 120 degrees. However, side lobes of each beam are relatively high. As these 4 beams are launched at the same time and the same frequency, so all beams can be interference to one another. On the other hand, when we apply our proposed OBFM to the systems, not only the main beams can be perfectly pointed to desired directions but also providing a large attenuation in interference directions as seen in Figure 5.12.

One another parameter that can indicate the wireless communication performance is SINR. When we focus on one pre-defined beam, all the rest beams become interference as they operate at the same time and frequency. This SINR can be calculated as follows: *SINR (dB) = desired signal (dB) – interference signal (dB)*. Note that desired signal (dB) shown in the expression presents the level of normalized beam pattern in the desired direction. Table 5.1 reveals SINR values when employing proposed OBFM compared with BFM for all 4 pre-defined directions. As expected, the OBFM provides higher SINR compared to BFM. This implies that the proposed concept can also provide a higher system throughput.

Case 2: signals are coming from 7, 50, 90 and113 degrees. The directions of signal are randomly given in order to see the orthogonal beamforming performance if distances between adjacent beams are not equal. All parameters for simulation in this case are similar the ones of case 1, except the directions of incoming signals.

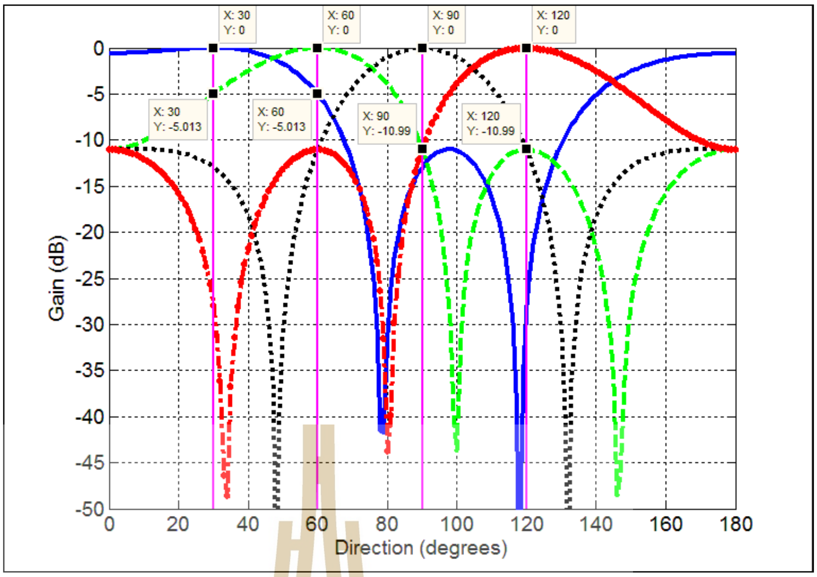

Figure 5.11 Beam patterns of BFM when signals are coming from 30, 60, 90 and 120 degrees (case 1)

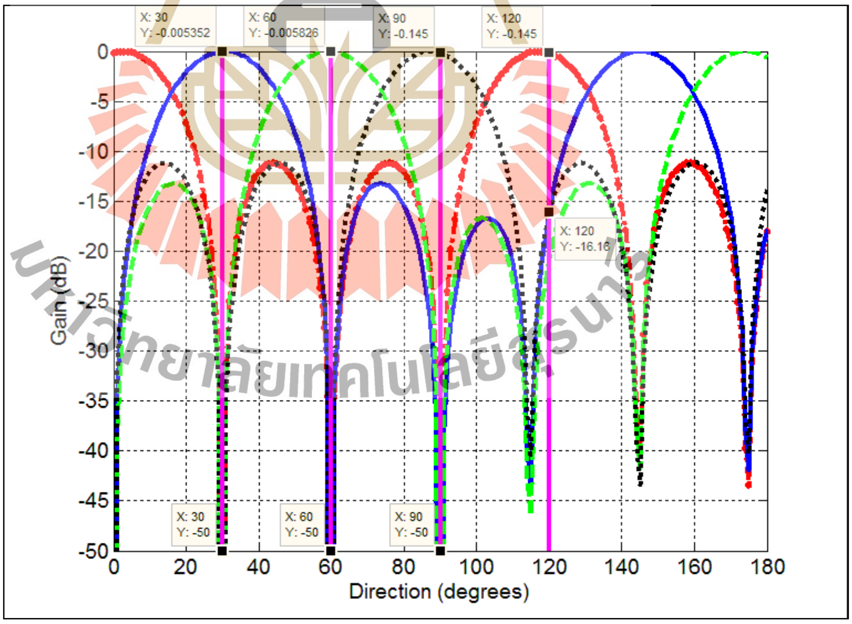

Figure 5.12 Beam patterns of proposed OBFM when signal are from 30, 60, 90 and 120 degrees (case 1)

Table 5.1 Signal to Interference plus Noise Ratio (SINR) when signals are coming from 30, 60, 90 and 120 degrees (case 1)

User Direction (degrees)	**SINR (dB)**	
	BFM	**OBFM**
30	5.013	49.9945
60	5.013	49.9942
90	10.99	49.855
120	10.99	16.015

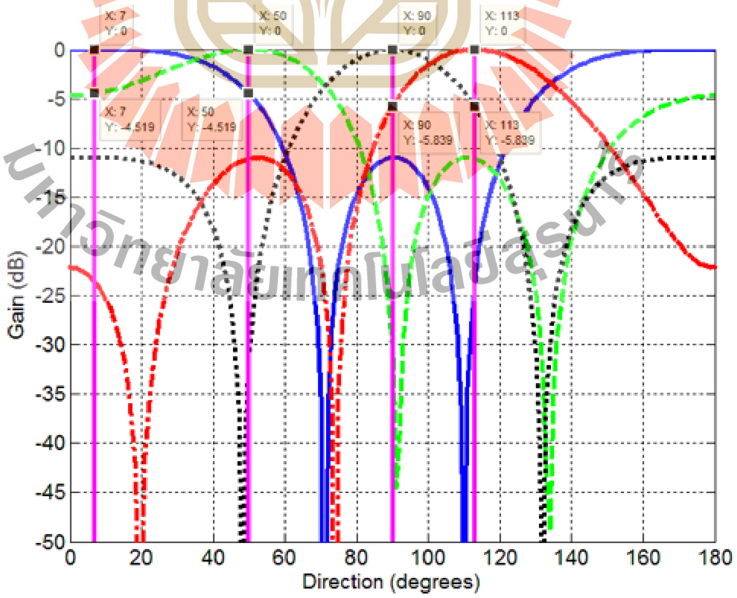

Figure 5.13 Beam patterns of BFM when signals are coming from 7, 50, 90 and 113 degrees (case 2)

Figures 5.13 and 5.14 show that the proposed OBFM provides a better performance compared with BFM even though the orthogonal beamformer cannot properly place nulls to interference directions. Furthermore, Table 5.2 reveals some calculations in terms of system SINR. As we can see, higher SINR values are resulted from utilizing the OBFM compared with BFM.

The simulation results in Figures 5.12, 5.14 and Table 5.1, 5.2 have revealed that high SINR values cannot be achieved for all directions such as table 5.1 at 120 degrees. Then, some computer simulations have been conducted to investigate the causes of this problem. Figure 5.15 shows the results when assuming the same scenario for Figure 5.12 except that there is no NLOS signal in the systems. As we can see, the maximum SINR can be obtained for all directions. This confirms that NLOS signal degrades the performance of proposed concept resulting in low SINR for some directions. However, the overall performance of proposed OBFM concept still provides higher performance compared to the conventional beamforming. Figure 5.16 shows the average SINR when varying the number of antennas for proposed orthogonal beamforming and conventional beamforming, when the number of antennas (N) at BS is equal to the number of users (M). Then, we can see from the figure that the average SINR decreases when the number of antennas (or users) increases. This is because more number of users results in higher NLOS signals. However, the overall performance of the proposed concept is better that conventional beamforming.

The previous simulation results have revealed that when a number of users occupy the same channel at the same time slot, the proposed OBFM scheme gives a maximum gain in the direction of desired users while nulling the direction of interference signals. According to this, the system SINR obtained in the case of

OBFM is relatively higher compared with the BFM. This implies that the OBFM can improve a data transmission speed and also a system throughput for multi-user communications.

5.4 Impact of distance and transmitted power on the system

This section shows the impact of distance and transmitted power on the system SINR. Figure 5.17 shows the plots of simulated average SINR vs. distance between users and BS where the BS is equipped with 4 omni-directional antennas. The 4-users are located at 30, 60, 90 and 120 degrees when all transmitted power are equally given at 0 dBW. For the simulation, a practical indoor scenario with the path-loss exponent of 1.6 (D.Tse and P.Viswanath, 2005) was assumed. Some parameters were substituted into (4.15) and distance was varied from 1 to 5 meters. Then, we can see from the figure that the average SINR decreases when users are moving away from the BS. This is because of the path-loss effect. However, the proposed OBFM provides a higher overall average SINR comparing to the cases of BFM for all distances. This is because the weighting coefficients obtained using an orthogonal property is able to provide nulls at interference directions.

In addition, Figure 5.18 shows the average SINR when varying the transmitted power. In (4.15), the BS was assumed to be equipped with 4 antennas operating for 4 users located at 30, 60, 90 and 120 degrees when the distance between users and BS is 1 meter. The average SINR increases when the transmitted power of user increases. Furthermore, the proposed OBFM provides a higher average SINR comparing to a BFM. This confirms that the proposed OBFM can increase the performance of multi-user communications.

5.5 Performance comparison of proposed orthogonal beamforming and zero forcing

This section investigates into the system performance in terms of Bit Error Rate (BER) for the proposed Orthogonal BeamForMing (OBFM) and Zero Forcing (ZF) for two cases including perfect and imperfect communication channel feedback. The ZF refers to a form of linear processing algorithm used in communication systems which nulls out interference signal. The ZF applies the inverse of the channel with frequency response to the received signal in order to restore the signal after passing through channel (Navdeep Singh Randhawa, 2014). As the channel response for a particular channel is $\boldsymbol{H}$ given in (4.2), the interference nulling algorithm multiplies the reciprocal of $\boldsymbol{H}$ to the input signal which removes the effect of channel from the output signal. As the ZF weighting coefficients is given as $\boldsymbol{w}_{ZF}$, then the relationship with the channel is

$$\boldsymbol{w}_{ZF}\boldsymbol{H} = 1 \tag{5.3}$$

Thus, the weighting coefficients of ZF is

$$\boldsymbol{w}_{ZF} = \boldsymbol{H}^{\dagger} = \boldsymbol{H}^{*}(\boldsymbol{H}\boldsymbol{H}^{*})^{-1} \tag{5.4}$$

where, $\boldsymbol{H}^{\dagger}$ denotes the Moore-Penrose pseudoinverse of $\boldsymbol{H}$. According to (5.3) and (5.4), if the communication channel is perfectly known, all interference will be completely eliminated. However, the system efficiency is not maximal as we cannot know the exact channel in real environment. On the other hand, the proposed OBFM utilizes an inverse of DOA instead of channel information. So, this section reveals the system performance comparing between OBFM and ZF for various cases of multipath signals. Figures 5.19 and 5.20 show the system BER when perfect and imperfect channel feedbacks are assumed. The number of multipath is 10 and 90 paths for Figures 5.19 and 5.20, respectively. Note that the number of multipath signals was referred to the calculation methods available in literatures (K.Pahlavan, P.Krishnamurthy, and J. Beneat,1998 and M.Heidari, F.O. Akgul, N.Alsindi, and K. Pahlavan, 2007). Then, the random direction of multipath was repeated for 30 times to achieve the average BER as shown in the figures. As the result, if the perfect channel feedback is assumed, ZF provides a lower BER comparing to the proposed OBFM. However, ZF is relatively sensitive to the channel property. As we can see in the figures, ZF provides a high BER when the channel feedback is not perfect (so called channel error). Please note that the channel error was given by adding noises into (5.4). Furthermore, comparing these two figures, a lower BER is obtained when having less multipath signals. Also, as expected, the proposed OBFM outperforms ZF algorithm when the real channel property having rich multipath signals is assumed.

In fact, the channel is not possible to be perfectly known. Therefore, the proposed OBFM outperforms ZF in the scenarios which are close to real environment. However, next section discusses how the accuracy of DOA estimation affects the proposed concept. Also, next chapter demonstrates the performance of proposed OFBM in real environment in terms of beam patterns and SINR with a constructed prototype.

5.6 Limitations of orthogonal beamforming

In this section, some simulation results will be shown in order to identify the limitation of proposed systems including DOA estimation error, distance and mutual coupling effect between antenna elements.

5.6.1 Direction of arrival estimation error

As the direction of incoming signal is one of key success factors for the proposed Orthogonal BeamForMing (OBFM), this section shows the effect of estimation accuracy on the beamforming performance. Figure 5.21 shows that the average SINR decreases as DOA error increases, for both OBFM and BFM. This is because when accuracy of beam steering, both main beam and nulls, is reduced, the interference between beams become stronger. However, the WLAN standards allow the minimum SINR value of 4 dB (Wireless Site Survey, Document ID: 68666). According to this given information including with the plot shown in Figure 5.21, the maximum value of 18-degrees is allowed for DOA estimation error. So far, there are lots of literatures regarding the performance of DOA algorithms (Janis Werner et al, 2015 and Xiurong Ma, Xuhao Dong, and Yufeng Xie, 2016) which have proposed some simple algorithms providing an error not higher 2 degrees.

5.6.2 Angular separation between adjacent users

In general, the interference cannot be eliminated when it comes in the region of main beam. This means that the beam width directly affects the distance between adjacent users. In this section, investigations into the limitation of distance between users according to the width of formed main beam for proposed concept will be discussed. In the simulation results, there are two cases: 4 and 8 linear array antennas. Note that the omni-directional antennas are employed for this simulation. Figure 5.22 shows the average SINR with the distance between of users for both cases. These plots shows that, when users are too close to one another, the interference cannot be effectively rejected as they are all stay in the region of main beam, resulting in a low SINR. However, the system SINR increases when angular separation between two adjacent users increases as the systems are able to steer nulls to interference directions. Also, as expected, the proposed OBFM outperforms the conventional one. In summary, the angular separation between users is limited according to the nature of array antennas. The more number of antenna elements, the closer users can be. This is because a lower beam width is achieved when employing the array antennas with a higher number of antenna elements.

5.6.3 Mutual coupling

As the multiple antenna elements are employed in the proposed systems, one interesting question is how the mutual coupling effect between elements affects the beamforming performance. Therefore, this section takes into account the mentioned effect as follows. The concept proposed in (Bin Liao et al,2012) is adopted to create a mutual impedance matrix. This must be inserted into the expression of received signal vector at BS (before weighting) which can be written as

$$\boldsymbol{y} = \sqrt{P}\boldsymbol{C}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{5.5}$$

where $\boldsymbol{C}$ is the coupling matrix of array antennas, which can be written using fundamental electromagnetic circuit theory as presented in (J. L. Allen and B. L. Diamond, 1966). The simulation results including mutual coupling effect shown in Figure 5.21. As we can see, the average SINR decreases when taking into account the mutual coupling between antenna elements. However, the OBFM still provides a better SINR comparing to the convention one. In addition, the remedies of mutual coupling effect have been popularly proposed in literatures (Ramakrishna Janaswamy, 2002; Hon Tat Hui, 2002 and Aaron J. Kerkhof, Hao Ling, 2011). However, the real beamforming performance including mutual coupling effect will be revealed through the experimental results in next section.

5.7 Chapter summary

This chapter has given some information as follows. The multi-user communications provide a higher performance in terms of SNR and throughput comparing to single-user communications. Furthermore, the MIMO and BFM techniques have different the benefits. The results obtained from computer simulation have revealed that both SU-MIMO and MU-MIMO provide higher data rate and average throughput at 20 m (high SNR) comparing to the case of SU-BFM and MU-BFM. Furthermore, at distance 45 m (low SNR), both SU-BFM and MU-BFM give rise to data rate and average throughput over the case of SU-MIMO and MU-MIMO. Therefore, this research focuses on developing the performance of multi-user communications with the BFM technique as the BFM technique does not require any channel feedback and it has less computational complexity when comparing the MIMO technique. Then, the results have shown the performance of proposed OBFM when comparing with BFM in the multi-user communications. All produced beams operating at the same frequency and the same time are orthogonal to one another in which one can point it nulls to the direction of the other's main beams at the same time, while maintaining maximum gain in the direction of users of interest. A number of computer simulations in various scenarios have been produced to reveal the performance of proposed concept. The simulation results have shown that the proposed OBFM provides the highest SINR among all simulation cases. Furthermore, the comparison to a famous ZF algorithm has been taken into account. The results have revealed that the proposed concept outperforms ZF algorithm when real circumstance having an imperfect channel estimation is considered. Then, the last section has described the limitation of proposed OBFM. The parameters affect to the proposed system are DOA estimations error, distance between users and mutual coupling between antenna elements. However, all simulation results presented earlier have confirmed the beamforming performance of proposed OBFM. Next chapter validate the proposed concept via testing a constructed prototype of proposed orthogonal beamformer under real circumstances.

CHAPTER VI

PROTOTYPE OF ORTHOGONAL BEAMFORMER AND EXPERIMENTAL RESULTS

6.1 Introduction

The previous chapter has focused on the concept of Orthogonal BeamForMing (OBFM) technique in which the concept has been confirmed by simulation results. The aim of proposed technique is to propose an alternative beamforming algorithm for multi-user communications avoiding any feedback channel or information from users. This chapter presents the design and construction of beamformer prototype in order to validate the proposed OBFM. The prototype is designed for operating at 2.4 GHz. The prototype consists of three core parts: array antennas, weighting networks and processing unit. Then, the experimental results include the performance comparison between the constructed prototype and conventional one.

6.2 Prototype of orthogonal beamformer

6.2.1 Antennas

A monopole antenna operating at 2.4 GHz was chosen for this thesis work as its simplicity. Also, it is compact enough to be arranged to form the array having inter-element spacing of half wavelength. The geometrical configuration of 4 monopole antennas is shown in Figure 6.1.

6.2.2 Weighting networks

In the beamformer construction, the weighting systems consist of 2 major components: phase shifters and power splitter/combiners. The details of each component are shown as follows:

1. The first component is phase shifters. The received signals from each antenna are weighted by phase shifters to adjust their phases according to the calculated weighting coefficients. The size and dimension of phase shifters is shown in Figure 6.2. The phase shifter is designed by (Pozar, 1998) according to the following equations.

$$\frac{W}{d}=\begin{cases}\dfrac{8e^{A}}{e^{2A}-2} & \text{for } W/d<2\\[2ex] \dfrac{2}{\pi}\left[B-1-\ln\left(2B-1\right)+\dfrac{\varepsilon_r-1}{2\varepsilon_r}\left\{\ln\left(B-1\right)+0.39-\dfrac{0.61}{\varepsilon_r}\right\}\right] & \text{for } W/d>2\end{cases} \tag{6.1}$$

where

$$A=\frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}}+\frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right) \tag{6.2}$$

$$B=\frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \tag{6.3}$$

where W is the width of microstrip line and d is substrate thickness. Also, Z_0 is characteristic impedance and ε_r is dielectric constant. The line length of phase shifter can be express by

$$l=\frac{\phi}{B} \tag{6.4}$$

where l is the line length of microstrip line and ϕ is a desired phase shift. Please note that phase shifters are created using single-layer printed circuit board using FR4-substrate with dielectric constant of 4.5 (at 2.4 GHz) and substrate thickness of 1.6 mm. The phase shifters were designed from CST Microwave Studio. Then, the fabricated phase shifter was tested using Network Analyzer. The prototype was designed for 2 users located at 30 and 90 degrees. The user terminal employed a single antenna and the Access Point (AP) employed 4 antenna elements. Therefore, the phase shifting values were calculated and designed with direction of arrival (DOA) of users according to weighting coefficient equation shown in chapter IV. The phase shifters of conventional BeamForming (BFM) and Orthogonal BeamForming (OBFM) were manufactured as their photographs are shown in Figures 6.3 and 6.4, respectively. The measurement parameters for phase shifters at 2.4 GHz are given in Table 6.1. The obtained results indicate that its return loss is lower than -10 dB and there is a slight insertion loss throughout the designated band.

2. The power splitter and combiners shown in Figures 6.5 and 6.6 are separated into 2 different types, which are 2:1 operating in frequency range from 1.6 to 3.3 GHz and 4:1 operating in frequency range from 0.5 to 2.7 GHz. They are ZX10-2-332+ and ZN4PD-272+ from Mini-circuits® respectively. The first one splits signals from receiving antenna and another one combines all output signals from the first one and phase shifter.

6.2.3 Processing unit

At first, please note that the measurements of this work are based on static scenario and indoor environment. However, the results from testbed can be used to predict the performance of the Orthogonal BeamForMing (OBFM) technique in multi-user communication systems in comparing to the conventional BeamForMing (BFM) technique. The constructed beamformer was connected to Universal Software Radio

Peripheral (USRP) to perform a full two-way communication. A photograph of USRP can be shown in Figure 6.7.

In this thesis work, USRP1 and USRP B100 were employed. The USRP1 is the original USRP that provides entry-level RF processing capability. It is intended to provide software defined radio development capability for cost-sensitive users and applications. The architecture includes an Altera Cyclone FPGA, 64 MS/s dual ADC, 128 MS/s dual DAC and USB 2.0 connectivity to provide data to host processors. A modular design allows the USRP1 to operate from DC to 6 GHz. The USRP1 platform can support two complete RF daughter boards. This feature makes the USRP ideal for applications requiring high isolation between transmit and receive chains, or dual-band dual transmit/receive operation. The USRP1 can stream up to 8 MS/s to and from host applications, and users can implement custom functions in the FPGA fabric.

The USRP B100 can be transmitted through the USB2.0 host interface MHz bandwidth of 8 RF. The product offers flexible timing features to meet specific application requirements. USRP board includes a FPGA, ADC and DAC, and connected to the computer via Gigabit Ethernet or USB. USRP products are divided into three different series, including the bus series (low cost and entry-level), network interface series (high performance) and embedded series (independent of the application) also offers more than 13 kinds of fender RF frequency, performance and price. USRP B100 providing a low cost RF processing power was designed for system bandwidth applications which require special handling capabilities and dynamic range. All part discussed in section 6.2 are assembled to form a constructed prototype of BFM and OBFM as shown in Figure 6.8.

6.3 Experimental results

A prototype of OBFM was constructed with some fixed beamforming networks. Note that directions of incoming signal are assumed at 30 and 90 degrees and the operating frequency is given at 2.4 GHz. The measurement was performed focusing on Received Signal Strength Indicator (RSSI), Bit Error Rate (BER) and throughput under real circumstance. The constructed beamformer was connected to USRP shown in Figure 6.8 to perform a full two-way communication. Figure 6.9 shows the experiments including 4 different cases as follows:

Case A: Single user communications: in this case, there are only one transmitter and one receiver. Both USRPs, each for transmitter and receiver, are connected to a single dipole antenna without any beamforming networks.

Case B: Two-user communications: in this case, two users are stationary at directions of 30 and 90 degrees. There are two transmitters and two receivers in which each of them is connected to USRP. Also, a single dipole antenna operating at 2.4 GHz is individually employed at transmitters and receivers. Note that the beamforming scheme is not applied for this case.

Case C: Multi-user communications with conventional beamforming (MU-BFM): in this case, there are two transmitters and two receivers. One transmitter is positioned at 30 degrees while another one is placed at 90 degrees. Two fixed beamforming networks are employed to perform beamforming at 30 and 90 degrees. Note that 4×1 dipole antennas are employed, which are equally spaced by half-wave length at 2.4 GHz. On the receiving side, a single dipole antenna is individually employed to convey the received signal to USRPs in order to record the RSSI and BER.

Case D: Multi-user communications with the proposed orthogonal beamforming (MU-OBFM): the experiment scenario in this case is similar to the ones described in previous case (case C), except the proposed orthogonal beamforming networks are employed instead of conventional one. Also, USRPs are individually connected to the receivers to record the RSSI and BER in real time. Figure 6.10 shows a photograph of experiment setup at the receiving side for case D, multi-user communications with OBFM.

All experiments were performed in 6×6 m^2 room at F4 building, Suranaree University of Technology, Thailand. This indoor environment was chosen as it includes lots of multi-paths coming from partitions and walls. Also, Figure 6.11 shows the experiment setup when the transmitters are placed at 30 and 90 degrees. Both transmitters transmit data through the same array antennas at the same time. As we can see, the USRPs at both receivers are connected to laptop computer to record RSSI and BER in real time. In addition, the USRP parameters for the experiments are listed in Table 6.2.

Figure 6.12 shows the RSSI obtained from experiments versus sampling time. This RSSI represents a signal strength value of received signal. In this case, the distance between transmitters and receiver is 2 meters. As we can see in the figure, case A provides the lowest RSSI because, in this case, there is only one transmitter. On the other hand, the cases B C and D provide the highest RSSI. Furthermore, the RSSI is twice for the cases of multi-user communications (cases B, C and D) compared with single user communications (case A). This is because the two transmitters operate at the same time and the same frequency. Therefore, those transmitted signals are somehow constructively combined at the receiver gaining the signal strength. However, this leads to a question whether a high RSSI value indicates any benefits to system operators or users. So, the system performance in terms of some other indicators e.g., BER and throughput have to be further investigated in next section.

Figure 6.13 presents the measured BER when the users are located at 30 and 90 degrees. As we can see in the figure, single user communications provide the lowest error of transmitted data. This is because there is no interference when only one transmitter and one receiver are communicated. But when the two transmitters (case B: two users) operate at the same time and the same frequency, the BER value significantly increases, which means we lose the accuracy of received data. This is because one becomes interference to each other. The impairment can be healed with the use of

beamforming networks as the results obtained from cases C and D (MU-BFM and MU-OBFM). However, the proposed MU-OBFM outperforms the conventional one (MU-BFM) as its orthogonal property gives nulls at interference directions. The measured results also reveal that a high received signal strength as shown in Figure 6.12 cannot guarantee the accuracy of received data as seen in Figure 6.13, especially for case B.

Next, the system throughput is investigated. The BER obtained from experiments were recorded to calculate the system throughput under 4 different scenarios as aforementioned (cases A to D) using the following calculations.

$$1 - PER = (1 - BER)^L \tag{6.5}$$

where *PER* stands for Packet Error Rate, BER stands for Bit Error Rate and *L* is data packet length.

The Transmission Control Protocol (TCP) throughput, which is the rate that data is successfully delivered over a TCP connection, is an important parameter to measure the quality of a network connection. Generally speaking, TCP throughput is measured as *data rate per cycle / time per cycle*. The work presented in Matthew Mathis (1997) has come up with a model for the throughput calculation, which takes into account some link characteristics such as the Maximum Segment Size (*MSS*), Round Trip Time (*RTT*) and packet loss. Then, throughout can be determined by

$$Throughput = \left(\frac{MSS}{RTT}\right)\left(\frac{1}{\sqrt{PER}}\right) \tag{6.6}$$

where *MSS* stands for Maximum Segment Size in bytes and *RTT* represents Round Trip Time in second.

From previous results (Figure 6.13), case A (single user communications) provides the best BER (lowest value) as there is no co-channel interference at all. However, this cannot guarantee the rate of successful messages delivered over a communication channel. So the system throughput must be investigated. Figure 6.14 shows that case A provides the lowest throughput. But when the number of transmitter and receiver increases, the system throughput is higher. Note that the throughput value was calculated for a single user, then the throughputs from every user are averaged to be plotted in this figure. Among all 4 cases, the highest throughput can be obtained from the use of proposed OBFM, approximately double of the throughput of single user case. Also, the system throughput drops when users move away from BS for all cases. This is because, at far distance, the signals both from desired user and interferences are weak while noise is constant. Then, the throughput converges to the same point for cases B, C and D. However, the overall performance of proposed beamforming is higher than other cases.

All experimental results presented earlier have confirmed the beamforming performance of proposed OBFM that it provides high signal strength and throughput compared with the use of the BFM. Also, the proposed systems provide a low packet error rate.

6.4 Chapter summary

This chapter has shown the design and the construction of a full prototype of OBFM which consists of the three core components: array antennas, weighting networks and processing unit. Each component has been discussed and some testing have confirmed the performance as expected. Furthermore, the experimental results were performed in indoor environment which includes the effect of rich shadowing and multipath. The measured results have revealed that the proposed MU-OBFM provides high RSSI and throughput but low packet error rate compared with other 3 cases: single user, two-users and MU-BFM. This is because all produced beams are orthogonal so that they do not interfere each other when they are launched at the same frequency and the same time.

CHAPTER VII

THESIS CONCLUSION

7.1 Conclusion

Wireless communication systems have been rapidly developed so far. The goal of the mentioned development is to support an increasing number of users with a rapid transmission rate and also to extend a coverage area. The standard of wireless communications has been developed from single user to multiple users which require an data transmission from base station to a number of users simultaneously and independently at the same time and the same frequency. Moreover, a multiple antenna technology has been taken into account to upgrade the wireless communication systems for example: Multiple-Input Multiple-Output (MIMO) technology, Per-User Unitary Rate Control technique (PU^{2}RC), Distributed beamforming and Opportunistic beamforming. However, these techniques require feedback channel or feedback information in order to achieve a good performance. In fact, the feedback information leads to a complicated process and energy consumption. Also, the feedback channel has never been perfect as communication channel alters all the time. One technique that does not require feedback information is a conventional BeamForming (BFM) using an acknowledge of Direction Of Arrival (DOA) estimation. As a result, the main lobe can be directed towards one specific direction while turning nulls or side lobes towards directions of interference signals. However, there are some limitation when applying the BFM to multiple users when the base station is serving a number of users at the same time and the same frequency. As we can see in Chapter II, minor lobes from some other beams interfere the desired signal coming in the direction of main beam. According to this, Signal-to-Interference plus Noise Ratio (SINR) and also throughput of the systems are relatively low.

Therefore, the aim of this thesis work is to propose an alternative beamforming algorithm for multi-user communications. This thesis has introduced a concept of an Orthogonal BeamForMing (OBFM) which provides multiple-beam formation at the same time and the same frequency for multi-user communications. The proposed idea requires only information of DOA of incoming signal without the requirement of information or channel feedback. All produced beams operating at the same frequency are orthogonal to one another in which one can point it nulls to the direction of the other's main beams at the same time, while maintaining maximum gain in the direction of users of interest. A number of computer simulations in various scenarios have been produced to reveal the performance of proposed concept. The simulation results have shown that the proposed OBFM provides the highest SINR among all simulation cases. Furthermore, the comparison to a famous Zero Forcing (ZF) algorithm has been taken into account. The results have revealed that the proposed concept outperforms ZF algorithm when real circumstance having an imperfect channel estimation is considered. Then, the further studies of proposed OBFM include the effect of DOA estimation error, angular separation between adjacent users and mutual coupling effect between antenna elements.

Afterwards, a prototype of OBFM has been constructed and tested in real environment in order to validate the proposed concept. The experiments have been performed in indoor environment which includes the effect of rich shadowing, multipath and mutual coupling between antenna elements. The measured results have revealed that the proposed OBFM scheme provides a higher signal strength and throughput but lower bit error rate compared with the other 3 cases: single user, two users without beamforming and multi-user with conventional beamforming (MU-BFM). This is because all produced beams are orthogonal to each other so that they do not interfere to one another when they are launched at the same time with the same frequency.

In summary, the contributions of proposed OBFM for multi-user communications can be categorized into three major issues. Firstly, the OBFM concept is attractive because it avoids channel or information feedback for multi-user communications. Secondly, the proposed OBFM allows users to access the base station (vice versa) and can reduce interference from other users at the same time and the same frequency. Finally, this thesis has shown the construction of OBFM prototype, which can increase the performance of multi-user communications comparing to conventional BFM.

For the future work, it is very interesting to consider the case when more than one user stay in the same direction but they are located in different distances. In this case, the proposed OBFM cannot handle as it can only horizontally form one beam to one particular user. One interesting idea performing vertical beam formation may be taken into account to provide more degrees of freedom when users stay in the exact direction but different distances.

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APPENDIX A

TECHNICAL PUBLICATIONS

List of publications

International Journal Papers

Paleerat Wongchampa, Monthippa Uthansakul. **Orthogonal Beamforming for Multi-User Wireless Communications**. **IEEE Antennas and Propagation Magazine** (accepted 13 Nov, 2016)

Paleerat Wongchampa, Monthippa Uthansakul and Norhudah (2015). **Cooperative Mode Between MIMO and Beamforming Schemes in WLANs.** Suranaree Journal of Science and Technology, (accepted 6 Dec, 2016)

International Conference Papers

Wongchampa, P., Uthansakul, M., Uthansakul, P.,(2014). **Data Rate and Throughput Enhancement base on IEEE802.11n Standard employing Multiple Antenna Elements.** The Electrical Engineering Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand - Conference 2014, 14-17 May 2014.

Wongchampa, P., Uthansakul, M., Uthansakul, P.,(2014). **Tradeoff Between MIMO and Beamforming Schemes for 802.11n.** King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand, The 2014 Thailand-Japan Microwave (TJMW2014), 26-28 November 2014.

feedback signal. Significantly, the feedback signal may be distorted as the communication channel is always unpredictable.

According to the drawbacks of feedback transmission mentioned earlier, we herein propose a multi-user transmission without feedback channel information in order to reduce any complicated procedure. The concept of utilizing multiple antennas is adopted to provide maximum gain in the direction of interest while proving a cruel attenuation in undesired directions. However, this technique has limitation when applied to multi-user communications. As there are many users operating at the same time and same frequency, they can be interferences among themselves, hence the Signal to Interference plus Noise Ratio (SINR) and throughput are relatively low. In addition, the null steering schemes proposed in literatures cannot handle the mentioned impairment as they cannot perform a multiple-direction operation at the same time and frequency. Therefore, this paper proposes an alternative approach for a beam formation when all beams operate at the same time and same frequency. The proposed concept needs a help of Direction Of Arrival (DOA) estimation from some signal processing methods available in literatures. The systems can utilize this predicted knowledge to form a number of orthogonal beams in which all beams perform self-maximized gain in one direction and null steering to the rest pre-defined beams, so called an orthogonal beamforming. Please note that all beams operate at the same time and frequency.

II. BRIEF CONCEPT OF WIRELESS COMMUNICATION SYSTEMS

In this section, we briefly introduce the concept of single-user and multi-user communication systems. As mentioned in the last section, most of wireless communication standards have been developed from point-to-point to point-to-multipoint communications, so called multi-user communications, enabling users to have a higher effectiveness of data transmission, a reduced energy consumption and a larger coverage area. Here is a brief discussion regarding a background of single-user and multi-user communications where we can see advantages and disadvantages for these two distinguished communication systems.

A. Single-User Communication Systems

Single-user systems are point-to-point communications between a base station and a single user terminal. In these systems, a base station transfers data to one user at a specific time or with a given frequency as shown in Fig. 1 (a). Recently, a multiple-antenna technology has been adopted to help the systems to increase their gain and coverage area, usually attached at base station. For this case, the data transmission rate is relatively low as the base station cannot simultaneously send data to all users. Vice versa, if all users utilize the same time slot but occupy different individual frequencies, then a user congestion occurs. Nonetheless, the advantages of these communication systems are that the systems are not complicated and the co-channel interference is not much pronounced. However, the disadvantages of these systems are a non-fascinating transmission speed and throughput.

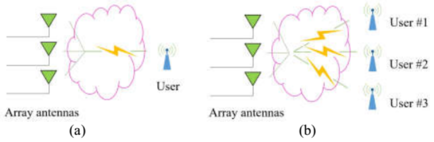


Fig. 1. Configuration of (a) *single-user* and (b) *multi-user* communications.

B. Multi-User Communication Systems

With the rapid growth of wireless communications, lots of attempts have been push to allow several users to communicate at the same time employing the same frequency in order to increase a data transmission speed, a channel capacity and a system throughput, so called multi-user communications. Fig. 1 (b) depicts the configuration of multi-user communication systems with a number of antenna elements employed at the base station. Not only a frequency spectrum can be efficiently utilized in these systems, but also a data transmission speed increases without the use of multiple antennas at user terminals. From literatures, there have been lots of studies regarding a comparison of system effectiveness between single-user and multi-user communications. According to the advantages of multi-user communications, they have been so far applied to various wireless communication standards such as 4G/IMT-Advance, 5G, 802.16m/WIMAX, 802.11ac, 802.11ad and 802.11af.

Focusing on multi-user communications, the most popular methods including a MIMO technology, a PU^2RC, a distributed beamforming and an opportunistic beamforming need feedback channel or feedback information in order to meet the system requirements for a low bit error rate while gaining a high system throughput. The procedure to obtain an accurate feedback information is relatively complicated and also consumes lots of energy. However, one technique avoiding the feedback information is a beamforming technique employing the estimation of DOA. This technique preserves a desired signal by pointing the main beam to the desired direction while eliminating interference signal by creating nulls or side lobes to undesired directions. Lots of advantages from having a beam formation are such as an increased coverage area, a decrease in power consumption and an improved link quality/reliability. In this paper, we herein define this kind of beam formation as a conventional beamforming. In general, the weighting coefficients for conventional beamforming can be simply calculated from the knowledge of user location. However, this conventional beamforming cannot be applied to multi-user communications as all users employing the same time slot and the same frequency become interference among themselves. As we can see in Fig. 2, minor lobes from a given beam interfere the other main beams. According to this, the system SIR and also throughput are relatively low. In this paper, we propose an orthogonal beamforming for multi-user communications which is envisaged to tackle the mentioned problem.

Unfortunately, most of null steering schemes available in literatures cannot be applied to this scenario as nulls and main

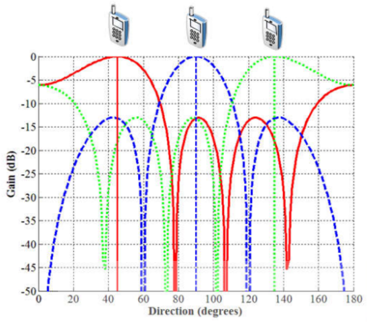


Fig. 2. Beam patterns of conventional beamforming for the scenario when 3 users are operating at the same time and the same frequency.

beams have to be produced in exactly the same direction. Recently, researchers have pursued the remedy of the mentioned problems by proposing some promising techniques employing a feedback information between transmitter and receiver. However, this has introduced a complicated signal processing. Furthermore, the system stability is difficult to be achieved as the communication channel between base station and user terminals is uncertain.

Therefore, the aim of this paper is to propose an alternative approach to perform multiple-beam formation without any feedback procedure for multi-user communications in which all users operate at the same time and the same frequency. In this case, all beams are orthogonally formed in pre-defined directions, so called orthogonal beamforming, which will be detailed in next section.

III. SYSTEM MODEL

In this paper, we focus on the multi-users communications having the system model as shown in Fig. 3. In this figure, there are desired signals from *M* users arriving at the same time. Also, those *M* users are employing the same frequency. The *M* users are individually equipped with a single antenna element and a Base Station (BS) is equipped with *N* antenna elements which are linearly aligned.

When all users transmit their signal to BS, the received signal vector at BS (before weighted) can be written as

$$\boldsymbol{y} = \sqrt{P}\boldsymbol{Hx} + \boldsymbol{n} \tag{1}$$

where *x* is the $M\times1$ signal vector containing the user data x_1, x_2, ..., x_m, when x_m is the data of the m^{th} user. Also, *y* is the received signal vector at each antenna element containing y_1, y_2, ..., y_n and $\boldsymbol{w}$ is weighting coefficient vector of each antenna element at BS. Let $\boldsymbol{y}$ is the received signal matrix at BS after performing beam formation and *P* is the transmitted power of each user. The channel coefficient vector between all *M* users and BS can be formulated as

$$\boldsymbol{H} = \boldsymbol{B}^{LOS}\boldsymbol{A}^{LOS} + \sum_{l=1}^{L}\boldsymbol{B}_l^{NLOS}\boldsymbol{A}_l^{NLOS} \tag{2}$$

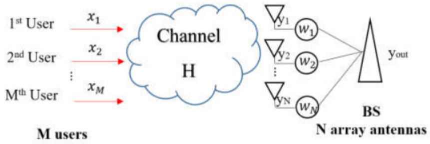


Fig. 3. System model of multi-user communications.

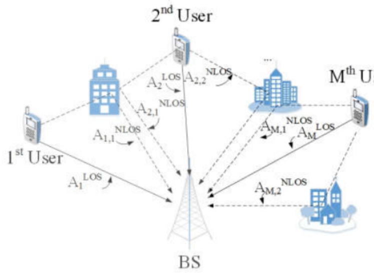


Fig. 4. Propagation channel model of multi-user communications.

where $\boldsymbol{A}^{LOS}$ is the Line-Of-Sight (LOS) signal vector, $\boldsymbol{A}^{NLOS}$ is the Non-Line-Of-Sight (NLOS) signal vector, $\boldsymbol{B}^{LOS}$ is the steering vector of LOS signal and $\boldsymbol{B}^{NLOS}$ is the steering vector of NLOS signal.

Considering the scenario where the users are surrounded by local scattering structures, a multipath environment with *M* users is assumed as depicted in Fig. 4. This figure shows that each user transmits signal to BS including LOS and multipath or NLOS signals. These NLOS signals may occur in several directions as the antenna employed at mobile terminal is omni-directional. Then, the LOS signal coming from m^{th} user (A_m^{LOS}) can be modelled using a simplified path loss as expressed in (3).

$$A_m^{LOS} = PK\left(\frac{d_0}{d_m}\right)^{\gamma} \tag{3}$$

where *K* is the unitless constant that depends on the antenna characteristics and free-space path loss up to distance d_0 which is the reference distance between user and BS [9], d_m is the distance between the m^{th} user and BS, and γ is a path-loss exponent with typical values ranging from 1.6 to 1.8 [10]. Note that these values were chosen as we only consider indoor environment.

The NLOS signals coming from m^{th} user and l^{th} path (${A_{m,l}}^{NLOS}$) can be modelled using a Rayleigh fading channel consideration as follows.

$${A_{m,l}}^{NLOS} = \alpha_{m,l}e^{j(\ _{m,l}+2\pi f_D t cos\theta_{m,l})} \tag{4}$$

where $\alpha_{m,l}$ is the real number describing the difference in amplitude of the l^{th} path component from the m^{th} user, $\ _{m,l}$ is the random phase of each l^{th} path uniformly distributed over [0,2π], $\theta_{m,l}$ is DOA for l^{th} path and f_D stands for Doppler frequency.

In addition, the channel model considers the DOA of each path so let $\boldsymbol{B}^{LOS}$ and ${\boldsymbol{B}_l}^{NLOS}$ be the steering vectors of LOS and

NLOS signals, respectively. Then, we herein derived the expression of SINR from (5) - (15) as follows. As we consider linear array antennas in this paper, the steering vectors for both cases are given as

$$\boldsymbol{B}^{LOS} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \qquad \boldsymbol{a}(\theta_M)]_{N\times M} \tag{5}$$

$$\boldsymbol{B_l}^{NLOS} = [\boldsymbol{a}(\theta_{1,l}) \quad \boldsymbol{a}(\theta_{2,l}) \qquad \boldsymbol{a}(\theta_{M,l})]_{N\times M} \tag{6}$$

where $\boldsymbol{a}(\theta_m)$ and $\boldsymbol{a}(\theta_{m,l})$ are the steering vector of LOS and NLOS respectively. When θ_m is DOA of mth user in case of LOS, $\theta_{m,l}$ is DOA of mth user as it is reflected or scattered from objects (lth path) for NLOS consideration, k is wave number which equals $2\pi/\lambda$ and d is the inter-element spacing of the array.

Therefore, the channel coefficient vector given in (2) contains both LOS and NLOS signals. Note that, the power level for both LOS and NLOS components is given by (7) as it is the path loss calculation for indoor environment [11].

$$pat \quad loss = 37 \quad 30\log d + 13.8n^{\left(\frac{n+2}{n+1}-0.46\right)} + X_\sigma \tag{7}$$

where d is the distance between the BS and user, n is the number of floors. Also, X_σ is zero mean Gaussian distributed random variable (in dB) with standard deviation σ. Referring to the technical specification of 3GPP [11], the standard deviation of LOS path is 4 dB and the standard deviation of NLOS is 12 dB.

In this paper, the BS is equipped with linear array antennas for the purpose of beam formation. The beamforming technique or array signal processing is an action to create a beam having maximum gain in a desired direction while providing a large attenuation in other directions which are usually the directions of interference signals. The beamforming systems normally consist of array antennas and signal processing units. The processing units are normally used to identify DOA of incoming signals and to point the main beam to the direction of the desired signal. The incident signal at each antenna element will be multiplied by the weighting coefficients at BS according to the DOA of each user. So, the received signals at BS after performing beam formation is

$$\boldsymbol{y_{out}} = \boldsymbol{wy} \tag{8}$$

Then, substituting (1) back to (8) yields

$$\boldsymbol{y_{out}} = \sqrt{P}\boldsymbol{wHx} + \boldsymbol{n_s} \tag{9}$$

where $\boldsymbol{n_s} = \boldsymbol{wn}$. Then, substituting (2) back to (9) yields

$$\boldsymbol{y_{out}} = \sqrt{P}\boldsymbol{w}(\boldsymbol{B}^{LOS}\boldsymbol{A}^{LOS} + \textstyle\sum_{l=1}^{L} \boldsymbol{B}_l^{NLOS}\boldsymbol{A}_l^{NLOS})\,\boldsymbol{x} + \boldsymbol{n_s} \tag{10}$$

The output signal ($\boldsymbol{y_{out}}$) at BS as appeared in (10) contains an information of each user. The proposed concept in this paper is to introduce an alternative beamforming scheme which is able to perform multiple-beam formation when all beams operate at the same frequency and the same time. Moreover, all produced beams are orthogonal to each other, hence one's nulls can be generated at the directions of others' main beams. Users transmit data to the receiver but it is essential that the receiver should be able to receive every data completely and accurately. The received signals are the same as the signal vector containing the user data vector ($\boldsymbol{x}$). The proposed concept is to find the appropriate weighting coefficients ($\boldsymbol{w}$) to avoid interference in the main beam direction as all beams are launched at the same time and the same frequency.

From (9), the weighting coefficients ($\boldsymbol{w}$) is multiplied by channel coefficient matrix ($\boldsymbol{H}$). If $\boldsymbol{w} = \boldsymbol{H}^{-1}$, the output signal will contain only information of each user plus noise. However in real environment, as the changes in physical environment occur all the time, knowing the exact channel ($\boldsymbol{H}$) is impossible. This makes the weighting coefficients ($\boldsymbol{w}$) unstable. In turn from (10), B^{LOS} is easier to eliminate when we know the DOA of LOS signal. In addition, referring to the technical specification of 3GPP, the power of NLOS components is relatively small comparing to LOS component. However, the effect of NLOS components will be taken into account later in Section IV.

The key element to accomplish the proposed orthogonal beamforming is to find steering vectors according to incoming signal from users as expressed in (5).

$$\boldsymbol{w} = (\boldsymbol{B}^{LOS})^{-1} \tag{11}$$

The equation (11) indicates that the steering matrix $\boldsymbol{B}^{LOS}$ must be non-singular matrix so that it can be invertible. However, if the system employs a higher number of antennas comparing to the number of users, the matrix $\boldsymbol{B}^{LOS}$ cannot be directly inversed. For this case, the Moore-Penrose preudoinverse can be helpful [12]. Then, the weighting coefficients ($\boldsymbol{w}$) is given by

$$\boldsymbol{w} = \left(\boldsymbol{B}^{LOS}\right)^{\dagger} = \left(\boldsymbol{B}^{LOS}\right)\,\left(\boldsymbol{B}^{LOS}\left(\boldsymbol{B}^{LOS}\right)\,\right)^{-1} \tag{12}$$

where, $\left(\boldsymbol{B}^{LOS}\right)^{\dagger}$ denotes the Moore-Penrose pseudoinverse of $\boldsymbol{B}^{LOS}$.

This equation also shows an independent relation between weighting coefficients and steering vectors, so called orthogonal property. As all beams are orthogonal to one another, users are not an interference to themselves anymore.

Furthermore, the SINR can be obtained by considering individual channel for each user as given by

$$\boldsymbol{H_m} = \boldsymbol{a}(\boldsymbol{\theta_m})A_m^{LOS} + \textstyle\sum_{\boldsymbol{l=1}}^{\boldsymbol{L}} \boldsymbol{a}(\boldsymbol{\theta_{m,l}})A_{m,l}^{NLOS} \tag{13}$$

where $\boldsymbol{H_m}$ is a communication channel for mth user. Then, the signal output of mth user is

$$y_{out,m} = \sqrt{P}\boldsymbol{w_m}\boldsymbol{H}_m x_m + \textstyle\sum_{\boldsymbol{j\neq m}}^{\boldsymbol{M}} \sqrt{P}\boldsymbol{w_m}\boldsymbol{H_j} x_j + n_{s,m} \tag{14}$$

So, the SINR of mst user can be expressed as

$$SINR_m = \frac{P(w_m\boldsymbol{H_m})\boldsymbol{H_m}\ \boldsymbol{w_m}\ |x_i|^2}{\sum_{j\neq m}^{M} P(w_m\boldsymbol{H_j})\boldsymbol{H_j}\ \boldsymbol{w_m}\ |x_j|^2 + |n_{s,m}|^2} \tag{15}$$

As we can see in (5), the $\boldsymbol{B}^{LOS}$ is a steering vector matrix which can be formed using the knowledge of directions (DOA) of incoming signal employing DOA estimation algorithms available in literatures e.g., MUSIC and ESPRIT. The evaluation of proposed concept in terms of beamforming performance and SINR is initially demonstrated via computer simulation in next section.

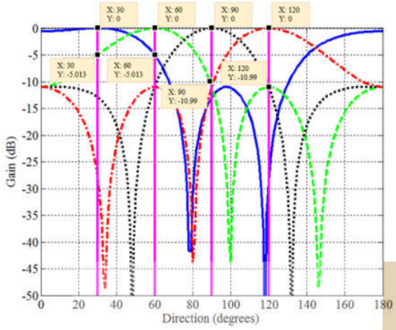


Fig. 5. Beam patterns of *conventional beamforming* when signals are coming from 30 60 90 and 120 degrees (case 1)

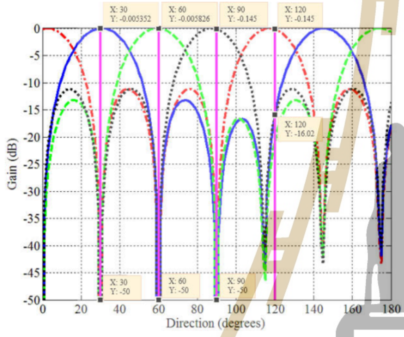


Fig. 6. Beam patterns of *proposed orthogonal beamforming* when signals are coming from 30 60 90 and 120 degrees (case 1).

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we present simulation results to show the performance of proposed orthogonal beamforming in multi-user communications compared with a conventional beamforming. The impact of different parameters, such as the distance between users and BS, and also the transmitted power on the average SINR are also investigated.

A. Beam Formation

Firstly, we study the simulated radiation pattern of orthogonal beamforming comparing to conventional beamforming as defined in Section II. Please note that the weighting coefficients of conventional beamforming is $\boldsymbol{w} = (\boldsymbol{B}^{LOS})$. Note that 4 users requiring 4 individual beams are assumed to be operated at the same time and same frequency. All simulation results are compared with the case of conventional beamforming which only aims to have a maximum gain at the desired direction. In this simulation, the 4 omni-directional antenna elements are equally spaced by λ/2 at 2.4 GHz and arranged in linear manner. Signals are coming from 30 60 90 and 120 degrees. In this case, the direction of 4 beams are evenly separated by 30 degrees throughout a 120-degrees sector. In practical, these pre-defined angles can be calculated using DOA estimation algorithms available in literatures. Then, an own developed programming was created using Matlab according to the given parameters mentioned earlier. Firstly, the weighting coefficient matrix was calculated using a steering vector matrix according to those 4 pre-defined beams. Then, beam patterns and SINR were generated in computer to see the performance of proposed concept.

TABLE I
SIGNAL TO INTERFERENCE PLUS NOISE RATIO (SINR) WHEN SIGNALS ARE COMING FROM 30 60 90 AND 120 DEGREES

User Direction (degrees)	**SINR (dB)**	
	Conventional beamforming	**Orthogonal beamforming**
30	5.013	49.9945
60	5.013	49.9942
90	10.99	49.855
120	10.99	16.015

Fig. 5 shows beam patterns employing a conventional beamforming. As we can see, all 4 beams can be perfectly directed to pre-defined angles: 30 60 90 and 120 degrees. However, side lobes of each beam are relatively high. As these 4 beams are launched at the same time and the same frequency, so all beams can be interference to one another. On the other hand, when we apply our proposed orthogonal beamforming to the systems, not only the main beams can be perfectly pointed to desired directions but also large attenuations are provided in interference directions as seen in Fig. 6. This is because the proposed algorithm gives an orthogonal property to the beams.

Another parameter indicating the wireless communication performance is SINR. When we focus on one pre-defined beam, all the rest beams become interference as they are operated at the same time and frequency. This SINR can be calculated as follows: *SINR (dB) = desired signal (dB) – interference signal (dB)*. Note that desired signal (dB) and interference signal (dB) shown in the expression present the level of normalized beam pattern in the desired and interference directions, respectively. Table I reveals SINR values when employing the proposed orthogonal beamforming compared with conventional beamforming for all 4 pre-defined directions. As expected, the orthogonal beamforming provides higher SINR comparing to conventional beamforming. This implies that the proposed concept can also provide a higher throughput.

Moreover, we have run a number of computer simulation for the cases when the direction of main beam is random within 120-degree sector. The results are in good agreement with the ones when the 4 beams are evenly separated by 30 degrees. The simulation results have revealed that when a number of users occupy the same channel at the same time slot, the proposed orthogonal scheme gives a maximum gain in the direction of desired users while keeping nulling in the direction of interference signals. According to this, the system SINR obtained in the case of orthogonal beamforming is relatively higher compared with the conventional beamforming. This implies that the orthogonal beamforming can improve a data transmission speed and also a system throughput for multi-user communications. However, the limitation on the beam separation will be further investigated in Section V.

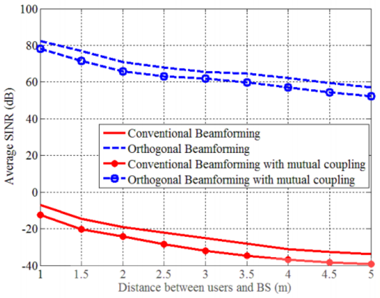


Fig. 7. Average SINR vs. distance between users and BS for 4 users located at 30, 60, 90 and 120 degrees and $P_t = 0$ dBW.

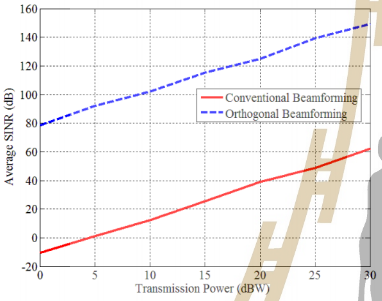


Fig. 8. Average SINR vs. transmitted power for 4 users located at 30, 60, 90 and 120 degrees when distance between users and BS is 1 meter.

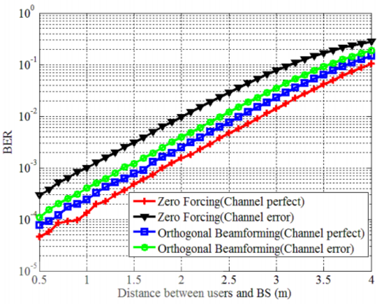


Fig. 9. BER vs. distance when having 90 multipath signals.

B. SINR vs Distance and Transmitted Power

Next, we show the impact of distance and transmitted power on the system SINR. Fig. 7 shows the plots of simulated average SINR vs. distance between users and BS where the BS is equipped with 4 omni-directional antennas. The 4-users are located at 30, 60, 90 and 120 degrees when all transmitted power are equally given at 0 dBW. For the simulation, we assume a practical indoor scenario with the path-loss exponent of 1.6 [10]. We substitute parameters into (15) and vary distance from 1 to 5 meters. Then, we can see from the figure that the average SINR decreases when users are moving away from the BS. This is because of the path-loss effect. However, the proposed orthogonal beamforming provides a higher overall average SINR comparing to the cases of conventional beamforming for all distances. This is because the weighting coefficients obtained using an orthogonal property is able to provide nulls at interference directions.

In addition, Fig. 8 shows the average SINR when varying the transmitted power. In (15), we assume that the BS is equipped with 4 antennas operating for 4 users located at 30, 60, 90 and 120 degrees when the distance between users and BS is 1 meter. The average SINR increases when the transmitted power of user increases. Furthermore, the proposed orthogonal beamforming provides a higher average SINR comparing to a conventional beamforming. This confirms that the proposed orthogonal beamforming can increase the performance of multi-user communications.

C. Orthogonal Beamforming vs. Zero Forcing

In this section, we investigate into the system performance in terms of BER for the proposed Orthogonal BeamForMing (OBFM) and Zero Forcing (ZF) for two cases including perfect and imperfect communication channel feedback. The ZF refers to a form of linear processing algorithm used in communication systems which nulls out interference signal. The ZF applies the inverse of the channel with frequency response to the received signal in order to restore the signal after passing through channel. As the channel response for a particular channel is $\boldsymbol{H}$ given in (2), the interference nulling algorithm multiplies the reciprocal of $\boldsymbol{H}$ to the input signal which removes the effect of channel from the output signal. As the ZF weight vector is given as $\boldsymbol{w}_{ZF}$, then the relationship with the channel is

$$\boldsymbol{w}_{ZF}\boldsymbol{H} = 1 \tag{16}$$

Thus, the weighting coefficients of ZF is

$$\boldsymbol{w}_{ZF} = \boldsymbol{H}^{\dagger} = \boldsymbol{H}\ (\boldsymbol{H}\boldsymbol{H}\ )^{-1} \tag{17}$$

where, $\boldsymbol{H}^{\dagger}$ denotes the Moore-Penrose pseudoinverse of $\boldsymbol{H}$. According to (16) and (17), if the communication channel is perfectly known, all interference will be completely eliminated. However, the system efficiency is not maximal as we cannot know the exact channel in real environment. On the other hand, the proposed OBFM utilizes an inverse of DOA instead of channel information. So, this section reveals the system performance comparing between OBFM and ZF for various cases of multipath signals. Fig. 9 shows the system BER when perfect and imperfect channel feedbacks are assumed. The number of multipath is 90. Note that the number of multipath signals was referred to the calculation methods available in literatures [13]. Then, the random direction of multipath was repeated for 30 times to achieve the average BER as shown in the figures. As the result, if the perfect channel feedback is assumed, ZF provides a lower BER comparing to the proposed OBFM. However, ZF is relatively sensitive to the channel

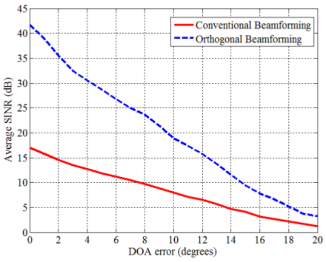


Fig. 10. Average SINR vs. DOA estimation error for 4 users.

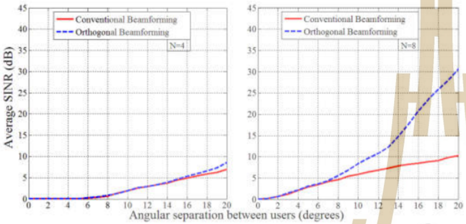


Fig. 11. Average SINR vs. distance between users for 4 users when $N=4$ and $N=8$

property. As we can see in the figures, ZF provides a high BER when the channel feedback is not perfect (so called channel error). Please note that the channel error was given by adding noises into (17). Furthermore, we have run a number of computer simulation for the cases having rich mutipaths e.g., 90 paths. As a result, a lower BER is obtained when having fewer multipath signals. Also, as expected, the proposed OBFM outperforms ZF algorithm when the real channel property having rich multipath signals is assumed.

In fact, the channel is not possible to be perfectly known. Therefore, the proposed OBFM outperforms ZF in the scenarios which are close to real environment. However, next section discusses how the accuracy of DOA estimation affects the proposed concept. Also, next section demonstrates the performance of proposed OFBM in real environment in terms of beam patterns and SINR with a constructed prototype.

V. LIMITATIONS OF ORTHOGONAL BEAMFORMING

In this section, we show some simulation results in order to identify the limitation of the proposed systems including DOA estimation error, distance and mutual coupling effect between antenna elements.

A. DOA Estimation Error

As the direction of incoming signal is one of key success factors for the proposed orthogonal beamforming, this section shows the effect of estimation accuracy on the beamforming performance. Note that the DOA estimation error was calculated by averaging from 4 users. Fig. 10 shows that the average SINR decreases as DOA error increases, for both orthogonal beamforming and conventional beamforming. This is because when accuracy of beam steering, both main beam and nulls, is reduced, the interference between beams become stronger. However, the WLAN standard allows the minimum SINR value of 4 dB [14]. According to this given information including with the plot shown in Fig. 10, the maximum value of 18-degrees is allowed for DOA estimation error. So far, there are lots of literatures regarding the performance of DOA algorithms which have proposed some simple algorithms providing an error not higher 2 degrees.

B. Angular Separation between Adjacent Users

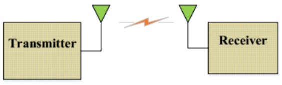
In general, the interference cannot be eliminated when it comes in the region of main beam. This means that the beam width directly affects the distance between adjacent users. In this section, we investigate into the limitation of distance between users according to the width of formed main beam for proposed concept. In the simulation results, there are two cases: 4 and 8 linear array antennas. Note that the omni-directional antennas are employed for this simulation. Fig.11 shows the average SINR with the distance between of users for both cases. These plots shows that, when users are too close to one another, the interference cannot be effectively rejected as they are all stay in the region of main beam, resulting in a low SINR. However, the system SINR increases when angular separation between two adjacent users increases as the systems are able to steer nulls to interference directions. Also, as expected, the proposed OBFM outperforms the conventional one. In summary, the angular separation between users is limited according to the nature of array antennas. The more number of antenna elements, the closer users can be. This is because a lower beam width is achieved when employing the array antennas with a higher number of antenna elements. However, the effect of angular separation between users is an interesting issue which will be further investigated in the near future.

C. Mutual Coupling

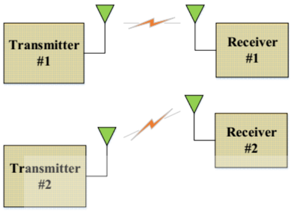
As the multiple antenna elements are employed in the proposed systems, one interesting question is how the mutual coupling effect between elements affects the beamforming performance. Therefore, this section takes into account the mentioned effect as follows. The concept proposed in [15] is adopted to create a mutual impedance matrix. This must be inserted into the expression of received signal vector at BS (before weighting) which can be written as

$$\boldsymbol{y} = \sqrt{P}\boldsymbol{C}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{18}$$

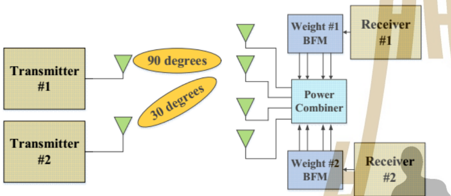
where $\boldsymbol{C}$ is the coupling matrix of array antennas, which can be written using fundamental electromagnetic circuit theory as presented in [16]. The simulation results including mutual coupling effect have been previously presented in Fig. 8. As we can see, the average SINR decreases when taking into account the mutual coupling between antenna elements. However, the orthogonal beamforming still provides a better SINR comparing to the convention one. In addition, the remedies of mutual coupling effect have been popularly proposed in literatures [17-19]. However, the real beamforming performance including mutual coupling effect will be revealed through the experimental results in next section.



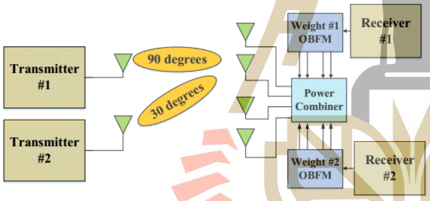
Case A: Single user communications.



Case B: Two-user communications.



Case C: Multi-user communications employing conventional beamforming (MU-BFM).



Case D: Multi-user communications employing proposed orthogonal beamforming (MU-OBFM).

Fig. 12. Experiment configurations for 4 cases: A to D.

VI. EXPERIMENTAL RESULTS AND DISCUSSIONS

A prototype of orthogonal beamformer was constructed with some fixed beamforming networks. Note that directions of incoming signal are assumed at 30 and 90 degrees and the operating frequency is 2.4 GHz. The measurement was performed focusing on Received Signal Strength Indicator (RSSI), Bit Error Rate (BER) and throughput under real circumstance. The constructed beamformer was connected to Universal Software Radio Peripheral (USRP) to perform a full two-way communication. Fig. 12 shows the experiments including 4 different cases as follows:

Case A: Single user communications: in this case, there are only one transmitter and one receiver. Both USRPs, each for transmitter and receiver, are connected to a single dipole antenna without any beamforming networks.

Case B: Two-user communications: in this case, two users are stationary at directions of 30 and 90 degrees. There are two transmitters and two receivers in which each of them is connected to USRP. Also, a single dipole antenna operating at 2.4 GHz is individually employed at transmitters and receivers. Note that the beamforming scheme is not applied for this case.

Case C: Multi-user communications with conventional beamforming (MU-BFM): in this case, there are two transmitters and two receivers. One transmitter is positioned at 30 degrees while another one is placed at 90 degrees. Two fixed beamforming networks are employed to perform beamforming at 30 and 90 degrees. Note that 4×1 dipole antennas are employed, which are equally spaced by half-wave length at 2.4 GHz. On the receiving side, a single dipole antenna is individually employed to convey the received signal to USRPs in order to record the RSSI and BER.

Case D: Multi-user communications with the proposed orthogonal beamforming (MU-OBFM): the experiment scenario in this case is similar to the ones described in previous case (case C), except the proposed orthogonal beamforming networks are employed instead of conventional one. Also, USRPs are individually connected to the receivers to record the RSSI and BER in real time.

All experiments were performed in 6×6 m^2 room at F4 building, Suranaree University of Technology, Thailand. This indoor environment was chosen as it includes lots of multi-paths coming from partitions and walls. Also, Fig. 13 shows the experiment setup when the transmitters are placed at 30 and 90 degrees. Both transmitters transmit data through the same array antennas at the same time. As we can see, the USRPs at both receivers are connected to laptop computer to record RSSI and BER in real time.

Fig. 14 shows the RSSI obtained from experiments versus sampling time. This RSSI represents a signal strength value of received signal. In this case, the distance between transmitters and receiver is 2 meters. As we can see in the figure, case A provides the lowest RSSI because, in this case, there is only one transmitter. On the other hand, the cases B C and D provide the highest RSSI. Furthermore, the RSSI is twice for the cases of multi-user communications (cases B, C and D) compared with single user communications (case A). This is because the two transmitters operate at the same time and the same frequency. Therefore, those transmitted signals are somehow constructively combined at the receiver gaining the signal strength. However, this leads to a question whether a high RSSI value indicates any benefits to system operators or users. So, the system performance in terms of some other indicators e.g., BER and throughput have to be further investigated in next section.

Fig. 15 presents the measured BER when the users are located at 30 and 90 degrees. As we can see in the figure, single user communications provide the lowest error of transmitted data. This is because there is no interference when only one transmitter and one receiver are communicated. But when the two transmitters (case B: two users) operate at the same time and the same frequency, the BER value significantly increases, which means we lose the accuracy of received data. This is

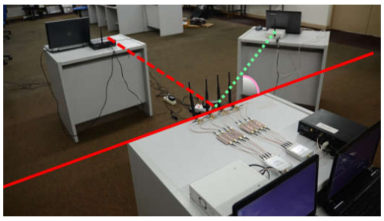


Fig. 13. Photograph of experiment setup when transmitters are placed at 30 and 90 degrees.

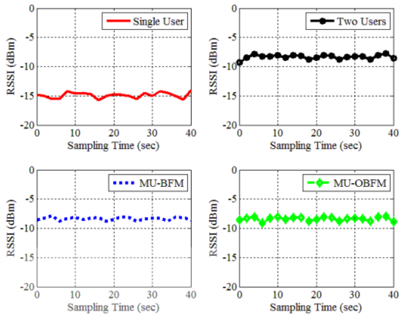


Fig. 14. Measured Received Signal Strength Indicator (RSSI) for 4 cases: A to D.

because one becomes interference to each other. The impairment can be healed with the use of beamforming networks as the results obtained from cases C and D (MU-BFM and MU-OBFM). However, the proposed orthogonal beamforming (MU-OBFM) outperforms the conventional one (MU-BFM) as its orthogonal property gives nulls at interference directions. The measured results also reveal that a high received signal strength as shown in Fig. 14 cannot guarantee the accuracy of received data as seen in Fig. 16, especially for case B.

Next, the system throughput is investigated. The BER obtained from experiments were recorded to calculate the system throughput under 4 different scenarios as aforementioned (cases A to D) using the following calculations.

$$1 \quad PER = (1 \quad BER)^L \tag{19}$$

where, *PER* stands for Packet Error Rate, BER stands for Bit Error Rate and *L* is data packet length.

The Transmission Control Protocol (TCP) throughput, which is the rate that data is successfully delivered over a TCP connection, is an important parameter to measure the quality of a network connection. Generally speaking, TCP throughput is measured as *data rate per cycle / time per cycle*. The work presented in [20] has come up with a model for the throughput calculation, which takes into account some link characteristics such as the Maximum Segment Size (*MSS*), Round Trip Time (*RTT*) and packet loss. Then, throughout can be determined by

$$T \ roug \ put = \left(\frac{MSS}{RTT}\right)\left(\frac{1}{\sqrt{PER}}\right) \tag{20}$$

where *MSS* stands for Maximum Segment Size in bytes and *RTT* represents Round Trip Time in second. The MSS of cases B, C and D are doubled of case A because the cases B, C and D have 2 users which is double comparing to case A.

From previous results (Fig. 15), case A (single user communications) provides the best BER (lowest value) as there is no co-channel interference at all. However, this cannot guarantee the rate of successful messages delivered over a communication channel. So the system throughput must be investigated. Fig. 16 shows that case A provides the lowest throughput. But when the number of transmitter and receiver increases, the system throughput is higher. Note that the throughput value was calculated for a number of the users in each case, then the average throughputs from every user are plotted in the figure. Among all 4 cases, the highest throughput can be obtained from the use of proposed orthogonal beamforming, approximately double of the throughput of single user case. Also, the system throughput drops when users move away from BS for all cases. This is because, at far distance, the signals both from desired user and interferences are weak while noise is constant. Then, the throughput converges to the same point for cases B, C and D. However, the overall performance of proposed beamforming is higher than other cases.

All experimental results presented earlier have confirmed the beamforming performance of proposed orthogonal beamforming that it provides high signal strength and throughput compared with the use of single user systems. Also, the proposed systems provide a low packet error rate.

VII. CONCLUSION

This paper has introduced a concept of an orthogonal beamforming which provides multiple-beam formation at the same time and the same frequency for multi-user communications. The proposed idea requires only information of DOA of incoming signal without the requirement of feedback information of channel. All produced beams operating at the same frequency are orthogonal to one another in which one can point it nulls to the direction of the other's main beams at the same time, while maintaining maximum gain in the direction of users of interest. A number of computer simulations in various scenarios have been produced to reveal the performance of proposed concept. The simulation results have shown that the proposed orthogonal beamforming provides the highest SINR among all simulation cases. Furthermore, the comparison to a famous Zero Forcing (ZF) algorithm has been taken into account. The results have revealed that the proposed concept outperforms ZF algorithm when real circumstance having an imperfect channel estimation is considered. Then, a prototype of orthogonal beamformer has been constructed and tested in real environment in order to validate the proposed concept. The experiments have been performed in indoor environment which includes the effect of rich shadowing,

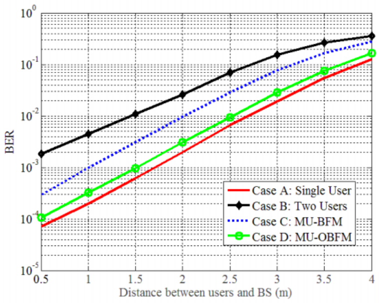


Fig. 15. Measured BER vs. distance between transmitter and receiver when users are located at 30 and 90 degrees.

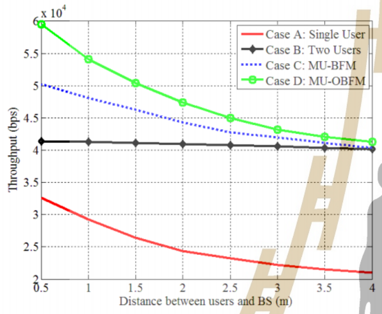


Fig. 16. Measured throughput vs. distance for 4 cases: A to D.

multipath and mutual coupling between antenna elements. The measured results have revealed that the proposed beamforming scheme provides a high signal strength and throughput but low bit error rate compared with the other 3 cases: single user, two users without beamforming and multi-user with conventional beamforming. This is because all produced beams are orthogonal to each other so that they do not interfere to one another when they are launched at the same time with the same frequency.

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COOPERATIVE MODE BETWEEN MIMO AND BEAMFORMING SCHEMES IN WLANS

Running head: Cooperative Mode Between MIMO and Beamforming Schemes in WLANs

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Abstract

The Multiple-Input Multiple-Output (MIMO) and Beamforming (BFM) techniques have become one of the key techniques of wireless communications system and been regarded as a significant role in the development of single-user communication and multi-user communication performance. This paper shows their different advantages and disadvantages in terms of data transmission rate and Signal to Noise Ratio (SNR). The MIMO technique is the use of multiple antennas at both transmitter and receiver to improve the performance of data transmission rate while BFM increases SNR performance. To fully deploy those advantages, we propose the integration of MIMO and BFM techniques to improve the data transmission rate and SNR,

so-called cooperative mode. Furthermore, the proposed cooperative mode can improve the average throughput for both single- user and multi- user communications. The obtained simulation results reveal that the proposed concept provides a higher average throughput over both MIMO and BFM techniques.

Keywords: **MIMO, beamforming, cooperative, multi-user, single-user, WLANs**

Introduction

Wireless communications have become a part of daily life as people needs to give, receive or exchange information to one another all the time. According to this, the growth of wireless technologies has been exponentially increased from the past and also has been continually developed to support higher performance in terms of transmission rate and quality. One of the most popular wireless systems is Wireless Local Area Networks (WLANs) based on IEEE802.11 standard. The standard has been firstly developed from IEEE802.11a supporting data transmission only 54 Mbps with a small coverage (Jansons, Janis, et al, 2012 and IEEE 802.11 WG, 1999). Afterwards, IEEE802.11b IEEE802.11g and IEEE802.11n standards have been established to support higher data rate transmission with wider coverage (Position paper, 2012 and Sendra, Garcia, Turro and Lloret, 2011). Recently, the attention has gone to IEEE802.11ac and IEEE802.11ad standards as they are envisaged to provide a tremendous rate of data transmission for WLANs (IEEE

P802.11ac™ / D3.0, 2012; IEEE Std 802.11ad™, 2012 and IEEE Std 802.11.ad/D9.0 draft specification, 2012). Also, Worldwide Interoperability for Microwave Access (WIMAX) has been developed to support broadband technologies based on IEEE802.16 standard providing high speed data transmission in some areas where non-line of sight signal is dominant (Daan Pareit, 2011). All mentioned standards for wireless communications have been originated with the aim of supporting an increase in the number of users, which is relatively higher year by year. Also, the requirement of video steaming or transmitting for a huge packet size drives the ongoing developments.

From the beginning, the wireless technology standard was developed for a point-to-point communication, so-called single-user system, in which a base station can communicate with one user at a time whereas someone else has to wait or use some other channels. According to this, the system is able to provide a high Signal-to-Interference Ratio (SIR). Unfortunately, this single-user system is low of channel capacity and throughput. Therefore, upcoming wireless technology standards e.g. IEEE802.11ac, IEEE802.11ad, IEEE802.16 or LTE-A release 12-15 have been initiated for a point-to-multipoint communication, so called multi-user system. For this system, a base station can convey messages to a number of users at the same time and same frequency. This alternative communication provides an increase in channel capacity and throughput. From literatures, lot of research articles have demonstrated the advantages of multi-user communication over signal-user system in terms of data transmission rate (Hieu Duy Nguyen, 2013; Liangbin Li, 2013; Pei Xiao and Mathini Sellathurai, 2010).

However, a multi-user communication is facing a problem of co-channel interference coming from neighbour cells. From literatures, lots of works have been proposed to tackle this impairment e.g. the utilization of array antennas or frequency reuse techniques. The works presented in (Emil Björnson, 2013; Peter J. Smith, 2014; Rafik Addaci, 2014 and Mohammad Hassan Shariat, 2013) have demonstrated an increase in channel capacity and coverage employing array antennas at base station. This is because they are able to provide high value of directivity. Nowadays, lot of attentions have been paid to a multiple-antenna technology as it is low of cost and also not complicated. So far, the multiple-antenna technology has been usually reflected by Multiple-Input-Multiple-Output (MIMO) or Beamforming (BFM) technologies. These two unique technologies have different advantages and disadvantages. The MIMO technology allows a number of users sending their information through a number of antenna elements at the same time. So the system capacity and throughput can be tremendously increased comparing to the system employing only single antenna element. However, the success of MIMO technology totally depends on the knowledge of communication channel which alters all the time. Moreover, the mentioned impairment is more pronounced for long distance communication due to some phenomena e.g. path loss, shadowing or multipath fading, which make the communication channel crucially unexpected. This degrades the system capacity and throughput. On the other hand, beamforming technology provides a higher stability for long distance communication as the system provides high directivity gain in the desired direction. For this system, a user conveys the same information into a number of antennas which are properly weighted to coherently adjust the signal phase in order to be constructively combined at destination. Unfortunately, the beamforming technology cannot provide a high rate of data transmisiion.

As mentioned above, MIMO and beamforming technologies have different prominent points. From previous work (Paleerat, Monthippa, Peerapong, 2014), we have compared the data rate and average throughput with respect to distance between Single-User MIMO (SU-MIMO) vs. SingleUser BeamForming (SU-BFM) and Multi-User MIMO (MU-MIMO) vs. Multi-User BeamForming (MU-BFM) schemes when the number of users is 2 operating in multi-rate WLANs. The obtained results have shown that both techniques are able to improve the average throughput. The SU-BFM and MU-BFM schemes provide higher data rate and throughput at long distance. On the other hand, SU-MIMO and MU-MIMO schemes give rise to data transmission rate and throughput at a short distance.

According to both mentioned advantages, this paper investigates into a cooperative mode between MIMO and beamforming in order to give the best performance for multiple- antenna systems. This paper proposes an idea to cooperate between MIMO and beamforming technologies without the use of feedback signal. The key factor for switching modes between MIMO and beamforming is Signal to Noise Ratio (SNR) at users for multi-rate WLAN systems. This is because MIMO provides better data rate when the received signal or SNR is strong or users stay near the base station while beamforming gives better performance in terms of data rate when users move away from the base station. The remainders of this paper are as follows. After brief introduction, section II shows the benefit of MIMO and beamforming technology in single-user and multi-user communications. Section III presents some simulation results. Section IV shows the proposed concept of the cooperative mode. Finally, Section V concludes the paper.

Benefits of MIMO and Beamforming in Single-user and Multi-user Communications

The wireless communications have been developed to respond to user's needs such as a higher data transmission rate, a higher capacity, a higher reliability and a wider service coverage. Therefore, all standards of wireless communications have been developed from single-user to multi-user communications. Furthermore, the MIMO and beamforming techniques have been used in wireless communications for increasing the data rate, throughput, Signal to Interference plus Noise Ratio (SINR) and capacity. This section shows the performance comparison between MIMO and beamforming for single-user and multi-user communications.

A. Single-user Communications

Figure 1 shows MIMO and beamforming schemes for single-user communications. In these schemes, the Access Point (AP) transfers data to one user at a specific time or frequency. The MIMO technique is an antenna technology in which multiple antennas are used at both transmitter and receiver. Figure 1(a) shows the SU-MIMO scheme in which the AP is equipped with *N* antenna elements. Usually, those elements are linearly aligned. Furthermore, *M* is the number of antennas at a user terminal. The simulation was assumed that the number of transmitting antennas at AP and receiving antennas at user are the same ($N = M$). Then, another scheme applies beamforming technique into single user communication, so called SU-BFM as shown in Figure 1(b). We consider the case of a single user with a single antenna element employed at the user. The number of antenna elements at the AP is more than 1 ($N > 1$) which is linearly aligned.

For the simulation, we assume that all users are uniformly distributed and they adaptively select their data rates based on their average SNR. In addition, the system parameters referring to literatures (H. Jin, B. C. Jung, H. Y. Hwang, and D. K. Sung, 2011) and (IEEEStd802.11a, 1999) were adopted. Then, the average SNR at a user with distance *d* apart from AP can be expressed as

$$SNR = SNR_0 - 44.2 - (10 \times PLe)\log d \tag{1}$$

Where SNR_0 is the transmitted SNR for each antenna. The path loss at 1 meter is also set to 44.2 dB and *PLe* is the path loss exponent which is 4. Also, *d* is distance between user and AP.

In wireless communications, the users exploit high SNR as they are close to the AP. On the other hand, the SNR is degraded when users are moving out from AP. The performances in terms of data rate for SU-MIMO and SU-BFM when employing $N = 2$ and $N = 4$ through the computer simulation are shown in Figures 2 and 3 respectively. As the results, the SU-MIMO (solid line) provides a higher data rate comparing to the SU-BFM (dash line) when the system SNR is high. Conversely, at a low SNR, the results obtained from employing SU-BFM provide a higher data rate comparing to the cases of SU-MIMO. Figure 3 shows the similar simulation, but $N = 4$ at AP. As expected, the SU-MIMO provides a better data rate than the SU-BFM when the system experiences a high SNR. This is because the MIMO technique can increase the spectrum efficiency and improve data rate performance. On the other hand, the SU-BFM provides better performance in terms of data rate when staying low SNR situation. This is because beamforming technique has a high directive gain. So, it works well for a long distance communication (low SNR). In addition, the feedback channel for MIMO is dramatically degraded when the users stay at long distance.

B. Multi-user communications

Figure 4 shows MIMO and beamforming schemes in multi-user communications. The systems independently transmit data from AP to a number of users at the same time and at the same frequency. The MU-MIMO scheme is shown in Figure 4 (a). For this case, we consider a single antenna employed at each user. The number of transmitting antennas (N) at AP is equal to the number of receiving users, $N = M$. The MU-BFM scheme shown in Figure 4 (b) employing the transmitting antennas at AP can perform the beamforming and its main lobe can be directed to each user. In this case, the number of antenna at each user is 1. The number of users (M) and the number of transmitting antennas (N) are the same as the ones for MU-MIMO scheme.

In the simulation results, the data rate and SNR between MU-MIMO vs. MU-BFM when the number of user $M = 2$ and $M = 4$ are shown in Figures 5 and 6 respectively. Please note that the data rate is considered per 1 user. As the results, the MU-MIMO provides a higher data rate than MU-BFM at high SNR. At the longer distance or low SNR, the MU-BFM outperforms MU-MIMO instead.

From the simulation results, we have compared the performance of wireless communications with the utilization of SU-MIMO, SU-BFM, MU-MIMO and MU-BFM schemes in terms of data rate with respect to SNR. The results have revealed that both SU-MIMO and MU-MIMO provide a higher data rate comparing to the case of SU-BFM and MU-BFM at high SNR. Instead, both SU-BFM and MU-BFM provide a higher data rate over the case of SU-MIMO and MU-MIMO at low SNR. Both single-user and multi-user communications have same the results. So, the MIMO and beamforming techniques have different benefits. Next section, we proposed concept of the cooperative mode between MIMO and BFM.

Proposed cooperative Mode

In the previous section, the simulation results show that MIMO and BFM techniques have different advantages and disadvantages. Therefore, this paper proposes a cooperative mode to give the best performance for WLANs. This section proposes the concept of the cooperative mode which chooses the best performance for both MIMO and BFM schemes as shown in Figure 7. The configuration of proposed cooperative mode for WLANs consisting of a transmitter and a receiver. The transmitter will select MIMO or BFM technique from data rate of the user according to its SNR value to maintain the good data rate at all time.

The proposed cooperative mode is employed for single user communications (SU-MIMO and SU-BFM) with $N = 2$ and $N = 4$ shown in Figure 8. Then, 9 shows the proposed concept for MU-MIMO and MU-BFM with $M = 2$ and $M = 4$. As the results, the cooperative mode in both figures are similar. Employing 4-element provides a higher SNR comparing the case of 2 elements. This is because employing a higher antenna element provides higher degree of freedom. Also, the proposed cooperative mode can improve overall SNR and data rate due to the system is able to choose the best values at all time (between MIMO and BFM).

Next, we present the simulation results of proposed cooperative mode between MIMO and BFM for single-user and multi-users communications in term of average throughput. The system throughput is considered based on IEEE 802.11 network which employs Distributed Coordination Function (DCF). We assumed that the system is at the best scenario in which the channel is perfect without any error. The formula of throughput for IEEE802.11 standards has been derived in (IEEEStd802.11a, 1999). The scenarios of the simulations are assumed for MIMO, BFM and cooperative schemes. Please note that random distribution for 100 users is given in the simulation.

Figures 10 and 11 show the average throughput when varying the payload size for single-user and multi-user communications respectively. There is a comparison of the cases: MIMO, BFM and cooperative mode. As we can see, the proposed cooperative mode provides a higher average throughput compared with MIMO and BFM techniques. This is because the cooperative mode can select the operating mode based on the system SNR. The system will employ MIMO when experiencing high SNR at short distance but will select beamforming when the users move away from AP facing low SNR. According to this, the system is able to keep the good values at all time.

Conclusion

This paper has introduced the concept of cooperative mode. The cooperative mode is integration between MIMO and beamforming techniques for improving the performance of single-user and multi-user communications. Also, we have compared the performance of WLANs with the utilization of SU-MIMO, SU-BFM, MU-MIMO and MU-BFM schemes in terms of data transmission rate vs. SNR. The results obtained from computer simulation have revealed that both SU-MIMO and MU-MIMO provide a higher data rate at a high SNR comparing to the case of SU-BFM and MU-BFM. However, at a low SNR, both SU-BFM and MU-BFM provide a higher data rate instead. Also, we can see that there is a tradeoff between utilization of MIMO and BFM (both SU- and MU-) schemes. The proposed cooperative mode is combination the advantages of the MIMO and beamforming techniques. The simulation results have shown that the proposed cooperative mode can increase the average throughput among all simulation cases.

Acknowledgement

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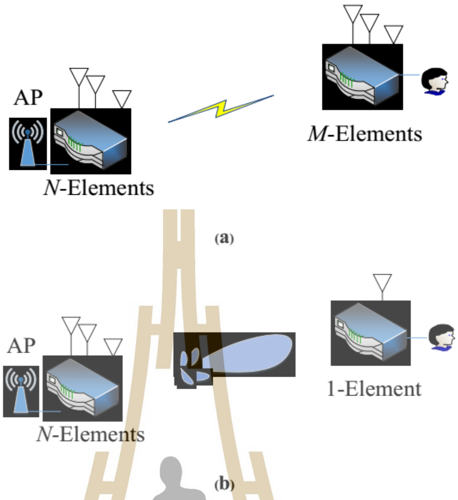


Figure 1. Single-user communications employing (a) MIMO (b) beamforming.

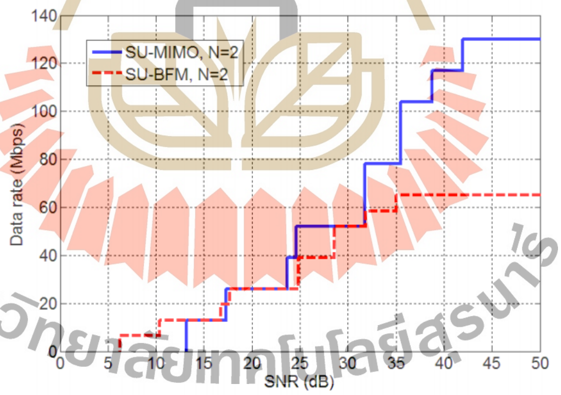


Figure 2. Data rate vs. SNR for SU-MIMO and SU-BFM with $N = 2$.

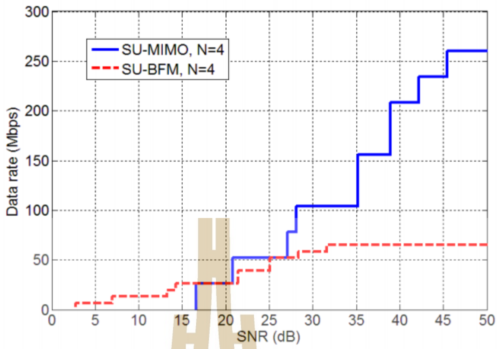
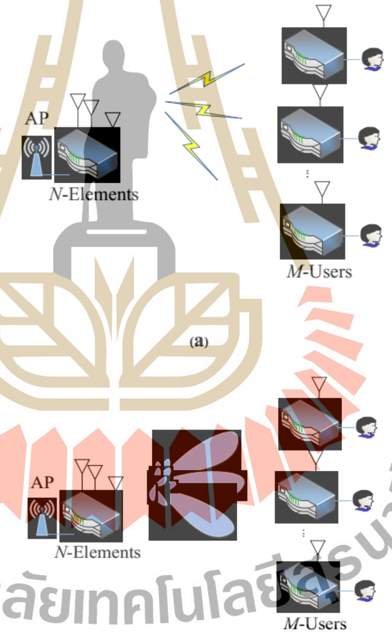


Figure 3. Data rate vs. SNR for SU-MIMO and SU-BFM with $N = 4$.



(a)

(b)

Figure 4. Multi-user communications employing (a) MIMO (b) beamforming.

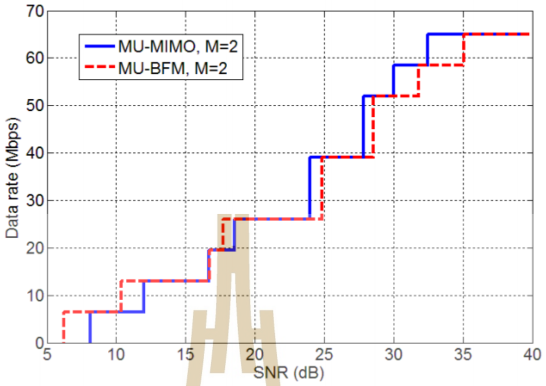


Figure 5. Data rate vs. SNR for MU-MIMO and MU-BFM with *M*=2.

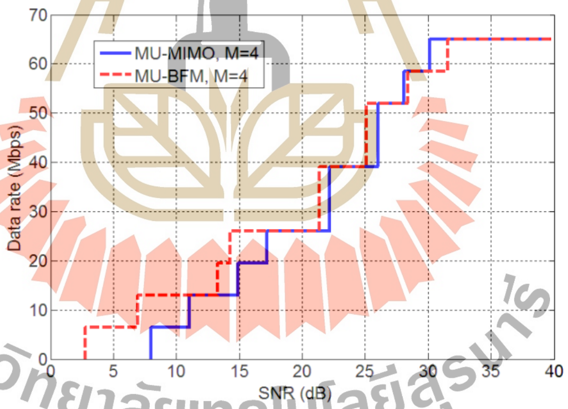


Figure 6. Data rate vs. SNR for MU-MIMO and MU-BFM with *M*=4.

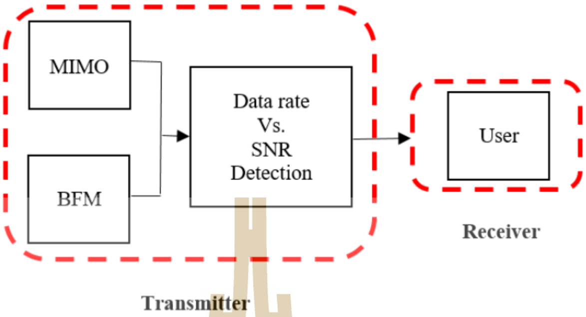


Figure 7. Configuration of proposed cooperative mode for WLANs.

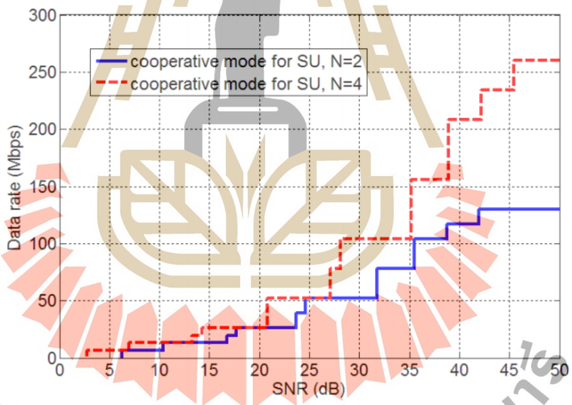


Figure 8. Cooperative mode between MIMO and BFM for single-user communications employing $N = 2$ and $N = 4$.

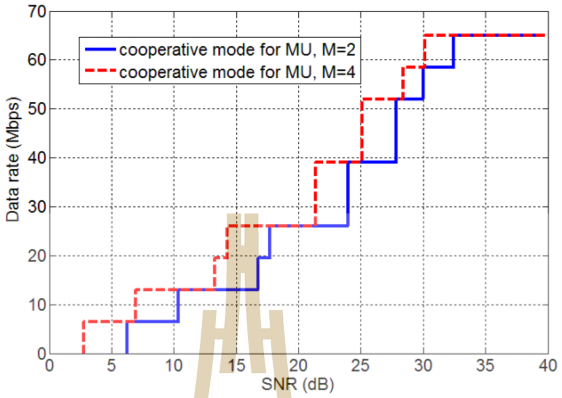


Figure 9. Cooperative mode between MIMO and BFM for multi-users communications employing $M = 2$ and $M = 4$.

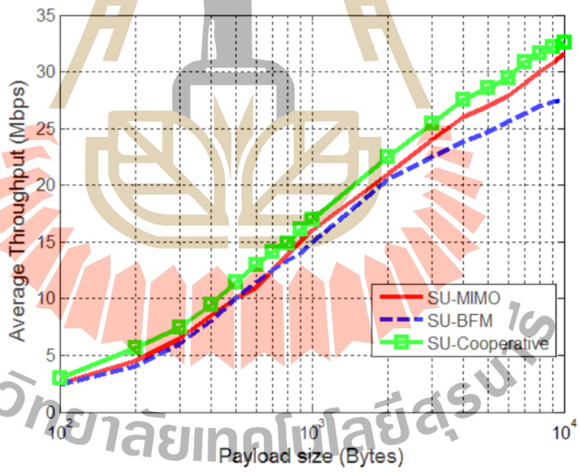


Figure 10. Average throughput vs. payload size for single-user communications.

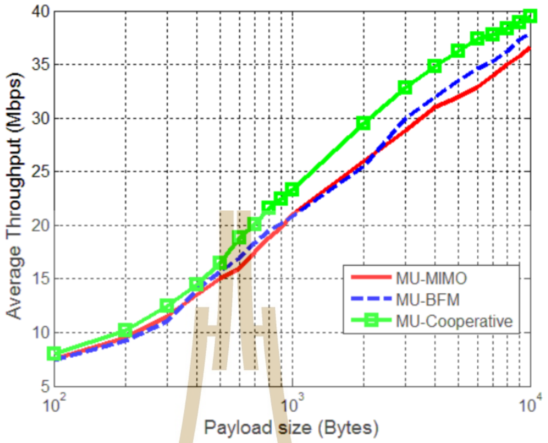


Figure 11. Average throughput vs. payload size for multi-user communications.

Data Rate and Throughput Enhancement base on IEEE802.11n Standard employing Multiple Antenna Elements

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***Abstract*— In this paper, the performance of wireless local area networks (WLANs) with Single-User MIMO (SU-MIMO) vs. Single-User Beamforming (SU-BFM) and Multi-User MIMO (MU-MIMO) vs. Multi-User Beamforming (MU-BFM) schemes in terms of data rate and average throughput has been investigated. The MIMO technique is the use of multiple antennas at both transmitter and receiver to improve data rate performance while beamforming increases the Signal to Noise Ratio (SNR) resulting in large coverage area. The tradeoff between both schemes is the main focus for this paper. The obtained results show that MIMO and beamforming techniques are able to improve the average throughput. The SU-BFM and MU-BFM schemes provide higher data rate and throughput at long distance. On the other hand, SU-MIMO and MU-MIMO schemes give rise to data transmission rate and throughput at short distance.**

Keywords*— *Multi-user MIMO, Beamforming, 802.11n standard.

I. INTRODUCTION

IEEE802.11 is a set of standards for implementing Wireless Local Area Networks (WLANs). The WLANs have been popularly installed around the world due to its simplicity [1]. The current IEEE 802.11n standard has already adopted a Single-User MIMO (SU-MIMO) technique which enables each user to transmit multiple streams through its multiple antennas [2]. Moreover, a Multi-User MIMO (MU-MIMO) technique has been adopted by the ongoing IEEE 802.11ac standard [3]. Furthermore, IEEE802.11 WLANs support multi-rate data transmission where senders select a proper data rate suitable for current channel conditions.

The MIMO technique has been adopted by many systems to achieve high spectral efficiency in recent years. Transmission data rates can be increased by simultaneously transmitting several independent data streams through different antennas. The Multi-User (MU) is simultaneous transmissions from multiple users. Moreover, a beamforming technique is currently in focus as it is able to enhance the performance of wireless communication systems. The beamforming technology is a utilization of an antenna array capable of beam formation in which its main lobe is directed to one specific direction while turning nulls or sidelobes to directions of interference signals. This phenomenon gives rise to wireless systems performance in terms of Signal to Noise Ratio (SNR).

From literatures, the work presented in [4] has compared the performance of uplink WLANs when employing SU-MIMO and MU-MIMO schemes under an assumption of multi-rate WLAN environment. Therefore, this paper introduces a beamforming concept into the WLAN systems as it is envisaged to give rise to the performance of proposed systems. In this paper, we compare SU-MIMO vs. Single-User BeamForming (SU-BFM) and MU-MIMO vs. Multi-User BeamForming (MU-BFM) schemes in terms of data rate and average throughput with respect to distance.

II. SYSTEM MODEL

In this paper, we assume some scenarios as shown in Fig.1. The detail of parameters for simulation are as follows.

A. SU-MIMO Scheme

The number of transmitting antennas (M) and receiving antennas (N) are the same, M = N as shown in Fig. 1(a). The transmitting power at each antenna is given at P/M. Since the encoded symbol stream is directly mapped to N antennas, collisions may occur when there are multiple transmissions from multiple users. Since the transmission power, P, is limited at each user, the transmit power at each antenna of the user is set to P/N.

B. SU-BFM Scheme

For the SU-BFM scheme shown in Fig. 1(b), we assume

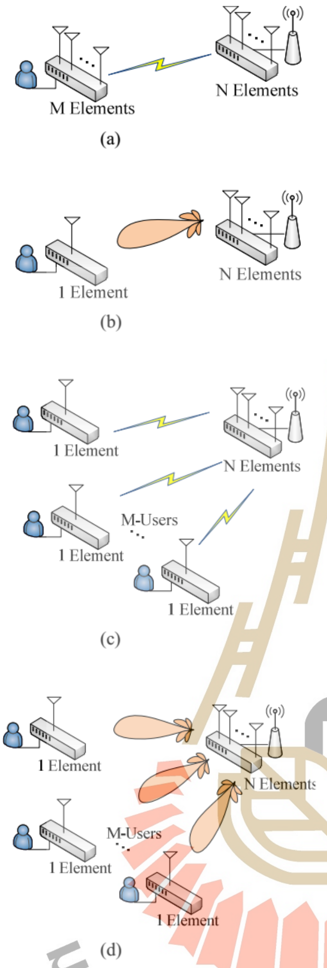

Fig.1. System model for (a) SU-MIMO (b) SU-BFM
(c) MU-MIMO (d) MU-BFM.

the case of a single antenna transmission and single user transmission as follows. The number of receiving antennas is 1 (M = 1) and the systems can form its mainbeam to a desired direction using N > 1, so called beamforming.

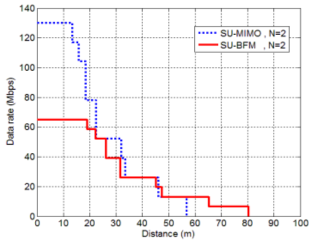

Fig.2. Data rate for SU-MIMO vs. SU-BFM, $N = 2$.

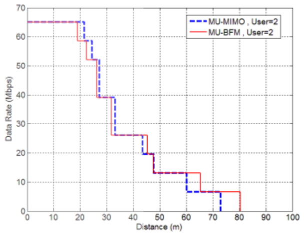

Fig.3. Data rate for MU-MIMO vs. MU-BFM at 2 users.

C. *MU-MIMO Scheme*

Fig. 1(c) shows the MU-MIMO scheme. We consider the case of a single antenna transmission for each user. The number of receiving antennas are equal to the number of simultaneous transmitting users. Since each user has no CSI information due to the lack of RTS/CTS frame exchange in the basic access mechanism, the users cannot perform antenna selection to enhance the channel quality and they just randomly select one transmitting antenna. With channel estimation at the access point (AP), it can recover the transmitted data streams originated from different STAs with MIMO decoding techniques. If the number of simultaneous transmissions (M) is smaller than the number of transmitting antennas (N) at AP, the AP can perform MIMO decoding. In the case of employing M ≥ N, although there is a successful decoding possibility for some data streams, we do not consider this kind of capture effect in this paper.

D. *MU-BFM Scheme*

For this case, the number of antennas at each user and the number of receiving antennas are given as the same as given for the case of MU-MIMO scheme. The receiving antennas can perform the beamforming and its main lobe is directed to each user as shown in Fig. 1(d).

As mentioned above, we analyze the system performance in terms of throughput for both SU-MIMO vs. MU-MIMO and SU-BFM vs. MU-BFM schemes. In simulation, all users are uniformly distributed and adaptively select their data rates based on their average received SNR. In addition, the system parameters are listed according to the works presented in [4] and [5] as shown in Table II.

The average SNR at individual user with respect to distance d from the receiver can be expressed as

$$SNR = SNR_0 - 44.2 - (10 \times PLe) \log d \qquad (1)$$

where path loss is given as 44.2 dB at 1 m and PLe is path loss exponent which is given as 4 as listed in Table I. The parameter d stands for distance between user and AP. Then, the system throughput can be obtained by the following equation:

$$Throughput = \frac{\sum_{m=1}^{user} m \cdot P_{tr}^{m} \cdot [payload\ size]}{(1 - P_{tr}^{sys})SlotTime + \sum_{m=1}^{user} P_{tr}^{m} T_{tr}^{m} + \sum_{m=2}^{N} P_{tr}^{m} T_{c}^{m}} \qquad (2)$$

where m is the number of simultaneous transmitting users. The probability for m users is given for transmission in one time slot. Also, the probability represents the case having at least one user transmitting a signal in one time slot. In addition, is the time used to transmit m simultaneously transmitted frames including overhead and is the time for the number of users higher than M simultaneously users transmitting a signal which is considered as a collision. Also, payload size is given for 1000 bytes.

III. SIMULATION RESULTS

Figs. 2 and 3 show data rate with respect to distance between SU-MIMO vs. SU-BFM at N=2 and MU-MIMO vs. MU-BFM when the number of users is 2 for the case of multi-rate WLANs. As the results at distance 0-44 m, the systems employ SU-MIMO and MU-MIMO provide higher data rate comparing with the cases of SU-BFM and MU-BFM. Also, at longer distance, the results obtained from employing SU-BFM and MU-BFM provide higher data rate comparing to the cases of SU-MIMO and MU-MIMO. We also see that the data rate decreases when the distance between transmitter and receiver increases. This is because beamforming gives rise to SNR so that we can gain coverage area with a specific data rate.

Figs. 4 and 5 show the average throughput when varying the number of users. Please note that payload size is set to 1000 bytes and cell radius is given at 20 m and 45 m. The results obtained at distance 20 m for the cases of SU-MIMO and MU –MIMO provide higher average throughput comparing to the cases of SU-BFM and MU–BFM. Also, the results at 45 m for SU-BFM and MU–BFM provide higher average throughput comparing to the cases of employing SU-MIMO and MU–MIMO.

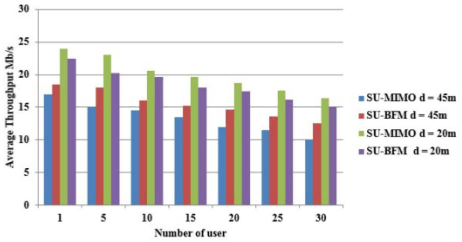

Fig.4. Average throughput vs. number of users for SU-MIMO and BFM at $N = 2$.

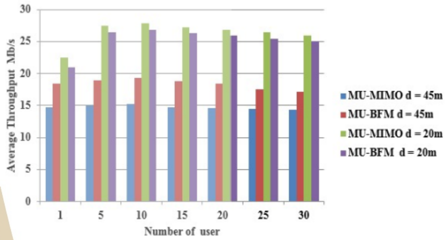

Fig.5. Average throughput vs. number of users for MU-MIMO and MU-BFM at 2 users.

IV. CONCLUSIONS

In this paper, we have compared the performance of multi-rate WLANs with the utilization of SU-MIMO vs. SU-BFM and MU-MIMO vs. MU-BFM schemes in terms of data rate and average throughput with respect to distance. The results obtained from computer simulation have revealed that both SU-MIMO and MU-MIMO provide higher data rate and average throughput at 20 m comparing to the case of SU-BFM and MU-BFM. Furthermore, at distance 45 m, both SU-BFM and MU-BFM give rise to data rate and average throughput over the case of SU-MIMO and MU-MIMO. Also, we can see that there is a tradeoff between utilization of MIMO and BFM (both SU- and MU-) schemes.

ACKNOWLEDGMENT

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Tradeoff Between MIMO and Beamforming Schemes for 802.11n

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Abstract In this paper, the performance of wireless local area networks 802.11n with Single-User MIMO (SU-MIMO) vs. Single-User Beamforming (SU-BFM) and Multi-User MIMO (MU-MIMO) vs. Multi-User Beamforming (MU-BFM) schemes in terms of data rate and average throughput have been investigated. The MIMO technique is the use of multiple antennas at both transmitter and receiver to improve data rate performance while beamforming increases the Signal to Noise Ratio (SNR) resulting in large coverage area. The tradeoff between both schemes are the main focus for this paper. The obtained results show that MIMO and beamforming techniques is able to improve the average throughput as a function of distance. The SU-BFM and MU-BFM schemes provide better data rate and throughput performance for a long distance. On the other hand, SU-MIMO and MU-MIMO schemes give rise to data transmission rate and throughput performance for a short distance.

Keyword Multi-user MIMO, Beamforming, 802.11n standard

1. SYSTEM MODEL IN MULTI-RATE WLANS

In this paper, we assume a scenario as shown in Fig.1. The parameter detail for simulation is as follows.

1.1. SU-MIMO Scheme

The number of transmitting antennas (M) and receiving antennas (N) are the same (M=N) as shown in Fig. 1(a). The transmitted power at each antenna is given of P_t/M.

1.2. SU-BFM Scheme

For the SU-BFM scheme shown in Fig. 1(b), we assume the case of a single antenna transmission and single user transmission as follows. The number of receiving antennas is 1 element (N>1) higher and the systems can form its mainbeam to a desired direction, so called beamforming.

1.3. MU-MIMO Scheme

Fig. 1(c) shows MU-MIMO scheme. The system utilizes a single antenna element at individual user. The number of receiving antennas is equal to the number of simultaneous transmitting users.

1.4. MU-BFM Scheme

For this case, the number of antenna at each user and the number of receiving antennas are given as the same as given for the case of MU-MIMO scheme. The receiving antennas can perform the beamforming and its main lobe is directed to each user as shown in Fig. 1(d).

As mentioned above, we analyze the system performance in terms of throughput for both SU-MIMO vs. MU-MIMO and SU-BFM vs. MU-BFM schemes. In simulation, all users are uniformly distributed and adaptively select their data rates based on their average received SNR. In addition, the system parameters are listed according to the works presented in [1] and [2] as shown in Table II.

The average SNR at individual user with distance d from the receiver can be expressed as

$$SNR = SNR_0 - 44.2 - (10 \times PLe)\log d \qquad (1)$$

where path loss is given of 44.2dB at 1 m and PLe is path loss exponent which is given as 4 as listed in Table I. The parameter d stands for distance between user and access point. Then, the system throughput can be obtained by the following equation:

$$Throughput = \frac{\sum_{m=1}^{user} m \cdot P_{tr}^{m} \cdot [payload\ size]}{(1 - P_{tr}^{sys})SlotTime + \sum_{m=1}^{user} P_{tr}^{m} T_{tr}^{m} + \sum_{m=2}^{N} P_{tr}^{m} T_{c}^{m}} \qquad (2)$$

Where m is the number of simultaneous transmitting users. The probability P_{tr}^{m} for m users is given for transmission in one time slot. Also, the probability P_{tr}^{sys} represents the case having at least one user transmitting a signal in one time slot. In addition, T_{tr}^{m} is the time used to transmit m simultaneously transmitted frames including overhead and T_{c}^{m} is the time for the number of users higher than M simultaneously transmitting a signal which is considered as a collision. Also, payload size is given for 1000 bytes

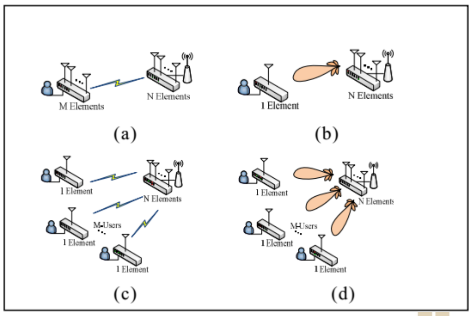


Fig.1. System model for (a) SU-MIMO (b) SU-BFM (c) MU-MIMO (d) MU-BFM.

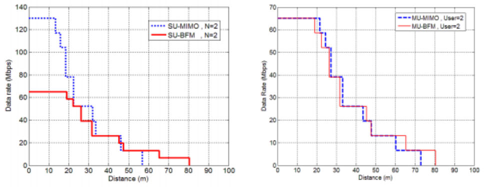
2. SIMULATION RESULTS

Figs.2(a) and 2(b) show data rate and distance between SU-MIMO vs. SU-BFM at *N*=2 and MU-MIMO vs. MU-BFM at the number of users = 2 of multi-rate WLANs. The results at distance 0-44 m for the cases of SU-MIMO and MU-MIMO provide better data rate performance comparing with the cases of SU-BFM and MU-BFM. Also, at longer distance, the results obtained from employing SU-BFM and MU-BFM provide better data rate performance over the cases of SU-MIMO and MU-MIMO. We also see that the data rate decreases when the distance increases. This is because beamforming gives rise to SNR so that we can gain coverage area with a contant data rate.

Figs.3(a)and 3(b) show the average throughput when varying the number of users. Please note that payload size is set to 1000 bytes and cell radius is given at 20 m and 45 m. The results obtained at distance 20 m for the cases of SU-MIMO and MU –MIMO provide better average throughput comparing to the cases of SU-BFM and MU–BFM. Also, the results at 45 m for SU-BFM and MU–BFM provide better average throughput comparing to the cases of employing SU-MIMO and MU–MIMO.

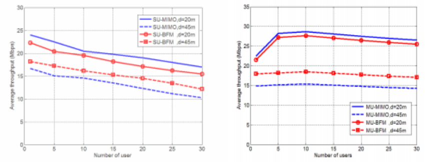
3. CONCLUSIONS

In this paper, we have compared the performance of multi-rate WLANs with the utilization of SU-MIMO vs. SU-BFM and MU-MIMO vs. MU-BFM schemes in terms of data rate with distance and average throughput. The results obtained from computer simulation have shown that both SU-MIMO and MU-MIMO provide better data



(a) (b)

Fig.2.(a)SU-MIMO and SU-BFM N=2. (b)MU-MIMO and MU-BFM at user = 2



(a) (b)

Fig.3. Average thrughput vs number of users (a) SU-MIMO and SU-BFM at number of element(N)= 2 (b) MU-MIMO and MU-BFM at user = 2

rate and average throughput at 20 m comparing to the cases of SU-BFM and MU-BFM. Furthermore, at distance 45 m, both SU-BFM and MU-BFM give rise to data rate and average throughput over the cases of SU-MIMO and MU-MIMO. Also, we can see that there is a tradeoff between utilization of MIMO and BFM (both SU- and MU-) schemes.

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BIOGRAPHY

Miss Paleerat Wongchampa was born in Nakhonpathom, Thailand, in 1987. She graduated with the Bachelor Degree and Master Degree of Engineering in Telecommunication Engineering in 2009 and 2011 respectively from Suranaree University of Technology, Nakhon Ratchasima, Thailand. Then she is currently pursuing her PhD program in Telecommunication Engineering, School of Telecommunication Engineering, Suranaree University of Technology. Her current research interests include smart antenna, 5G mobile network and wireless communication technologies.