TWO DIMENSIONAL SWITCHED BEAM ANTENNA AT 28 GHz FOR FIFTH GENERATION WIRELESS SYSTEM

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This work is specially dedicated to the Almighty God for his protection, provision and guidance all through the period of my PhD and to my beloved husband Pastor Stanley Orakwue for his prayers, love, cares, patience, encouragement and support all through the period of my doctoral study.

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ABSTRACT

Fifth generation (5G) wireless system is expected to enable new device-to-device (D2D) and machine-to-machine (M2M) applications that will impact both consumers and industry. Moreover, for efficient M2M communication, both one dimensional (1-D) and two dimensional (2-D) beam switching is highly needed for high data-rate wireless radio links. A planar array with 2-D beam switching capabilities is highly desirable in 5G system. This thesis proposes a new technique of achieving simple and cost effective 2-D beam switching array antenna at 28 GHz for 5G wireless system. The technique involves lateral cascading of Butler matrix (BM) beamforming network (BFN). However, designing a planar BM at 28 GHz that will allow K-connector is not a trivial issue because the distances between the ports are $\lambda/4$ electrical length apart. Nevertheless, two branch line coupler (BLC) with unequal ports separation at 28 GHz on a single substrate are designed and applied to design 1-D switched beam antennas based on BLC and 4 × 4 BM. Then two of these antennas are laterally cascaded to achieve 2-D beam switching antenna. This novel concept is the basis for choosing BM BFN in the design. The proposed 1-D array antennas on BLC and BM have wide measured impedance bandwidth of 18.9% (5.3 GHz) and 21.7% (6.1 GHz) and highest gain of 14.6 dBi and 15.9 dBi, respectively. The 2-D switched beam antenna on cascaded BLC has highest realized gain of 14.9 dB, radiation efficiency of 86%, 86.8%, 85.5%, and 83.4% at ports 1 to 4, respectively. The switching range of from -25^{o} to +18^{o} in the *x-z* plane and from -18^{o} to 24^{o} in the *y-z* plane, while the 2-D switched beam antenna based on cascaded 4 × 4 BM has switching range of -41^{o} to 43^{o} in the *x-z* plane and -43^{o} to 42^{o} in the *y-z* plane with highest realized gain of 14.4 dBi. The proposed antennas have great potentials for 5G wireless communication system applications.

ABSTRAK

Sistem tanpa wayar generasi ke-lima (5G) dijangka membolehkan aplikasi peranti-ke-peranti (D2D) yang baru dan mesin-ke-mesin (M2M) yang akan memberi impak kepada pengguna dan industri. Tambahan pula, bagi komunikasi M2M yang cekap, pensuisan alur satu dimensi (1-D) dan dua dimensi (2-D) amat diperlukan untuk pautan radio tanpa wayar dengan kadar data tinggi. Satu tatasusunan satah dengan keupayaan pensuisan alur 2-D adalah sangat diperlukan dalam sistem 5G. Tesis ini mencadangkan satu teknik baru bagi menghasilkan antena pensuisan alur 2-D pada 28 GHz yang ringkas dan kos efektif untuk aplikasi sistem 5G tanpa wayar. Teknik ini melibatkan rangkaian pembentuk alur (BFN) matrik Butler (BM) sisi melata. Walau bagaimanapun, mereka bentuk BM satah pada 28 GHz dengan menggunakan penyambung-K bukan isu mudah kerana jarak terminal yang berhampiran iaitu pada jarak panjang elektrik $\lambda/4$. Untuk itu, dua BLC dengan pemisahan terminal yang tidak sama pada 28 GHz di atas substrat tunggal telah direka dan digunakan untuk mereka bentuk antena alur bertukar 1-D berdasarkan BLC dan BM 4 × 4. Kemudian dua daripada antena ini telah sisi dilatakan untuk mencapai antena pensuisan alur 2-D. Konsep asli ini adalah asas untuk memilih BM BFN dalam reka bentuk. Tatasusunan antena 1-D yang dicadangkan menggunakan BLC dan BM mempunyai jalur lebar galangan diukur yang luas masing-masing sebanyak 18.9% (5.3 GHz) dan 21.7% (6.1 GHz) dan gandaan tertinggi 14.6 dB dan 15.9 dB masing-masing. Manakala tatasusunan antenna alur bertukar 2-D menggunakan gandingan cabang bertalian (BLC) yang dilatakan mempunyai gandaan terealisasi tertinggi sebanyak 14.9 dB, kecekapan radiasi 86%, 86.8%, 85.5%, dan 83.4% masing-masing di terminal 1 hingga 4, masing-masing. Jarak pensuisan sebanyak -25^o ke + 18^o dalam satah *x-z* dan dari -18^o ke 24^o dalam satah *y-z*, antena alur bertukar 2-D berdasarkan BM 4 × 4 dilatakan mempunyai jarak pensuisan dari -41^o ke 43^o dalam satah *x-z* dan -43^o ke 42^o dalam satah *y-z* dengan gandaan terealisasi tertinggi sebanyak 14.4 dBi. Antena yang direka bentuk berpotensi untuk digunakan bagi aplikasi sistem perhubungan tanpa wayar.

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LIST OF ABBREVATIONS

1-D	-	One Dimensional
2-D	-	Two Dimensional
4G	-	Fourth Generation
5G	-	Fifth Generation
AF	-	Array Factor
AUT	-	Antenna Under Test
AWR	-	Applied Wave Research
BFN	-	Beamformng Network
BLC	-	Branch Line Coupler
BM	-	Butler Matrix
CST	-	Computer Simulation Technology
D2D	-	Device To Device
DOA	-	Direction Of Arrival
DSP	-	Digital Signal Processing
EBG	-	Electronic Band Gap
FFT	-	Fast Fourier transform
FIR	-	Finite Impulse Response

FR4	-	Frame Resistance 4
HPBW	-	Half Power Beamwidth
IMT	-	International Mobile Telecommunications
ITU	-	International Telecommunication Union
LC	-	Lump Circuit
LHCP	-	Left Hand Circular polarization
LMS	-	Least Mean Squares
LTCC	-	Low Temperature Co-fired Ceramics
M2M	-	Machine to Machine
MIMO	-	Multiple Input Multiple Output
MMIC	-	Monolithic Microwave Integrated Circuit
MUSIC	-	Multiple Signal Classification
MWS	-	Microwave Studio
NLOS	-	Non-Line of Sight
PCB	-	Printed Circuit Board
PIN	-	Positive-Intrinsic-Negative
QoS	-	Quality of service
RF	-	Radio Frequency
RHCP	-	Right Hand Circular polarization
RSS	-	Received Signal Strength
SAS	-	Smart Antenna System
SBSA	-	Switched Beam Smart Antenna
SDMA	-	Spatial Division Multiple Access

SIR	-	Signal to Interference Ratio
SIW	-	Substrate Integrated Waveguide
SLL	-	Side Lobe Level
VNA	-	Vector Network Analyzer

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Wireless communication systems rely on spectrum bands to transfer information through the air. The bandwidth of a system is proportional to the frequency of operation. According to International Telecommunication Union (ITU) report, it is anticipated that by the year 2020 wireless mobile communication traffic would have 25 to 100-fold growth ratio compared to 2010 [1]. The latest and fastest cellular standard, fourth generation (4G) wireless network, operates in 2600 MHz spectrum. In order to accommodate all these growth, the underutilized spectrum in millimeter wave frequency, capable of achieving tens to hundreds of time more compare to 4G, with transmission rate up to Gbps has been proposed for fifth generation (5G) wireless communication. It is expected to provide gigabyte experience to users anywhere, provide more than times 100 peak data rate than 4G, offers data transmission speeds of up to several tens of Gbps per base station and have less than 1milisecond latency. It will enable new device-to-device (D2D) and machine to machine (M2M) applications that will impact both consumers, and industry.

However, for efficient M2M communication, both one dimensional (1-D) and two dimensional (2-D) beam steering is highly needed for high data-rate wireless radio links [2]. In such systems, a fast tracking system is needed to constantly track the users and then adapt the radiation pattern of the antenna to direct multiple narrow beams of switched beam smart antenna (SBSA) to desired users and nulls interfering sources. SBSA uses beamforming network (BFN), radio frequency (RF) switches and antenna array to enhance sensitivity in the direction with strongest received signal strength (RSS) as the target moves throughout the footprint [3]. It offers many of the advantages of the fully adaptive systems at less expense and complexity [4]. Adaptive array on the other hand uses direction of arrival (DOA) estimation and digital signal processing (DSP) to strengthen sensitivity and steer its beam towards the target. In this way the received power is maximized but with the trade-off of high cost and more complexity. These two types of smart antenna system (SAS) have been recommended to combat the problem of free space loss at millimeter wave frequency [5, 6]. However, SBSA has attracted great interest in modern wireless communication due to its ease of implementation and flexibility for use in multiple applications [7]. The performance of a SBSA depends on the design of BFN that provides constant beam directions. Many BFN configurations have been designed such as Blass Matrix [8], Rotmans Lens [9], and Butler Matrix (BM). SBSA studied using BM BFN as the basic component has received so much attention [10-15] due to its simplicity and ease of implementations and has been chosen for this research work. It can support beam switching operation and allows 1-D switching [10, 16, 17] at $\pm 45^o$ and $\pm 135^o$. They are completely passive, minimizing front-end power consumption. 2-D beam switching antenna array based on BM BFN have also been studied. Recently, a lot of efforts have been made on modifying BM BFN to achieve 2-D beam switching at millimeter wave frequency. Few techniques have been proposed and reported [2, 18-22] and this study will focus on realising 2-D beam switching based on cascaded BM BFN.

1.2 Problem Statement

The conventional branch line coupler (BLC) is composed of four sections separated by quarter-wavelength transmission line. At lower frequency of the microwave, the size of a BLC is too large that size reduction is one major design requirement. However, at high frequency (millimeter wave), the size is reduced drastically that the quarter-wavelength separation [23-26] becomes a big issue especially when there is need to use connectors. Take for instance, 28 GHz has been recommended for 5G network application [5, 27], but to feed array antenna with a conventional BLC at 28 GHz as was done in [28] at 2.4 GHz, the input port separation should be large enough (at least 10 mm apart) to accept K- connectors, while the output port should be $\lambda/2$ apart;but quarter-wavelength separation of 28 GHz is about 2.68 mm, which is too small for K-connectors. Therefore, to overcome these challenges, there is need to modify BLC to unequal input / output port separations, considering the fact that, due to transient time effect, any extension of transmission line at millimeter wave will definitely affect the frequency response of the S-parameters.

A conventional BM was designed at 60 GHz by [17], but due to the same challenge (closeness of the ports), only one port was connected to K-connector to demonstrate the performance through measurement. Alternative methods have been demonstrated to achieve planar BM at millimeter wave by integrating BLCs. But most of these design although compact but achieved beam switching at reduced switching angle [13] and low radiation efficiency [2]. Moreover, the network arrangement is not suitable for further improvement of array gain by increasing the number of element and also for printed circuit board (PCB) implementation.

Planar arrays with 2-D beam switching capabilities are highly desirable for future 5G networks aiming to operate at millimeter waves. Several 2-D beam switching array antennas based on modified BM BFN have been proposed [2, 18-22]. Nevertheless, the complex realization and large size of most of these designs are not suitable at 28 GHz frequency band. For instance, [18] utilizes twenty two crossovers and twelve 3-dB BLCs to achieve 2-D beam switching at 60 GHz. While [29] utilised two 4 × 4 BM and one 8 × 8 BM to achieve 2-D at 2.45 GHz. These would be outrageous if applied to 28 GHz frequency. In [2] and [19] four orthogonal beams were realised at the two principal planes by integrating BLCs on multi-layer substrate. Nevertheless, the multi-layered substrate resulted in 2-D beam switching array antenna with high-profile, more complexity and high cost.

1.3 Aim and Objectives

The aim of this research is to design a simple and less complex 2-D beam switching array antenna using BM BFN. In other words, once the BM BFN is designed, 2-D beam switching can be easily realized by lateral cascading of two of such network, giving rise simple, less complex and cost effective 2-D switched beam antenna on a single substrate. The completion of this research work will be beneficial in the field of 5G wireless networks with the following objectives that will encourage application of SBSA at millimeter wave frequency.

i. To design BLC with unequal input /output port transmission line extension that will demonstrate a tight coupling of -3 ± 1dB and high isolation at 28 GHz and allow physical integration of K-connectors.
ii. The physical size of BM at higher frequencies is inherently diminished. Therefore, a 1-D switched beam antenna operating at 28 GHz will be designed based on BM with BLC of the first objective. The aim is to design a BM that would allow the use of K-connectors.

iii. To design and fabricate a 2-D millimeter wave beam switching antenna based on 1-D beam switching array antenna of the second objective, which can operate at 28 GHz for 5G applications.

1.4 Scope of Work

This research focuses on the 1-D and 2-D beam switching with BM BFN at 28GHz frequency band. The development of a BM comprised of couplers, phase shifters, and crossover. These components will be designed, simulated, optimized using Computer Simulation Technology (CST) Microwave Studio (MWS) before integrating together to form BM. The 1-D BM BFN designed will be integrated to array antenna to form 1-D beam switching antenna. This will be later modified and integrated to planar array antenna designed at the same frequency to achieve 2-D beam switching.

The successful completion of this project will cover the theoretical antenna analysis and prototype design of 1-D and 2-D beam switching array antenna and validation with measurement.

1.5 Contribution of the Research

In this research, three major contributions are recorded and published in both journals and conferences. These are:

1. A planer BLC with enough space to accommodate K-connectors at 28 GHz was realized.

2. A 1-D beam switching array antenna based on BLC and 4 × 4 BM at 28GHz for 5G wireless systems was achieved.

3. A 2-D beam switching array antenna based on cascaded two BLC and two 4 × 4 BM at 28 GHz for 5G wireless systems was achieved.

1.6 Thesis Outline

This thesis is organized into six chapters. Chapter 1 contains the overview of the whole project, which includes the project background, problem statement, research objectives, and contributions to knowledge, the research scope and the thesis organization.

Chapter 2 focuses on the literature reviews. Introduction and basic concepts of smart antenna systems are presented. Also, presented are, antenna for 5G, the requirements and challenges of 5G antennas, BM and applications and related array factors are discussed. Finally review on1-D and 2-D beam switching antennas on BM BFN are all studied and their limitations highlighted.

In Chapter 3 the methodology used to achieve the proposed designs are discussed starting with the research framework in form of algorithm. The design parameters and specifications are introduced as a guide to achieving the desired results. In addition, all the design equations are introduced; the fabrication and measurement procedures are all documented.

Chapter 4 and Chapter 5 present the design of the steerable antenna on BLC and 4 × 4 BM for 5G applications, respectively. Four different steerable antennas were proposed, designed and presented. Two are 1-D array antenna, while the second two are 2-D array antenna. The first two are based on BLC and presented in Chapter 4, while the second two are based on 4 × 4 BM and presented in Chapter 5. The simulation and measurement results for all proposed antennas are compared and discussed. All parametric studies done to optimize the design are analysed and presented.

Finally, Chapter 6 presents the conclusion and recommendation for further work. In this chapter, the findings and recommendations for future works are proposed and presented. Finally, the list of references and appendices are provided at the end.

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