

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

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

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requirements for the award of the degree of
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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° to $+18^\circ$ in the x - z plane and from -18° to 24° in the y - z plane, while the 2-D switched beam antenna based on cascaded 4×4 BM has switching range of -41° to 43° in the x - z plane and -43° to 42° 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 antenna 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 antenna alur bertukar 1-D berdasarkan BLC dan BM 4×4 . Kemudian dua daripada antenna ini telah sisi dilatakan untuk mencapai antenna pensuisan alur 2-D. Konsep asli ini adalah asas untuk memilih BM BFN dalam reka bentuk. Tatasusunan antenna 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° ke $+18^\circ$ dalam satah x - z dan dari -18° ke 24° dalam satah y - z , antenna alur bertukar 2-D berdasarkan BM 4×4 dilatakan mempunyai jarak pensuisan dari -41° ke 43° dalam satah x - z dan -43° ke 42° 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.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xiii
	LIST OF FIGURES	xv
	LIST OF ABBREVIATIONS	xxii
	LIST OF APPENDICES	xxv
1	INTRODUCTION	1
	1.1 Research Background	1
	1.2 Problem Statement	3
	1.3 Aim and Objectives	4
	1.4 Scope of Work	5
	1.5 Contribution of the Research	5
	1.6 Thesis Outline	6

2	LITERATURE REVIEW	8
2.1	Introduction	8
2.2	Antennas for 5G	8
2.2.1	Antenna Requirements for 5G Applications	13
2.2.2	Possible Challenges on Antenna for 5G	15
2.3	5G Base Stations	16
2.4	Smart Antenna System	18
2.5	Beamforming Matrices Applied in Switched Beam Smart Antenna	20
2.6	Factors Affecting Antenna Beam Switching Based on Butler Matrix	21
2.7	Butler Matrix	22
2.7.1	The 3-dB Branch line coupler	24
2.7.2	Crossover (0-dB)	32
2.7.3	The Phase Shifters	33
2.7.4	Applications of Butler Matrix	34
2.8	Antenna Array	35
2.8.1	Linear Array Antenna	35
2.8.2	Planar Array Antenna	39
2.9	Review of Related Works	41
2.9.1	Review on 3-dB Branch-Line Coupler	42
2.9.2	One Dimensional Beam Switching Antenna Array with Butler Matrix	43
2.9.3	Two Dimensional Beam Switching Antenna Array with Butler Matrix Beamforming Network	48
2.10	Summary	51

3	RESEARCH METHODOLOGY	53
	3.1 Introduction	53
	3.2 Research Framework and Flowchart	54
	3.3 Design Considerations	55
	3.4 Design, Simulation and Optimization of Component Parts of Butler Matrix	57
	3.5 Microstrip Antenna Design	60
	3.5.1 Design of a Single Rectangular Microstrip Patch Antennas	60
	3.5.2 Series Fed Antenna Array	63
	3.5.3 Microstrip Mitred Bend	64
	3.6 Fabrication and Measurement	65
	3.7 Summary	67
4	SWITCHED BEAM ANTENNA ARRAY ON BRANCH LINE COUPLER	68
	4.1 Introduction	68
	4.2 Design and Analysis of Branch Line Coupler	69
	4.2.1 Simulation Results of the Proposed Branch Line Coupler	71
	4.2.2 Design and Analysis of the proposed Switched beam antenna on Branch Line Coupler	74
	4.2.3 Radiation Pattern of the Proposed Beam switching Array Antenna Based on Branch Line Coupler	79
	4.2.4 Fabrication and Measurement Discussion	81

4.3	Design of a 28 GHz 2-D Beam switching Array	
	Antenna by Cascading Branch Line Coupler	85
4.3.1	Design of series fed array antenna for 2-D Switched	
	Beam Antenna on Branch Line Coupler	86
4.3.2	Bandwidth Optimization of a 2-D Beam switching	
	Array Antenna on Cascaded Branch Line Coupler	89
4.4	Comparison of Performance of 3×3 Array with and	
	Without Branch Line Coupler	99
4.5	Fabrication and Measurement of the Proposed 2-D	
	Beam Switching Array Antenna	100
4.5.1	Return Loss Measurement of the Proposed 2-D	
	Array on Branch Line Coupler	101
4.5.2	Radiation Pattern Measurement of the Proposed	
	2-D Array on Branch Line Coupler	104
4.6	Summary	105

5	SWITCHED BEAM ARRAY ANTENNA ON 4×4	
	BUTLER MATRIX	106
5.1	Introduction	106
5.2	Beam switching Array Antenna for 5G Wireless	
	Communications based on 4×4 Butler Matrix.	107
5.2.1	The Branch Line Coupler Design for 4×4 BM	
	Beam Switching Array Antenna	107
5.2.2	Design of Crossover for 4×4 Butler Matrix	
	Beam Switching Array Antenna	112
5.2.3	Design of 45° and 0° Phase Shifters	113
5.2.4	The 4×4 Butler Matrix Design	114

5.3	Design Analysis of 1-D Beam Switching Array	
	Antenna on 4×4 Butler Matrix	120
5.3.1	Analysis of Bandwidth Optimization of the Proposed	
	Beam Switching Array Antenna	121
5.3.2	The Radiation Pattern of the Proposed Beam	
	Switching Array Antenna	129
5.4	Fabrication and Measurement of the 1-D Array Antenna	
	on 4×4 Butler Matrix	131
5.4.1	Reflection Coefficient Measurement of the Propose	
	1-D Array on 4×4 Butler Matrix	132
5.4.2	Radiation Pattern Measurement of the Proposed	
	1-D Array on 4×4 Butler Matrix	134
5.5	A 2-D Beam Switching Array Antenna for 5G Wireless	
	Communications based on cascaded 4×4 Butler Matrix.	136
5.5.1	Bandwidth Optimization of the Proposed 2-D	
	Beam Switching Array Antenna	137
5.6	Fabrication and Measurement Results of the Proposed	
	2-D Switched Beam Antenna on 4×4 Butler Matrix	147
5.6.1	Reflection Coefficient Measurement of the Proposed	
	2-D Array on 4×4 Butler Matrix	148
5.6.2	Radiation Pattern Measurement of the Proposed 2-D	
	Array on 4×4 Butler Matrix	150
5.7	Summary	152
6	CONCLUSION AND RECOMMENDATIONS FOR	
	FURTHER WORKS	153
6.1	Conclusion	153

6.2 Recommendations for further works	156
REFERENCES	158
Appendices A-D	170

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Phase shift characteristics of the standard BM [7]	23
2.2	The summary on BLC design	43
2.3	Millimeter wave 1-D antennas on BM	47
2.4	Millimeter wave 2-D array antennas on BM	50
3.1	The specifications of BM design parameters [102, 103]	55
3.2	The specifications of switched beam antenna parameters [17 , 18] 56	
4.1	Material properties of the proposed BLC	70
4.2	Material properties of the proposed BLC	73
4.3	Comparison of electrical characteristics of various BLC with the proposed.	74
4.4	The dimensions of the proposed antenna	78
4.5	The performance of three different array size for 2-D array antenna	87
4.6	Gain and switching angle of the three feeding positions	88
4.7	Realized Gain and switching angle of the three feeding positions	92
4.8	Summary of antenna performance of the proposed 2-D beam switching array antenna	96
4.9	Detailed Dimensions of the Proposed Antenna	97

4.10	Comparison of 3×3 Array with and without Branch Line Coupler	100
4.11	Comparison of performance of the proposed 2-D array and existing	103
5.1	Material properties of the proposed BLC	108
5.2	Summary of the simulated S-parameter and phase difference	111
5.3	Simulated Phase shift of the ports of the designed BM	120
5.4	The summary of the effect of W_t value on antenna gain	126
5.5	Optimized parameter of the beam switching antenna	128
5.6	Result Comparison with 4×4 BM at 28 GHz	134
5.7	Result comparison of different values of W_t	138
5.8	Antenna performance due to different W_t	139
5.9	Optimized parameter of the 2-D beam switching antenna	139
5.10	Antenna performance of all the ports	146

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	(a) Rain attenuation in dB/km across frequency at various rainfall rate [38] (b) Atmospheric absorption across mm-wave frequencies in dB/km [39]	10
2.2	The detailed view of the array antenna [40]	11
2.3	Geometry of the proposed LTCC based L-probe patch array [44]	12
2.4	The Geometries of the 28 GHz microstrip grid array antenna [45]	13
2.5	Heterogeneous Network utilizing mix of macro, pico, femto and relay base-stations [57]	17
2.6	Smart antenna system: (a) SBSA, (b) adaptive array [64]	19
2.7	Beam Switching Scenario using SBSA	20
2.8	The topology of a standard 4×4 BM.	23
2.9	Geometry of a conventional BLC: (a) Distributed form of impedance transformation in BLC (b) Lumped-element EC model [72]	25
2.10	Even-odd mode analysis: (a) the line symmetry (b) even mode (c) odd mode	28
2.11	Circuit segments for the ABCD parametric analysis of odd mode case	29

2.12	0-dB crossover (a) Function diagram of 0-dB [8], (b) Tandem connection of two 3-dB BLC	32
2.13	Four basic phase shifter configurations [78]	34
2.14	The geometry of N-elements linear array	36
2.15	The geometry of $M \times N$ planar array antenna [88]	40
2.16	(a) Layout of the switched-beam antenna based on BM BFN (b) excitation of port 1 (c) excitation of port 2 [17].	44
2.17	Geometry of the meander-line monopole antenna array [99]	46
2.18	Block diagrams of the proposed 2-D SBSA [29]	49
3.1	The workflow chart of the research methodology	54
3.2	BLC Schematic diagram with distributed form of impedance transformation	57
3.3	The structure of the microstrip patch antenna	61
3.4	A 4×1 array antennas with $\lambda/2$ mm element separation	64
3.5	The mitred bend [106]	65
3.6	The S-parameter measurement set-up	66
3.7	Set-up for radiation pattern measurement in the anechoic chambers	67
4.1	Geometry of: (a) conventional BLC, (b) proposed BLC	69
4.2	Study on L_3 extension: (a) $L_3 = 2.35$ mm, (b) $L_3 = 3.35$ mm, (c) $L_3 = 4.35$ mm, (d) $L_3 = 5.35$ mm,	71
4.3	Comparison between S-parameters of the conventional and proposed BLC: (a) conventional, (b) proposed	72
4.4	Comparison between the simulation and measurement results of the phase difference.	73
4.5	The proposed switched beam antenna array	75
4.6	The width size W_t optimization of the connecting transmission line: (a) Return loss ($ S_{11} $), (b) Radiation pattern	76

4.7	The width size W_t optimization of the connecting transmission line: (a) Return loss ($ S_{22} $), (b) Radiation pattern	77
4.8	S-parameter of the proposed beam steerable array antenna on BLC	78
4.9	Simulated radiation pattern of the BLC based beam steerable array antenna in the H plane: for Port 1 excitation (a) Polar plot, (b) Rectangular plot; for Port 2 excitation, (c) Polar plot, (d) Rectangular plot	80
4.10	Realized Gain and Radiation efficiency in percentage.	81
4.11	Measurement of the fabricated prototype	82
4.12	Comparison of simulated and measured results	83
4.13	Comparison of simulated and measured radiation pattern	84
4.14	Measured normalized plane radiation patterns as a function of theta (degrees) when fed from (a) port 1, and (b) port 2	84
4.15	The layout structure of the proposed lateral integration of BM BFN to achieve 2-D beam switching	85
4.16	The layout structure of the: (a) 2×2 array, (b) 3×3 array, and (c) 4×4 array	86
4.17	Study of the feeding position: case 1	87
4.18	Study of the feeding position: case 2	88
4.19	Study of the feeding position: case 3	88
4.20	Simulated isolation between the four ports: (a) Case 1, (b) Case 3	89
4.21	Return loss computed at different W/I thicknesses: (a) S_{11} , (b) S_{22} , (c) S_{33} , (d) S_{44}	91
4.22	The simulated result of the 2-D array antenna: For P1 (a) Return loss (b) Polar pattern, For P2(c) Return loss (d) Polar pattern, For P3 (e) Return loss (f) Polar pattern, For P4 (g) Return loss (h) Polar pattern	94

4.23	Simulated co- and cross polar radiation patterns in E- and H-plane of the 2-D array antenna corresponding to ports 1 to 4: (a) H-plane of P1, (b) E-plane of P1, (c) H-plane of P2, (d) E-plane of P2, (e) E-plane of P3, (f) H-plane of P3, (g) E-plane of P4, (f) H-plane of P4	96
4.24	Realized Gain in dB and Radiation efficiency in percentage: (a) P1, (b) P2, (c) P3, (d) P4	98
4.25	3×3 Array: (a) with Branch Line Coupler, (b) without Branch Line Coupler	99
4.26	The prototype of the proposed structure	101
4.27	Comparison of measured and simulated reflection coefficient: (a) P1, (b) P2, (c) P3, (d) P4	103
4.28	Comparison of measured and simulated radiation pattern	105
5.1	(a) Conventional, (b) Proposed	108
5.2	Study on L_3 extension: (a) $L_3 = 2.35$ mm, (b) $L_3 = 3.35$ mm, (c) $L_3 = 4.35$ mm, (d) $L_3 = 5.35$ mm,	109
5.3	Comparison between S-parameters of the conventional and proposed BLC: (a) conventional, (b) proposed	110
5.4	Comparison of the Phase difference of the conventional BLC and the	111
5.5	(a) Geometry of the crossover (b) S-parameter	112
5.6	The geometry of the proposed design layout and S-parameter	113
5.7	Layout of the proposed 4×4 BM beamformer.	114
5.8	Reflection coefficients of the designed 4×4 Butler matrix when P1 is excited	115
5.9	Magnitude of the transmission coefficients. (a) Port 1, (b) Port 2, (c) Port 3, (d) Port 4	116
5.10	Isolation coefficients of: (a) input ports and (b) output ports of the designed 4×4 BM	117

5.11	Simulation phase difference results of the output ports of the BM with respect to input ports: (a) P1, (b) P2, (c) P3, (d) P4	119
5.12	Layout of the proposed beam switching array antenna with BM beamformer	121
5.13	Patch Length (L_p) optimization for the 4×4 linear array antenna (a) S_{11} / S_{44} , (b) S_{22} / S_{33}	123
5.14	Patch position (dy) optimization for the 4×4 linear array antenna: (a) Return loss of P1 (b) Radiation Pattern of P1 (c) Return loss of P2 (4) Radiation pattern of P2	124
5.15	Inter connecting transmission line width (W_t) optimization for the 4×4 linear array antenna: (a) Return loss of port 1 (b) Radiation Pattern of port 1 (c) Return loss of port 2 (4) Radiation pattern of port 2	125
5.16	The optimal Return loss of the proposed beam switching array antenna	127
5.17	The isolation between the ports: (a) Port 1, (b) Port 3	128
5.18	Simulated radiation pattern of the four input ports in the xz -plane	130
5.19	The antenna gain of all the four ports	131
5.20	The prototype of the proposed antenna	132
5.21	Comparison of simulated and measured S-parameters for the proposed antenna	133
5.22	Simulated co-polarization (solid blue line), measured co-polarization (dashed dotted line), and simulated cross polarization (dashed line), measured cross polarization (dotted line) at 28 GHz	135
5.23	Geometry of the proposed 2-D beam switching array antenna	136
5.24	The isolation between the ports: (a) Port 1, (b) Port 5	140
5.25	The isolation between the ports: (a) Port 1, (b) Port 5	141

5.26	Beam switching in the xz -plane at 28 GHz by P1: (a) Polar pattern of the realized beam (b) Rectangular plot	142
5.27	Beam switching in the xz -plane at 28 GHz by P2: (a) Polar pattern of the realized beam (b) Rectangular plot	142
5.28	Beam switching in the xz -plane at 28 GHz by P3: (a) Polar pattern of the realized beam (b) Rectangular plot	143
5.29	Beam switching in the xz -plane at 28 GHz by P4: (a) Polar pattern of the realized beam (b) Rectangular plot	143
5.30	Beam switching in the yz -plane at 28 GHz by P5: (a) Polar pattern of the realized beam (b) Rectangular plot	144
5.31	Beam switching in the yz -plane at 28 GHz by P6: (a) Polar pattern of the realized beam (b) Rectangular plot	144
5.32	Beam switching in the yz -plane at 28 GHz by P7: (a) Polar pattern of the realized beam (b) Rectangular plot	145
5.33	Beam switching in the yz -plane at 28 GHz by P8: (a) Polar pattern of the realized beam (b) Rectangular plot	145
5.34	The antenna gain of all the all the ports	147
5.35	The fabricated prototype of the proposed 2-D beam switching antenna	148
5.36	The comparison of simulation and measurement reflection coefficient of the proposed 2-D beam switching array antenna. (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, (f) P6, (g) P7, (h) P8	150
5.37	The comparison of simulation and measurement radiation pattern of the proposed 2-D switched beam array antenna. (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, (f) P6, (g) P7, (h) P8	152
B.1	CST simulation tool	173
B.2	Parametric Analytical tool	174
B.3	CST MWS optimizer user interface settings	175
C.1	AWR TXLine Calculator user interface	176
D.1	2.92mm PCB Receptacles Connectors	177

D.2	Data diagram of the 2.92mm PCB Receptacles Connectors	178
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LIST OF ABBREVIATIONS

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

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	List of publications	171
B	Computer Simulation Technology (CST) Microwave Studio	172
C	Applied Wave Research (AWR)	176
D	A standard 2.92 mm edge mount receptacle connector	177

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 times more compared 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 100 times peak data rate than 4G, offers data transmission speeds of up to several tens of Gbps per base station and have less than 1 millisecond 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 $\pm 45^\circ$ and $\pm 135^\circ$. 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 ± 1 dB 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 on 1-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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