DUAL-SERIES 2 × 4 SWITCHED-BEAM NOLEN MATRIX FOR FIFTH GENERATION WIRELESS COMMUNICATION SYSTEM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

APRIL 2018

Specially dedicated and thankful to my beloved parents and family,
my inspirational supervisor, Dr Norhudah Seman,
my friends, lecturers & WCC staffs for their
endless support, encouragement and motivation throughout my research study.
A warm thanks to all

ACKNOWLEDGEMENT

Working on this research project was an infinite and rewarding experience. This dissertation is dedicated to everyone in the field of radio frequency and microwave who embarks the journey of broadening the knowledge and transcendent passion for radio frequency and microwave.

First and foremost, it is my immense pleasure to express my sincere gratitude to my supervisor, Associate Professor Dr. Norhudah binti Seman whom her extensive knowledge in the engineering field, especially in the radio frequency have been instrumental in the success of this research project. Her insightful advice, noble guidance and patience throughout the short time made it such a fantastic experience for me to overcome all the obstacles that I have encountered. I take this opportunity to record my sincere thanks to Professor Amin Abbosh for supervising me as well as Emad Al-Abbas for sharing his knowledge during my research attachment in The University of Queensland (UQ), Australia.

I would like to extend my utmost gratitude to all technical staffs of Wireless Communication Centre (WCC) and The University of Queensland, Australia who have assisted me in using the network analyzer and other related equipment in the laboratory. Last but not least, I would like to dedicate my regards and blessing towards all of my family members and fellow friends for staying beside me through thick and thin as well as giving me moral support during the execution of this research project.

ABSTRACT

A new evolvement towards 5G technology requires a super high frequency to provide large channel capacity, low power consumption and low interference. Up to the present, the passive microwave devices with the super high frequency range are becoming necessity to be deployed due to the great features that are capable in representing significant advances in wireless communications. However, high interference occurs due to multiple signals coexisting in the super high frequency. Integration of switched-beam antenna that employs scanning of multi-beams with a proposed Nolen Matrix can be a solution to overcome this issue. The coupler with loaded T-shaped stubs, loaded stubs and Schiffman phase shifters as well as edge chamfered inset feeding microstrip patch array antenna are designed as the key components for the dual-series 2 × 4 switched-beam Nolen matrix. The loaded T-shaped stubs are introduced at each side of the microstrip lines nearby the square patch of the couplers to achieve various coupling values. All simulation results are obtained using Computer Simulation Technology software. The S-parameter measurement of the proposed couplers and dual-series 2 × 4 switched-beam Nolen matrix are performed using vector network analyzer, while its radiation pattern measurement is executed in an anechoic chamber. The amplitude and phase imbalances are ± 1 dB and 5° between 24.75 GHz and 27.25 GHz for the proposed couplers as well as between 25.75 GHz and 26.25 GHz for the phase shifters, respectively. Whereas, the respective amplitude and phase imbalances of 2 × 4 switched beam Nolen matrix are ± 3.5 dB and 10° across the designated frequency range of 25.75 GHz to 26.25 GHz. Meanwhile, at the center frequency of 26 GHz, the simulated and measured main beam directions are 10° and 12°, respectively when signal is fed at port 1, whereas -31° and -31.5°, respectively at port 2, with the highest measured gain of 10.19 dB and percentage of radiation efficiency of 59.98 %.

ABSTRAK

Perkembangan baru ke arah teknologi 5G memerlukan rangkaian frekuensi amat tinggi untuk menyediakan kapasiti saluran yang besar, penggunaan kuasa rendah dan gangguan rendah. Kini, peranti gelombang mikro pasif dengan frekuensi amat tinggi menjadi keperluan untuk digunakan kerana kehebatan ciri-cirinya yang mampu mewakili kemajuan yang signifikan dalam komunikasi tanpa wayar. Namun, gangguan tinggi berlaku disebabkan oleh kewujudan pelbagai isyarat bersama dalam julat frekuensi amat tinggi. Gabungan suis alur antena yang menggunakan pengimbasan pelbagai alur dengan matrik Nolen dapat menyelesaikan masalah ini. Pengganding dengan pemasangan puntung berbentuk T dan penganjak fasa Schiffman serta antena tatasusunan mikrojalur suapan sisipan bersisi serong direkabentuk sebagai komponen utama bagi dua siri 2×4 suis alur matrik Nolen. Pemasangan puntung berbentuk T diperkenalkan di setiap sisi garisan mikrostrip berdekatan tampalan empat segi pengganding bagi mencapai pelbagai nilai gandingan. Semua hasil simulasi diperoleh dengan menggunakan perisian Computer Simulation Technology. Pengukuran parameter-S pengganding berpuntung dan dua siri 2×4 suis alur matrik Nolen diperoleh dengan menggunakan Penganalisa Rangkaian Vektor, manakala pengukuran corak radiasi dilaksanakan dalam kebuk tak bergema. Ketidakseimbangan amplitud dan fasa adalah ± 1 dB dan 5° masing-masing di antara 24.75 GHz dan 27.25 GHz bagi pengganding dan di antara 25.75 GHz dan 26.25 GHz bagi penganjak fasa yang dicadangkan. Sementara, ketidakseimbangan amplitud dan fasa bagi 2×4 suis alur matrik Nolen adalah ± 3.5 dB dan 10° pada julat frekuensi di antara 25.75 GHz dan 26.25 GHz. Sementara itu, di frekuensi tengah 26 GHz, hasil simulasi dan ukuran arah alur utama adalah 10° dan 12° apabila isyarat diberikan pada terminal satu, manakala -31° dan -31.5° pada terminal dua dengan ukuran gandaan sebanyak 10.19 dB dan peratus kecekapan radiasi tertinggi sebanyak 59.98 %.

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LIST OF ABBREVIATIONS

AUT	-	Antenna Under Test
CST	-	Computer Simulation Technology
dB	-	Decibel
P1	-	Port 1
P2	-	Port 2
P3	-	Port 3
P4	-	Port 4
PC	-	Programmable Controller
PNA	-	Programmable Network Analyzer
RF	-	Radio frequency
RO 5880	-	Rogers 5880
SIW	-	Substrate Integrated Waveguide
S-parameters	-	Scattering parameters
VNA	-	Vector Network Analyzer

LIST OF SYMBOLS

$ß_o$ - Angular wave

f_c - Center frequency

x - Chamfering edge of microstrip line

ε_r - Dielectric constant of the substrate

d_o - Distance between two radiating element

λ - Free space wavelength

h - Height of substrate

X - Length of adjacent

L - Length of coupler structure

R - Length of hypotenuse

Y - Length of opposite

L_t - Length of square patch coupler

$\leq$ - Less than or equal

d - Notch's length

W_n - Notch's width

Ω - Ohm

M - Optimum miter percentage

L_{patch} - Patch's length

W_{patch} - Patch's width

$\Delta\Phi$ - Phase difference

$\Delta\Phi\text{rad}$ - Phase difference (in radian)

$\Phi\ S_{21}$ - Phase S_{21}

$\Phi\ S_{31}$ - Phase S_{31}

e_r - Radiation efficiency

r	-	Radius of circular slot
f_r	-	Resonant frequency
θ_o	-	Resulting pointing angle
c	-	Speed of light
λ_g	-	Guide wavelength
W_t	-	Width of 50 Ω feeding microstrip line
W	-	Width of coupler structure

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Up to the present, there are myriad evolvements from the first generation (1G) to fourth generation (4G) in the realm of communication technologies. In order to improve the current generation of technologies with better features concerning fast multi-services to end users, extreme data rates, energy efficient networks, ultra-low latency and large data bandwidth [1], a new evolution is targeted to be deployed beyond 2020 in all over the world by introducing the fifth generation (5G) mobile communication technology that covering all aspects in daily life, which include unlimited communication between humans, machine-to-machine and vehicle-to-vehicle.

In addition, higher capacity, lower power transmission and larger system coverage that expected to be offered by 5G technology can be achieved by using smart antenna systems such as switched-beam antenna and adaptive antenna array [2]. The switched-beam antenna and the adaptive antenna array are consisting of a beamforming network as a key component of multiple-input and multiple-output (MIMO) system, which provides the multiple beams looking in various directions. However, the adaptive antenna array has a more complex design because an individual RF transceiver chain at end of each antenna element and a precise real-time calibration are required [3]. Moreover, the adaptive antenna array has more extortionate price than the switched-beam antenna due to the presence of a sophisticated digital signal processing algorithm [2]. Therefore, the beamforming network of the switched-beam antenna system is more frugal to be developed because no device is required for downconverting the received signal to a baseband [2]. There are myriad examples of these beamforming networks [4] such as Butler matrix [5], [6], Nolen matrix [7], [8], Blass matrix [9], [10] and Rotman lens [11], [12].

The configuration circuit of Butler matrix consists of passive components such as couplers, crossovers and phase shifters. As stated in [13], the Butler matrix has N input (beam) and N output (antenna) ports according to a standard squared number of integer ($N = 2^n$) and generates orthogonal beams, whereas the Blass and Nolen matrices have distinct M input and N output ports. In term of loss, the Blass matrix becomes lossy when matched loads are connected at the end port of every transmission line [13]. Besides that, the presence of power loss due to the non-perfect pointing of the rays limits the performance of the Rotman lens [14]. In contrast with the Butler matrix, the planar realization of the serial Nolen matrix becomes more interesting since the crossovers are eliminated. Moreover, flexibility in deciding the number of ports enables the Nolen matrix to be easily matched with any specific application [15].

By comparing to the other aforementioned beamforming networks, the serial configuration of output ports facilitates the Nolen matrix to be easily connected to the antenna array to develop switched-beam beamforming network. Therefore, the best configuration design of the beamforming networks to be selected in this research project is the Nolen matrix.

1.2 Problem Statement

The innovation of mobile and wireless communication applications towards 5G technology requires a higher frequency range compared to 4G technology. The World Radiocommunication Conference 2015 (WRC-15) [16] decides to invite the International Telecommunication Union Radiocommunication Sector (ITU-R) to investigate the spectrum requirements for International Mobile Communication (IMT) between 24.25 GHz and 86.0 GHz. The European Conference of Postal and Telecommunications Administrations (CEPT) supports compatibility studies at 26 GHz [17]. Owing to the relatively small wavelength at super high frequency towards 5 G [7], [8], the adjacent ports of the couplers, phase shifters, antenna array and switched-beam matrix designs must be fixed with suitable distance to ensure easy connection of RF cables between the ports. Therefore, the appropriate type of configuration design needs to be taken into account due to this issue.

In addition, the appropriate beamforming configuration with low hardware complexity and ease fabrication will be the vital design keys. The crossovers are required in Butler and Blass matrices except in Nolen matrix [7], [8] and Rotman lens [11], [12]. The crossovers in Butler matrix suffers from mismatch loss, cross-coupling and high path loss [15]. The Rotman lens provides multiple beam directions, broad beam scanning and wideband operation due to a true time delay (TTD) characteristic, which develops frequency independent beam steering [18], however, it suffers from presence of phase error across the aperture, power loss within the lens [19] and high ohmic loss [20]. Meanwhile, the Blass matrix becomes lossy due to inherent loss when matched loads are connected to the ports [13]. Therefore, Nolen matrix is the most suitable beamforming network to be chosen as no crossovers are needed [15].

Another arising issue is flexibility on a standard number of beam ports. The Butler matrix requires a standard number of beam ports to be equal to a power of two, whereas the Nolen and Blass matrices flexible in deciding the number of beam ports [15]. Furthermore, both Butler and Nolen matrices develop orthogonal beams that are not couple to each other wherein other beams are at the trough while one beam reaches a certain highest point [21]. The orthogonal beams have limitations on the beam shape, beam direction and sidelobe level [22]–[24] but provide lossless characteristic. The Blass matrix has flexibility in the number of non-orthogonal beams but has higher insertion loss [15]. The Nolen matrix can be developed by altering the diagonal couplers with some simple bent lines of the Blass matrix [25].

The suitable layer topology either a single layer or multi-layer technique needs to be considered to develop simple designs of the couplers, phase shifters and Nolen matrix. The recent reported beamforming networks in [11], [26]–[35] have been developed using the multi-layer technique at less than 14 GHz. The multi-layer technique enhances the bandwidth of the basic beamforming network configurations such as Butler matrix that eliminates the crossovers [36], which consequently reduce the insertion loss, mismatched junctions and size. However, it needs much attention in aligning the two substrate layers since the fabrication tolerance between each layer is difficult to handle. The existence of air gap [37] between substrate layers will yield degradation in the performance. Therefore, a single layer technique is chosen in this research project to avoid the air gap between the substrate layers.

Besides, the antenna array is required to be integrated with the beamforming network. The antenna array maximizes gain and directivity in the required signal direction [38]. The antenna gain is directly proportional to the number of antennas, N when the spacing between the antennas, d is unchanged [2]. Meanwhile, the distance of the inter-element antenna array should be in the range of $\lambda/2 \leq d < \lambda$ to improve the array spatial resolution as well as to prevent aliasing when d is greater than $\lambda/2$ [38] and grating lobe when $d_{\max}$ less than λ [2].

In order to circumvent these arising issues towards achieving the requirements of 5G technology at the super high frequency, the most suitable beamforming network without crossover to be proposed is Nolen matrix that has the flexible number of standard beam ports using single layer technique. In this research project, the number of antennas, $N = 4$ and spacing between the antennas, $d = 0.67\ \lambda$ are taken into account in order to develop high gain, good beam-shaping, narrow main lobe and reduce sidelobes of the antenna array. A suitable configuration of an antenna array is developed and integrated with the Nolen matrix to implement the switched-beam Nolen matrix.

1.3 Objectives of the Research

The works undertaken in this research are aiming on the following objectives:

i) To design the couplers with loaded T-shaped stubs and, loaded stubs and Schiffman phase shifters that can operate at center frequency of 26 GHz.

ii) To design a Nolen matrix that formed by the designed couplers with loaded T-shaped stubs and, loaded stubs and Schiffman phase shifters at center frequency of 26 GHz.

iii) To integrate Nolen matrix with antenna array to perform switchable beams at center frequency of 26 GHz.

1.4 Scope of the Research

This research emphasizes on the designs of cross-slotted couplers with loaded T-shaped stubs, loaded stubs and Schiffman phase shifters, four elements inset feeding microstrip patch antenna array as well as the switched-beam Nolen matrix that can operate at the center frequency of 26 GHz. The selected type of couplers, phase shifters and antenna array are designed using single layer technique. The Nolen matrix is developed by interconnecting the designed couplers and phase shifters. The traditional 4 × 4 Nolen matrix architecture is reduced to the dual-series 2 × 4 switched-beam Nolen matrix due to a limitation of additional path loss which is attributed by extending the lengths of the feed lines for the proposed couplers. The dual-series 2 × 4 switched-beam Nolen matrix is developed by integrating the antenna array to the output ports of the designed Nolen matrix in order to produce radiation pattern with two beam directions.

The individual components and the Nolen matrix are simulated and optimized using Computer Simulation Technology (CST) Microwave Studio software. The design is fabricated onto a Rogers RO5880 board with thickness, h of 0.254 mm and dielectric constant, ε_r of 2.2. The measurement process is carried out using a vector network analyzer (VNA). The performance results of the designed Nolen matrix are studied and analyzed at the center frequency of 26 GHz. The radiation patterns of the switched-beam Nolen matrix are measured at 26 GHz in anechoic chamber to investigate the beam directions.

1.5 Contributions of the Research

One of the contributions in this research is the design of compact coupling tuning based T-shaped stubs-loaded patch couplers as a new approach of coupling tuning for the cross-slotted patch couplers to achieve the required coupling values, S_{31} such as 1.26 dB, 1.76 dB and 3 dB. The T-shaped stubs are introduced at every side of the microstrip lines nearby the square patch coupler. This approach has the ability to exchange the values of S_{21} and S_{31} for the cross-slotted patch couplers at the super high frequency. The performance effects of the microstrip cross slot, rectangular shaped patch slots, circularly slots and T-shaped stubs around the square patch of the coupler are investigated. The parametric studies regarding length variations on performances of scattering parameters and phase differences between the output ports are studied and discussed for each coupler.

The second contribution is the topology of the dual-series 2 × 4 switched-beam Nolen matrix. An additional 0° phase delay is added in the first row of the Nolen matrix configuration to maintain the flatness of phase differences between the output ports across the designated frequency range. The dual-series 2 × 4 switched-beam Nolen matrix which consists of loaded T-shaped stubs couplers (1.76 dB, 1.26 dB and 3.00 dB), loaded stubs (0° and 45°) and Schiffman phase shifters (0°, 90°, 135°, 180°) as well as an additional 0° phase delay are designed. In this research work, the phase shifters ranging from 45°, 90°, 135°, 180° are set as main lines, whereas the 0° loaded stubs and 0° Schiffman phase shifters are set as reference lines. The performance of S-Parameters, phase differences and radiation pattern of the dual-series 2 × 4 switched-beam Nolen matrix is investigated and analyzed. The dual-series 2 × 4 switched-beam Nolen matrix demonstrates good performance in terms of S-Parameters, phase differences and radiation pattern with low phase imbalance and small deviations of transmission coefficients. The highest deviation of the simulated transmission coefficients, phase differences and main beam directions (when the signal is fed at port 1 and port 2) compared to the theoretical values at the center frequency of 26 GHz are ± 3.46 dB, ± 2.86° and ± 3.36°, respectively.

1.6 Thesis Organization

Basically, the entire content of this thesis is divided into six main chapters. The contents of Chapter 1 are concerning the research project overview, problem statement, research objectives, research scope, contributions of the research and last but not least, the thesis organization.

Chapter 2 covers the relevant theoretical background involved in this research project. The literature review describes the related previous works that have been carried out by other researchers. It also contains all relevant terms, theories and equations regarding the smart antenna system, beamforming network, coupler and phase shifter. The qualitative comparisons between various configuration designs of the beamforming network, coupler as well as phase shifter are well described.

Meanwhile, Chapter 3 emphasizes the methodology of the research project, which constitutes a research flowchart to represent graphically the logical decisions and progression of each step involved while completing this research project. The design specifications of the proposed couplers, Nolen matrix and antenna array are discussed in details. The substrate specifications and measurement setups of the proposed couplers and switched-beam Nolen matrix are described in this chapter.

In Chapter 4, the designed couplers with respect to various coupling values for this research are presented. The design parameters and requirements of the couplers are also introduced. The operation and performance results of the designed couplers are analyzed. The simulation software, Computer Simulation Technology (CST) Microwave Studio is utilized to get a comprehensible visualization of the entire design. The performance results of the proposed couplers are verified by the experimental validation between 24.75 GHz and 27.25 GHz.

Chapter 5 presents the proposed antenna array and Nolen matrix. The design parameters and requirements of the antenna are also introduced. The performance results for the designed switched-beam Nolen matrix are further discussed and analyzed. The simulation results are performed by CST software. The performance of scattering parameters and radiation pattern results of the dual-series 2×4 switched-beam Nolen matrix are verified by the experimental validation between 25.75 GHz and 26.25 GHz.

Last but not least, the conclusion of the overall progress in this research project is drawn in Chapter 6. Several future works are recommended and described in this chapter.

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