MICROSTRIP PATCH BEAMFORMING LINEAR ANTENNA ARRAY WITH COMPLEMENTARY SPLIT RING RESONATOR FOR FIFTH GENERATION APPLICATIONS

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DEDICATION

I dedicate this dissertation
To my beloved Father “Selvaraju” and Mother “Malarkodi”,
To my dearest Sister “Karthiga” for their support and encouragement.

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ABSTRACT

The next generation cellular standard which is called fifth generation ($5G$) requires high gain beamforming antenna array to provide high speed and secured communication. Therefore, the proposed research work investigates the design and development of a four-element linear microstrip patch array operating at 25 GHz for $5G$ beamforming application. To investigate the radiation characteristics of the proposed array, five beamforming radiation patterns (main beam at 0°, ±15° and ±20°) have been considered. The mutual coupling between array elements raise the challenge of designing the antenna array system. The coupling alters the array element input impedance and distorts the overall radiation performance. Hence, a simple complementary split ring resonator (CSRR) structure has been developed to alleviate the coupling problem. The modeled configuration is numerically analyzed, verified and implemented between the array elements. The existence of the CSRR configuration in antenna array, controls the unnecessary surface current flow between the array elements, thus the mutual coupling between array elements has been significantly reduced from −23 dB to −55 dB. The effect of coupling on the array radiation patterns has been studied in the presence and absence of CSRRs. Most importantly, the effectiveness of CSRR has been studied by steering the main beam as well as the nulls in different angles. By implementing the CSRR elements in array antenna, the distorted array patterns have been recovered and are presented. The proposed CSRR implemented in antenna array have the advantage of easy and low cost fabrication and it offers excellent coupling suppression without changing the antenna profile. Moreover, to the best of the authors knowledge, it was observed for the first time that the CSRR worked efficiently in reducing the effect of mutual coupling when the beam was steered off from broadside direction from −20° to +20°. The simulation tools such as MATLAB and Ansys HFSS have been used for array weights calculation and antenna design respectively. Finally, the fabricated prototype has been experimentally verified, and it shows that the analytical and computed results agree well with the measured results.

ABSTRAK

Piawai generasi selular yang seterusnya dikenali sebagai generasi kelima ($5G$) memerlukan gandaan antena tatasusunan pembentuk alur yang tinggi bagi menyediakan sistem komunikasi berkelajuan tinggi dan selamat. Oleh itu, cadangan kerja penyelidikan ini adalah untuk mereka bentuk dan mengeksplotasi empat elemen tatasusunan tampalan mikrostrip linear yang beroperasi pada 25 GHz untuk aplikasi pembentuk alur $5G$. Untuk menyelidik ciri-ciri tatasusunan radiasi yang dicadangkan, lima corak radiasi (alur utama at 0°, ±15° and ±20°) pembentuk alur telah dipertimbangkan. Gandingan saling di antara elemen tatasusunan meningkatkan cabaran untuk mereka bentuk sistem tatasusunan antena. Gandingan tersebut mengubah galangan masukan elemen tatasusunan dan menganggu prestasi radiasi keseluruhannya. Oleh itu struktur penyalun gelang terpisah lengkap (CSSR) telah dibangunkan untuk mengurangkan masalah gandingan. Model konfigurasi secara berangka telah dianalisis, disahkan dan dilaksanakan di antara elemen tatasusunan. Kewujudan konfigurasi CSSR di dalam tatasusunan antena mengawal aliran arus permukaan yang tidak perlu di antara elemen tatasusunan, oleh itu gandingan saling di antara elemen tatasusunan telah dikurangkan dengan ketara dari −23 dB hingga −55 dB. Kesan dari gandingan pada bentuk radiasi tatasusunan dikaji dengan ketiadaan dan kehadiran CSSR. Yang paling penting, keberkesanan CSSR telah dikaji dengan mengarahkan alur utama serta nol di dalam pelbagai sudut. Dengan melaksanakan elemen CSSR pada tatasusunan antena, bentuk radiasi yang terganggu telah kembali pulih dan dipersembahkan. Cadangan CSSR yang dilaksanakan di dalam tatasusunan antena mempunyai kelebihan seperti antena mudah direka, murah dan pengurangan gandingan yang sangat baik tanpa menukar bentuk antena. Lagipun, mengikut kefahaman penulis, buat pertama kalinya bahawa CSSR beroperasi dengan baik sekali dalam mengurangkan gandingan saling ketika alur itu berubah-ubah dari arah sisi lebar, −20° kepada +20°. Alat simulasi seperti MATLAB dan Ansys HFSS telah digunakan untuk pengiraan pemberat tatasusunan dan reka bentuk antenna, masing-masing. Akhir sekali, prototaip yang direka telah diuji secara eksperimen, dan ia menunjukkan bahawa keputusan analitik dan pengiraan bertepatan dengan keputusan pengukuran.

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LIST OF ABBREVIATIONS

1G – First Generation

2G – Second Generation

3G – Third Generation

4G – Fourth Generation

5G – Fifth Generation

AEP – Active Element Pattern

AF – Array Factor

AMC – Artificial Magnetic Conductor

AOA – Angle of Arrival

AP – Array Pattern

AUT – Antenna Under Test

CSRR – Complementary Split Ring Resonator

DGS – Defected Ground Structure

DNG – Double Neagtive

EBG – Electromagnetic Band Gap Substrate

EM – Electromagnetic

EMF – Electromotive Force

Gbps – Gigabits per second

GSM – Group Special Mobile

HFSS – High Frequency Structure Simulator

HIS – High Impedance Surfaces

IMT – International Mobile Telecommunications

IoT – Internet of Things

ITU	–	International Telecommunication Union
Kbps	–	Kilobits per second
LAM	–	Linear Algebra Method
LMS	–	Least Mean Square
LTE	–	Long Term Evolution
Mbps	–	Megabits per second
MIMO	–	Multiple Input Multiple Output
MMS	–	Minimum Mean Square
mm-wave	–	Millimeter-wave
MTM	–	Metamaterial
PEC	–	Perfect Electric Conductor
PMC	–	Perfect Magnetic Conductor
RF	–	Radio Frequency
SINR	–	Signal to Interference plus Noise Ratio
SIM	–	Simulated
SNG	–	Single Neagtive
SNOI	–	Signal Not of Interest
SOI	–	Signal of Interest
S-Parameter	–	Scattering Parameter
SRR	–	Split Ring Resonator
TDMA	–	Time Division Multiple Access
UC-EBG	–	Uniplanar EBG
UHF	–	Ultra High Frequency
Z-Parameter	–	Impedance Parameter
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LIST OF SYMBOLS

AF – Array Factor

C – Capacitance

f – Frequency

k – Wave Number

L – Inductance

ε – Permittivity

β – Phase Progression

λ – Whatever

Ψ – Scalar Wave Function

γ – Angle Between Z-axis and Reference Axis

δ – Loss Tangent

ε – Permittivity

ε_0 – Permittivity of Free Space

ε_r – Relative Permittivity

ε_{reff} – Effective Permittivity

μ – Permeability

μ_0 – Permeability of Free Space

μ_r – Relative Permeability

μ_{reff} – Effective Permeability

Δ_l – Extended Length of Patch

θ_U – Angle of the Signal of Interest

θ_{Nn} – Angle of the Signal not of Interest

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CHAPTER 1

INTRODUCTION

1.1 Overview

Historically, due the expanded wireless-communication services, the telecommunication innovation has acquired phenomenal growth from the first generation (1G) to fifth generation (5G). Consequently, the world wide unique mobile subscriber numbers have exceeded up to 5 billion, and it has been expected to reach 6 billion within 2020 [1]. Furthermore, in recent years wireless gadgets and Internet of Things (IoT) devices usage has exponentially increased. As a result of these quick advancement the demand for mobile data services has increased a lot. Besides, the large number of communication devices usage causes a strong interference between the devices. In order to cope with the increased data rate demand and to address the interference problem, a new wireless standard is required. Particularly, to support the high-speed communication and improve the quality of services the data rate of forthcoming wireless standard (5G) should be in the range from 100 Mbps (Edge rate) to 1 Gbps (peak rate), respectively [2, 3].

Basically, wide operating frequency band is needed to obtain such high data rate. Essentially, to achieve the peak data rate (10 Gbps) of the 5G, the required frequency bandwidth must be up to several hundred megahertz or few gigahertz [4]. However, Ultra High Frequency (UHF) band (300 MHz to 3 GHz) which is currently used for mobile communication is almost saturated due to several applications. Therefore, wide band allocation for future communication at UHF band is unattainable. In the meantime, apart from UHF spectrum there are several higher frequency spectrum bands which has strong potential to meet some of the 5G demands identified until now [5]. Hence, the International Telecommunication Union Radio Communication Standards Sector (ITU-R) have allocated the frequencies above 6 GHz for the upcoming mobile standard (5G) research [6, 7]. Recently, the millimeter-wave frequencies have gained a substantial attention of the operators, vendors and academic researchers, due to its unique bandwidth characteristics [6]. But, the Friis equation asserts that in the higher frequencies the path loss will be increased due to its small wavelength [8]. So that the mm-wave signals can travel only short distance and easily deteriorated by the obstacles due to poor penetration. However, this problem can be mitigated by employing multiple antennas (antenna array) at transmitter and receiver ends [9]. In general, antenna array is a process of combining similar antenna elements together with a proper spacing and feeding. The array antennas possess numerous advantages such as, high gain, narrow beam width etc. While, these array antennas contain limited coverage in both azimuth and elevation planes. Technically the coverage of the antenna array can be enhanced by utilizing beamforming technique [10].

Basically, beam-forming array is an array, which direct the maximum radiation in the desired direction and placing nulls in the undesired directions. It has been achieved by exciting the array elements with variable phase shift or variable time delay [11, 12]. The beamforming array can be constructed using any type of radiating elements. However, printed type (microstrip patch) radiators are highly suitable to construct a compact and lightweight beamforming antenna array system. Another interesting advantage of it is that it can be easily integrated with beam-forming circuits. The aforementioned advantages encouraged the antenna designers to pay greater attention on microstrip patch beamforming antenna arrays. Besides the numerous advantages, the performance of these arrays systems is severely affected by most common mutual coupling effects.

Mutual coupling is an electromagnetic phenomenon which exists in antenna array when all the array elements are excited [10]. Mutual coupling in antenna arrays is under investigation for several decades. Mutual coupling alters the individual element patterns as compared to its isolated patterns, causing mismatch, impedance variation and correlation of the signals. This alteration depends upon the position of the element in the array. The result of this is a degraded array performance which results in the overall system performance degradation. Various mathematical methods have been discussed in the literature to compensate the effect of mutual coupling [13, 14]. However, these mitigation methods are well suitable only for small arrays. Because, higher number of elements in an array increase the calculation complexity of these methods. Apart from the mathematical compensation methods recently, the metamaterials gained much attention in the field of electromagnetic due to its peculiar characteristics.

In general, the materials which has negative characteristics (negative electrical permittivity or negative magnetic permeability or permittivity and permeability both negative) are referred as meta-materials [15, 16]. Periodic arrangements of these negative materials do not allow the surface current flow from one antenna to another, thus the mutual coupling between antenna elements are highly reduced. Various metamaterials configurations such as, High Impedance Surfaces (HIS) [17, 18], Meander Line Structures [19–21], Electromagnetic Band Gap Substrate (EBG) [22–24], Split Ring Resonator (SRR) [25, 26] and Complementary Split Ring Resonator (CSRR) [27–29] have been reported in past studies for reducing the mutual coupling between antenna array elements.

Specifically, among the all, the SRR and CSRR configurations offers higher mutual coupling reduction than others. Furthermore, these structures are compact in size, simple in design and easy to integrate with the antenna arrays. The detail study about the split ring and complementary split ring resonators will be discussed in the next section. In accordance with all the above discussion, the development of a beam-forming antenna array with high gain and less mutual coupling is most essential for future wireless (5G) system. Therefore, in this research work it is addressed in handsome detail.

1.2 Problem Statement

The intense demand for boundless data rates has led the telecommunication field to implement a new wireless standard. In the meantime, the increase of usage and the demand for simultaneous communication between devices causes higher interference. Different multiple antenna approaches like massive MIMO and beam-forming have been proposed to satisfy this ever-growing need. The MIMO system offers high quality of service and support large number of subscribers in single cell. However, MIMO systems are not sufficient to fulfill the high data rate need. The beam-forming system, which can be achieved by a one-dimensional linear or two-dimensional planar array, can further increase the channel capacity by increasing the Signal to Interference plus Noise Ratio (SINR). Microstrip patch antennas are being considered as a good candidate for beamforming applications. However, the performance of the microstrip patch beamforming array is severally affected due to the mutual coupling.

In order to mitigate the mutual coupling and improve the performance of the beam-forming array, different mathematical solutions like open circuit voltage method, calibration method, receive mutual impedance approach etc. have been used. However, for these mathematical solutions several complex measurement results are required to mitigate the mutual coupling. Therefore, metamaterials based decoupling structures like defected structures, electromagnetic band gap structures (EBG), split ring resonators (SRR) and complementary split ring resonators (CSRR) are preferred. The defected structures which could be located in ground place is large in size, therefore it will increase the back-radiation. Next, the EBG configurations are complex in design because multi-layer substrate and vertical via's are required to construct these structures. Implementing these EBGs increase the design complexity of the beamforming array.

Compare to all, the SRR and CSRR configurations are compact and simple designs therefore several research works proposed different CSRR configurations for mutual coupling reduction. However, those CSRR elements were implemented in arrays with broadside radiation pattern only and almost no study was carried out on on the effectiveness of CSRRs in a smart beamforming array when the main beam as well as position of nulls was changed to different angles. Hence, in this research work the CSRR configuration is chosen to decrease the mutual coupling between beamforming antenna array and the radiation performance of the beamforming antenna array has been verified along with CSRR elements when the main beam and nulls are steered to different angles. By doing so it will be justified that CSRRs not only suppress mutual coupling when the main beam is pointing in the broadside direction (as discussed in most studies) but are also effective when the main beam is scanned off from the broadside direction to other angles $-20°$to $20°$.

In order to address these issues, this research work focuses on two major aspects; beamforming microstrip patch array and reducing mutual coupling in beamforming array using complementary split ring resonators. Design of beamforming microstrip patch antenna array and performance enhancement of beamforming array using CSRRs are discussed in Chapter 4. Moreover, in the same chapter, the simulation and experimental results are explained in detail. Finally, the overall work is concluded in Chapter 5.

1.3 Research Objectives

1. To model and design, a four element linear microstrip patch antenna array operating at 25 GHz and estimate the array elements weights to perform the beamforming.
2. To model and design, a complementary split ring resonator operating at 25 GHz and study their band rejection characteristics.
3. To implement the configured complementary split ring resonator in between the array elements to reduces the mutual coupling and to recover the distorted individual element patterns and array element pattern.

1.4 Scope of the Research

The primary aims of this research are to design a beamforming antenna array for next generation wireless standard application. Various frequency bands from 24.25 to 86 GHz has been suggested for 5G research study [30]. The frequency band 24.25 - 27.5 GHz have been chosen for this study with a resonant frequency of 25 GHz. This range of frequency is the lowest possible band from the ITU-R suggested 5G frequencies, which can provide feasibility of optimized fabrication with available beamforming RF components. Next, due to several advantages widely used rectangular microstrip patch antenna has been used as radiating element in this research. Furthermore, the coaxial probe fed method have been used to feed antenna elements because it is easy to fabricate and offer better impedance matching.

Antenna arrays come in different configurations like linear, circular, planar and conformal. In this research work, a simple, wideband (1GHz), high gain (12dB) and low cost linear array antenna has been proposed for 5G applications. Basically, the bandwidth of the proposed antenna array is defined based on where the frequency range S_{11} is less than -10 dB. Followed by, the complex array element weights (Magnitude and Phase) has been calculated by using the array factor equation to steer the main beam from the broadside direction to other angles $-20°$to $20°$. The proposed linear array antenna consist of four identical patch antenna elements, the four elements are chosen because of certain short comings in purchasing expensive RF components like attenuators, phase shifters, power dividers and amplifiers which are used to practically provide the required magnitude and phase to the array elements for beamforming.

Generally, the mutual coupling severely degrades the performance of a smart beamforming array. Basically, the maximum acceptable level of mutual coupling (S_{12}) between the array elements are considered as -15 dB. Different mathematical methods (open circuit voltage method, decoupling method, calibration method) and use of metamaterials based decoupling structures have been used to compensate the effect of mutual coupling. In this work, complementary split ring resonator (CSRR) has been chosen to reduce the mutual coupling between antenna array elements because it is simple and compact in design and it is easy to fabricate. As a first step of mutual coupling reduction, a simple and compact complementary split ring resonator which has sharp band rejection at 25 GHz has been designed and analyzed. Followed by, the surface current flow from one antenna element another is reduced by implementing the modeled CSRR configurations in between the array elements.

After accomplishing the optimum designs, to practically investigate and validate the concept, a four-element antenna array with and without CSRRs has been fabricated and experimentally verified. The fabrication accuracy entirely depends on how much accurate the design is printed on the transparent sheet. Therefore, in this work a high quality Epson L200 ink-jet printer has been used for printer purpose. A perfect printed output has been obtained when the dimensions of the configuration is maintained ≥ 0.15 mm. Finally, the proposed antenna array has been experimentally verified in terms of S-parameter and radiation pattern. The real time beamforming setup includes several RF components which increase the losses. In order to get better performance the losses of each RF component is properly analyzed and modeled.

The software used in this research work are: Matlab and Ansys HFSS. Matlab has been used to carry out the dimension calculations of beamforming antenna array and CSRR. Next, the Matlab has been used to calculate and verify the CSRR constitutive parameters such us permittivity and permeability. Finally, Matlab has also been used for the calculation of complex array element weights required for beam-forming. Ansys HFSS has been used for the simulation and optimization of all the beam-forming array and CSRR.

1.5 Research Contributions

The main contributions of this research work can be summarized as:

1. Innovative design of a beam-forming antenna array with four elements for 5G application (25 GHz). This includes the fabrication and measurements of the beamforming antenna array.
2. Innovative and compact design of complementary split ring resonator based filtering structure. The band rejection characteristics and effective permittivity and permeability responses are verified by numerical methods.
3. Finally, the CSRR configurations are implemented in between the array elements to suppress the mutual coupling, by reducing the mutual coupling the active impedance of the each array elements are exactly maintained as $50 + i0\ \Omega$. Moreover, the distorted individual element patterns are recovered by reducing the mutual coupling between the array elements. Therefore, the overall array pattern which is the linear combination of element patterns are recovered successfully. The overall results are verified by extensive measurement procedures.

A lot of work has been done on traditional antennas for beamforming applications and mutual coupling compensation. In this research work an extensive study has been carried out on beamforming antenna array and the compensation of mutual coupling effect in this antenna array.

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