UNEQUALLY SPACED MICROSTRIP LINEAR ANTENNA ARRAYS FOR FIFTH-GENERATION BASE STATION

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Specially dedicated to my lovely husband Abdul Halim Zaini, my lovely kids Muhammad Adam and Muhammad Ammar, my mother Norsiah Abdul Rahman, my dearest sibling, and in the memories of my father, Zainal Yahya.

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ABSTRACT

Wireless technology communication has been continuously evolving towards future fifth generation (5G), whereby multi-beam, multi-frequency, and low sidelobe characteristics are required in the mobile base station. However, the low sidelobe level of conventional mobile base station antenna led to more complex of feeding network design in order to give an adequate excitation coefficients (amplitude and phase) to array elements. Thus, the current base station antennas are difficult for wide frequency use due to frequency range is limited. Subsequently in this research, an unequally spaced microstrip linear antenna arrays is proposed. The radiation pattern synthesis for low sidelobe and grating lobes suppression over wide frequency use are investigated. In the first stage, a single antenna is designed at frequency 28 GHz followed by 16 element linear arrays in order to achieve the gain requirement for mobile base station antenna. Next, the design of antenna arrays with sidelobe reduction is proposed. Three configurations of linear antenna arrays are designed, which are equally spaced array (ESA), unequally spaced array 1 (USA 1) and unequally spaced array 2 (USA 2) at frequency $f_\circ$ = 28 GHz, f_1 = 42 GHz and f_2 = 56 GHz with a similar array aperture, in order to investigate the antenna performance in wide frequency use characteristics. USA 1 and USA 2 are having different center spacing of array (d_c), which are $d_{c(USA1)} = 0.6$ *mm* and $d_{c(USA2)} = 0.5$ *mm,* respectively. The simulation results are obtained by using High Frequency Structure Simulator (HFSS). The good results were observed, where the performance of sidelobe reduction are constant even though the frequency changes. Due to the lack of measurement facilities at higher frequency than 18 GHz, the antenna arrays are redesigned at lower frequency, which are 12 and 18 GHz. In order to achieve a wide frequency operation, a wide frequency use of ESA*, USA 1* and USA 2* feeding network (which notation * indicates that the frequency of 12 GHz is chosen as reference) are designed by using Advanced Design System (ADS). An equal line lengths (l_n) with equal power ratio dividers were constructed. The sidelobe reduced from -13 dB for ESA* to -19 dB for USA 2*. The measurement of S-parameter and radiation pattern are performed using a vector network analyzer (VNA) and anechoic chamber, respectively. The measured results were presented and a good correlation with simulations was observed. From the observation, the sidelobe level and grating lobe suppression of USA 2* is reduced rather well and recommended for wide frequency band for 5G mobile base station antenna.

ABSTRAK

Teknologi komunikasi tanpa wayar terus berkembang untuk ke arah generasi kelima (5G), di mana pelbagai alur, pelbagai frekuensi dan cuping sisi rendah diperlukan di stesen pangkalan mudah alih. Walaubagaimanapun, stesen pangkalan mudah konvensional bercuping sisi rendah rangkaian penyuapan menyebabkan rangkaian penyuapan yang lebih komplek untuk menghasilkan pengujaan (amplitud dan fasa) yang cukup bagi setiap elemen. Maka, ketika ini, antena stesen pangkalan mudah alih adalah sukar untuk mencapai penggunaan julat frekuensi yang lebar kerana jalur frekuensi yang terhad. Seterusnya, tatasusunan antena mikrojalur linear bersela tidak sama dicadangkan. Sintesis corak radiasi untuk pengurangan cuping sisi dan cuping jeriji bagi penggunaan frekuensi yang lebar dikaji. Pada peringkat permulaan, antena tunggal pada frekuensi 28 GHz direkabentuk diikuti dengan rekabentuk tatasusunan linear 16 elemen bagi mencapai gandaan yang diperlukan oleh antena stesen pangkalan mudah alih. Seterusnya, rekabentuk tatasusunan antena dengan pengurangan cuping sisi dicadangkan. Tiga konfigurasi tatasusunan antena linear telah direkabentuk, iaitu tatasusunan sama jarak (ESA), tatasusunan tidak sama jarak 1 (USA 1) dan tatasusunan tidak sama jarak 2 (USA 2) pada frekuensi $f_o = 28$ GHz, $f_1 = 42$ GHz dan $f_2 = 56$ GHz dengan bukaan tatasusunan yang sama untuk kajian ke atas prestasi antena dalam ciri frekuensi lebar. USA 1 dan USA 2 mempunyai jarak antara elemen di tengah tatasusunan yang tidak sama, di mana $d_{c(USA\,1)} = 0.6\,mm$ dan $d_{c(USA\,2)} = 0.5\,mm$. Simulasi dilakukan menggunakan *High Frequency Structure Simulator* (HFSS). Hasil keputusan yang baik diperolehi, iaitu tahap pengurangan cuping sisi adalah tetap walaupun frekuensi berubah. Disebabkan oleh kekurangan fasiliti pengukuran pada frekuensi tinggi melebihi 18 GHz, tatasusunan antena telah direkabentuk semula pada frekuensi 12 dan 18 GHz. Untuk mencapai operasi frekuensi yang lebar, rangkaian penyuapan antena berfrekuensi yang lebar untuk ESA*, USA* dan USA 2* (di mana tanda * menunjukkan frekuensi 12 GHz dipilih sebagai rujukan) direkabentuk menggunakan *Advanced Design System* (ADS). Rangkaian pembahagi kuasa dengan panjang laluan (*ln*) yang sama telah direkabentuk. Cuping sisi telah dikurangkan daripada -13 dB bagi ESA* kepada -19 dB bagi USA 2*. Pengukuran ke atas parameter-S dan corak radiasi masing-masing dibuat menggunakan *Vector Network Analyzer* (VNA) dan ruang bebas gema. Keputusan yang baik ditunjukkan untuk simulasi dan pengukuran. Daripada pemerhatian, pengurangan cuping sisi dan cuping jeriji yang baik bagi tatasusunan tidak sama jarak 2* (USA 2*) telah diperolehi dan ia dicadangkan untuk jalur frekuensi yang lebar bagi antena pangkalan mudah alih generasi kelima (5G).

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LIST OF ABBREVIATIONS

ADS	-	Advanced Design System
ASP	-	Aperture-stacked patch
AUT	-	Antenna under test
CDMA	-	Code Division Multiple Access
CFN	-	Corporate feed network
DEA	-	Differential evolution algorithm
DR	-	Dielectric Resonator
EM	-	Electromagnetic
ESA	-	Equally spaced array
5G	-	Fifth Generation
FBW	-	Fractional bandwidth
FCC	-	Federal Communications Commission
FDMA	-	Frequency Division Multiple Access
FM	-	Frequency modulation
FR4	-	Flame Retardant 4
FSL	-	Free space loss
GL	-	Grating lobe
GSM	-	Global System for Mobile
HFSS	-	High Frequency Structure Simulator
HPBW	-	Half power beamwidth
IES	-	Inter element spacing
LMDS	-	Local Multipoint Distribution Services
LTCC	-	Low-temperature co-fired ceramic substrate
ITU	-	International Telecommunications Union
MIMO	-	Multiple input multiple output
MPA	-	Microstrip patch antenna
NLOS	-	Non-line-of-sight
PCA	-	Planar connected array
PCB	-	Printed circuit board

PPW	-	Parallel plate waveguide
PTFE	-	Polytetrafluoroethylene
QWT	-	Quarterwave transformer
RET	-	Remote Electrical Tilt
RF	-	Radio frequency
SLL	-	Sidelobe level
SMA	-	Sub Miniature version A
TDMA	-	Time-Division Multiple Access
UV	-	Ultraviolet
US	-	United State
USA 1	-	Unequally spaced array 1
USA 2	-	Unequally spaced array 2
VNA	-	Vector network analyser
VSWR	-	Voltage standing wave ratio
WRC	-	World Radio Communications

LIST OF SYMBOL

f_o	-	Operating frequency
l_n	-	Line length
ε_o	-	Permittivity of free space
ε_r	-	Relative permittivity / Dielectric constant
ε_{reff}	-	Effective dielectric constant
μ_o	-	Permeability of free space
v_o	-	Space velocity of light
δ	-	Tangent loss
N	-	A group of element
d_n	-	Element spacing
w_n	-	Complex weight
k	-	Free space wave number
β_n	-	Phase excitation
λ	-	Wavelength
R	-	Distance
h	-	Substrate thickness
Z_o	-	Impedance of transmission line
L_{eff}	-	Effective length
ΔL	-	Extension of length
L_{ml}	-	Length of microstripline
W_{ml}	-	Width of microstripline
W	-	Width of radiating patch
S_{11}	-	Reflection coefficient
S_{21}	-	Transmission coefficient
T_x	-	Transmit antenna
R_x	-	Receive antenna
G_t	-	Transmit gain
G_r	-	Receive gain

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Mobile communications systems have continuously evolved and revolutionized the way people communicate, where the systems changed from fixed "point-to-point" to wireless that has more advantages. In future, the fifth generation (5G) mobile system is the new technology that will drive the future communication evolution, through increase data capacity and lower latency [1, 2]. However, the spectrum below 6 GHz is congested, therefore the spectrum above 6 GHz is being considered for the upcoming 5G mobile technology [3].

The Federal Communications Commission (FCC) of the United States (US) allocated the frequency of spectrum bands above 24 GHz as operation band for mobile services [4], where operation in a new millimeter frequency band is a way to avoid the overcrowded lower frequency spectrum. This frequency band provides large amount of spectrum to exploit large bandwidths in order to achieve very high data rates communication systems for high speed and efficient use [5].

In order to support 5G demands, wideband, low cost and low interference base station antenna design has attracted the attention from both academia and industry. For this next 5G mobile communication system the distance between the antennas is getting closer due to high frequency use. Thus base station antennas are requested to achieve multi-band and low sidelobe level (SLL) characteristics [6, 7], where the SLL should be less than -15 dB to reduce the interference from the other signal [8, 9]. Multi-band base station antenna design is one of the ways to avoid crowded installation space due to limitation of the future antenna installation space such as on tower and the roof of a building [10, 11]. One of the interests of designing the low sidelobe level over wide frequency use antenna is on microstrip unequally spaced antenna arrays.

Unequally spaced antenna arrays is a nonuniform array or unequal spacing between adjacent element, which is able to control the radiation pattern [12]. Many techniques have been proposed which has been presented and reported in [13, 14, 15] where a lot of effort has been done on the unequally spaced antenna arrays. A configuration of unequally spaced arrays provides low sidelobe characteristics over wide frequency use, while this configuration is having uniform excitation coefficient (amplitude and phase) in all array elements.

An excitation coefficients to antenna arrays elements is determined by a feeding network, where the changes of frequency operations will change an electrical length of transmission line and resulting a phase shift [16, 17]. Parallel feed has a well controlled aperture distribution compared to series feed, which suffer from inherent phase difference caused by the differences in lengths of feed lines. Thus, the design of a parallel feed network achieving equal excitation coefficients in the wide frequency range is seemed to be the solution [18] .

Besides, it is required to have equal magnitude and phase coefficients with non-frequency dependence for wide frequency use implementation, which can be obtained by designing feeding network with uniform line length [18]. Thus, unequally spaced arrays are deemed as the potential candidates due to their ability to achieve low sidelobe levels and suppress grating lobes in wide frequency use operations [12, 13, 14].

Therefore, in this thesis, an unequally spaced microstrip linear antenna arrays using a wide frequency use of feeding network, that offers a low sidelobe level is presented. The spectrum above 6 GHz, which is 28 GHz is chosen as the designated frequency band due to the availability of the band for mobile services [3, 4] and also led to the increasing of bandwidth. However, the frequency will be scaled down to 12 and 18 GHz for realization purpose, due to the limitation of radiation pattern measurement in higher frequency. Commercial electromagnetic simulators were employed in designing the feeding network and antenna array. For the feeding network design, the Advanced Design System (ADS) is more easier to be employed. Then, the design of antenna arrays and their analysis performance are implemented in High Frequency Simulation Simulator (HFSS). Lastly, the feeding network from ADS will be exported to HFSS simulator and the analysis of performances are performed in HFSS.

1.2 Problem Statement

Practically, the higher frequency use caused a shorter wavelength, which leads the future base station antennas to have closer distance to each other compared to the present mobile base station antenna. Consequently, it will increase the interference with another communication. Thus, in order to counter the effects of attenuations, which reduce the strength of the signal, the mobile system shall deploy antenna with higher gain [19, 20, 21]. The higher gain antenna has a signal that is confined to a narrow solid angle [7] that can reduce the interference with another communication system. However, Andrews in [22] stated that high gain in the narrow beam communication is new to cellular communications. In addition, network modeling, analysis, design and optimization for preliminary status and spectrum 5G standardization are other challenges [22].

Besides, low sidelobes are required in order to reduce interference with another frequency reuse cell [23, 24, 25, 26], where interference can be reduced by the reduction of the unwanted upper sidelobes, that is directed towards the neighboring cells. Due to that, near-in sidelobe reduction methods by designing unequal array spacing have been proposed in [27, 28, 29, 30, 31]. However, these previous works were mainly focused on theoretical and numerical. Functional antenna configurations and the acquired antenna characteristics should be clarified in the applications of unequal spaced array for the upcoming 5G mobile. In addition, there has been no investigation made for the sidelobe level performance over wide frequency use.

For base station antenna, low sidelobe characteristics are achieved by giving adequate excitation coefficients (amplitude and phase) to array elements [32]. In this case, the feeding network is composed of many power dividers and feeder lines that have different values. Here, phase values, which is determined by feeder line lengths have severe frequency dependence. Therefore, the present base station antennas are difficult for wide frequency use. In order to achieve an unequally spaced array over a wide frequency use, a suitable feeding network circuit must be developed. Generally, excitation coefficients for unequally spaced array elements are uniform. Hence, T-junctions were proposed to be constructed with equal power division and phase. Therefore, the main design was subjected to the feeding network that must have equal line lengths from input point to the array elements which is placed in unequal spacing. The equality of line lengths ensures wide frequency use operation [13]. In addition, in future 5G mobile system, wide frequency or multi-band antenna is requested [33] to provide multifunctional operations for mobile communication [34].

Therefore, by considering these problems in designing the upcoming 5G base station antenna, the unequally spaced linear antenna arrays will be proposed in order to achieve low sidelobe over wide frequency use operation, which is one of the features for future 5G mobile base station antenna. Through this research, three configurations of microstrip linear antenna arrays with the same array aperture have been proposed that consist of equally spaced array (ESA), unequally spaced array 1 (USA 1) and unequally spaced array 2 (USA 2). The respective center spacing between element of USA 1 and USA 2 are $0.6\lambda_{\circ}$ and $0.5\lambda_{\circ}$, while the array apertures are similar for both designs. The ESA design is chosen as a benchmark of the array, where the results of USA 1 and USA 2 are compared to ESA.

1.3 Objectives of the Research

The objectives of this research are stated as follows:

i. To design a microstrip single patch antenna and unequally spaced microstrip linear antenna arrays for base station with high gain and low sidelobe level in 5G frequency band.
ii. To design the feeding network and integrate it with unequally spaced microstrip linear antenna arrays for high gain and low sidelobe level.
iii. To design the unequally microstrip linear antenna arrays at frequency 12 GHz and 18 GHz for realization due to the limitation of radiation pattern measurement in higher frequency in order to achieve high gain and low sidelobe over wide frequency use.

1.4 Scope of the Research

This research focuses on the design of an unequally spaced linear antenna arrays in the 5G frequency band. In order to achieve the research objectives, there are several steps to be completed. The designs consist of microstrip single patch antenna, microstrip antenna arrays, feeding network design and the combination of feeding network and microstrip antenna arrays. Firstly the microstrip single patch antenna at 28 GHz with the various types of feeding is designed, simulated and optimized. The characteristics of a feeding technique is studied based on antenna gain, return loss, bandwidth and radiation pattern, and the suitable feeding technique is selected for the use in the design of antenna arrays. Next, the characteristics and performance of the antenna arrays are investigated at frequency 28, 42 and 56 GHz.

In order to observe the microstrip linear antenna array's sidelobe level, measurement of radiation pattern was taken in an anechoic chamber. In this work, the characteristics of the antenna such as gain, impedance bandwidth, radiation pattern, reflection coefficient, amplitude and phase differences between output ports are considered and discussed based on the requirements of 5G mobile system applications. However, due to limitation of measurement in higher frequency, realization are done at 12 and 18 GHz. The designs are referred to the parameters and specifications listed in Table 3.1 in Chapter 3.

The simulation and optimization process of antenna design is performed using High Frequency Structure Simulator (HFSS). While the feeding network is easier to be designed by using Advanced Design System (ADS) due to the requirement of many output ports. The RT/Duroid 5880 substrate (relative permittivity, ε_r = 2.2 and tangent loss, $tan\delta$ = 0.0009) is chosen due to its low loss with thickness of 0.508 mm. The fabrication and measurement are performed to ensure that comparable performances between simulated and measured results. The measurement of S-parameter is carried out by using a vector network analyzer (VNA) and radiation pattern measurement is performed in an anechoic chamber.

1.5 Contributions of the Research

Two major contributions are presented in this research, which are as follows:

i. The designs of microstrip linear unequally spaced arrays over wide frequency use and its investigation on the effect of element spacing to the performance of radiation pattern. The unequally spaced antenna arrays are designed at 28, 42 and 56 GHz, which results in approximately 3 dB sidelobe reduction compared to equally spaced arrays. Then, realization at 12 and 18 GHz, which results an approximately 6 dB sidelobe reduction compared to equally spaced antenna array. All feeding ports having uniform amplitude and phase, then contribute to low sidelobe level over wide frequency use.

ii. The design of equal power division and non-frequency dependent of feeding network with uniform excitation coefficient for each output port. In previous works [13, 14, 27, 28, 29, 30, 35] were mainly theoretical and numerical in nature whereas practical examples are much needed in the applications of unequally spaced antenna array for the upcoming fifth generation (5G). Therefore in this research, the 16 parallel output ports for three configurations of arrays, which are the equally spaced array* (ESA*), unequally spaced array 1*(USA 1*) and unequally spaced array 2* (USA 2*) are evaluated from the perspective of equal amplitude and phase which notation * indicates frequency 12 GHz that chosen is as reference. The large arrays are designed to have 16 elements due to the better agreement between spaced tapered array (USA 1* and USA 2*) and reference patterns (ESA*) when optimum number of elements are used. The parallel feeding network achieving equal excitation coefficients in the wide frequency use has been designed, which is suitable for this antenna arrays' configuration. Thus, the wide frequency use antenna is achieved by employing this feeding network, which results in constant sidelobe reduction even though the frequency is changed. The sidelobe level is reduced from -13 dB, -16 dB and -19 dB for the respective antenna array of equally spaced array * (ESA*), unequally spaced array 2* (USA 2*) and unequally spaced array 1* (USA 1*).

1.6 Thesis Outline

This section discusses the thesis outline, which are organized into seven chapters. In Chapter 1, the overview of the whole project is discussed, which includes the research background, problem statement, objectives of the research, scope of the research, contributions to the research, and thesis outline.

While, Chapter 2 focuses on the literature reviews, which started from an overview of a 5G mobile communication system, followed by mobile base station, microstrip patch antenna (MPA) and linear arrays. Then, the previous related works are reviewed, which mainly focus on the design techniques, and characteristics of the unequally linear antenna arrays and feeding network design. Chapter 3 discusses the methodology of this research. This chapter presents the research work flows of the whole research. Also, the process of overall antenna design and feeding network design are shown by the flow chart. The design parameters and specifications, optimization and simulation and measurement process, are introduced.

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