MULTIBEAM DIELECTRIC LENS ANTENNA FOR 5G MOBILE BASE STATION

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DEDICATION

This thesis is dedicated to my husband, *Nurulhisham Musa* and children, *Imran, Ilham and Ihsan* who always enthusiast me along this colourful journey. It is also dedicated to my beloved parents, *Hj. Ansarudin Hj Mokhtar* and *Hjh. Maftuhah Hj. Abdul Syukur,* especially to my mother, who always taught me that even the hardest part will never stop me to move forward and definitely it can be accomplished with truly patience, embrace and trust the Almighty.

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ABSTRACT

The introduction of fifth-generation (5G) mobile communication technology has new features such as millimetre wave operation, small cell size and multibeam base station antenna to meet massive multiple-input multiple-output (MIMO) requirements. The introduction of fifth-generation (5G) mobile communication technology has new features such as millimetre wave operation, small cell size and multibeam base station antenna to meet massive multiple-input multiple-output (MIMO) requirements. At millimetre wave, the base station antenna size is expected to be less than 30 cm, and aperture antennas such as the reflector and the dielectric lens antenna can be among the alternatives to replace the present array antenna. Based on previous works, the dielectric lens antenna was designed to produce excellent multibeam radiation patterns as compared to the reflector antenna. Many lens antennas have been reported for various applications such as airborne radar and vehicle's collision avoidance system. For base station application, the lens antennas with small thickness and curvature are required for light weight and ease of installation. The main objective of this research is to propose a new lens design method for thin and small curvature antenna and ensure its multibeam characteristics. By developing the geometrical optics algorithm for lens shaping method in MATLAB software, the conventional Aperture Distribution Condition (ADC) and the Abbe's Sine Condition (ASC) are designed to ensure the accuracy of the developed algorithm. In order to achieve the thin lens and small curvature structure, a newly proposed design method, namely Straight-Line Condition (SLC) lens at designed frequency of 28 GHz and material with dielectric constant, ε_r of 4 was developed. At the lens size of 10 cm antenna with ratio focal length-to-diameter, *F/D*=1, the SLC lens structure provides thickness of 1.38 cm as compared to ADC and ASC with thickness of 1.7 cm and 1.48 cm, respectively. Multibeam radiation patterns of ADC, ASC and SLC were compared by using electromagnetic simulator FEKO. Good multibeam radiation patterns for SLC is ensured for scanning beam angle from 0° to 42.6°. To determine the optimum feed positions for multibeam performances, the focal region ray tracing was conducted in receiving mode by the Ray Launching-Geometrical Optics (RL-GO) solver of FEKO simulator. New feed positions locus for SLC was obtained and compared to ADC and ASC. For the practical application to install base station pole, the cylindrical structure of SLC lens antenna was designed at the *F/D* ratio of 0.6 and polycarbonate material with dielectric constant, ε_r of 2.9 was selected. The practical size of cylindrical height of lens antenna is 20 cm and the cylinder diameter is 29 cm with thickness of about 5.13 cm. New feed position locus for SLC cylindrical structure was obtained at *F/D* ratio of 0.6. From the near field distribution, phase constant and adequate amplitude distribution on the aperture plane is ensured. Fan beam radiation pattern was produced for the cylindrical lens. In the vertical plane, multiple beams radiation pattern was achieved. The beamwidth of fan beam is 45° and vertical beam is 3.28° with maximum antenna gain of 22.98 dBi. Good multibeam radiation patterns are obtained for wide scanning beam ranging from 0° to 47.1° in the vertical plane. Gain reduction is 6.56 dBi. As a result, the new proposed of cylindrical SLC dielectric lens antenna is suitable for the use of 5G multibeam base station application.

ABSTRAK

Pengenalan kepada teknologi komunikasi bergerak generasi ke-5 (5G) mempunyai ciri-ciri baru seperti operasi gelombang milimeter, saiz sel yang kecil dan antena berbilang alur stesen tapak untuk memenuhi keperluan besar pelbagai-input pelbagai-output (MIMO). Pada gelombang milimeter, saiz antena stesen tapak dijangka lebih kecil daripada 30 cm, dan antena bukaan seperti antena reflektor dan lens dielektrik merupakan antara alternatif untuk menggantikan sistem susunan antena sedia ada. Berdasarkan kajian lepas, antena lens dielektrik dapat menghasilkan corak radiasi berbilang alur yang lebih baik berbanding antena reflektor. Kebanyakan antena lens telah dilaporkan untuk pelbagai aplikasi tetapi terhad kepada radar bawaan udara dan sistem pencegahan kemalangan kenderaan. Untuk aplikasi stesen tapak, antena lens dengan ketebalan dan lengkungan yang kecil merupakan keperluan untuk pemasangan yang mudah dan ringan. Objektif utama kajian ini adalah untuk mencadangkan kaedah rekabentuk lens yang baru bagi menghasilkan antena yang nipis dan mempunyai lengkungan kecil dan untuk memastikan ciri-ciri radiasi berbilang alur. Dengan membangunkan algoritma optik goemetri untuk kaedah pembentukan lens menggunakan perisian MATLAB, lens lazim dengan Syarat Taburan Bukaan (ADC) dan Syarat Abbe Sine (ASC) telah direkabentuk untuk memastikan kejituan algoritma yang dibangunkan. Bagi memperoleh struktur lens yang nipis dan kelengkungan kecil, satu kaedah baru telah dicadangkan, iaitu lens Syarat Garis-Lurus (SLC) pada frekuensi tereka bentuk 28 GHz dan bahan dengan pemalar dielektrik, ε_r=4 telah dibangunkan. Struktur lens SLC antena dengan saiz 10 cm dan nisbah panjang fokal-terhadap-diameter, *F/D*=1 menghasilkan ketebalan 1.38 cm berbanding struktur ADC dan ASC masing-masing dengan ketebalan 1.7 cm dan 1.48 cm. Corak radiasi berbilang alur bagi ADC, ASC dan SLC telah dibandingkan menggunakan pensimulasi elektromagnet FEKO. Corak sinaran berbilang alur yang baik untuk SLC telah dipastikan untuk sudut imbasan alur dari 0° hingga 42.6°. Bagi menentukan kedudukan suapan yang optimum untuk pencapaian berbilang alur, kaedah penyurihan sinar rantau fokus telah dijalankan secara mod-penerima oleh penyelesai Pelancaran Sinar-Optik Geometri (RL-GO) dengan menggunakan pensimulasi FEKO. Lokus baru bagi kedudukan suapan telah diperolehi untuk SLC dan dibandingkan dengan ADC dan ASC. Bagi aplikasi yang praktikal untuk pemasangan tiang stesen tapak, struktur silinder antena lens SLC telah direkabentuk pada nisbah *F/D* bersamaan 0.6 dan bahan polikarbonat dengan pemalar dielektrik, ε_r bersamaan 2.9 telah dipilih. Saiz yang praktikal bagi tinggi silinder ialah 20 cm dan diameter silinder ialah 29 cm dengan ketebalan 5.13 cm. Lokus kedudukan suapan baru telah diperolehi untuk struktur silinder SLC pada nisbah *F/D* bersamaan 0.6. Daripada agihan medan dekat, pemalar fasa dan taburan amplitud yang mencukupi pada satah bukaan telah dipastikan. Corak sinaran alur kipas telah dihasilkan bagi lens silinder. Pada satah tegak, corak sinaran berbilang alur telah dicapai. Lebar alur bagi alur kipas ialah 45° dan bagi alur tegak ialah 3.28° dengan gandaan antena maksimum 22.98 dBi. Corak sinaran berbilang alur yang baik telah diperolehi untuk lebar imbasan alur antara 0° hingga 47.1° pada satah tegak. Penurunan gandaan ialah 6.56 dBi. Kesimpulannya, antena lens dielektrik silinder SLC baru yang dicadangkan amat sesuai digunakan untuk aplikasi stesen tapak berbilang alur 5G.

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LIST OF ABBREVIATIONS

FDMA	-	Frequency-Division Multiple Access
UWB	-	Ultra Wide Band
IMT	-	International Mobile Telecommunications
OFDM	-	Orthogonal Frequency-Division Multiplexing
FCC	-	Federal Communications Commission
MIMO	-	Multiple-input Multiple-output
IoT	-	Internet of Things
GSM	-	Global System for Mobile Communications
MATLAB	-	Matrix Laboratory
BS	-	Base Station
MSA	-	Microstrip Antenna
MoM	-	Method of Moment
MBA	-	Multibeam Antenna
DLA	-	Dielectric Lens Antenna
ECC	-	Energy Conservation Condition
ASC	-	Abbe’s Sine Condition
SLC	-	Straight-Line Condition
ULA	-	Uniform Linear Array
MLFMM	-	Multilevel Fast Multipole Method
RL-GO	-	Ray Launching-Geometrical Optics
PO	-	Physical Optics
UTD	-	Uniform Theory of Diffraction
FEM	-	Finite Element Method
FDTD	-	Finite Difference Time Domain
TO	-	Transformation Optics
GO	-	Geometrical Optics
CEM	-	Computational Electromagnetic
HPBW	-	Half Power Beam Width
MCMC	-	Malaysia Communication Multimedia Commission
ADC	-	Aperture Distribution Condition

ASC	-	Abbe's Sine Condition
SLC	-	Straight-Line Condition
FRRT	-	Focal Region Ray Tracing
PW	-	Plane Wave

LIST OF SYMBOLS

λ	-	Wavelength
f_o	-	Operating frequency
δ	-	Loss Tangent
D	-	Diameter
F	-	Focal Length
n	-	Refractive Index
T	-	Lens Thickness
P	-	Power
r	-	Radius
θ_m	-	Maximum Angle
L_t	-	Total Electrical Length
X_m	-	Maximum radius of S_2
d_o	-	Initial condition at lens edge
S_1	-	Surface 1
S_2	-	Surface 2
$E_d(x)$	-	Aperture Distribution
$E_p(\theta)$	-	Feed Radiation Pattern
ε_r	-	Dielectric Constant
F_s	-	Circle radius
θ_S	-	Beam Direction
θ_F	-	Feed Angle
R_{FF}	-	Far-field Distance
G_s	-	Simulated Gain
G_T	-	Theoretical Gain
η	-	Antenna Efficiency
L	-	Distance to Lens (SLC)
θ_{BT}	-	Theoretical Beam Width
θ_{BS}	-	Simulated Beam Width
θ_{in}	-	Incident Angle
ε_r	-	Dielectric Constant

μ	-	Permeability
R	-	Radius of Cylinder
a_1	-	Aperture Width
b_1	-	Aperture Height
L_H	-	Horn Length
a	-	Input Waveguide Width
b	-	Input Waveguide Height
ρ	-	Cylindrical Aperture Position
θ_{pw}	-	Plane Wave Angle Direction
m	-	Radiation Coefficient

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Over the past three decades, we have all witnessed the rapid development of mobile communication from devices to system as well as infrastructure. As mobile communications standards evolve generation to generation, and now fifth generation (5G), the number of air interfaces that base station must support has been increasing rapidly. The evolution of this technology is shown in Figure 1.1. First generation (1G) cellular systems that were analog telecommunications standards introduced in the 1980s. The voice channel typically used frequency modulation, and they used FDMA techniques. 2G refers to second generation and based on GSM. The greatest triumph in mobile communications boost the development of the third generation (3G) by introducing WiFi, WiMax, UWB and 4G based on all-IP network infrastructure using advanced wireless technologies such as MIMO-OFDM, these specifications display features characteristic for IMT-Advanced (Arun et. al, 2019; Hang Wong & Luk, 2009). To cover 3G and 4G systems, base station antenna typically to support both the low-band, ranging from 698 to 960 MHz and the high band, ranging from 1710 to 2690 MHz. (Guo and Bevan, 2019).

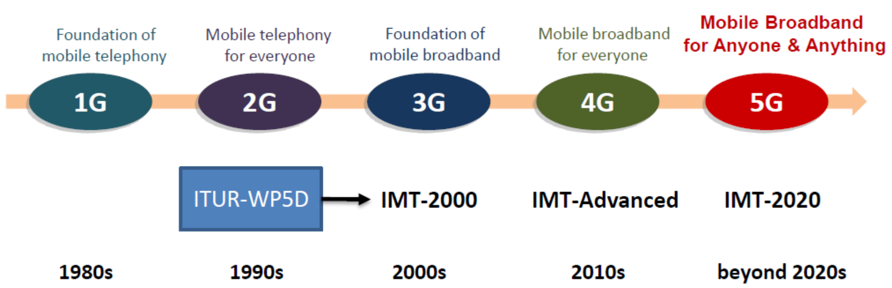

Figure 1.1 Evolution of Mobile System (MCMC, 2019)

Nowadays, 5G mobile system is emerging and driving to support increasing demand for broadband services of many kinds delivered over mobile networks and to support services for the Internet of Things (IoT) including for machine-to-machine applications (Alnoman & Anpalagan, 2017; Rappaport et al. 2013; Ericsson, 2015). In 5G mobile system, many new technologies are required such as millimetre wave (mm-wave), massive multiple-in multiple-out (MIMO) technology (Hong et al., 2017; Cheng-Xiang, 2014), small cell size of multi beam base station antenna, advanced multiple access and higher order modulation and coding. Most new base stations must support both new and legacy mobile communications standards. This has led to over more stringent requirements on base station antennas, such as isolation between antenna elements and subarrays, cross polarization levels and beam width consistency and for 5G particularly focus on a small cell base station antenna operating at millimetre-wave frequencies (Gupta & Jha, 2015). Operation at mm-wave frequencies is needed for 5G requires to provide high-speed communications. The frequency band is a promising spectrum for 5G communication system requirements including higher capacity for supporting simultaneous users. The current microwave frequency spectrum (4G) suffers from congestion and cannot support the demand for higher data rate mobile smartphone users due to the limitation of spectrum at these frequencies (Rappaport et al., 2013).

Existing base station antenna is designed to cover 1 km area effectively by one radiating beam and it is shared among users (3G and 4G). In the 5G base station, one radiating beam is assigned to one user as shown in Figure 1.2. Multiple radiating beams are requesting for 5G application in a base station antenna with approximately radius 200m of coverage area in one cell radio zone.

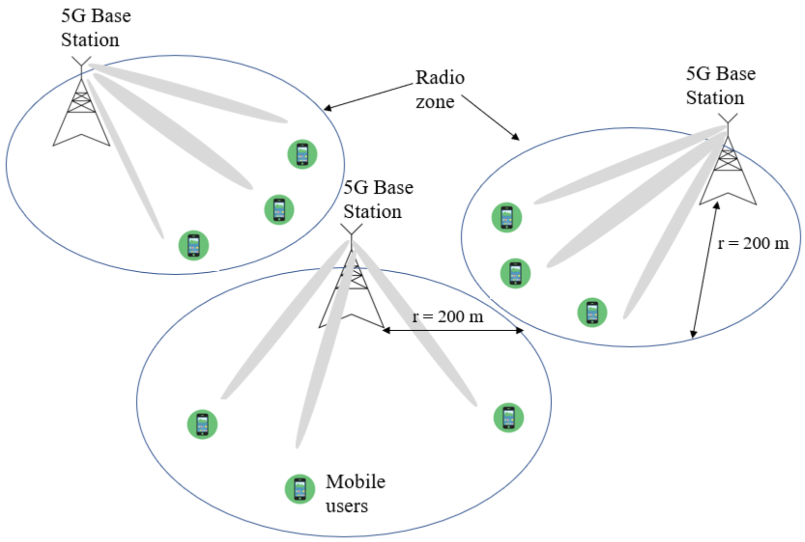

Figure 1.2 New 5G base station in each radio zone

Typical mobile base station antenna structure of an existing mobile communication system (4G) is shown in Figure 1.3. This antenna configuration is called a linear array antenna. The main difference to the existing base station antenna is multi beam achievement. The array antenna structure is quite different from the existing structure because it produces wide area coverage beam. The array feeding circuit is designed to achieve a beam shaped suitable for the coverage area. The present feed circuit should be replaced by a multibeam circuit that is required for new multibeam 5G applications.

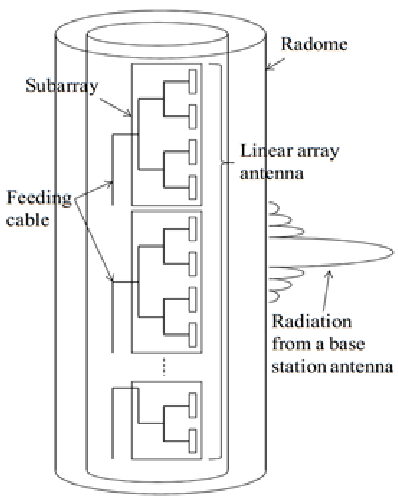

Figure 1.3 Typical mobile base station array antenna in 4G system (Tseng et. al, 2008)

In developing new base station antennas, antenna size becomes around 20λ (Mitsichita & Yamada, 2014; Volakis, 2019; Xi Wang et. al, 2021) at 28GHz which suitable for small cell size of 5G base station antenna requirement. Any antenna types such as array, reflector and dielectric lens antenna probably a promising candidate for base station application. Features of candidate antennas are summarized in Table 1.1.

Table 1.1 Comparison antenna candidates of multi beam application (Lo & Lee, 1993; Thornton & Huang, 2013)

Antenna Type	Advantages	Drawbacks
Patch Array	✓ Formed on one printed circuit board (PCB) ✓ Most simple structure ✓ Ease of fabrication	✓ Large feed circuit loss at 28 GHz ✓ Multi beam number has limitation of 2^N ✓ Multi beam shapes not excellent
Reflector	✓ Good multi beam radiation characteristic ✓ No feeder loss ✓ Any multi beam number can be achieved	✓ Large antenna volume
Lens	✓ Excellent multi beam radiation characteristic ✓ Simple structure than a reflector ✓ No feeder loss ✓ Any multi beam number can be achieved	✓ Large antenna volume. It can be reduced by the cylindrical structure.

In general, if a reflector can provide the required performance for a given application, it should be used. However, since lenses are more versatile, especially in wide scan angle performance, they are used in many applications that do not require greater flexibility of a phase array (Donald, 1993). The recent development of light-weight wideband artificial dielectric provides the possibility of conveniently implementing multibeam antennas using optical techniques (Matytsine et al., 2012). By taking into accounts on no feeder loss, very low network losses typically less than 0.5 dB, excellent multi beam shapes, a simple structure and good scanning performance, the dielectric lens antenna is selected. Besides, it can be easily contoured to any reasonable shape to produce a specified beam pattern (Lo & Lee, 1993). For practical base station installation, a cylindrical lens structure is likely to form slim and the lens thickness should be as thin as possible.

The proposed concept of a hollow cylinder structure is composed of a dielectric lens as shown in Figure 1.4. For multi beam operation, many feed horns are arranged around the vertical axis. The dielectric lens surfaces can be shaped to perform best radiation patterns of desired multi beams.

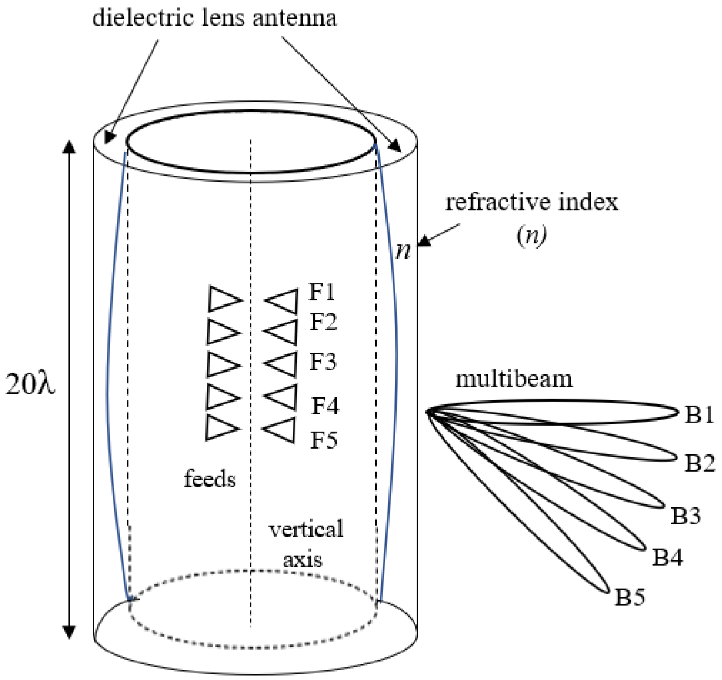

Figure 1.4 Proposed concept of cylindrical lens antenna

1.2 Problem Statement

As for the multibeam lens antenna, the Luneburg lens composed of spherical layered dielectric material is popular for achieving the same radiation patterns in wide-angle region (Angela & Yang, 2011; Li et. al, 2019; Volakis, 2019). However, forming the continuous varying material permittivity as a function of the lens radius is quite difficult to accomplish in practice. As a result, the lens antennas composed of single dielectric material and having many different types of lens surface curvatures have been studied for various communication applications as well as its feeding network (Li et al. 2019; Liang et al. 2014; Massimiliano et al. 2019). However, in those works, the capabilities of performing wide angular scanning for multi beam applications were not discussed in detail.

For multi beam operations, the shaped lens, designed based on Abbe's sine condition, has achieved good wide-angle multi beam characteristics (Jenkins & White, 1973). In achieving excellent radiation patterns, lens surfaces were shaped by ray tracing based on the Geometrical Optics (GO) method (Zhou et al., 2013; Yunxiang, 2008; Mozharovskiy, 2015), were typically, lens shaping can be done by the aperture distribution method or Abbe's sine method (Lo & Lee, 1993; Thornton & Huang, 2013). Dielectric lens shaping methods were developed for low side lobe radiation pattern and multi beam radiation pattern (Juha et al., 2016; Boriskin et al. 2011; Peebles 1988). The lens shaping method is composed of three differential equations such as two refraction law equations on the two lens surfaces and one lens forming equation. For low side lobe and multi beam shaping, different lens forming equations are employed. However, in order to satisfy the installation requirement, previous lens shaping methods were not suitable. The conventional method of lens shaping is used for single beam radiation pattern synthesis and the application were limited to airborne radar and collision avoidance system. In (Yamada & Tajima, 2006), multi beam radiation characteristics are studied sufficiently with Abbe's sine case. However, for a practical base station application in 5G system, the requirement of multi beam scanning, ease of installation in a thin pole and lightweight structure should be satisfied. The research questions for achieving suitable base station antenna are listed as follows:

(i) What lens structure is suitable for the use of 5G base station installation?

(ii) How to design the lens structure?

(iii) Is the designed lens having sufficient multi beam characteristics?

(iv) How to ensure the correctness of multi beam characteristics?

In addition to that, previous lens shaped scanning angles were limited to less than 30° of angular range. Therefore, a suitable structure is requested in a 5G antenna system to meet the requirements of multi beam scanning, ease-of-installation on a thin pole and lightweight structure. It is an advantage to discover an antenna that combines high gain and low interference levels with a very large coverage area.

1.3 Research Objective

The main objective of this research is to design a multi beam hollow cylindrical dielectric lens antenna for 5G mobile base station. The proposed antenna will have the capability to generate for wide angular coverage area of a 5G base station. The antenna system shall be able to produce multiple beams, each with narrow beam width and high gain. The specific objectives of the research are listed as follows:

i. To propose and model new lens design equation for lens shaping method and to identify antenna parameters for achieving thin lens and small curvature;
ii. To design suitable lens structure and to discover new locus feed position for multibeam radiation pattern performances;
iii. To design a cylindric dielectric lens antenna and validate locus feed position to ensure multi beam radiation performance for practical 5G base station installation.

1.4 Scope of Research

Lens antenna design for base station application is facing vast challenges due to the ever-increasing demand for efficient performance and compact structure. One of the scopes of this research is to design a light weight, small curvature and thickness lens for 5G base station with large angular coverage area. The focus in this study is to develop a new lens antenna shaping method for multi beam radiation pattern and base station installation. Based on the objectives of this study, the initial study of lens design shaping program is developed by MATLAB software and it is based on energy conservation equation and Abbe's sine equation for low side lobe and multi beam designing, respectively. Installation's condition and effort of trying new lens forming equation such as straight line and so forth are considered. Therefore, the development of a ray tracing model that can demonstrate all rays from feed to aperture plane involved during illumination of lens antenna is the main feature of this research.

In the thesis, ray tracing program is developed based on initial structures to demonstrate ray behaviours with respect to various parameters such as lens size, lens focal length and the direction of incident beam. Analysis of radiation characteristics and modifications of the antenna structures should be conducted. In order to find out suitable structure, many design examples of lens shaping are studied. Radiation pattern calculation program based on ray tracing of on-focus is calculated on a MATLAB software. The multi beam characteristics are ensured by the electromagnetic simulations, FEKO software for the performance analysis. Comparison of radiation characteristics between new proposed design with the conventional energy conservation and Abbe's sine is analysed to clarify the usefulness of a new proposed lens antenna from 0° to 50° scanning angle. Practical base station antenna is designed according to the performance obtained by the asymmetrical structure with a suitable dielectric material and ratio of focal length to lens diameter *(F/D)*. The small curvature and thickness of a cylindrical dielectric lens antenna is analysed for multibeam performance. Near field distribution is ensured to discover correct feed position in obtaining best performance of multibeam characteristics. Feed position analysis is performed with respect to this configuration, by varying the phase centre of the feed without changing the dielectric material and antenna structure. Furthermore, focal region ray tracing (FRRT) analysis is also conducted for the antenna configuration to determine a precise locus feed position for wide scanning performance.

1.5 Thesis Organization

The thesis is organized in six chapters as follows:

Chapter I presents the beginning and the scope of work of the thesis. The problem statements and research motivations are explained in this chapter. The research objectives of the thesis are also outlined to propose a new finding of the research.

Chapter II gives a brief introduction to evolution of various antenna used for base station application from 1G to 4G. Various 5G antenna development are also discussed by other researchers and its application. A comprehensive review of the antenna shaping concept and various methods for wide angle scanning beam is described according to power conservation and Abbe's sine condition for various types of lens antenna. Several feeding methods of lens antenna are described for the suitability for lens feed radiator.

Chapter III explains the methodology, including the essential steps of designing the lens shape and analysing the performance of the dielectric lens antenna. A comprehensive flow chart is presented to describe all processes involved modelling the ray tracing from feed to aperture plane, to ensure the shape is correctly design based on respective lens design equations, determining the feed arrangement, designing the antenna system comprises of designing feed and lens and analysing multi beam performance from overall perspective. In this chapter, the justification on parameters selection is discussed in conjunction with the particular design requirements and regulations of 5G base station applications. Performance analysis for analytical, simulations and measurement procedure are described in this chapter.

Chapter IV presents the important equations and algorithms involved in the ray tracing program for designing a newly proposed thin lens antenna. This chapter shows three design structures of axis-symmetrical lens antenna based on developed MATLAB program of lens shaping and the analysis of radiation characteristics and ensuring multi beam performance by electromagnetic simulation, FEKO. Three lens design equations are presented for the analysis of multibeam characteristics performance.

Chapter V elaborates the results and analysis obtained from ray tracing program to propose newly design equation for designing a cylindrical lens structure. The fundamental correlation of feed points with radiation beams is illustrated in this chapter. The positions of feed antenna are calculated on the basis of equation of feed locus derived in Chapter IV. The results obtained in FEKO electromagnetic solver are presented and discussed in this chapter. Several parameters are optimized to meet the mechanical and physical requirements of the base station antenna. Significant results are verified and compare with the modelling technique performed in the radiation ray tracing. A detailed description of the focal region ray tracing process, which comprises of transmitting mode and receiving mode ray tracing is shown. The principle and theoretical description of lens shaping and focal region plane wave excitation in FEKO is also addressed through detailed illustrations. Preliminary results of ray tracing for centre beam by RL-GO solver are used to verify the accuracy of locus feed positions for multibeam performances.

Chapter VI presents the concluding remarks of the works, analyses and results that have been performed and obtained in this thesis. The key contributions in this research are highlighted. Suggestions for future work are also presented in this chapter.

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