FIXED MULTI BEAM OFFSET SPHERICAL REFLECTOR ANTENNA AT 28 GHZ

AYUNI AFIQAH BINTI ARJUNAIDI

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

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JULY 2022

DEDICATION

This thesis is dedicated to my mother, who has always been
my biggest supporter to pursue Master study, and to always remind me to have faith
and put the Almighty Allah S.W.T in everything.

To my beloved husband,
I love you eternally for everything that you have done for me.

And to my friend, Siti Haifa.
Only God knows how much I indebted to you to begin this journey.

ACKNOWLEDGEMENT

Gratitude expression would not be enough to portray my gratefulness to everyone who willingly lends me their hands and shares their knowledge throughout the journey in completing this research.

All praises and thanks to the Almighty Allah for blessing me with good hearing, sight, and health to ease the challenging path that I encountered. A sincere gratitude goes towards my main supervisor, Professor Dr. Yoshihide Yamada for trusting me from the beginning until the end of this research. My sincere appreciation and thankfulness are extended for his guidance, suggestions, assistance, and motivation to gain the best accomplishment of my work. I am also thankful to my co-supervisor, Dr. Kamilia Kamardin for her continuous support and encouragement to finish this thesis.

Next, I would like to acknowledge and thank Malaysia-Japan International Institute of Technology (MJIIT) for awarding me with scholarship to support my Master study. As the recognition too, Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (MOHE) for funding my research and conference fee.

Last but not least, my deepest gratitude goes to my fellow postgraduate students in Communication Systems and Network (CSN) iKohza for being by my side in every joy and struggle whilst hustling with their own research. The enlightenment and lesson learnt from their sharing are much appreciated. Thanks for having my back, *kakak(s)*.

ABSTRACT

Multi beam antenna system is one of the requirements at the base station for fifth-generation (5G) mobile communication. These days, the implementation of array antenna to produce multiple beams by using digital beamforming technology (DBF) is often seen at the base station pole in urban district. However, this technology comes with expensive cost and high complexity. Therefore, multi beam reflector antenna with fixed multi beam operation is chosen as the alternative cheaper configuration for 5G base station at 28 GHz. Multi beam reflector antenna is prominent in producing high gain for long distance communication remarkably in satellite communications as the satellite mount antennas to achieve the specific area illumination on the Earth. Among the types of reflector antennas like parabola, shaped and spherical reflector, the spherical reflector antenna is superior in producing the same radiation patterns for multi beam performances. Despite that, the reliable design method to analyze the spherical reflector by identifying the effective aperture area and the best feed positions for high antenna efficiency and good multi beam radiation characteristics was not made clear. In this research, analysis of the spherical reflector by ray tracing method was developed for various incoming rays' direction. The algorithm of the focal region ray tracing equations of spherical reflector for horizontal and slant incident rays were developed and illustrated by MATLAB program to obtain the reflected rays at the focal region. From the focal region ray tracing results at slant incident rays, the effective reflector aperture area that contributed to the small focusing region were clarified. Subsequently, an offset spherical reflector antenna configuration was formed due the effective reflector area, and the feed positions for targeted multi beam in angular region 0 degree to 30 degree were calculated. The multi beam performance of offset spherical reflector was then verified in the electromagnetic simulations of FEKO simulator. Good multi beam radiation patterns and high antenna efficiency which exceeded 70% were ensured at the angular region of 10 degree to 30 degree. In conclusion, it is shown that the offset spherical reflector can achieve high gain and good multi beam characteristic in a wide radiation angle region. The proposed design of this offset spherical reflector configuration is an excellent multi beam reflector antenna and it also provides the industry with a guide in manufacturing accurate reflectors for high gain performance.

ABSTRAK

Sistem antena berbilang alur adalah salah satu keperluan di stesen pangkalan bagi komunikasi mudah alih generasi kelima (5G). Pada masa kini, penggunaan susunan antena untuk menghasilkan berbilang pancaran alur dengan menggunakan teknologi pembentuk pancaran digital (DBF) sering dilihat di tiang stesen pangkalan di dalam kawasan bandar. Walau bagaimanapun, teknologi ini mempunyai kos yang mahal dan begitu rumit. Oleh itu, antena pemantul berbilang alur dengan operasi berbilang alur yang tetap dipilih sebagai konfigurasi alternatif yang lebih murah untuk stesen pangkalan 5G pada 28 GHz. Antena pemantul berbilang pancaran alur terkenal dalam menghasilkan gandaan yang tinggi untuk komunikasi jarak jauh terutamanya bagi komunikasi satelit sebagai antena satelit untuk memastikan kawasan tertentu di bumi mendapat liputan. Antara jenis-jenis antena pemantul seperti parabola, pemantul berbentuk dan sfera, antena pemantul sfera adalah lebih unggul dalam menghasilkan sinaran yang sama untuk pencapaian berbilang pancaran alur. Walaupun begitu, kaedah reka bentuk yang terbaik untuk menganalisis pemantul sfera dengan mengenal pasti kawasan bukaan yang berkesan dan kedudukan antena suapan terbaik untuk gandaan antena tinggi dan ciri sinaran berbilang alur yang baik masih belum jelas. Dalam penyelidikan ini, analisis pemantul sfera dengan kaedah pengesanan sinar telah dibangunkan untuk pelbagai arah sinar masuk. Algoritma bagi persamaan pengesanan sinar kawasan fokus pemantul sfera untuk sinaran dalam kejadian mendatar dan serong telah dibangunkan dan digambarkan dengan program MATLAB untuk mendapatkan sinar pantulan di kawasan fokus. Daripada hasil pengesanan sinar di kawasan fokus pada sinar kejadian condong, kawasan bukaan pemantul yang menyumbang kepada kawasan pemfokusan yang kecil telah dapat dikenal pasti. Dengan ini, konfigurasi antena pemantul sfera secara *offset* telah terbentuk hasil daripada kawasan pemantul yang berkesan, dan kedudukan antena suapan untuk alur berbilang sasaran di rantau sudut 0 darjah hingga 30 darjah dikira. Prestasi pelbagai alur bagi pemantul sfera secara *offset* kemudiannya disahkan dalam simulasi elektromagnet simulator FEKO. Corak sinaran berbilang alur yang baik dan kecekapan antena yang tinggi yang melebihi 70% telah diperolehi pada kawasan sudut 10 darjah hingga 30 darjah. Kesimpulannya, pemantul sfera secara *offset* boleh mencapai gandaan yang tinggi dan ciri berbilang alur yang baik dalam kawasan sudut sinaran yang luas. Reka bentuk yang dicadangkan bagi pemantul sfera secara *offset* ini merupakan antena pemantul berbilang alur yang sangat baik dan ini memberi panduan kepada pihak industri dalam pembuatan antena pemantul yang tepat untuk prestasi gandaan yang tinggi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1G	-	First generation
2D	-	Two-dimensional
2G	-	Second generation
3D	-	Three-dimensional
3G	-	Third generation
4G	-	Fourth generation
5G	-	Fifth generation
5G-NR	-	5G-New radio
6G	-	Sixth generation
ADC	-	Aperture distribution lens
AMTS	-	Advanced Mobile Telephone Service
ASC	-	Abbe's sine lens
BDF	-	Beam deviation factor
BTS	-	Base transceiver station
CDMA	-	Code Division Multiple Access
CEM	-	Computational electromagnetics
DBF	-	Digital beamforming
EM	-	Electromagnetic
eMBB	-	Enhanced mobile broadband
EDGE	-	GSM Evolution
FEM	-	Finite element method
GO	-	Geometrical Optics
GSM	-	Global Systems for Mobile Communication
HOBF	-	Higher order basis functions
HPBW	-	Half-power beamwidth
HSPA	-	High-Speed Packet Access
IP	-	Internet Protocol
ITU	-	International telecommunication Union
ITU-R	-	International telecommunication Union Radiocommunication
JCSAT	-	Japan Communications Satellite Company

LE-PO	-	Large element physical optics
LTE	-	Long Term Evolution
MBA	-	Multi beam antennas
MIMO	-	Multiple input multiple output
MLFMM	-	Multilevel fast multipole method
mMTC	-	Massive machine-type communications
mmWave	-	Millimeter wave
MoM	-	Method of Moment
NTT	-	Nippon Telegraph and Telephone
PO	-	Physical optics
RL-GO	-	Ray launching geometrical optics
Rx	-	Receive
SCC	-	Space Communications Corporations
SLC	-	Small lens curvature
TDMA	-	Time Division Multiple Access
TE	-	Transverse electric
UMTS	-	Universal Mobile Telecommunication System
URLLC	-	Ultra-reliable low-latency communications
UTD	-	Uniform theory of diffraction
VoIP	-	Voice over Internet Protocol
WCDMA	-	Wideband Code Division Multiple Access

LIST OF SYMBOLS

θ	-	Aperture angle from center
θ_{BW}	-	Half-power beamwidth
θ_F	-	Offset aperture angle from horn
θ_H	-	Horn tilted angle
θ_o	-	Horn semi flare angle
θ_R	-	Offset aperture angle from center
α_0	-	Initial incident angle on main reflector
β_0	-	Initial sub-reflector angle from its center
β_i	-	Subsequent sub-reflector angle from its center
$\Delta\varphi$	-	Beam scanning angle
η	-	Antenna efficiency
a	-	Horn aperture radius
a_w	-	Circular waveguide radius
C_m	-	Main reflector center
c_n	-	y-intercept of normal vector
C_s	-	Sub-reflector center
c_p	-	y-intercept of line perpendicular to normal vector
D	-	Aperture diameter
F_i	-	Focal point of main reflector on z-axis
F_{si}	-	Focal point of sub-reflector on z-axis
G	-	Antenna gain
h	-	Horn height
H_c	-	Caustic length from z-axis
I_i	-	Horizontal incident ray
L	-	Horn axial length
ℓ_F	-	Focal region spread of sub-reflector
ℓ_i	-	Focal length from main reflector center
ℓ_m	-	Focal region spread of main reflector
m_n	-	Gradient of normal vector

m_p	-	Gradient of line perpendicular to normal vector
m_s	-	Gradient of reflected ray from sub-reflector
n	-	Normal vector
N_{si}	-	Midpoint on normal vector of sub-reflector
P_i	-	Intersection points between reflected rays
P_{si}	-	Reflected point of incident point from sub-reflector
R	-	Offset sphere radius
r_m	-	Sphere radius of main reflector
R_{m0}	-	Aperture radial length of main reflector
R_{mi}	-	Subsequent aperture radial of main reflector
r_s	-	Sphere radius of sub-reflector
R_{s0}	-	Aperture radial length of sub-reflector
R_{si}	-	Subsequent aperture radial of sub-reflector
S_i	-	Slant incident ray
S_{ni}	-	Midpoint on normal vector of main reflector
S_{ri}	-	Reflected point from main reflector
w	-	Circular waveguide length

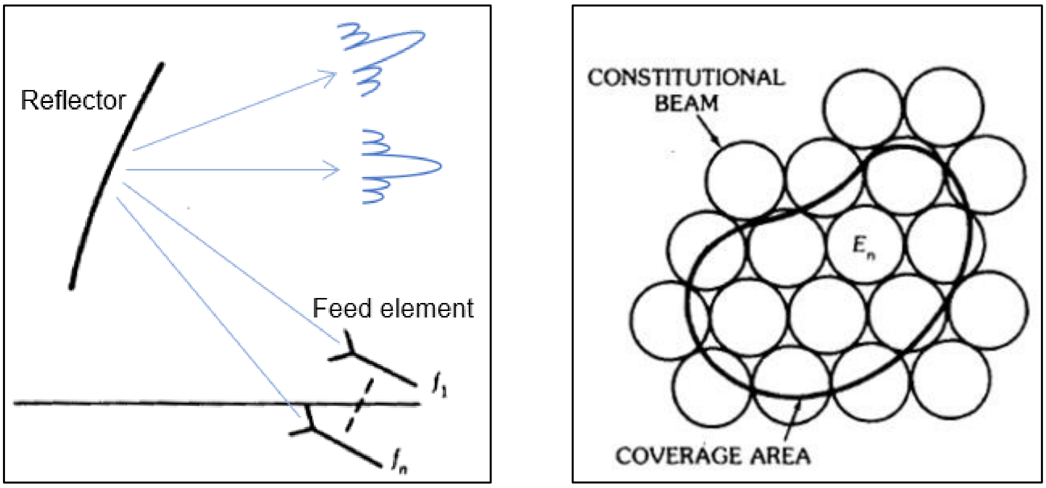
LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

In recent years, reflector antenna has been extensively designed to meet desired configuration for multi beam characteristic. Most of the demands come from the application in satellite communication systems and remote sensing. Multi beam reflector antenna has been among the preferable solution to produce numerous spot-beam coverages in geostationary communications satellites. Reflector antenna is known for its simple configuration to design multiple beam performance. Multi beam reflector antenna in satellite antenna systems consists of an array of feed elements in the focusing region as shown in Figure 1.1(a) [1]. Meanwhile, Figure 1.1(b) shows the constituent beam of shaped contour beam generated from the illumination of each feed element on the reflector by superposition principle. One important subject to be examined is the feed systems for its multi beam application in the context of the number and position of feed elements used to produce multiple or contour beams.



(a) (b)

Figure 1.1 (a) Multi beam reflector antenna system. (b) Shaping of beams [1, 2].

Among the popular shapes of reflector antenna, the parabolic reflector configuration is usually used because of the high gain beam achievement at the on-focus feed condition. As for the other beams radiated from the off-focus feeds, the antenna gains, and beam shapes are distorted. Therefore, in order to achieve the same beam shape of multi beams over the reflector surface, the spherical reflector structure is proposed. Although good multi beam shapes can be achieved, the antenna gains are degraded by the phase aberration of the spherical reflector.

Moving on, mobile telecommunications network has come a long way since the early days of the first generation (1G) until the fourth generation which sparked wireless evolution to everyone. By experiencing the technology of cellular communication, people felt the need for more which then led to the emergence of fifth generation (5G) these days and the successor, sixth generation (6G) that is still under development. The new 5G is not just an evolution from fourth generation (4G) system, but it uses a wide range of low, mid, and high spectrum bands for various standard of different use cases [3]. The main requirements for 5G and beyond mobile communication systems are the utilization of millimeter wave (mmWave), the deployment of small cells with a radius of 200 meters, and the use of a multi beam antenna for multiple input multiple output (MIMO) schemes [4, 5]. Though massive MIMO improves 5G performance significantly, it also increases the complexity of the antenna. Thus, multi beam antenna became a promising resolution for base station antenna in future networks mobile communication system as illustrated in Figure 1.2. There are few types of antennas that are commonly utilized at base station including array antennas, lens antennas, and reflector antennas.

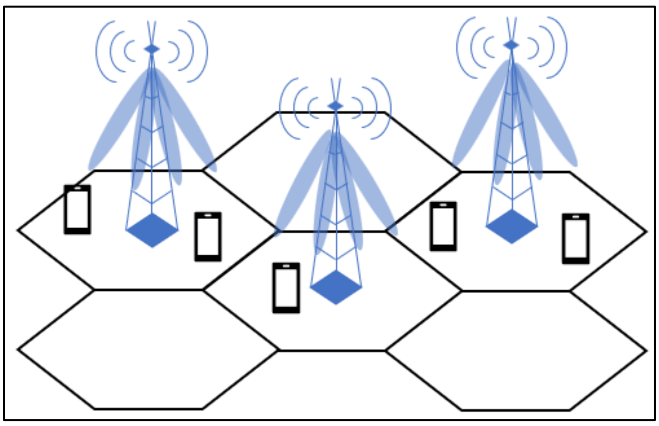


Figure 1.2 Multi beam base station antenna for cellular system.

By employing array antenna at base station, the beam steering is achieved by digital beamforming (DBF) technology [6, 7]. Array antenna is formed by more than 100 patch radiators and each patch has both up and down converters with the beam steering function is systematized by computer programming. This configuration literally becomes expensive due to its complexity and is mostly used in urban areas. Hence, the alternative way for cheaper configuration is to mechanically steer by using a fixed multi beam antenna at base station. The same function of steering beam can be acquired by switching the multi beam. As for lens antenna, it is less convenient due to its bulky and heavy structure. Thus, a reflector antenna which is lightweight is more suitable and the multi beam operation can be done by having multiple feeds or rotating a single feed over the reflector aperture area [6].

The alternative structure for good multi beam performance is by utilizing spherical structure. Spherical reflector has a symmetrical structure around the centerline axis. As its radius is rotating towards any direction, the focal point is also moving in which these beams in all directions have the same pattern. This implies that all the reflected rays from spherical reflector are not crossed at the same point. In short, spherical reflector does not have a single precise focus point but it is able to give similar radiation patterns for the feeds that moved off axis [7, 8]. Figure 1.3 illustrates the multi beam spherical reflector configuration for 5G and future networks mobile base station. The spherical reflector is implemented, and multiple feed elements are placed in the focusing region to achieve multi beams.

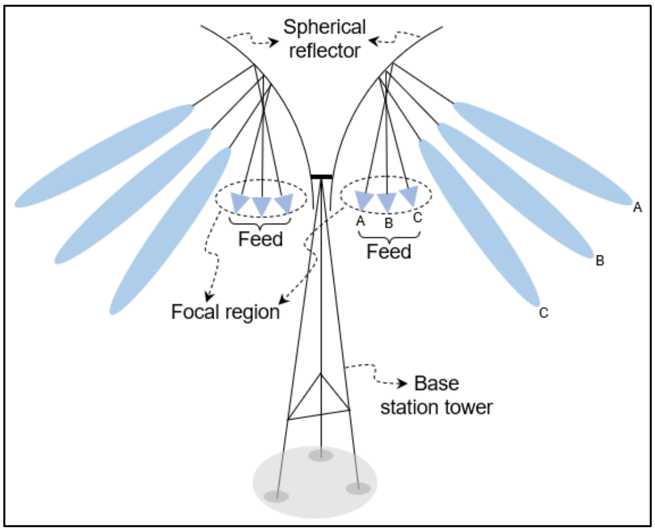
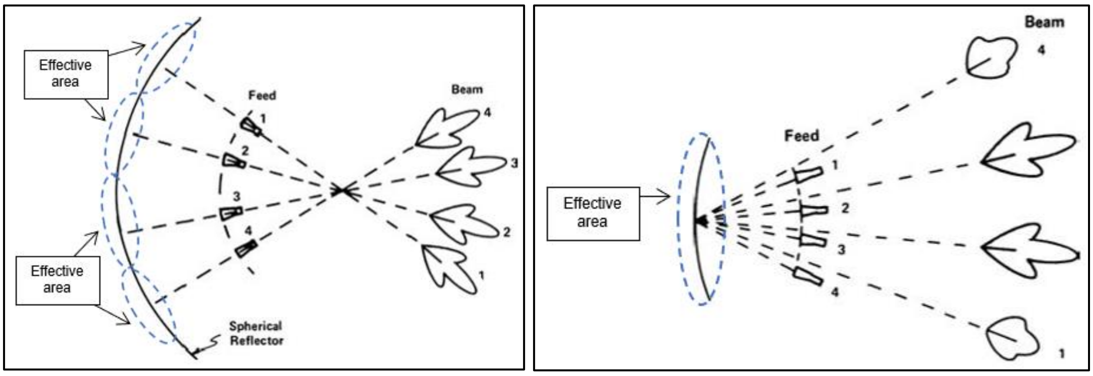


Figure 1.3 Multi beam spherical reflector antenna.

The conventional spherical reflector configuration and another efficient reflector sharing method for multi beam feed positions are shown in Figure 1.4(a) and 1.4(b) respectively. In the conventional case of Figure 1.4(a), multiple feeds for the spherical reflector are placed on the radial line of the sphere. The beam formed from each respective feed is coincident to the axis of the feed, which is the radial line. It is shown that the effective aperture area for each feed is separated. All the beams have similar gain and radiation patterns resulted from the symmetry of the surface. On the other hand, a more effective use of spherical reflector is by sharing the reflector area with all the feeds as shown in Figure 1.4(b). The location of feeds is positioned in a way the feed aperture is pointing towards the center of the reflector. The concept of beam steering is accomplished from this position. Some beams achieved good shapes and the other beam shapes are distorted [7].



(a) (b)

Figure 1.4 Conventional and alternative way of multi beam feed positions for (a) extended reflector aperture and (b) minimum reflector aperture [7].

While considering the reflector research at satellite communication and the installation convenience at base station pole, the reflector antenna becomes the promising candidate for 5G base station antenna. In regard to achieve good multi beam characteristics at base station, the spherical reflector shape is well suited. However, problem arose in order to achieve good multi beam and high gain performances simultaneously with the undefined accurate feed positions. Thus, this research is intended to study on spherical reflector antenna ability to produce an excellent multi beam performance with high antenna efficiency.

1.2 Problem Statement

In the receiving mode ray tracing analysis, the incoming rays is incapable to concentrate at one point when it is reflected on a spherical reflector [8, 9]. It generates a focusing region instead of a focus point as the result of the distorted focus. The focusing area appears to be diverged to some distances due to spherical aberration. In order to determine the location of the feed for spherical reflector, this geometrical optics method also known as "focal region ray tracing" is effective to analyze the focusing condition of spherical reflector antenna.

Previous works had carried out only the horizontal incident ray tracing for center beam condition on spherical reflector [8, 10]. In comparison with recent works by Rahman et al. in [11] and [12], the ray tracing was carried in few incoming angle directions to study the caustic region for multi beam feed positions of parabolic reflector. This comes in handy where the slant incident rays can be considered which corresponds to the incoming rays in another direction other than parallel with the reflector axis to analyze the multi beam condition of spherical reflector. If the caustic is found out at the focal region, the caustic area becomes the potential location for the feed elements.

From the previous conventional configuration that locate the feed elements on the radial line of reflector as shown in Figure 1.4(b) [7], it has led to an oversize shape of spherical reflector. Moreover, as the spherical reflector is used partially, the antenna efficiency becomes very low. Thus, the alternative method by having a shared efficient aperture of spherical reflector becomes the expected good configuration for multi beam condition. However, this approach leads to coma aberration and cause beam degradation. Therefore, the determination of effective reflector area as the optimum configuration of spherical reflector and the multi beam feed positions become significant in this research. The efficient structure of offset spherical reflector can be found out through the analysis of focal region ray tracing for multi beam condition. And the feed positions ought to be determined from the selection of multi foci for the desired direction of radiation beam.

Subsequently, the calculation of multi beam radiation patterns by computational electromagnetic (CEM) simulator must be conducted to verify the proposed offset spherical reflector antenna configuration. CEM simulation will ensure the effectiveness of focal region ray tracing method to achieve high gain and good multi beam radiation patterns of spherical reflector. As the summary of above discussion, the problem statements are as follows:

(1) The current work of focal region ray tracing method has not been developed for multi beam condition of spherical reflector antenna.
(2) The effective reflector area of spherical reflector configuration for high gain and best multi beam feed positions have not been specified.
(3) The evaluation of multi beam radiation characteristics for offset spherical reflector has not been carried out.

1.3 Objectives

The main objective of this research is to design a multi beam reflector antenna based on spherical structure at operating frequency of 28 GHz for base station in 5G mobile communication system. The followings are the specific objectives proposed for this study:

(1) To analyze the focal region ray performance of spherical reflector.
(2) To determine the effective reflector area such as offset reflector region based on focal region ray tracing.
(3) To design the offset spherical reflector and validate the multi beam radiation characteristics by using an electromagnetic simulator.

1.4 Scope of the Research

The speedy escalation of mobile communication system into 5G era which demands higher data traffic and data rates has acted as the catalyst in developing new base station antenna to achieve those requirements. Spherical reflector antenna design must also be examined appropriately to ensure the efficient conduct of multi beam application.

This research presents the design methodology of multi beam reflector antenna by using spherical configuration to produce multiple beams and operate at 28 GHz. The significant scope of this research is to find out the most optimal position to locate the feed elements in the focusing region of spherical reflector. The focal region ray tracing is developed to identify the off-axis focusing region. The incoming rays are incident at horizontal state and also is slanted at certain angles from 0° to 30°. This is equivalent to beam scanning angle in angular region from 0 degree to 30 degree to produce acceptable caustic region. Thus, the number of targeted multi beams can be varied at any step angle but the step angle is selected at 10° in this research. The reflected rays of slant incident rays then exhibit the focal region occurrence, thus feed positions for multiple beam directions are explored from this condition. Moreover, the effective reflector aperture as the optimum configuration of spherical reflector antenna can be discovered from focal region ray tracing analysis.

As for the multi beam application, the complete structure of offset spherical reflector antenna with the feed elements are simulated and optimized to obtain the desired radiation characteristics using FEKO, a computational electromagnetics software. Prior to that, a horn antenna as the feed element of the system is designed with the matched radiation pattern to the reflector and gave about -10 dB edge illumination on the spherical reflector. The radiation patterns and the antenna gain of multi beam spherical reflector antenna are then observed from the obtained feed positions for certain beam scanning angle. Near field measurement on the amplitude and phase distributions of the reflector aperture are also computed in FEKO.

1.5 Significance of the Research

The development of 5G and 6G has essentially intensified the quality of wireless communications. Antenna plays a significant role and crucial element for mobile wireless communications systems through cellular tower. This research will develop the new reflector antenna design method to achieve good multi beam and high antenna gain simultaneously. Hence, the utilization of spherical reflector antenna at base station will empower the antenna performance for multi beam application by capitalizing its symmetrical geometrical configuration perfectly. Moreover, the developed focal region ray tracing results can provide the important technical information for antenna designers. The development of focal region ray tracing on spherical reflector will improve the reflector design method, present the mechanism of selecting discrete feed position to produce radiation beams in particular directions, and generally contribute to analytical understanding of antenna performance. From the industrial viewpoint, 5G base station antenna technology and satellite multi beam antenna technology can be improved.

1.6 Structure of Thesis

This thesis consists of six chapters. Chapter 1 depicts the whole frame of the research where the research background, problem statement, objectives, scope, and significance of the research are elaborated. In Chapter 2, the literature review emphasizes on the multi beam antenna application and multi beam base station antennas in brief. Regardless, the fundamental of the discussion focuses on the principle of reflector antenna and the analysis on spherical reflector antenna. Chapter 3 explains the research methodology in designing the multi beam spherical reflector antenna. On top of that, MATLAB program and electromagnetic software FEKO are used as the simulation tools to obtain the results for further explanation. As for the results by both simulation tools, it was presented in Chapter 4 and 5 respectively including its theoretical calculation. Lastly, Chapter 6 concludes the thesis as it summarizes the overall studies of spherical reflector antenna. This chapter also explains the suggestion for continuation of future works.

REFERENCES

1. Lo, Y.T. and S.W. Lee, *Antenna Handbook III*. 1993, New York: Van Nostrand Reinhold.
2. Hwang, Y., *Satellite antennas.* Proceedings of the IEEE, 1992. 80(1): p. 183-193.
3. Thompson, J., et al., *5G wireless communication systems: Prospects and challenges [Guest Editorial].* IEEE Communications Magazine, 2014. 52: p. 62-64.
4. Alnoman, A. and A. Anpalagan, *Towards the fulfillment of 5G network requirements: technologies and challenges.* Telecommunication Systems, 2017. 65(1): p. 101-116.
5. Alsharif, M.H. and R. Nordin, *Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells.* Telecommunication Systems, 2017. 64(4): p. 617-637.
6. Stutzman, W.L. and G.A. Thiele, *Antenna Theory and Design*. 3rd ed. 2012: Wiley. 848.
7. Volakis, J., *Antenna Engineering Handbook*. Vol. 23. 2007.
8. Tingye, L., *A study of spherical reflectors as wide-angle scanning antennas.* IRE Transactions on Antennas and Propagation, 1959. 7(3): p. 223-226.
9. Balanis, C.A., *Antenna Theory Analysis and Design*. 3rd ed. 2005: Wiley. 1074.
10. Spencer, R. and G. Hyde, *Studies of the focal region of a spherical reflector: Geometric optics.* IEEE Transactions on Antennas and Propagation, 1968. 16(3): p. 317-324.
11. Rahman, N.H.A., et al. *Evaluation of caustics for parabolic reflector antennas through focal region ray tracings*. in *2013, 7th International Conference on Signal Processing and Communication Systems (ICSPCS)*. 2013.
12. Abd Rahman, N.H., et al., *Development of Ray Tracing Algorithms for Scanning Plane and Transverse Plane Analysis for Satellite Multibeam Application.* International Journal of Antennas and Propagation, 2014. 2014: p. 812461.
13. Schneider, M., C. Hartwanger, and H. Wolf, *Antennas for multiple spot beam satellites.* CEAS Space Journal, 2011. 2(1): p. 59-66.
14. *MEASAT Fleet*. MEASAT-3a [cited 2022; Available from: http://www.measat.com/measat-fleet/.
15. Rahman, N.A., et al. *Design and Verification of a Shaped-Beam Reflector Antenna for Malaysia Beam Coverage*. in *2013 IEEE International Conference on Space Science and Communication (IconSpace)*. 2013.
16. Rahman, N.H.A., et al., *Generating Contoured Beams for Malaysia Region by Using a Caustic Locus Graph.* IEEE Antennas and Propagation Magazine, 2014. 56(6): p. 328-336.
17. Rahman, N.H.A., et al. *Improvement of contoured beam characteristics of a parabolic reflector antenna by asymmetrically distributed array feed*. in *2015*

IEEE 4th Asia-Pacific Conference on Antennas and Propagation (APCAP). 2015.
18. Ostovarzadeh, M.H. and F. Farzaneh. *A proposed multibeam Ka-band satellite for providing high-speed internet service for Iranian universities and educational institutions*. in *2007 IEEE International Conference on Telecommunications and Malaysia International Conference on Communications*. 2007.
19. Amini, M.H., I. Aryanian, and S. Mirhadi. *Multi-feed Reflector Antenna Design using RADS*. in *2018 9th International Symposium on Telecommunications (IST)*. 2018.
20. Toso, G., C. Mangenot, and P. Angeletti, *Recent advances on space multibeam antennas based on a single aperture*. 2013. 454-458.
21. Rahman, N.H.A., et al. *Design and Analysis of a Satellite-Mount Array-Fed Parabolic Antenna by Electromagnetic Computations*. in *2015 21st Asia-Pacific Conference on Communications (APCC)*. 2015.
22. Yoshihiko Mizugutch, S.N., Fumio Watanabe, and Matsuichi Yamada, *A Multi-Focal Reflector Antenna for Multi-Beam Application*, in *International Symposium on Antennas and Propagation*. 1985: Japan.
23. Nomoto, S., et al. *Offset multi-focal reflector antenna*. in *1986 Antennas and Propagation Society International Symposium*. 1986.
24. Propagation, I.T.C.o.A.a. *History of Antennas*. Available from: https://www.ieice.org/cs/ap/misc/ant_history/ant_hist_tab/.
25. Aaron D. Bresler, E.S., M. Otto Erdmann, *Spherical Double Reflector Antenna*. 1972, International Telephone and Telegraph Corporation, Nutley, N.J., United States.
26. Plastikov, A.N., *A High-Gain Multibeam Bifocal Reflector Antenna With 40° Field of View for Satellite Ground Station Applications.* IEEE Transactions on Antennas and Propagation, 2016. 64(7): p. 3251-3254.
27. Meraj, M. and S. Kumar. *Evolution of Mobile Wireless Technology from 0G to 5G*. 2015.
28. Park, Y. and F. Adachi, *Enhanced Radio Access Technologies for Next Generation Mobile Communication*. 2007. 1-280.
29. Mumtaz, S., J. Rodriguez, and L. Dai, *mmWave Massive MIMO: A Paradigm for 5G*. 2016. 1-351.
30. Popovski, P., et al., *5G Wireless Network Slicing for eMBB, URLLC, and mMTC: A Communication-Theoretic View.* IEEE Access, 2018. 6: p. 55765-55779.
31. Niu, Y., et al., *A Survey of Millimeter Wave (mmWave) Communications for 5G: Opportunities and Challenges.* Wireless Networks, 2015. 21.
32. Uwaechia, A.N. and N.M. Mahyuddin, *A Comprehensive Survey on Millimeter Wave Communications for Fifth-Generation Wireless Networks: Feasibility and Challenges.* IEEE Access, 2020. 8: p. 62367-62414.
33. Ali, M.Y., T. Hossain, and M.M. Mowla. *A Trade-off between Energy and Spectral Efficiency in Massive MIMO 5G System*. in *2019 3rd International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE)*. 2019.
34. Valenzuela-Valdés, J.F., et al. *On the Ultra-Dense Small Cell Deployment for 5G Networks*. in *2018 IEEE 5G World Forum (5GWF)*. 2018.

35. Hong, W., et al., *Multibeam Antenna Technologies for 5G Wireless Communications.* IEEE Transactions on Antennas and Propagation, 2017. 65(12): p. 6231-6249.
36. Yamada, Y., et al. *Base Station Antennas for the 5G Mobile System*. in *2018 IEEE International RF and Microwave Conference (RFM)*. 2018.
37. *Allocation of Spectrum Bands for Mobile Broadband Service in Malaysia*. 2019, Malaysian Communications and Multimedia Commission (MCMC).
38. *Industry Performance Report 2019 - Empowering a Digital Nation*. 2019, Malaysian Communications and Multimedia Commission (MCMC).
39. Alexander, K., *Cellular System*, in *Introduction to Mobile Network Engineering: GSM, 3G-WCDMA, LTE and the Road to 5G*. 2018, Wiley. p. 5-17.
40. Amadori, P.V. and C. Masouros, *Low RF-Complexity Millimeter-Wave Beamspace-MIMO Systems by Beam Selection.* IEEE Transactions on Communications, 2015. 63(6): p. 2212-2223.
41. Foegelle, M.D. *What's in a Name? An Analysis of the True Meaning of MIMO and Beamforming*. in *2020 14th European Conference on Antennas and Propagation (EuCAP)*. 2020.
42. *Spectrum Plan*. 2017, Malaysian Communications and Multimedia Commission (MCMC).
43. Sklar, B., *Digital communications : fundamentals and applications*. 2001, Upper Saddle River, N.J.: Prentice-Hall PTR.
44. Rappaport, T.S., et al., *Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!* IEEE Access, 2013. 1: p. 335-349.
45. Qingling, Z. and J. Li, *Rain Attenuation in Millimeter Wave Ranges.* ISAPE 2006 - 2006 7th International Symposium on Antennas, Propagation and EM Theory, Proceedings, 2006. 2006.
46. Elijah, O., et al., *A Comprehensive Survey of Pilot Contamination in Massive MIMO—5G System.* IEEE Communications Surveys & Tutorials, 2016. 18(2): p. 905-923.
47. Idrus, I.I., et al. *Multibeam Characteristics of an Array Antenna for 5G Mobile Base Station*. in *2018 IEEE International RF and Microwave Conference (RFM)*. 2018.
48. Md Jizat, N., et al., *Insertion Loss and Phase Compensation Using a Circular Slot Via-Hole in a Compact 5G Millimeter Wave (mmWave) Butler Matrix at 28 GHz.* Sensors, 2022. 22(5).
49. Jizat, N.M., Y.o. Yamada, and Z. Yusoff. *Radiation Pattern of Array Antenna with the Dual-Layer Butler Matrix*. in *2020 IEEE International RF and Microwave Conference (RFM)*. 2020.
50. Lu, R., et al., *A 16-Element Fully Integrated 28-GHz Digital RX Beamforming Receiver.* IEEE Journal of Solid-State Circuits, 2021. 56(5): p. 1374-1386.
51. Ansarudin, F., et al., *Multi Beam Dielectric Lens Antenna for 5G Base Station.* Sensors, 2020. 20(20).
52. Hamid, S., et al., *Multibeam Characteristics of a Negative Refractive Index Shaped Lens.* Sensors (Basel, Switzerland), 2020. 20.
53. Chou, H.T. and Z.D. Yan, *Parallel-Plate Luneburg Lens Antenna for Broadband Multibeam Radiation at Millimeter-Wave Frequencies With Design Optimization.* IEEE Transactions on Antennas and Propagation, 2018. 66(11): p. 5794-5804.

54. Wang, X., Y. Cheng, and Y. Dong, *A Wideband PCB-Stacked Air-Filled Luneburg Lens Antenna for 5G Millimeter-Wave Applications.* IEEE Antennas and Wireless Propagation Letters, 2021. 20(3): p. 327-331.
55. Kuo, L., H. Chou, and S. Chou. *Shaped reflector antennas for outdoor BTS of 4G/5G mobile communications*. in *2017 IEEE Wireless Power Transfer Conference (WPTC)*. 2017.
56. Smolders, A.B., et al., *Building 5G Millimeter-Wave Wireless Infrastructure: Wide-Scan Focal-Plane Arrays With Broadband Optical Beamforming.* IEEE Antennas and Propagation Magazine, 2019. 61(2): p. 53-62.
57. Quzwain, K., et al., *New Reflector Shaping Methods for Dual-Reflector Antenna.* Radioengineering, 2022. 31: p. 39-53.
58. Blass, J. *Multidirectional antenna - A new approach to stacked beams*. 1960.
59. Butler, J., *Beam-forming matrix simplifies design of electronically scanned antennas.* Electronic Design, 1961. 9: p. 170-173.
60. Rotman, W. and R. Turner, *Wide-angle microwave lens for line source applications.* IEEE Transactions on Antennas and Propagation, 1963. 11(6): p. 623-632.
61. Lian, J., et al., *Reduced-Sidelobe Multibeam Array Antenna Based on SIW Rotman Lens.* IEEE Antennas and Wireless Propagation Letters, 2020. 19(1): p. 188-192.
62. Bhowmik, W., S. Srivastava, and L. Prasad, *Design of Multiple Beam Forming Antenna System Using Substrate Integrated Folded Waveguide (SIFW) Technology*. Progress In Electromagnetics Research B, 2014. 60: p. 15-34.
63. Barb, G., et al. *Digital Beamforming Techniques for Future Communications Systems*. in *2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*. 2020.
64. Lo, Y.T.L.S.W., *Antenna Handbook II*. 1993, New York: Van Nostrand Reinhold.
65. Lee, J. and R. Carlise, *A coma-corrected multibeam shaped lens antenna, part II: Experiments.* IEEE Transactions on Antennas and Propagation, 1983. 31(1): p. 216-220.
66. Maruyama, T., K. Yamamori, and Y. Kuwahara, *Design of Multibeam Dielectric Lens Antennas by Multiobjective Optimization.* IEEE Transactions on Antennas and Propagation, 2009. 57(1): p. 57-63.
67. Peebles, A.L., *A dielectric bifocal lens for multibeam antenna applications.* IEEE Transactions on Antennas and Propagation, 1988. 36(5): p. 599-606.
68. Abdellatif, A.S., M. Basha, and S. Safavi-Naeini, *Low-Cost and High-Efficiency Multibeam Antenna for Millimeter-Wave Applications.* IEEE Antennas and Wireless Propagation Letters, 2012. 11: p. 141-143.
69. Wu, X., G.V. Eleftheriades, and T.E.v. Deventer-Perkins, *Design and characterization of single- and multiple-beam mm-wave circularly polarized substrate lens antennas for wireless communications.* IEEE Transactions on Microwave Theory and Techniques, 2001. 49(3): p. 431-441.
70. Liu, K., et al., *A 3-D-Printed Multibeam Spherical Lens Antenna With Ultrawide-Angle Coverage.* IEEE Antennas and Wireless Propagation Letters, 2021. 20(3): p. 411-415.
71. Numan, A.B., J. Frigon, and J. Laurin, *Printed W-Band Multibeam Antenna With Luneburg Lens-Based Beamforming Network.* IEEE Transactions on Antennas and Propagation, 2018. 66(10): p. 5614-5619.

72. Mirmozafari, M., et al., *A Multibeam Tapered Cylindrical Luneburg Lens.* IEEE Transactions on Antennas and Propagation, 2021. 69(8): p. 5060-5065.
73. Xue, L. and V.F. Fusco, *24 GHz automotive radar planar Luneburg lens.* Microwaves, Antennas & Propagation, IET, 2007. 1: p. 624-628.
74. Lee, J.J. and G.W. Valentine. *Multibeam array using Rotman lens and RF heterodyne*. in *IEEE Antennas and Propagation Society International Symposium. 1996 Digest*. 1996.
75. Srikanth, S. *Comparison of spillover loss of offset Gregorian and Cassegrain antennas*. in *Antennas and Propagation Society Symposium 1991 Digest*. 1991.
76. Granet, C., *Designing classical offset Cassegrain or Gregorian dual-reflector antennas from combinations of prescribed geometric parameters.* IEEE Antennas and Propagation Magazine, 2002. 44(3): p. 114-123.
77. Quzwain, K., et al. *Design of Shaped Offset Dual-Reflector Antenna for 5G Mobile Base Station*. in *2018 IEEE International RF and Microwave Conference (RFM)*. 2018.
78. Chen, Y., et al. *Millimeter wave multi-beam reflector antenna*. in *2018 International Workshop on Antenna Technology (iWAT)*. 2018.
79. Llombart, N., et al., *Leaky wave enhanced feed arrays for the improvement of the edge of coverage gain in multibeam reflector antennas.* IEEE Transactions on Antennas and Propagation, 2008. 56(5): p. 1280-1291.
80. Kanso, A., et al. *Multifeed EBG dual band antenna to feed a reflector antenna*. in *2011 41st European Microwave Conference*. 2011.
81. Jian, D., et al. *A Sparse Antenna Array with offset Parabolic Cylinder Reflector at Millimeter Wave Band*. in *2008 International Conference on Microwave and Millimeter Wave Technology*. 2008.
82. Dai, Z., et al. *Design of wide-angle scanning parabolic torus reflector antenna realized by rotation of sub-reflector*. in *2013 5th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*. 2013.
83. Bi, Y., Y. Li, and J. Wang. *3D-Printed Multi-Beam Planar Dual-reflector Antenna for 5G Millimeter-Wave Applications*. in *2019 IEEE Asia-Pacific Microwave Conference (APMC)*. 2019.
84. Abdullah, N., Y. Yamada, and K. Kamardin. *Comparison of Multibeam Radiation Performance of Parabolic and Spherical Reflector Antenna*. in *2021 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*. 2021.
85. Quzwain, K., et al., *New Reflector Shaping Methods for Dual-Reflector Antenna*. 2021.
86. Atef Z. Elsherbeni, P.N., C. J. Reddy, *Antenna Analysis and Design Using FEKO Electromagmetic Simulation Software*. 2014: SciTech Publishing, Edison, NJ. 245.
87. Ishimaru, A., I. Sreenivasiah, and V. Wong, *Double spherical cassegrain reflector antennas.* IEEE Transactions on Antennas and Propagation, 1973. 21(6): p. 774-780.
88. Rahman, N.H.A., et al. *Design of a satellite antenna for Malaysia beams by ray tracing method*. in *2012 International Symposium on Antennas and Propagation (ISAP)*. 2012.

89. Fauzi, N.F., et al., *Feed System Design of a Parabolic Reflector Antenna for Malaysia Shaped Beam Coverage.* Journal of Telecommunication, Electronic and Computer Engineering (JTEC), 2018. 10(2): p. 55-59.
90. Yamada, Y. and S. Sasaki. *Estimations of radiation characteristics of an off-focus feed shaped dielectric lens antenna by a ray tracing method*. in *IEEE Antennas and Propagation Society International Symposium (IEEE Cat. No.02CH37313)*. 2002.
91. Sharma, S.K., S. Rao, and L. Shafai, *Handbook of Reflector Antennas and Feed Systems. Volume I: Theory and Design of Reflectors*. 2013, London: Artech House. 323.
92. Quzwain, K.M.C., *A Novel Reflector Shaping Method for Multi Beam Dual Reflector Antenna Design*. 2021, Universiti Teknologi Malaysia. p. 147.
93. Pedrotti, L.S., *Fundamentals of Photonics*. 2008: SPIE. 100.
94. Ahsan, M.R., et al., *Ray Tracing Technique for Shaping Dual Reflector Antenna System.* Turkish Journal of Electrical Engineering and Computer Sciences, 2016. 24: p. 1223-1234.
95. Ansarudin, F., T.A. Rahman, and Y. Yamada. *MATLAB Program for Dielectric Lens Antenna Shaping*. in *2018 2nd International Conference on Telematics and Future Generation Networks (TAFGEN)*. 2018.
96. Hyperworks, A., *Altair FEKO 2019.1 User Guide*. 2019. 1489.
97. Quzwain, K., et al. *Caustic Analysis of Reflected Rays from a Spherical Reflector Antenna*. in *2020 IEEE International RF and Microwave Conference (RFM)*. 2020.
98. Muehldorf, E., *The phase center of horn antennas.* IEEE Transactions on Antennas and Propagation, 1970. 18(6): p. 753-760.
99. Woods, B. *Calculate the far field phase centre*. 2021.