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ANTENNA DESIGN ANALYSIS FOR MILLIMETER WAVE PROPAGATION: A REVIEW

[1, *] Oladimeji, T. T., [2] Idowu, O. D., and [3]Adewale, A. S.
[1, 2, & 3] Department of Electrical and Electronics Engineering, The Federal Polytechnic Ado – Ekiti, Nigeria
*Corresponding author email: tolulopett@yahoo.com

ABSTRACT

Millimeter wave communication technologies have attracted a lot of attention due to the growing demand for extremely fast data connectivity. The effects of radiation through developed millimeter-wave antennas incorporated in handheld devices are composed of various surface currents on the chassis, guided waves confined in dielectric layers, superstrates, and the operator's hand, which are employed for mobile antenna design in fifth-generation (5G) transmission. This study also includes a full and complete comparison of several antennas to the offered designs. The functionality of different antenna components of 5G communication systems was evaluated and reviewed. Antenna design is critical in wireless system transmission, especially in the 5G network, which travels via millimeter wave. Accurate communication of signals is critical in increasing the productiveness as well as the dependability of channel models. Using customized antenna technologies that are adapted to the individual characteristics of the issue under research is critical to obtaining reliable results. To summarize, accurate wireless signal connectivity through proper antenna design and characterization of 5G channels are critical, as they will have a significant impact on the future evolution and improvement of wireless communication technologies in the years ahead.

KEYWORDS: Antenna; bandwidth; frequency; gain; millimeter wave

INTRODUCTION

The revolution of the fifth generation of 5G wireless networks will see significant modifications in the standards for both services as well as technologies, such as a peak data throughput of 20 Gbps. To address these developments, rates in the order of 1 GHz are required. However, such high rates are only accessible on carrier frequencies over 6 GHz (Tang et al., 2017; Rappaport et al., 2013) and it is widely acknowledged that millimeter wave (mm wave) technological advancements will have a substantial impact on the 5G revolution. The channel characteristics of the mm wave spectrum must be investigated and modeled prior to system design. Network measurements in a real telecommunication environment are a reliable way to evaluate the radio transmission channel. However, the parameters retrieved from the data collected are strongly dependent on the measurement configuration, such as the delay resolution, center frequency, and bandwidth. The principal propagation technique differs, particularly for millimeter waves, when compared with bands less than 6GHz (Belbase et al 2015; Oladimeji et al., 2022; Oladimeji et al., 2023; Oladimeji et al., 2024). This is due to the potential of diffraction to decrease with frequency (Molisch, 2011). As a result, measurements must be made to precisely simulate millimeter wave networks.

Previously, certain academic institutes and industries did research experiments on extremely high-frequency channels. Aalto University in Finland employed a sweeper as the transmission device for gathering channel data at 81-86 GHz (Kyro et al., 2010), with situations including street canyon as well as roof to street, with a maximum distance of 685 m.

T.S. Rappaport's NYU team monitored mm waves at several bands, spanning 28, 38, and 60, along with 73 GHz, by spinning the horn antenna. Based on the obtained data, they examined mm wave channel features such as path loss (PL), and angle and delay facts, and presented some empirically based propagation network models (Rappaport et al., 2015). To acquire channel information, however, an omnidirectional or sectored antenna with a wide half-power beam width (HPBW) is required. In an indoor situation, the Beijing University of Posts and Communications (BUPT) utilized an omnidirectional biconical antenna to carry out experiments at numerous bands of frequencies, including 3.5, 6, 14, 23, 26, and 28 GHz (Huang et al., 2016).

Recently, several studies on 5G mm Wave wireless antennas have been undertaken. Various types of mm Wave array antennas are being designed to provide full-spherical coverage (Xu et al., 2018; Helander et al., 2016; Ojaroudiparchin et al., 2016; Huo et al., 2017; Hong et al., 2017., Yu et al., 2018., Zhang et al., 2017). From the standpoint of mobile antennas, user impact on mm Wave channel modeling as well as radio link budgets were examined (Zhang et al., 2017; Hejselbæk et al., 2017; Syrytsin et al., 2018; Ying et al., 2016; Zhao et al., 2017; Syrytsin et al., 2017). Xu et al. (2017), Colombi et al. (2018), Xu et al. (2016), Colombi et al. (2015), Zhao et al. (2016), He et al. (2018), and Thors et al. (2016) investigated human interaction with mm Wave antennas located near the bodies of humans.

Review of relevant works

Several novel antenna configurations for 5G mm Wave handheld devices were presented (Zihir et al., 2016; Syrytsin et al., 2016; Park et al., 2016; Wang et al., 2017; Hsu et al., 2017; Wang et al., 2018). However, previous research on 5G mobile antennae has been limited to antenna topologies with frames along with their beam-scanning capabilities. There has been an absence of research on mm Wave antenna efficiency in wireless interface building environments (MTHE). Mobile terminal dimensions in the mm wave range can be multiple wavelengths, however in contemporary 2G-4G cellular frequencies (700 MHz-6 GHz), wireless terminal sizes are typically just half of to a couple wavelengths. Furthermore, for mm Wave frequencies, the electrical dimension of dielectric layers increases significantly, as do the additional parts in terminals that are mobile. These wavelength alterations have a substantial impact on the design procedures and emission effectiveness assessment of mm Wave antennas incorporated into 5G mobile devices (Xu et al., 2018).

Broadband antenna uses in millimeter wave propagation

In the past few years, the application of characteristic mode analysis (CMA) to affect antenna building has been a hot topic in antenna research. To meet the antenna's parameters, designers can add parasitic patches (Jang et al., 2016), etch slots (Cao et al., 2015), or change the patch form. Nevertheless, the majority of these solutions rely on firsthand knowledge rather than institutional direction. The feature mode theory may adequately describe the antenna's actual radiation properties while also providing theoretical direction for the antenna's layout. The emergence of 5G mm wave connectivity has significantly reduced the scarcity of spectrum resources. The academic community has demonstrated considerable success in constructing 5G mm wave antennas utilizing characteristic mode analysis (CMA). Lamminen et al. (2008) lowered the actual permittivity by introducing an air cavity, resulting in wideband as well as high gain. In a separate investigation, scientists designed a broadband antenna using patches of differing widths to trigger characteristic patterns at different frequencies (Xue et al., 2021). In the work of Li et al. (2021), the authors used a double-layer metasurface architecture to accomplish small size as well as bandwidth.

To meet the demands of a 5G millimeter wave connection, Li et al. (2023) propose a comprehensive dual-polarized antenna deployed in the 5G mm waveband. The antenna is built in a double-layer patch configuration, with the upper patch featuring a 2 by 2 metasurface to give the broadband effect, which is evaluated using CMA theory. The proposed antenna gets its supply via a slot coupling setup. The coupling slot as well as the air cavity framework boosts the antenna's bandwidth. Simulation results show that the antenna's -10 dB bandwidth for each of its terminals is 26.25-40.83 GHz and 25.91-41.05 GHz, respectively. Throughout the operational capacity, port isolation surpasses 21 dB, as well as antenna gain ranges from 4.9 dBi to 6.7 dBi. The antenna measures 0:56 〖 λ〗 _0 x 0:56 〖 λ〗 _0 x 0:13 〖 λ〗 _0, making it low profile (Li et al., 2023).

CATR and near-field measurement at millimeter wave frequency

At CSIRO, there appears to be a rising interest in building antennas operating at 200 GHz for photography purposes (Hay et al., 2005; Brothers et al., 2007; Li et al., 2007; Li et al., 2009; Granet et al., 2006; Timms et al., 2010; Hislop et al., 2007). A number of beam-scanning pillbox antennas were designed and manufactured to be used in systems for imaging. The pattern of radiation intensity of the large aperture pillbox antennas was measured using an outdoor range (ODR), and positive results were obtained, Hay et al (2005). Current imaging techniques employ signal correlations that are reliant on both the strength along with phase of the antenna emission characteristics. To properly describe the antennas, an assessment of the antenna phase and magnitude radiation patterns is required, as well as an analysis of image generation procedures along with antenna evaluation testing methods.

The ODR's limited range of motion as well as air absorption render it inappropriate for amplitude measurements. Determining the phase of an antenna's radiation that travels at millimeter wave bands is tricky. Lower bandwidths are often monitored using a basic heterodyne antenna measurement technique with a baseline signal and harmonic blending (Dyson, 1966). This method gets more difficult at mm Wave frequencies, due mostly to phase mistakes produced by cable flex along with ambient conditions. Previous research demonstrated amplitude-only measurements in a CATR up to 200 GHz using a heterodyne device (Parini & Prior (1988). A 200-GHz near-field heterodyne-based method was also used (Yang et al., 1999). The researchers estimate short-term (1 second) as well as long-term (15-20 minute) stability of phase values of 0.5 and 2, accordingly A near field scan at these ranges requires a high number of points for sampling, which takes longer and emphasizes the system's phase as well as stability. Two recently published articles address the problem of phase and amplitude adjustment in millimeter as well as submillimeter wave near field antenna systems for measurement (Fuerholz & Murk 2009; Rensburg & Hindman 2009). Several approaches are being proposed to improve phase detection at millimeter and submillimeter bands in both the CATR and close field regions (Li et al., 2007; Li et al., 2009; Granet et al., 2006; Timms et al., 2010; Hislop et al., 2007). The differential phase approach, which uses two or more receivers to determine phase, first came into use in the 1990s (Li et al., 2007; Li et al., 2009; Granet et al., 2006). This method has been utilized effectively to determine the phase of horn antennas up to 190 GHz; nevertheless, it is unlikely to be appropriate for big aperture, high gain antennas that require observations in a CATR. The variation in phase approach involves placing the AUT at the signal transmitter and using two independent receive antennas. In a CATR, the sender horn along with AUT is not comparable.

Understanding the direction of antenna radiation patterns by phaseless approaches remains a hot topic (Timms et al., 2010). It was first presented as an alternative for amplitude-only measuring techniques to reduce the expense and complexity of near-field detection methods that require magnitude and phase to detect the AUT's far-field radiation pattern. The advantages of the strategy, also known as phase retrieval, were rapidly apparent in the mm-wave spectrum (Hislop et al., 2007). The method works by first constructing two near field planar maps at various locations from the antenna under evaluation, and then employing procedures for reestablishing the phase. The gathering time is twice that of a conventional near-field evaluation, the data analysis is time-consuming, and errors can be significant, as indicated by the vast number of papers dedicated to reducing these errors.

In this study by Dyson (1966), the creation and use of a small antenna test range (CATR) to accurately assess both the phase and magnitude radiation characteristics of big aperture millimeter-wave antennae in a controlled setting was explained. The CATR's practical effectiveness with a heterodyne magnitude as well as a system of measurement is shown for the initial time at 200GHz. The CATR technology is unusual in that it employs shaped-beam horn feeds as well as a tiny paraboloidal reflector to give light to the antenna under test (AUT) via a plane wave-like field. The CATR technique was reported in a previous publication, which included amplitude readings of the quiet zone at 20 GHz as well as predicted amplitude and phase at 200 GHz, Zhao et al (2017). This work did not show the CATR's true capability at frequencies over 20 GHz, did not give any information about radiation pattern observations within the CATR for performance evaluation, and did not include the 200 GHz phase or magnitude monitoring equipment.

The development as well as verification of the horn feeds had earlier been described, and the estimated and observed outcomes agreed well (Granet et al., 2006). Examination of the quiet-zone field exposing the AUT at 20 and 200 GHz, presuming a perfect reflector surface, revealed sufficiently minimal diffraction effects, which were validated at lower frequencies by measuring the quiet-zone field (Dyson, 1966). A basic geometric optics calculation shows that a reflector contact precision is required for attaining an ideal quiet zone phase error of 200 GHz. Photogrammetry revealed that the reflector surface is approximately the same precise as the reported precision (0.016 mm) of the photogrammetry approach. Previous studies have published measurements of the phase as well as the magnitude of a hologram-based CATR's quiet zone at millimeter wave bands (Hirvonen et al., 1997; Saily et al., 2000; Lonnqvist et al., 2005). The main findings of the study in Dyson (1966) are outlined as follows:

i) The assessment of the CATR and ODR results for the intensity radiation patterns produced by a novel 186 GHz pillbox antenna was applied. This validates the CATR at that bandwidth while also incidentally confirming the accuracy of the CATR reflector as well as distance dispersion impacts (Smith et al., 2012).

ii) The development of a phase measurement framework for the CATR's operating range of 182-194 GHz was utilized. The setup is a heterodyne device that detects phase stability and cable flex-induced phase faults. This tracking permits the use of calibration processes to reduce the effects of phase drift and errors. The examination of the findings provided by Smith et al. (2012) demonstrates that validation is required for phase equilibrium, however, inaccuracies due to cable flex cannot be deemed significant. The outcomes show that the heterodyne technique is viable at these frequencies and might be used for other methods of measurement.

iii) The use of CATR to determine the amplitude and phase radiation distributions of the freshly constructed pillbox antenna at 186 GHz was applied. These are the first published phase as well as magnitude radiation pattern data from the CATR. This verifies the antenna design's basic performance parameters and demonstrates CATR applications, Smith et al (2012). Scintillations render the ODR inappropriate for determining the radiation-pattern phase.

Wideband planar antenna array for millimeter wave

The substrate-integrated waveguide (SIW) is a flat transmission line that has been the standard microwave technology for mm wave applications in previous generations. While its architecture is similar to a traditional dielectric-filled waveguide system, its side walls are made up of a number of metallized via holes that confine EM transmission inside a certain wave channel. The complete framework is contained in a thin metal-backed dielectric platform (Nitas et al., 2017; Hirokawa & Ando, 1998; Hiroshi et al., 1998; Deslandes & Wu, 2003; Xu & Wu, 2005; Deslandes & Wu, 2006; Chen et al., 2006).

The SIW delivers reasonable propagation inefficiencies in the millimeter-wave area, significantly lower than standard planar lines such as microstrips or coplanar waveguides, while maintaining its plane structure. Its most prominent feature, however, is its ability to serve as a basis for incorporating multiple parts on one substrate, including couplers, power dividers, mixers, amplifiers, and even antennas, making it suitable for combined or system-on-chip manufacture. It is not unexpected that it is one of the key instruments for building a broad spectrum of mm-wave circuits and antennas. (Chen et al., 2006; Yan et al., 2004; Chen et al., 2009; Cheng et al., 2011; Cheng & Fan , 2011). Although SIW-based circuits are established, they are afflicted by the need to create numerous via gaps and insert metallization through the substrate, which necessitates harder manufacturing techniques than fully planar circuits. It could therefore be quite interesting to investigate alternate planar designs that govern transmitted waves within a given guiding channel. Thus, the justification for the study in Nitas et al. (2017) is to investigate the possibility of developing planar structures that have the same effects as a number of metallized vias, i.e. to block in-plane transmission of waves at a point adjacent to the needed transmission orientation, alongside the goal of maintaining losses, particularly because of radiation, at a satisfactory level as well as, in all likelihood, equivalent to the ones provided by standard SIW. It demonstrates that a very appealing foundation for such an inquiry comes from the well-known topic of materials with synthetic electric and magnetic features, often known as metamaterials (Solymar & Shamonina, 2009). While there are numerous unit cell setups that compensate for an array of characteristics, such as metal wires, split-ring resonators (SRR), omega-cells, fishnet structures, and so on, we are looking for a form that can be included in the metal-backed base without significantly altering its planar structure, while still providing the necessary characteristics to prevent in-plane transmission. The complementary split-ring resonator (CSRR) (Baena et al., 2005; Bonache et al., 2006; Aznar et al., 2010). is an excellent contender for this goal, since it has been shown to provide the essential features required to build a completely planar substrate-integrated waveguide due to the closeness of the substrate's metal grounds. As a consequence, we first examine common comparable circuit models of the CSRR unit cell to offer initial values for its geometric variables, followed by an extensive examination of the recommended guiding things using a new linear periodic eigenmode formulation centered on the finite-element method (FEM).

The examination of the structure is particularly important because SIW constructions encourage a variety of complex transmission methods that govern the estimation of distribution graphs in terms of the two transmission and distortion variables, including all reduction processes including conductor, dielectric, and, most importantly, radiation emissions from the side walls. The recommended SIW topologies are extensively investigated and synthesized utilizing parametric research focused on the eigenmode solver, and their efficacy is evaluated and checked by modeling longer waveguide structures.

MATERIALS AND METHOD

The cross-sectional study follows a qualitative research approach to explore the mm wave propagation as well as antenna designs from different authors dated from 1996 to 2024 with 97 articles in both journal and conference proceedings covered. The antenna designs utilized in this study apply to different microwave frequency bands and particularly the ones used in the mm wave spectrum were comprehensively explored. Also, indoor and outdoor measurement methods were put to use in some of the articles considered making the study for interior and exterior applications in designing antennas for mm wave propagation, especially for the upcoming 6G application in mobile communication networks.

RESULTS AND DISCUSSION

Performance of various antenna elements in 5G communication systems

The directional characteristics of the recommended antenna in (Sehrai et al., 2009) are juxtaposed to those of three arrays with varied matrix sizes that use the antenna. The single-component antenna has a gain of 7.6 dBi. This improvement is enough for a mobile handset but inadequate for 5G mm wave terminals, which have to cope with signal deterioration due to path loss, multipath impacts, as well as environmental attenuation. The 8×8 array has a total gain equal to 13 dBi, however, the lateral lobes have a value lower than -6 dB in the phi=0 degree plane while they are less than -3 dB in the phi=90 degree plane. The 8×16 array, with a gain of 15.3 dBi, is ideal for base stations. Nonetheless, the side lobes have values less than -6 dB in the phi=0 degree plane and lower than -4 dB in the phi=90 degree field. The 8×32 array offers an impressive gain of 21.2 dBi, with the flanking lobes below -10 dB in the phi=0 degree field as well as a lower than -12 dB in the phi=90 degree plane, which makes it acceptable for daily use. According to Sehrai et al 2009), the angular width of a single antenna component is 82.5 degrees, whereas an 8×8 array is 18.4 degrees, an 8×16 array is 7.2 degrees, as well as an 8×32 array, is 4.1 degrees.

The study on the evaluation of slotted complementing antennas for mm wave operations proposed an antenna architecture framework with variable width gain along with directivities, however, directivity should not be less than 6dBi, (Sudhakar et al., 2009). The 3.5 mm width will satisfy the requirements. As directivity increases, it falls below 6 dBi. In the framework, bid channels are employed for establishing the connections. These connections are also taken into account in the simulation framework as a whole. Validated results differ from simulation findings whenever a fraction alteration happens in the context of creation, causing a significant shift in the outcomes. The outcomes of the simulation indicate 10 GHz of bandwidth; whereas the verification findings give 6.5 GHz of bandwidth, covering the entire spectrum without licenses of frequencies spanning 57 GHz to 64 GHz. The effectiveness was noticed across H-Plane and E-Plane. At 60 GHz, a gain of 6.54 dB was reported with 60% efficiency. In principle, the framework's conductor, radiation, and losses from dielectric are computed. Based on the contrast, it is clear that the suggested tree-shaped slotted SIW antenna configuration produces superior results. Indoor usage typically demands a directivity of 5dBi or more than that of a single antenna component (Sudhakar et al., 2009).

While focusing on directivity as well as spectrum, the suggested antenna outperforms prior designs. However, for measuring purposes, the structure's connector width was altered to 12 mm. The tree-shaped slotted antenna was employed as an array antenna (1/4), reducing area while enhancing gain by up to 20 dBi.

The S-parameters along with the gain of the suggested antenna in Li et al (2023) are estimated using the -10 dB impedance bandwidth of the two ports, which are 45.2% (25.91-41.05 GHz) and 43.5% (26.25-40.83 GHz), respectively. The tip of the antenna has strong port isolation (less than -21 dB) throughout the operational frequency spectrum; along with the antenna gain fluctuating between 4.9 dB to 6.7 dB. The antenna's emission sequence at 28 and 38 GHz is symmetrical and has excellent orientation. The feed line is stuffed at the antenna's base, resulting in a wider rear lobe (Li et al., 2023).

The effectiveness of the horn in the Simionato et al. (2022) study was investigated utilizing a full-wave electromagnetic assessment with the ANSYS High-Frequency Structure Simulator's FEM model. The overall measurement of the location's reflection factor was used as the primary evaluation indicator. Given the large number of optimization factors and the laborious FEM evaluation, genetic algorithm (GA) optimization was used. The GA was selected since HFSS includes a GA optimizer. In a word, GA is a popular iterative approach for simulating species development. In this case, GA optimization was used merely to determine a restricted range of parameters from which an acceptable conclusion might be obtained; hence the conventional HFSS configuration was used, Simionato et al (2022).

Discussion on comparison of various antennas with presented designs

Scholars have recommended many antennas for propagating electromagnetic radiation in this band (Chen et al., 2009; Ding & Leung, 2009; Yeom et al., 2014; Sabri et al., 2014; Liu et al., 2016; Lee et al., 2008; Li et al., 2017; Li & Chen, 2018; Awan et al., 2019; Marzouk et al., 2019; Mungur & Duraikannan, 2018; Jandi et al., 2017; Shereen, 2018; Rizvi et al., 2022) which is illustrated in Table 1. Typical design approaches include patch change, metamaterial integration, plus antenna geometry variation. In Chen et al (2009), and Ding and Leung (2009), a geometrically simple and DRA-slot antenna with sizes along with peak gains of 3.8dB to 5.02dB is presented. The design included spectrum ranges of 2.42 GHz as well as 5.69 GHz. The researchers additionally introduced the U-slot as well as stack patches in Lee et al (2008), and Li et al (2017). The peak increases ranged from 8 dB to 17.4 dB. There was additionally a record of a rectangle direction antenna having a feed line and a resistor-loaded patch antenna (Jandi et al., 2017; Shereen, 2018) with a higher frequency operation range than those described before in the investigation. However, Rizvi et al., (2022)) offered an elliptical as well as rectangular stub loaded to patch antenna with nearly excellent output specifications along with the ability to function in the most powerful frequency ranges. It has a gain of 3 dB to 7.01 dB as well as a spectrum ranging from 2.1GHz to 4.45GHz.

Table 1: Comparison of various antennas with presented designs

Author/Year	Frequency	Bandwidth (GHz)	Peak Gain (dB)	Design Method
Chen et al., (2009)	2.42/5.69	3.3/5.7	4.3/3.8	DRA- Slot
Ding & Leung (2009)	2.45/5.19	4.48/6.17	5.02/4.09	DRA-Slot
Yeom et al., (2014)	2.44/5.35	3.42/17.5	6.99/10.37	Sist-Path
Sabri et al., (2014)	10/12	7.3/7.76	8.5/8.5	SIW-Fed Slots
Liu et al., (2016)	2.6/3.5	26.9/7.1	7.1/7.4	Stack Patches
Lee et al., (2008)	5/6.3	7.6/15.9	8/8	U-Slot Patch
Li et al., (2017)	21/26	3.8/2.7	16/17.4	SIW Cavity
Li & Chen (2018)	26.45/38.77	31/11.8	16.3/16.7	Metasurface

Awan et al., (2019)	27.12/28.56	1.38	7.67	Y-shaped plane Patch
Marzouk et al., (2019)	27.58/38.643	1.06/1.43	9.49	Patch Antenna With large Substrate size
Mungur & Duraikannan (2018)	27.6/28.18	0.582	6.69	Variable feed line width planer Antenna
Jandi et al., (2017)	9.99/28.77	0.27/1.02	5.5/8	Rectangular path with simple feedline
Shereen (2018)	26.06/29	3.8	3.9	Resistor-loaded Patch Antenna
Rizvi et al., (2022)	25.4-38	4.45/2.1	7.01/3	Elliptical and Rectangular Stub loaded to patch

CONCLUSIONS AND RECOMMENDATIONS

This article provided many kinds of antenna designs for the millimeter transmission of waves. Antenna design is a key aspect in wireless communication propagation, particularly in the 5G network, which propagates via the millimeter wave. The polarizer, which was fully examined in this study, consists of multiple airs as well as dielectric slabs that can change the orientation of antenna dispersion from linear to circular alongside various radiation patterns. Additionally, the polarizer may also be utilized to increase antenna gain. The overview of these antennas discussed in this paper will assist scholars in improving their understanding of the architectural layout of an antenna with an improved gain, low cost, and efficiency for broad spectrum in broadcasting of wireless communication signals appropriate for use in the current 5G and approaching 6G radio transmission.

REFERENCES

Awan, W. A., Zaidi, A., & Baghdad, A. (2019). Patch antenna with improved performance using DGS for 28GHz applications. *International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS, Fez Morocco, 1 – 4.* doi: 10.1109/WITS.2019.8723828.

Aznar, F., Velez, A., Duran-Sindreu, M., Bonache, J., & Martin, F. (2010). Open complementary split ring resonators: physics, modeling and analysis. *Microwave and Optical Technology Letters, 52* (7), 1520 - 1526.

Baena, J. D., Bonache, J., Martin, F., Marques, R. (2005). Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission Lines. *IEEE Transaction on Microwave Theory and Techniques, 53* (4), 1451 - 1461.

Barker, S., Granet, C., Forsyth, R., Greene, K., Hay, S., Ceccato, F., Smart, K., & Doherty, P. (2005). The development of an inexpensive high-precision mm-wave compact antenna test range. Proceeding of AMTA, 337 - 340.

Belbase, K., Kim, M., & Takada, J. I. (2015). Study of propagation mechanisms and identification of scattering objects in indoor multipath channels at 11 GHz, *9th European Conference on Antennas and Propagation (EuCAP), Lisbon*, 1 - 4.

Bonache, J, Gil, I, Garcia-Garcia, J., & Martin, F. (2006). Complementary split rings resonators (CSRRs): Towards the miniaturization of microwave device design, Journal of Computational Electronics, 5 (2), 193 – 197.

Brothers, M., Timms, G. P., Bunton, J., Archer, J. W., Tello, J. Y., Rosolen, G., Li, Y., & Hellicar, A. D. (2007). A 190 GHz active millimeter-wave imager. *Proceedings of SPIE –The International Society for Optical Engineering, Orlando, FL, 6548*.

Cao, Y. F., Cheung, S. W., & Yuk, T. I. (2015). A multiband slot antenna for GPS/WiMAX/WLAN systems. *IEEE Transactions on Antennas and Propagation, 63* (3), 952 - 958.

Capozzoli, A., Curcio, C., D'Elia, G., & Liseno, A. (2008). Millimeter-wave phaseless antenna characterization. *IEEE Transactional Antennas and Propagation, 57* (7), 1330 - 1337.

Chen, H. M., Wang, Y. K., Lin, Y. F., Lin, S. C., & Pan, S. C. (2009). A compact dual-band dielectric resonator antenna using a parasitic slot. *IEEE Antennas and Wireless Propagation Letter, 8*, 173 - 176.

Chen, J-X., Hong, W., Hao, Z-C., Li, H., & Wu, K. (2006). Development of a low cost microwave mixer using a broad-band substrate integrated waveguide (SIW) coupler. *IEEE Microwave and Wireless Component Letters, 16* (2), 84 - 86.

Chen, P., Hong, W., Kuai, Z., Xu, J., Wang, H., Chen, J., Tang, H., Zhou, J., & Wu, K. (2009). A multibeam antenna based on substrate integrated waveguide technology for MIMO wireless communications, *IEEE Transactions on Antennas and Propagation, 57* (6), 1813 - 1821.

Cheng, Y. J., Hong, W., Wu, K., & Fan, Y. (2011). Millimeter-wave substrate integrated waveguide long slot leaky-wave antennas and two-dimensional multibeam applications, *IEEE Transactions on Antennas and Propagation, 59* (1), 40 - 47.

Cheng, Y. J., & Fan, Y. (2011). Millimeter-wave miniaturized substrate integrated multibeam antenna. *IEEE Transactions on Antennas and Propagation, 59* (12), 4840 - 4844.

Colombi, D., Thors, B., & Törnevik, C. (2015). Implications of EMF exposure limits on output power levels for 5G devices above 6 GHz. *IEEE Antennas and Wireless Propagation Letters, 14*, 1247 - 1249.

Colombi, D., Thors, B., Törnevik, C., & Balzano, Q. (2018). RF energy absorption by biological tissues in close proximity to millimeter-wave 5G wireless equipment. *IEEE Access, 6,* 4974 - 4981.

Deslandes, D., & Wu, K. (2006). Accurate modeling, wave mechanisms, and design considerations of a substrate integrated waveguide. *IEEE Transactions on Microwave Theory and Techniques, 54* (6), 2516 - 2526.

Deslandes, D., & Wu, K. (2003). Single-substrate integration technique of planar circuits and waveguide filters. *IEEE Transactions on Microwave Theory and Techniques, 51* (2), 593 - 596.

Ding, Y., & Leung, K. W. (2009). On the dual-band DRA-slot hybrid antenna. *IEEE Transactions on Antennas and Propagation, 57* (3), 624 - 630.

Dyson, J. D. (1966). The measurement of phase at UHF and microwave frequencies. *IEEE Transactions on Microwave Theory and Technology, MTT-14* (9), 410 - 423.

Fuerholz, P., & Murk, A. (2009). Phase-corrected near field measurements of the TELIS telescope at 637 GHz. *IEEE Transactions on Antennas and Propagations, 57* (9), 2518 - 2525.

Granet, C., Rabanus, D., Luthi, T., Murk, A., Smith, S., & Barker, S. J. (2006). Millimeter-wave, sub-millimeter-wave and terahertz-frequency applications of spline-profile horn technology, EuCAP Proc., pp. 014702–014702-5.

Hay, S. G., Archer, J. W., Timms, G. P., & Smith, S. L. (2005). A beam-scanning dual-polarized fan-beam antenna suitable for millimeter wavelengths. *IEEE Transactions on Antennas and Propagation, 53* (8), 2516 - 2524.

He, W., Xu, B., Gustafsson, M., Ying, Z., & He, S. (2018). RF compliance study of temperature elevation in human head model around 28 GHz for 5G user equipment application: Simulation analysis. *IEEE Access, 6*, 830 - 838.

Hejselbæk, J., Nielsen, J. Ø., Fan, W., & Pedersen, G. F. (2017). Measured 21.5 GHz indoor channels with user-held handset antenna array. IEEE Transactions on Antennas and Propagations, 65 (12), 6574 - 6583.

Helander, J., Zhao, K., Ying, Z., & Sjöberg, D. (2016). Performance analysis of millimeter-wave phased array antennas in cellular handsets. *IEEE Antennas and Wireless Propagation Letters, 15*, 504 - 507.

Hirokawa, J., & Ando, M. (1998). Single-layer feed waveguide consisting of posts for plane TEM wave excitation in parallel plates. *IEEE Transactions on Antennas and Propagations, 46* (5), 625 - 630.

Hiroshi, U., Takeshi, T., & Fujii, M. (1998). Development of a laminated waveguide. IEEE Transactions on Microwave Theory and Techniques, 46 (12), 2438 - 2443.

Hirvonen, T., Ala-Laurinaho, J. P. S., Tuovinen, J., & Raisanen, A. (1997). A compact antenna test range based on a hologram. *IEEE Transactions on Antennas and Propagations, 45* (8), 1270 - 1276.

Hislop, G., Hay, S. G., & Hellicar, A. (2007). Efficient sampling of electromagnetic fields via the adaptive cross approximation. *IEEE Transactions on Antennas and Propagations, 55* (12), 3721 - 3725.

Hong, W, Baek, K-H., & Ko, S. (2017). Millimeter-wave 5G antennas for smartphones: Overview and experimental demonstration. *IEEE Transactions on Antennas and Propagation, 65* (12), 6250 - 6261.

Hsu, Y-W., Huang, T-C., Lin, H-S., & Lin, Y-C. (2017). Dual-polarized quasi Yagi-Uda antennas with endre radiation for millimeter-wave MIMO terminals. *IEEE Transactions on Antennas and Propagations, 65* (12), 6282 - 6289.

Huang, F., Tian L., Zheng, Y., & Zhang. J, (2016). Propagation characteristics of indoor radio channel from 3.5 GHz to 28 GHz. *IEEE 83rd Vehicular Technology Conference (VTC Spring), Nanjing, 2016.*

Huo, Y., Dong, X., & Xu, W. (2017). 5G cellular user equipment: From theory to practical hardware design, *IEEE Access, 5*, 13992 - 14010.

Isernia, T., Leone, G., & Pierri, R. (1996). Radiation pattern evaluation from near-field intensities on planes. *IEEE Transactions and Antennas Propagation,44* (5), 701 - 710.

Jandi, Y., Gharnati, F., & Said, A. O. (2017). Design of a compact dual bands patch antenna for 5G applications. *International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)*.

Jang, T. H., Kim, H. Y., Song, I. S., Lee, C. J., Lee, J. H., & Park, C. S. (2016). A Wideband Aperture Efficient 60-GHz Series-Fed E-Shaped Patch Antenna Array with Copolarized Parasitic Patches. *IEEE Transactions on Antennas and Propagation, 64* (12), 5518 - 5521.

Kyro, M, Ranvier S, Kolmonen V, Haneda K, Vainikainen P, (2010). Long Range Wideband Channel Measurements at 81-86 GHz Frequency Range, 2010 EuCAP, April, 2010.

Lamminen, A. E. I., Saily, J., & Vimpari, A. R. (2008). 60-GHz patch antennas and arrays on LTCC with embedded-cavity substrates. *IEEE Transactions on Antennas and Propagation, 56* (9), 2865-2874.

Lee, K-F., Lung, S., Yang, S., & Kishk, A. A. (2008). Dual and multiband U-slot patch antennas. *IEEE Antennas Wireless and Propagation Letters,7,* 645 - 647.

Lehto, A., Tuovinen, J., Boric, O., & Raisanen, A. (1992). Accurate millimeter wave antenna phase pattern measurements using differential phase method with three power dividers. *IEEE Transactions on Antennas and Propagation, 40* (7), 851 - 853.

Li, L., He, Y., Zhang, L., Li, W., & Song, C. (2023). A broadband dual-polarized metasurface antenna for 5G mmWave communication using characteristic mode analysis. *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI), 641 - 642.*

Li L, He Y, Zhang L, Li W, and Song C, (2023). A broadband dual-polarized metasurface antenna for 5G mmWave Communication Using Characteristic Mode Analysis. *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI), Portland, OR, USA, 2023, pp. 641-642*.

Li, T., & Chen, Z. N. (2018). Design of dual-band metasurface antenna array using characteristic mode analysis (CMA) for 5G millimeter-wave applications. *IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), Cartagena, Colombia,* 721 – 724. doi: 10.1109/APWC.2018.8503769.

Li, T., Bhutani, A., Su, Y., Dou, W., & Zwick, T. (2021). Design of wideband dual-polarized metasurface antenna using characteristic mode analysis. *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI), Singapore,* 1287 - 1288.

Li, W., Xu, K. D., Tang, X., Yang, Y., Liu, Y., & Liu, Q. H. (2017). Substrate integrated waveguide cavity-backed slot array antenna using high order radiation modes for dual-band applications in K-band. *IEEE Transactions on Antennas and Propagation, 65* (9), 4556 - 4565.

Li, Y., Archer, J. W., Rosolen, G. R., Hay, S. G., Timms, G. P., & Guo, Y. J. (2007). Fringe management for a T-shaped millimeter-wave imaging system. *IEEE Transaction Microwave Theory and Technology, 55* (6), 1246 - 1254.

Li, Y., Archer, J. W., Tello, J., Rosolen, G., Ceccato, F., Hay, S. G., Hellicar, A., & Guo, Y. J. (2009). Performance evaluation of a passive millimeter-wave imager. *IEEE Transactions on Microwave Theory and Technology, 57* (10), 2391 - 2405.

Liu, S., Wu, W., & Fang, D-G., (2016). Single-feed dual-layer dual-band Eshaped and U-slot patch antenna for wireless communication application. *IEEE Antennas Wireless and Propagation Letters, 15,* 468 - 471.

Lonnqvist, A., Koskinen, T., Hakli, J., Saily J., Ala-Laurinaho, J., Mallat, J., Viikari, V., Tuovinen, J., & Raisanen, A. V. (2005). Hologram-based compact range for submillimeter-wave antenna testing. *IEEE Transactions on Antennas and Propagation, 53* (10), 3151 - 3159.

Marzouk, H. M., Ahmed, M. I., & Shaalan, A. H. A. (2019). Novel dual-band 28/38 GHz MIMO antennas for 5G mobile applications. *Progress in Electromagnetics Research C 93,* 103 - 117.

Molisch, A. F. (2011). *Wireless communications*. (2nd ed.). Wester Sussex, United Kingdom: Wiley Publishing.

Mungur, D., & Duraikannan, S. (2018). Microstrip patch antenna at 28 GHz for 5G applications. *Journal of Science Technology Engineering and Management-Advanced Research & Innovation 1.1,* 20-22.

Nitas, M., Passia, M-T., Yioultsis, T. V. (2017). Analysis and design of a CSRR-based fully planar substrate-integrated waveguide for millimeter-wave circuits and antennas. *11th European Conference on Antennas and Propagation (EUCAP),* 3510 - 3505.

Ojaroudiparchin, N., Shen, M., Zhang, S., & Pedersen, G. F. (2016). A switchable 3-D-coverage-phased array antenna package for 5G mobile terminals. *IEEE Antennas Wireless and Propagation Letters, 15*, 1747 - 1750.

Oladimeji, T. T., Kumar, P., & Elmezughi, M. K. (2023). Performance analysis of improved path loss models for millimeter-wave wireless network channels at 28 GHz and 38 GHz. PLOS ONE, 18, 1 - 27. https://doi.org/10.1371/journal.pone.0283005.

Oladimeji, T. T., Kumar, P., and Elmezughi, M. K. (2024). An improved path loss model for 5G wireless networks in an enclosed hallway. *Wireless Networks*, 1 – 12. https://doi.org/10.1007/s11276-024-03675-8.

Oladimeji, T. T., Kumar, P., & Oyie, N. O. (2022). Propagation path loss prediction modelling in enclosed environments for 5G networks: A review. *Heliyon, 8* (12), 1 - 16. https://doi.org/10.1016/j.heliyon.2022.e11581

Parini, C. G., & Prior, C. J. (1988). Radiation pattern measurements of electrically large antennas using a compact antenna test range at 180 GHz. *Electronic Letters, 24* (25), 1552 - 1554.

Park, S-J, Shin, D-H., & Park, S-O, (2016). Low side-lobe substrate integrated- waveguide antenna array using broadband unequal feeding network for millimeter-wave handset device. *IEEE Transactions on Antennas and Propagation, 64* (3), 923 - 932.

Raisanen, A., Lehto, A., & Tuovinen, J. (1990). Phase pattern and phase center measurements of antennas at 105–190 GHz with a novel differential phase method. *20th European Microwave Conference*, 347 -352.

Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., Wong, G. N., Schulz, J. K., Samimi, M., & Gutierrez, F. (2013). Millimeter wave mobile communications for 5G Cellular: It will work!. *IEEE Access, 1*, 335 - 349.

Rappaport, T. S., MacCartney, G. R., Samimi, M. K., & Sun, S. (2015). Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design. *IEEE Transactions on Communications, 63* (9), 3029 - 3056.

Rizvi, S. N. R., Sarfraz, M., Alibakhshikenari, M., Dalarsson, M., & Falcone, F. (2022). Compact millimeter-wave antenna operating in 28/38 GHz Spectrum. *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), Denver, CO, USA*, 2026-2027, doi: 10.1109/AP-S/USNC-URSI47032.2022.9886943.

Sabri, L., Amiri, N., & Forooraghi, K. (2014). Dual-band and dual-polarized SIW-fed microstrip patch antenna. *IEEE Antennas Wireless and Propagation Letters, 13*, 1605 - 1608.

Saily, J., Ala-Laurinaha, J., Hakli, J., Tuovinen, J., Lehto, A., & Raisanen, A. V. (2000). Test results of 310 GHz hologram compact antenna test range. *Electronic Letters, 36* (2), 111 - 112.

Sehrai, D. A., Khan, J., Abdullah, M., Asif, M., Alibakhshikenari, M., Virdee, B., Shah, W. A., Khan, S., Ibrar, M., Jan, S., Ullah, A., & Falcone, F. (2023). Design of high gain base station antenna array for mm-wave cellular communication systems. *Scientific Report, 13* (4907), 1 - 8. doi: 10.1038/s41598-023-31728-z.

Shereen, M. K., Khattak, M. I., Shafi, M., & Saleem, N. (2018). Slotted Y-shaped millimeter wave reconfigurable antenna for 5G applications. *International Conference on Computing, Mathematics and Engineering Technologies (iCoMET), Sukkur, Pakistan*, 1 - 5, doi: 10.1109/ICOMET.2018.8346402.

Simionato, E., Zang, S. R., Aldaya, I., de Oliveira, J. A., Rosa, G. S., & Penchel, R. A. (2022). Novel coaxial transition for shaped coaxial horn antennas operating at millimeter wave frequencies. *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), Denver, CO, USA*, 551 - 552, doi: 10.1109/AP-S/USNC-URSI47032.2022.9886866.

Smith, S. L., Archer, J. W., Timms, G. P., Smart, K.W., Barker, S. J., Hay, S. G., & Granet, C. (2012). A millimeter-wave antenna amplitude and phase measurement system. *IEEE Transactions on Antennas and Propagation, 60* (4), 1744 - 1757.

Solymar, L., & Shamonina, E. (2009). *Waves in metamaterias*. Oxford, England: Oxford University Press

Sudhakar, R., Naveen, K., Dharani, N. P., Kumar, S. A. (2023). Analysis of slotted matching antenna for millimeter wave applications. *Alexandria Engineering Journal, 16* (1), 237 - 243

Syrytsin, I., Zhang, S., & Pedersen, G. F. (2018). User impact on phased and switch diversity arrays in 5G mobile terminals. *IEEE Access, 6*, 1616 - 1623.

Syrytsin, I., Zhang, S., Pedersen, G. F., & Morris, A. S. (2018). Compact quad-mode planar phased array with wideband for 5G mobile terminals. *IEEE Transactions on Antennas and Propagation, 66* (9), 4648 – 4657. doi: 10.1109/TAP.2018.2842303

Syrytsin, I., Zhang, S., Pedersen, G. F., Zhao, K., Bolin, T., & Ying, Z. (2017). Statistical investigation of the user effects on mobile terminal antennas for 5G applications. *IEEE Transactions on Antennas and Propagation,65* (12), 6596 - 6605.

Tang, P., Tian, L., & Zhang, J. (2017). Analysis of the millimeter wave channel characteristics for urban micro-cell mobile communication scenario. *11th*

European Conference on Antennas and Propagation (EUCAP), 2880 - 2884.

Thors, B., Colombi, D., Ying, Z., Bolin, T., & Törnevik, C. (2016). Exposure to RF EMF from array antennas in 5G mobile communication equipment. *IEEE Access,* 4, 7469 - 7478.

Timms, G. P., Brothers, M. L., Bunton, J. D., Archer, J. W., Rosolen, G. C., Li, Y., Hellicar, A. D., Tello, J. Y., & Hay, S. G. (2010). Design and testing of an active 190-GHz millimeter-wave imager. *Journal of Electronic Imaging, 19* (4), p. 043019 (1 – 6).

Tuovinen, J., Lehto, A., & Raisanen, A. (1991). Phase measurements of millimeter wave antennas at 105 – 190 GHz with a novel differential phase method. *IEEE Proceedings H (Microwaves, Antennas and Propagation), 138* (2), 114 – 120.

Van-Rensburg, D. J., & Hindman, G. (2009). Sub-millimeter wave planar near-field antenna testing. *EuCAP Proceeding, 1988–1992, 64*, 237-243. https://doi.org/10.1016/j.aej.2022.08.028.

Wang, J., Li, Y., Ge, L., Wang, J., & Luk, K-M, (2017). A 60 GHz horizontally polarized magnetoelectric dipole antenna array with 2-D multibeam endre radiation. *IEEE Transactions on Antennas and Propagations, 65* (11), 5837 - 5845.

Wang, Y., Zhu, L., Wang, H., Luo, Y., & Yang, G. (2018). A compact, scanning tightly coupled dipole array with parasitic strips for next-generation wireless applications. *IEEE Antennas and Wireless Propagation Letters, 17* (4), 534 - 537.

Xu, B., Gustafsson, M., Shi, S., Zhao, K., Ying, Z., & He, S. (2019). Radio frequency exposure compliance of multiple antennas for cellular equipment based on semidefinite relaxation. *IEEE Transactions on Electromagnetic Compatibility, 61* (2), 327 - 336. doi: 10.1109/TEMC.2018.2832445

Xu, B., Zhao, K., Thors, B., Colombi, D., Lundberg, O., Ying, Z., & He, S. (2017) Power density measurements at 15 GHz for RF EMF compliance assessments of 5G user equipment. *IEEE Transactions on Antennas and Propaganda, 65* (12), 6584 - 6595.

Xu, B., Ying, Z., Scialacqua, L., Scannavini, A., Foged, L. J, Bolin, T, Zhao, K., He, S, & Gustafsson, M. (2018). Radiation performance analysis of 28 GHz antennas integrated in 5G mobile terminal housing. *IEEE Access, 6*, 48088 - 48101.

Xu, F., & Wu, K. (2005). Guided-wave and leakage characteristics of substrate integrated waveguide. *IEEE Transactions on Microwave Theory and Techniques, 53* (1), 66 - 73.

Xue, M., Wan, W., Wang, Q., & Cao, L. (2021). Low-profile millimeter- wave broadband metasurface antenna with four resonances. *IEEE Antennas and Wireless Propagation Letters*, *20* (4), 463 - 467.

Yan, L., Hong, W., Hua, G., Chen, J., Wu, K., & Cui, T. J. (2004). Simulation and experiment on SIW slot array antennas. *IEEE Microwave and Wireless Components Letters, 14* (9), 446 - 448.

Yang, S. C., Chin, C. C., Hu, R., & Shen, S. S. (1999). A 200 GHz near-field measurement system. *Review of Scientific Instruments, 70* (5), 2526 - 2532.

Yeom, I., Kim, J. M., & Jung, C. W, (2014). Dual-band slot-coupled patch antenna with broad bandwidth and high directivity for WLAN access point. *Electronic Letters, 50* (10), 726 - 728.

Ying, Z., Zhao, K., Bolin, T., He, S., Scannavini, A, Foged, L. J., & Nicolas, G. (2016). Multiplexing efficiency of high order MIMO in mobile terminal for 5G communication at 15 GHz. *International Symposium of Antennas Propagations (ISAP), Oct. 2*016, 594 - 595.

Yu, B., Yang, K., Sim, C-Y-D., & Yang, G. (2018). A novel 28 GHz beam steering array for 5G mobile device with metallic casing application. *IEEE Transactions on Antennas and Propagation, 66* (1), 462 - 466.

Zhang, S., Chen, X., Syrytsin, I., & Pedersen, G. F. (2017). A planar switchable 3-D-coverage phased array antenna and its user effects for 28-GHz mobile terminal applications. *IEEE Transactions on Antennas and Propagations, 65* (12), 6413 - 6421.

Zhao, K., Helander, J., Sjöberg, D., He, S., Bolin, T., & Ying Z. (2017). User body effect on phased array in user equipment for the 5G mmWave communication system. *IEEE Antennas and Wireless Propagation Letters,16,* 864 - 867.

Zhao, K., Ying, Z., & He, S. (2016). EMF exposure study concerning mmWave phased array in mobile devices for 5G communication. *IEEE Antennas and Wireless Propagation Letters, 15,* 1132 - 1135.

Zhao, K., Gustafson, C., Liao, Q., Zhang, S., Bolin, T., Ying Z., & He, S. (2017). Channel characteristics and user body effects in an outdoor urban scenario at 15 and 28 GHz. *IEEE Transactions on Antennas and Propagations, 65* (12), 6534 - 6548.

Zihir, S., Gurbuz, O. D., Kar-Roy, A., Raman, S., & Rebeiz, G. M., (2016). 60-GHz 64- and 256-elements wafer-scale phased-array transmitters using fullreticle and sub reticle stitching techniques. IEEE Transactions on Microwave Theory and Techniques, 64 (12), 4701 - 4719.