ASEAN Engineering Journal

Full Paper

3.5 GHz Vivaldi Antennas: A Comprehensive Parametric Analysis for Unleashing 5G Communication Technology

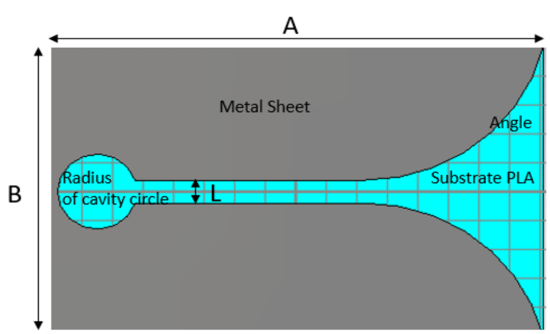
Article history
Received
01 February2023
Received in revised form
10 April 2023
Accepted
12 April 2023
Published online
31 August 2023

Mohd Azlishah Othman[a,b*], Nur Aishah Shahirah Ruslan[a], Mohamad Harris Misran[a], Maizatul Alice Meor Said[a], Redzuan Abdul Manap[b], Abd Shukur Jaafar [b], Nurmala Irdawaty Hassan[c], Shadia Suhaimi [d]

[a]Microwave Research Group (MRG), Faculty of Electronic and Computer Engineering (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
[b]Broadband & Networking Reasearch Group (BBNet), Faculty of Electronic and Computer Engineering (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
[c]Electrical & Electronic Engineering Programme, School of Engineering & Physical Sciences, Heriot-Watt University Malaysia, No. 1, Jalan Venn P5/2, Precinct 5, 62200 Putrajaya, Malaysia
[d]Faculty of Business, Multimedia University, Jalan Ayer Keroh Lama, 75450 Bukit Beruang, Melaka, Malaysia

*Corresponding author
azlishah@utem.edu.my

Graphical abstract



Abstract

In this study, we discuss the design and testing of a Vivaldi antenna operating at 3.5 GHz, which is well-suited for mobile mid-band 5G connection. CST Microwave Studio software was used to simulate and evaluate the suggested antenna design, which was printed utilising state-of-the-art 3D printing processes and materials (polylactic acid (PLA) and FR-4 circuit board material). The measured results show that the antenna has a reflection frequency of 3.51 GHz and a gain of -23.695 dB. Parametric analysis was carried out to examine the relationship between antenna performance and design parameters, with special focus on the separation between the antenna and the PLA material in the middle of the spherical construction. The Vivaldi antenna is an attractive choice for 5G mid-band applications because of its wideband features, ease of manufacture using typical industrial processes, and simplicity of impedance matching to the feeding line using microstrip line modelling.

Keywords: Vivaldi antennas; 3D printed antenna; return loss, antenna gain, Mid Band 5G, Polylactic Acid (PLA).

1.0 INTRODUCTION

The fifth generation (5G) wireless mobile network is the most talked-about issue in the area of communication technology right now. The improvements of the 5G network have created several chances for researchers to investigate and improve its capabilities. The move from 4G to 5G technologies has significantly raised the bar [1]. Cellular wireless networks have improved dramatically since the first 1G system was deployed in 1981, with a new mobile generation appearing about every 10 years [2]. Wireless specialists are developing 5G networks to replace the well-known 4G networks. This 5G upgrade is intended to create a large infrastructure capable of supporting the rising number of connected devices and providing the necessary connection. The development of 5G networks will have a substantial influence on future technological progress [3].

Broadband antennas are in high demand in different RF target modelling systems, electronic countermeasure systems, and electronic reconnaissance systems due to advances in electromagnetic theory and antenna technology [4]. The advent of 5G, the Internet of Things (IoT), and networks capable of operating at millimetre Wave frequencies will result in a significant increase of connected sensors [5]. To account for the propagation issues as well as the cheap cost of metallic radiating structures, high gain antennas will be required [6]. When there is a greater demand for frequencies, public information agencies such as the FCC efficiently allocate available or free frequency bands. The operating licence for previously allotted 5G frequencies is issued via re-framing [7-8]. An antenna is a significant component of the fundamental structure of wireless communications systems and is essential for their functioning.

Fifth generation (5G) technology employs a large number of antennas that operate on a limited number of frequency bands, the majority of which are decided by the appropriate antenna [9-10]. The mobile industry is developing and preparing 5G networks for deployment. This 3.5 GHz frequency range was chosen for 5G networks as part of the global rollout of International Mobile Telecommunications beginning in 2012. (IMT).

The Vivaldi antenna is a type of antenna that has received a lot of attention recently because of its great performance and compatibility with the 5G network. In 1978, Peter Gibson developed the Vivaldi antenna, commonly known as a tapered slot antenna (TSA). It was originally known as the Vivaldi Aerial [11]. A slot antenna is a ground plane made of metal with holes bored out of it. Researchers are interested in the Vivaldi antenna's high gain, wide bandwidth, low cross polarisation, and stable radiation properties [12-13].

The Vivaldi antenna, in contrast to other UWB antennas, has a two-dimensional design with a low profile [14]. Vivaldi antennas with typical microstrip feeds have a restricted bandwidth in addition to being large [15]. This Vivaldi antenna has multiple works. Paul developed a super wideband directional tiny Vivaldi antenna for satellite applications and lower 5G bands at sub-6 GHz in his research (S, C, X, Ku, and K band). This antenna performs well, with a returning loss of 40.322 dB, a fairly wide working bandwidth of 23.19 GH, and a maximum gain of 10.2 dB [16]. In addition, Troung presented in his work a microstrip Vivaldi antenna array with a maximum gain of roughly 16.5 dB and a bandwidth of 140 MHz for 3.5 GHz 5G applications [17]. Other researchers' work on Vivaldi antennas in 5G applications is also documented in multiple articles [18-21].

A Vivaldi antenna for the 3.5 GHz 5G communication system is constructed and assessed in this work utilising 3D printing technologies. PLA, a thermoplastic monomer, is made from organic, renewable sources such as sugar cane or maize starch.

2.0 ANTENNA DESIGN

The design of a Vivaldi antenna at 3.5 GHz involves a comprehensive analysis and consideration of various parameters, as depicted in Figures 1 and 2. The Vivaldi antenna is a broadband planar antenna that features a low profile and operates over a wide frequency range. The radiating element of this antenna is a metal strip that is bent into a spiral shape and placed on a dielectric substrate, with the ground plane placed on the opposite side.

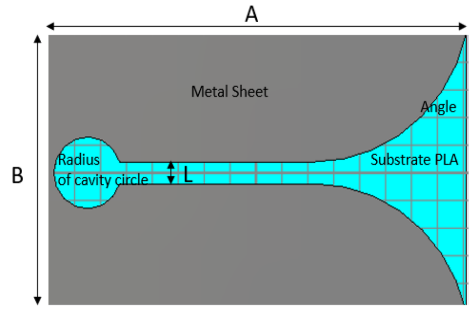


Figure 1 Drawing diagram of the proposed Vivaldi antenna

In the present design, various parameters such as A, B, TPEC, R, Centre, TSUBS, L, W1, W2, W3, W4, W5, and W6 have to be considered. The values of these parameters influence the frequency response and performance of the antenna. As shown in Table 1, the dimensions of these parameters at 3.5 GHz have been provided.

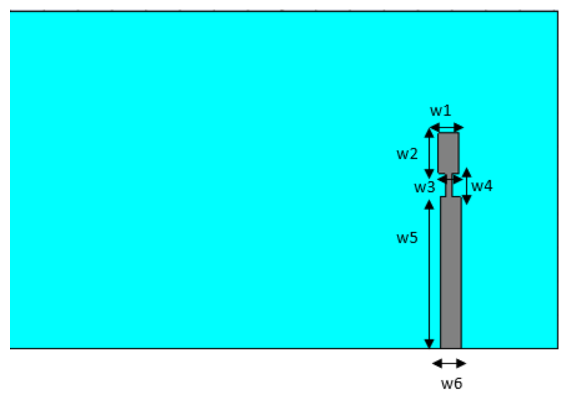


Figure 2 Drawing diagram of the proposed back view Vivaldi antenna

Table 1. Dimension of Vivaldi Antenna

Parameter	Dimension (mm)
A	81
B	50
TPEC	0.035
R	13
Centre	65
TSUBS	3.4
L	4
W1	52
W2	46
W3	48
W4	50
W5	46.5
W6	52.5

The characteristic impedance of the proposed antenna is 50. The zero position refers to the point where the slot line and slot cavity coincide with each other. The feed line stub can be moved along the axis of the antenna, which is referred to as the longitudinal stub displacement, and positive or negative integers can be used to represent this displacement. The sectored line and feed line are integrated into the waveguide port, which is designed to maximise the efficiency of the antenna.

The antenna was designed and simulated using CST software, a specialist tool for modelling elements with a range of frequencies from low to high. CST offers a user-friendly interface and the ability to instantly gain insight into the electromagnetic behaviour of high-frequency devices.

In conclusion, the design of a Vivaldi antenna at 3.5 GHz requires a thorough understanding of antenna design best practices and electromagnetic theory. The dimensions provided in Table 1 play a crucial role in determining the antenna's frequency response and performance. It is essential to carefully consider these parameters to ensure the desired results in the final design.

3.0 RESULTS AND DISCUSSIONS

The Vivaldi antenna design makes use of a substrate material of polylactic acid (PLA), which has a permittivity of 2.575. Because of this, it is an alternative that is suited for and effective in 5G applications that operate at 3.5 GHz. It is recommended that simulations be run using CST software in order to confirm that the antenna has an input impedance of 50 ohms, which is provided by the microstrip line that it contains.

An investigation was carried out in order to discover which parameters at 3.5 GHz were the most productive so that the best performance of the Vivaldi antenna could be determined. The primary goal of the study was to determine the optimum value for the S-parameter, which at the resonant frequency should fall somewhere in the region of -20 dB to -25 dB. Figure 3 depicts the results of the study, which displays the S-parameter analysis of the length for PLA. Table 2 gives the characteristic analysis of the PLA Vivaldi antenna.

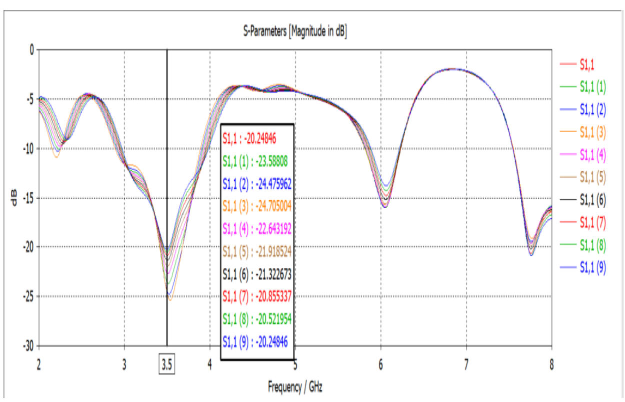


Figure 3 S-parameter analysis of length for PLA

Table 2 Characteristics Analysis of the Vivaldi Antenna made of PLA

Length W6	Main lobe magnitude	S11 (dB)	Gain (dB)
46.5	2.63	- 20.238	6.912
47.5	2.61	- 20.521	6.807
48.5	2.56	- 20.855	6.694
49.5	2.50	- 21.322	6.564
50.5	2.45	- 21.919	6.427
51.5	2.39	- 22.643	6.282
52.5	2.33	- 23.588	6.116
53.5	2.27	- 24.475	5.934
54.5	2.18	- 24.476	5.685

Table 2 displays the parametric performance of the Vivaldi antenna, which was manufactured with Polylactic Acid (PLA) as the substrate material. The table displays different antenna properties, including the length (W6), magnitude of the primary lobe (S11), and gain. The information gives insight into the link between antenna length and performance.

The results indicate that as antenna length rises, the size of the main lobe reduces, resulting in enhanced S11 and gain values. The S11 parameter, which measures the return loss of the antenna, reveals that the lowest value is reached at 47.5, where it reaches -20.521 dB, and the highest value is reached at 54.5, where it reaches 24.476 dB. The gain measurements reveal that the maximum gain is obtained at 46.5, hitting 6.912 dBi, then gradually decreases as the length rises.

The ideal length for the Vivaldi antenna in terms of main lobe magnitude, S11, and gain, according to these measurements, is 47.50 metres. The use of PLA as the substrate material was shown to be successful in constructing a high-performance Vivaldi antenna with a permittivity of 2.57 and an input impedance of 50 ohm, as demonstrated by simulations conducted with CST software. Figure 4 depicts the S-parameter value in decibels vs distance from the centre circle for the S11 frequency at 3.5 GHz. It indicates that the S-parameter improved as the length increased.

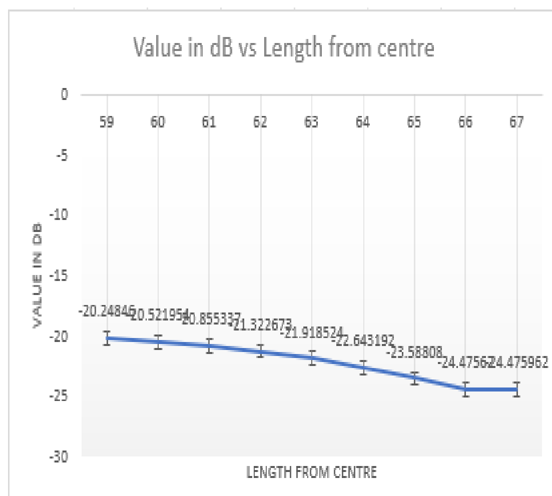


Figure 4 S-parameter value of dB vs length from center circle for S11 frequency at 3.5 GHz

Figure 5's return loss graph gives significant information about the performance of the Vivaldi antenna after its simulation with CST software. As seen in the graph, the intended frequency for this antenna was 3.5 GHz, and the simulation was conducted over a wide frequency range spanning 2 GHz to 8 GHz. According to the modelling findings, the antenna works at 3.51 GHz with a return loss of -23.695 dB.

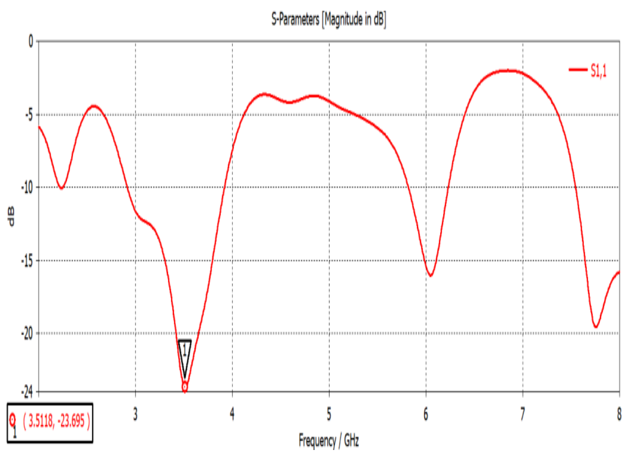


Figure 5 Return loss of the proposed Vivaldi antenna

Return loss is a crucial metric that reveals information about the performance of an antenna. A negative return loss number indicates that the antenna absorbs part of the incident power, and the size of the return loss provides an indication of the antenna's efficiency. The measurement of -23.695 dB shows that the Vivaldi antenna is performing effectively, with good performance.

In addition, this information is crucial for establishing the antenna's appropriateness for various applications. A low return loss value is desired in communication systems because it indicates little signal loss and excellent signal quality. In conclusion, the simulation findings give significant data for the design and optimization of the Vivaldi antenna for particular applications.

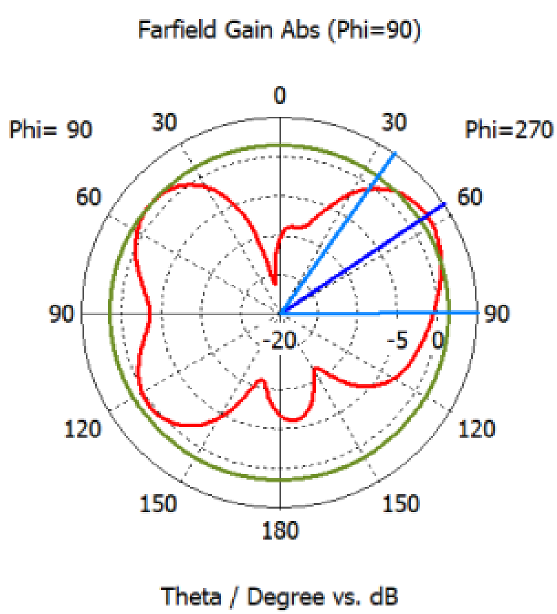


Figure 6 Gain of the proposed Vivaldi antenna

The antenna's gain is a crucial property that defines its capacity to radiate electromagnetic energy. Simply said, it represents the signal intensity that an antenna sends in a certain direction. The findings of the simulation suggest that the Vivaldi antenna has a gain of 6,116 dB, which is a measure of its capacity to focus its energy output. This increase is accompanied by a total efficiency of -0.805 dB and a radiation efficiency of -0.7862 dB, showing that a portion of the transmitted energy is wasted.

The accompanying diagram illustrates the antenna's radiation pattern, which demonstrates that the high radiation is a result of its far-field finding. Figure 6 demonstrates the gain performance of the proposed Vivaldi antenna, offering a visual picture of its capacity to focus energy output in a particular direction. The gain of an antenna is vital in determining its overall performance, and the findings of the Vivaldi antenna are encouraging in this respect.

In addition, the high gain of the Vivaldi antenna is due to its distinctive design and material selection. The antenna's shape has been refined to provide for a broader bandwidth and enhanced radiation characteristics, making it suitable for use in a variety of frequency ranges. Due to its high gain, broad bandwidth, and small size, this type of antenna is extensively utilised in wireless communication systems. Gain performance of the Vivaldi antenna is crucial for attaining high data rates and dependable wireless communication networks, especially in tough propagation situations.

The simulation results for the proposed Vivaldi antenna illustrate its high gain, overall efficiency, and radiation efficiency, all of which contribute to its successful signal transmission. This makes it an excellent choice for a variety of wireless communication applications, and its performance will continue to attract the attention of scientists and engineers.

4.0 CONCLUSION

In conclusion, the purpose of this research was to assess the efficiency of a 3D printed Vivaldi antenna operating at 3.5 GHz for 5G applications. The characterization of the return loss, gain, radiation pattern, and efficiency, in addition to any other pertinent factors, was the primary emphasis of the inquiry. According to the findings, the Vivaldi antennas displayed a level of performance that was sufficient at the specified frequency of 3.5 GHz. As the results of earlier research have shown, there are a variety of methods that can be utilised, such as array configurations, to improve the performance of the antenna and obtain a greater gain in the work that will be done in the future. In conclusion, this effort has contributed to the existing understanding of the performance of Vivaldi antennas when used in 5G applications, and more research in this field has the potential to lead to enhanced design solutions for high-performance wireless communication systems.

Acknowledgement

The authors would like to express their thanks to the Faculty of Electronics and Computer Engineering (FKEKK) at the Universiti Teknikal Malaysia Melaka (UTeM) for their assistance in acquiring the essential information and resources for the successful completion of the research. The authors would also like to extend their gratitude to their collaborators at Heriot-Watt University Malaysia and Multimedia University of Malaysia for the financial and scientific support they provided.

References

[1] Hao, Y., 2021. Investigation and Technological Comparison of 4G and 5G Networks. *Journal of Computer and Communications.* 9: 36-43. DOI: https://10.4236/jcc.2021.91004

[2] M. H. Mohamed,. 2021 Review of 5th Generation Wireless Mobile Network, *International Journal of Systems Engineering,* 7(2): 9-14, DOI: https://10.11648/j.awcn.20210702.11

[3] Dangi, R., Lalwani, P., Choudhary, G., You I., Pau G. 2021 Study and Investigation on 5G Technology: A Systematic Review. *Sensors* (Basel)., 22(1): 1-32. DOI: https://doi.org/10.3390/s22010026

[4] Matuszewski J., Pietrow D. 2021. Specific Radar Recognition Based on Characteristics of Emitted Radio Waveforms Using Convolutional Neural Networks. *Sensors.* 21(24): 8237. DOI: https://doi.org/10.3390/s21248237

[5] Attaran, M. 2021 The impact of 5G on the evolution of intelligent automation and industry digitization. *Journal of Ambient Intelligence and Humanized Computing*, 1-17, DOI: https://doi.org/10.1007/s12652-020-02521-x

[6] Ikram, M., Sultan, K., Lateef, M. F., Alqadami, A.S.M., 2022. A Road towards 6G Communication—A Review of 5G Antennas, Arrays, and Wearable Devices. Electronics, 11: 169. DOI: https://doi.org/10.3390/electronics11010169

[7] Kamal, M. A., Raza, H. W. Alam, M. M., Su'ud, M.M., Sajak, A.b.A.B. 2021. Resource Allocation Schemes for 5G Network: A Systematic Review. *Sensors,* 21: 6588. DOI: https://doi.org/10.3390/s21196588

[8] Shafi, M., Molisch, A. F., Smith, P. J., Haustein, T., Zhu, P., De Silva, P., Tufvesson, F., Benjebbour, A., 2017. 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice, *IEEE Journal on Selected Areas in Communications,* 201735(6): 1201-1221. DOI: https://10.1109/JSAC.2017.2692307

[9] Kumar, S., Dixit, A.S., Malekar, R.R., Raut, H.D., Shevada, L.K. 2020. Fifth Generation Antennas: A Comprehensive Review of Design and Performance Enhancement Techniques. IEEE Access, 8, 163568–163593. DOI: https://dx.doi.org/10.11113/jt.v79.9987

[10] Azpilicueta, L.; Lopez-Iturri, P.; Zuñiga-Mejia, J.; Celaya-Echarri, M.; Rodríguez-Corbo, F.A.; Vargas-Rosales, C.; Aguirre, E.; Michelson, D.G.; Falcone, F. 2020, Fifth Generation (5G) mmWave Spatial Channel Characterization for Urban Environments' System Analysis. Sensors 20: 5360. DOI: https://doi.org/10.3390/s20185360

[11] Gibson, P. J. Vivaldi Aerial, 1979. Conference Proceedings - European Microwave Conference. 101–105

[12] Dixit A. S., Kumar S., Urooj, S., Malibari, A., A. 2021Highly Compact Antipodal Vivaldi Antenna Array for 5G Millimeter Wave Applications. Sensors. 21 (7): 2360. DOI: https://doi.org/10.3390/s21072360

[13] Sun H-H., Lee, Y. H, Luo, W., Ow, L. F., Yusof M. L. M., Yucel, A. C. Compact Dual-Polarized Vivaldi Antenna with High Gain and High Polarization Purity for GPR Applications. Sensors. 21(2): 503, 2021. DOI: https://doi.org/10.3390/s21020503

[14] Saleh, S., Ismail, W., Abidin, I. S. Z., Jamaluddin, M. H., M. H. Bataineh, A. S. Alzoubi. Compact UWB Vivaldi Tapered Slot Antenna, *Alexandria Engineering Journal,* 61(6): 4977 – 4994, 2022. DOI: https://doi.org/10.1016/j.aej.2021.09.055

[15] Rao, B. M. S. S., Rajasekar, B. 2019. Improvement of Antipodal Vivaldi Antenna Performance for Wireless Application, International Journal of Innovative Technology and Exploring Engineering (IJITEE), 9(1):m4321 – 4324. DOI: https://10.35940/ijitee.A4957.119119

[16] Ullah, R., Ullah, S., Faisal, F., Ullah, R., Choi, D-y., Ahmad A., Kamal B. 2021. High-Gain Vivaldi Antenna with Wide Bandwidth Characteristics for 5G Mobile and Ku-Band Radar Applications. Electronics, 10(6): 667, DOI: https://doi.org/10.3390/electronics10060667

[17] Truong, L. X., Giang T. V. B. and Tuan T. M. 2019.Design of Vivaldi Antenna Array with a Back Reflector for Low Side Lobe Level and High Gain, 2019 International Conference on Advanced Technologies for Communications (ATC), Hanoi, Vietnam, 1-6, DOI: https://10.1109/ATC.2019.8924533

[18] Ismail, N., Gunawan, T. D., Kartika, S. S., Praludim T., Hamidi, E. A. Z., K. Muzaffar, M. I. Magray, G. S. Karthikeya and S. K. Koul, 2019. High Gain Broadband Vivaldi Antenna for 5G Applications, 2019 International Conference on Electromagnetics in Advanced Applications (ICEAA), 496-497, DOI: https://10.1109/ICEAA.2019.8878970

[19] Dixit, A.S., Kumar, S. 2021. Gain Enhancement of Antipodal Vivaldi Antenna for 5G Applications Using Metamaterial. *Wireless Personal Communication* 121: 2667–2679, DOI: https://doi.org/10.1007/s11277-021-08842-0

[20] Cherif, A., Himdi, M., Dakhli, S., Castel X. and Choubani F., 2022. Broadband Reconfigurable Vivaldi Antenna for 5G Communication, 2022 IEEE 22nd Annual Wireless and Microwave Technology Conference (WAMICON), 1-4, DOI: https://10.1109/WAMICON53991.2022.9786132.

[21] Kapoor, A., Kumar, P., Mishra, R., 2022. High gain modified Vivaldi vehicular antenna for IoV communications in 5G network. *Heliyon,* 8(5) DOI: https://doi.org/10.1016/j.heliyon.2022.e09336.