

Inverse-Dash Rectangular Slot 2x4 Array 5.8 GHz Antenna for Multiple Access Integration of IoT Systems and Terrestrial Satellite Communication Networks

Irfan Mujahidin¹, Budi Basuki Subagio^{1*}, Roni Apriantoro¹, Muhlasah Novitasari Mara¹, Siti Hasanah², Akio Kitagawa²

¹ Department of Telecommunication Engineering, Faculty of Electrical Engineering, Semarang State Polytechnic Semarang City, INDONESIA

² Department of Islamic Banking, Faculty of Accounting, Semarang State Polytechnic Semarang City, INDONESIA

³ Department of Electrical Engineering and Computer Science, Graduate School of natural Science and Technology, Kanzawa University, JAPAN

*Corresponding Author: irfan.mujahidin@polines.ac.id

DOI: <https://doi.org/10.30880/ijie.2025.17.02.028>

Article Info

Received: 22 November 2024

Accepted: 12 July 2025

Available online: 8 August 2025

Keywords

Satellite communication, IoT integration, microstrip antenna, 5.8 GHz WLAN, remote area connectivity

Abstract

LEO satellites provide a phenomenal solution for the provision of internet networks around the world, especially in remote areas. Along with this, the increasing demand for fast and stable information and communication network access technology, especially in applications such as the Internet of Things (IoT) and satellite communications, demands innovative solutions to overcome infrastructure limitations in remote areas. Right Now, this need is expected to increase by around 25%. IoT technology, which is key in the industrial revolution 4.0 and the development of smart cities, relies heavily on the support of communication networks, especially in remote areas that are underserved by mobile and fiber optic infrastructure. This study proposes an optimal antenna design for point-to-point applications on WLAN-IoT networks integrated with LEO satellite communication systems. The antenna design uses a rectangular inverted-dash patch-shaped array configuration with an operating frequency of 5.8 GHz, designed to improve communication range and efficiency. The antenna has a high gain of 5 dBi and a directional radiation pattern that is suitable for difficult environments in remote areas. The prototype antenna test showed positive results with a return loss of -15.78 dB, a VSWR of 1.39, and a radiation efficiency of 96%. The test results also showed a significant increase in transmission signal strength compared to the reference antenna, providing an innovative solution to extend the range of the satellite communication system with high efficiency. This study emphasizes the importance of antenna design that takes into account technical specifications and environmental conditions to optimize the performance of communication networks in remote areas.

1. Introduction

The demand for fast and stable information and communication network access technology by society, industry, and governments in various technology applications, including the Internet of Things (IoT) and terrestrial satellite

This is an open access article under the CC BY-NC-SA 4.0 license.



communications is increasing by about 25% from 2022 to 2026 [1], [2] IoT technology has become one of the key innovations in supporting the success of the industrial revolution 4.0 and realizing smart cities, where the rapid development of IoT and the promotion of new technologies in various applications bring extraordinary convenience to human life [3], [4], [5] On the other hand, the successful deployment of IoT devices cannot be separated from the vital support of communication networks, both access networks and main networks, especially in remote areas that support urban areas in providing commodities for plantations, agriculture, livestock, mining, and forest products [6], [7], [8] However, these remote areas still do not have adequate internet infrastructure, both from cellular and fiber optic infrastructure. Therefore, the presence of Low-Earth-Orbiting (LEO) satellites is a major breakthrough in accommodating the provision of reliable and flexible internet communication networks for IoT devices in remote areas [8], [10], [11], [12]

In general, the LEO satellite internet network architecture can only be utilized in a limited scope for a range of no more than 100 m2. The network works by applying a dish antenna in the user segment as a transceiver to connect to LEO (core network) satellites, then internet access is spread through the Wi-Fi 5 Router which provides operational frequencies of 2.4 GHz and 5 GHz. This can be seen in Fig. 1.

Therefore, for the provision of wider IoT network coverage in remote areas, a more complex network topology is needed by adding an Outdoor Access Point Router (OAPR) as a relay to integrate simultaneously between the IoT device cluster network and the LEO satellite internet network [13]. In this case, the OAPR relay is tasked with providing wireless access (WLAN) to IoT devices using the 2.4 GHz operational frequency. Then, the OAPR relay is connected point-to-point with the central OAPR using the 5.8 GHz operational frequency with the consideration of less interference, a greater number of channels, and a wider bandwidth to accommodate the heavy data traffic of IoT devices [14].

Nonetheless, the integration between IoT device wireless communication systems and LEO satellite communication networks requires the right antennas to ensure optimal availability, reliability, and performance on communications in relay networks (OAPR relays with central OAPR). Therefore, the antenna design for such applications must consider variables such as operational frequency accuracy, gain, directivity, and proper radiation patterns to provide more efficient connectivity in IoT systems [15], [16] Furthermore, environmental variables such as weather and topographic conditions are also considered in designing antennas [15].

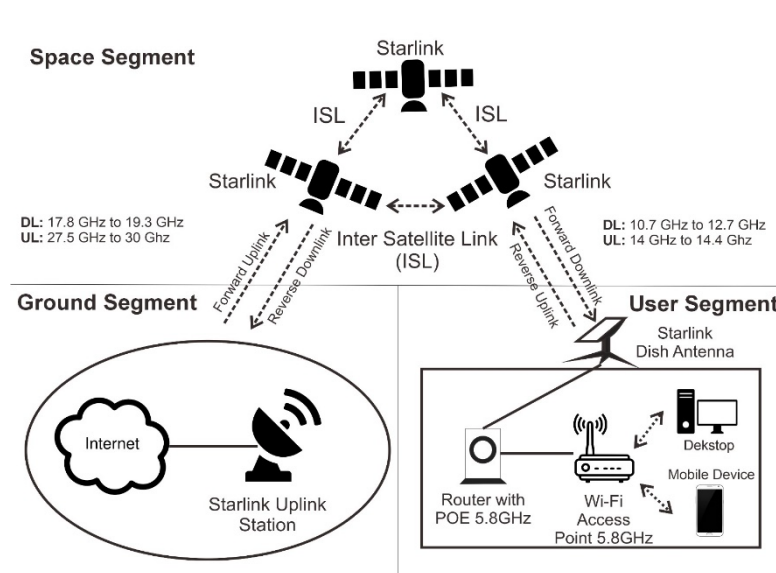


Fig. 1 Existing LEO-Satellite communication system

Various studies have explored the design and performance of 5.8 GHz antennas for WLAN-IoT network applications. Wang, et al. in [17] created the antenna patch design using Chinese characters. The antenna is fabricated using an FR-4 substrate and produces an omni-directional radiation pattern. In another study conducted by Chen, et al. in [18] antennas were designed with a combination of a triangular structure, an inverted-F shape, and an M-shape, which was rotated 90o counterclockwise. The antenna is fabricated using FR-4 substrate, produces an omni-directional radiation pattern, and is applied as an access point relay antenna. Furthermore, Fakhridinovich, et al. in [19] have designed a monopole coplanar waveguide (CPW) antenna with a T-shaped strip-shaped patch, L-shaped mirror, strip, and coplanar ground plane to accommodate ISM-band and WLAN. Just like the other studies, the antenna was fabricated using an FR-4 substrate and produced an omni-directional radiation pattern. Olan-Nunez, et al. in [20][21] also designed the antenna to accommodate applications in the

ISM-band. The antenna is crafted using two radiating rectangular slots, with an upper Split Ring Resonator (SRR) to enhance the radiation pattern at 5.8 GHz. It also includes a Complementary Split Ring Resonator (CSRR) and three Split Rings (SR) to improve the input reflection coefficient. The antenna is constructed on a Poly-lactic Acid (PLA) substrate. Another study conducted by Jamlos, et al. in [22] resulted in antenna designs with array and circular polarized configurations. The antenna will be used for point-to-point WLAN[23].

Based on previous research, antennas designed to operate at the 5.8 GHz frequency have an average omnidirectional radiation pattern and have a wide band in addition to having a directivity that is less specific to the target area. Meanwhile, in remote areas have a fairly difficult environment and require antennas with high gain to ensure network reliability and availability. Therefore, in this study, an antenna design that is suitable for point-to-point WLAN applications is proposed with an array configuration to expand the range of the satellite communication system with a frequency of 5.8 GHz, a compact rectangular inverted-dash patch shape that accommodates the specifications of the expansion of the satellite communication system, has an S Parameter value of 5.75GHz-5.85 GHz, a high gain of 5 dBi, and a specific directivity angle in the antenna directional area.

2. Antenna Design

In accommodating the provision of antennas for point-to-point communication of relay networks in the expansion of more reliable satellite connectivity systems, this paper designs antennas to meet the requirements in the form of operational frequency, gain, and directivity[24], [25]. The antenna fabrication method begins with creating the geometric design of the antenna as described in Sub-chapter 2.1. Next, simulations are carried out to analyze the suitability of the required parameters, as detailed in Sub-chapter 2.2.

2.1 Antenna Geometry and Configuration

The proposed antenna geometry and configuration have a resonant frequency of 5.8 GHz, as illustrated in Fig. 3. The antenna is designed using CST Studio software. The substrate used in the design is FR-4 epoxy which has a thickness of 1.6 mm, a tangent of 0.02, and a relative permittivity of 4.4. The proposed antenna has a rectangular shape with dimensions of 150 x 110 mm. The antenna patch is designed in a square shape with inverse-dash slotted and configured with a 2x4 array. This structure is supplied by 50 microstrip transmission lines. The antenna ground plane consists of a rectangular patch with a width of W_g and a length of L_g . The complete geometric size of the antenna design can be seen in Table 1.

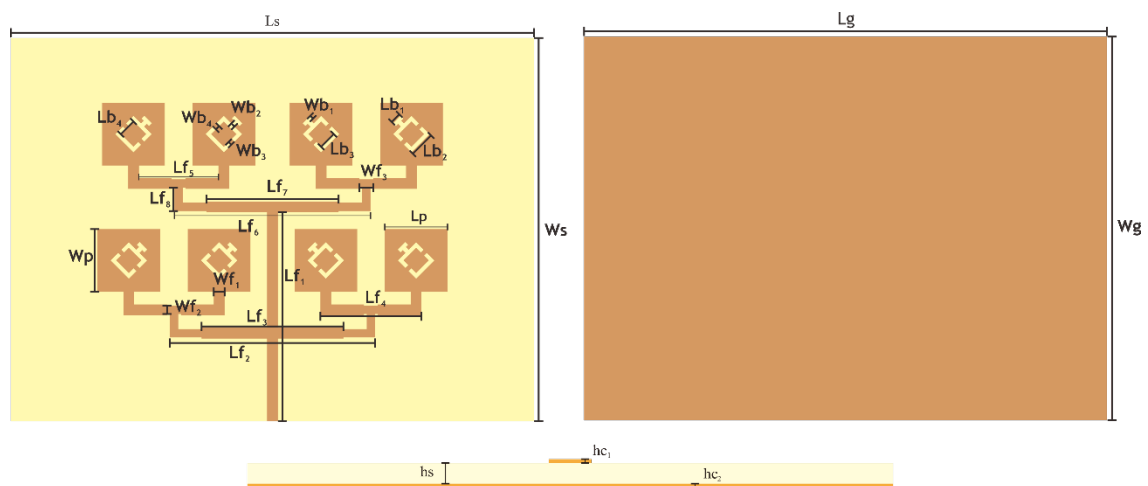


Fig. 3 Proposed antenna design

Table 1 Design parameters of proposed antenna

Parameters	Dimension (mm)
Substrate Thickness (hs)	1.6
Copper Thickness (hc1 & hc2)	0.035
Ls, Lg	150
Ws, Wg	110
Wp, Lp	18
Lf1	60
Lf2	58.94
Lf3	40.68
Lf4	29.02
Lf5	22.82
Lf6	56.25
Lf7	38
Lf8	6.71
Lb3, L4	5.14
Wb1, Wb3	1.12
Wb2, Wb4	1.29
Lb2	7.38

The geometric size of each single patch (length and width of the patch) is determined using Equations (1) and (2) [26]. as follows:

$$W_p = \frac{\lambda_0}{2(\sqrt{0.5(\xi_r+1)})} \tag{1}$$

The substrate's relative permittivity and its wavelength in free space at the operating frequency are ξ_r and λ_0 respectively. The most effective W_p options ensure optimal impedance matching. To determine the suitable patch length, Equation (2) can be employed

$$L_p = \frac{c_0}{2f_0\sqrt{\xi_{eff}}} - 2\Delta L_p \tag{2}$$

In this equation, c_0 , ΔL_p , and ξ_{eff} represent the speed of light, The change in patch length due to fringing and the effective dielectric constant are considered. The relative effective permittivity is subsequently calculated using Equation (3).

$$\xi_{ff} = \frac{\xi_r+1}{2} + \frac{\xi_r-1}{2} \left(\frac{1}{\sqrt{1+12\frac{h_s}{W_p}}} \right) \tag{3}$$

where h_s is the substrate's height. Lastly, the fringe effect can be estimated using Equation (4)

$$\Delta L_p = 0.421 h_s \frac{(\xi_{eff} + 0.300) \left(\frac{W_p}{h_s} + 0.264 \right)}{(\xi_{eff} - 0.258) \left(\frac{W_p}{h_s} + 0.813 \right)} \tag{4}$$

2.2 Parametric Simulation

After completing the antenna design, simulations are conducted to evaluate several key parameters, including return loss and Voltage Standing Wave Ratio (VSWR), radiation patterns, gain and directivity. The first parameter tested is the return loss indicated by the S-Parameter (S_{11}) [27], [28]. Return loss on an antenna is a measure of how well the energy emitted by a signal source (such as a transmitter) is transmitted through the antenna and how little energy is reflected back to the signal source. In simple terms, return loss indicates the efficiency of the antenna in transmitting signals. The higher the return loss value, the less energy is reflected back and the more efficient the antenna is. Fig. 4. shows the S parameter (magnitude in dB) of the microstrip array antenna at a frequency of 5.8 GHz. At this frequency there is a decrease of about -40.99602 dB, indicating that the efficient matching impedance represents the radiation efficiency value so that based on the simulation it reaches 99%.

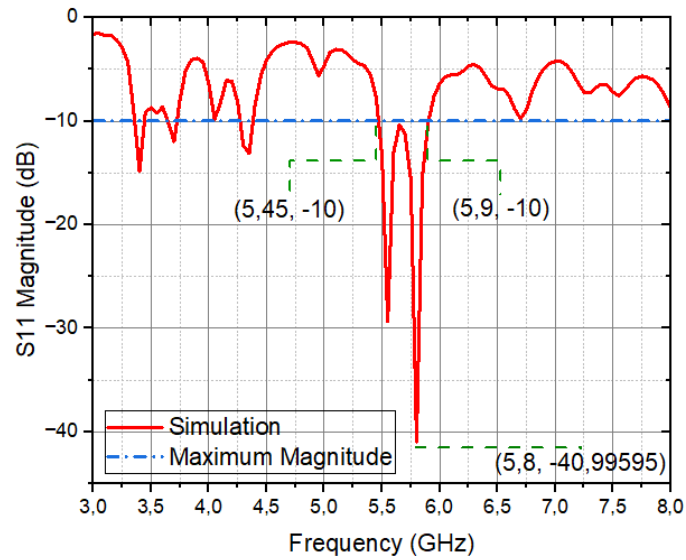


Fig. 4 *S-Parameters test simulation*

Furthermore, the parameter targeted in the design is VSWR. VSWR is a measure that determines how well the impedance between the antenna and the transmission line is matched. Ideally, a perfect impedance match will result in a VSWR of 1:1 [29], [30]. This means that no energy is reflected back to the source and all energy is transmitted to the antenna. Based on the simulations that have been carried out, the VSWR value generated in the proposed antenna design is 1.0179936. This can be seen in Fig. 5.

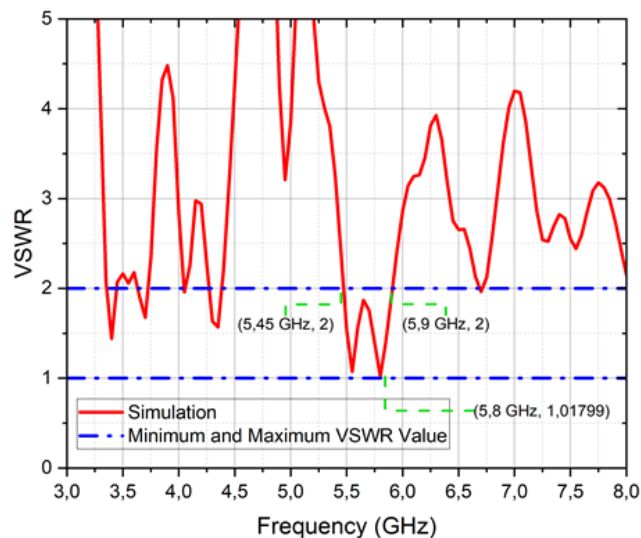


Fig. 5 *VSWR test simulation*

In addition to return loss and VSWR, the parameter targeted in the next design is the radiation pattern. The radiation pattern of the antenna is a graphical depiction of how power is distributed when it is emitted or received by the antenna within the target space of the end-to-end satellite communication network. This pattern shows the intensity of the electromagnetic field in various directions relative to the antenna which leads to the reception of the system of the satellite service user [30], [31]. At this stage, the radiation pattern of the antenna design is depicted in 2D planes at $\Phi=90$ and $\Theta=90$ shown in Fig. 6a and Fig. 6b, respectively. Based on Fig. 6, the antenna forms a directional radiation pattern suitable for point-to-point applications.

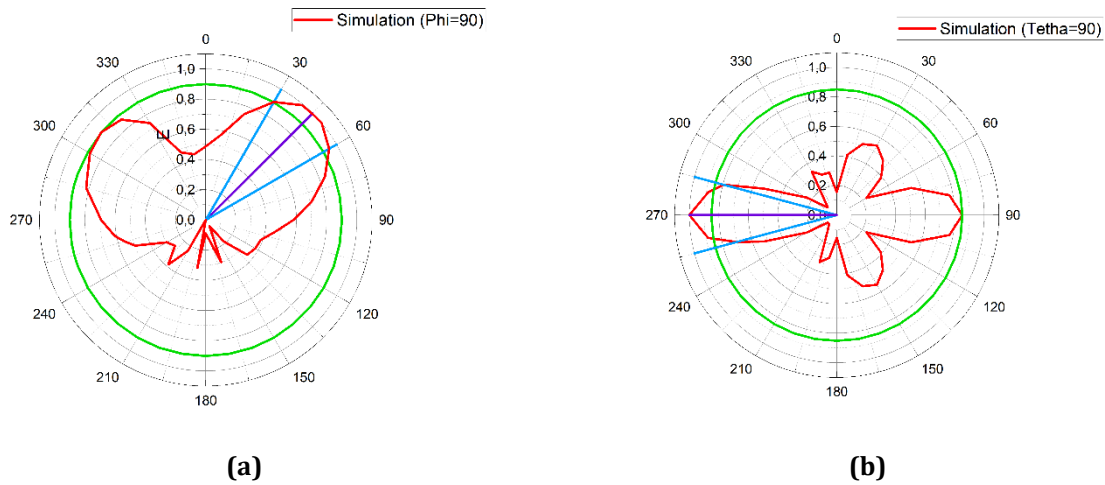


Fig. 6 Simulation of radiation pattern (a) $\Phi=90$; (b) $\Theta=90$

The last parameters that are targeted in the simulation stage are gain and directivity. Gain is a measure of how effectively an antenna converts input power into electromagnetic radiation in a particular direction compared to a reference (isotropic) antenna [32], [33]. While directivity is a measure of how well an antenna focuses its radiant power in a particular direction compared to the uniform power distribution of an isotropic antenna, without taking into account the efficiency of the antenna. Based on the simulation results, the gain of the antenna at the frequency of 5.8 GHz is 5.65 dBi with a directivity of 460. This is shown in the Fig. 7.

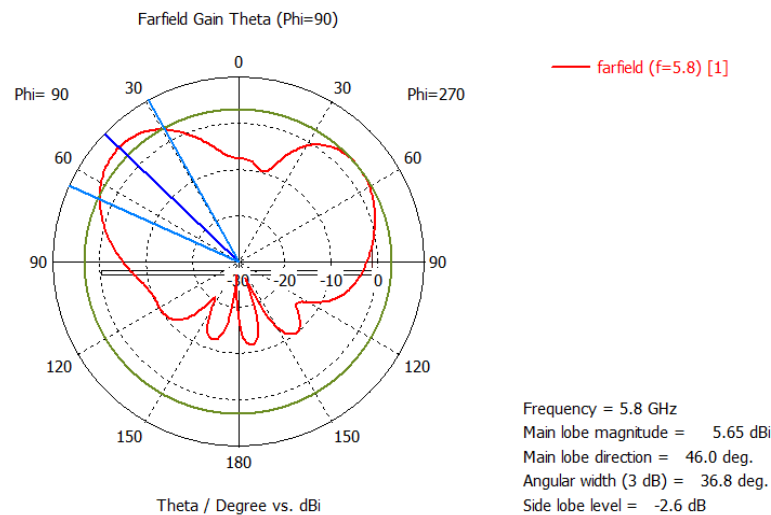


Fig. 7 Gain and directivity simulation

3. Result and Discussion

After obtaining the appropriate simulation results, then proceed to the antenna fabrication process. The antenna design that has been made is then fabricated. The fabrication results are then implemented on FR-4 substrate that has been cut with dimensions of 150x110 mm using a vacuum heating technique [34], [35], [36]. The next step is to dissolve the required copper layer using a solution of HCl, H₂O₂, and H₂O in a ratio of 1:2:2. The results of the

antenna prototype fabrication are shown in Fig. 8. The prototype of the fabricated antenna was then tested using the scheme as shown in Fig. 9.

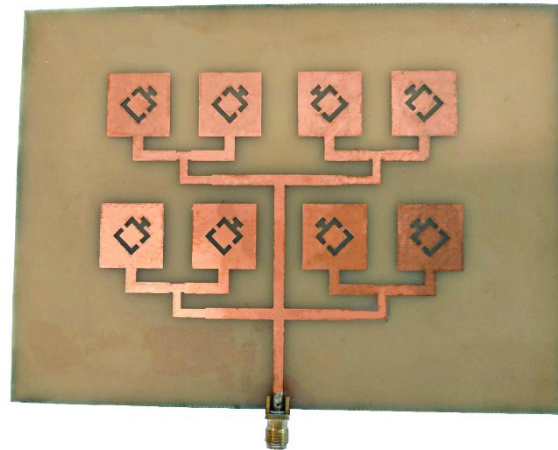


Fig. 8 Manufactured prototype antenna

The antenna prototype was tested in the antenna measurement chamber, where the dipole antenna antenna was configured as a transmitter that emitted electromagnetic signals with a frequency of 5.8 GHz generated by the signal generator. Then the electromagnetic signal is received by the antenna prototype, then read by the Vector Network Analyzer (VNA). The prototype antenna is rotated up to 360° to produce measurements complete with the schematic in fig. 9.

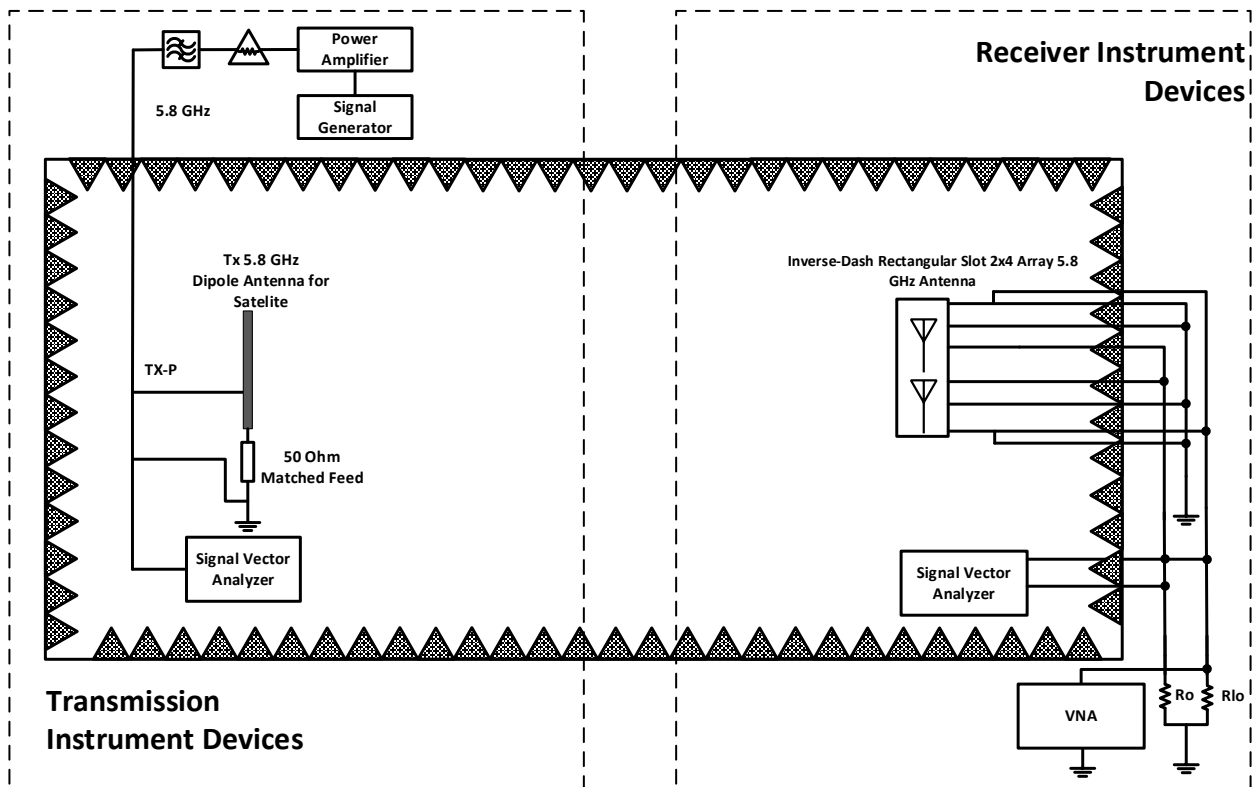


Fig. 9 Antenna measurement scheme

The antenna parameters tested in the measurement include return loss (S_{11}), VSWR, and Radiation Pattern. Based on the measurement results, the return loss value at the operational frequency is -15.77994 dB. The storage that occurs between simulation and measurement is -25 dB. Despite this, the resulting radiation efficiency is 96%.

Meanwhile, the result of the VSWR measurement is 1.38822. The VSWR value is still within the tolerance threshold, even though there is a value storage of 0.3 dBi of reinforcement. On the other hand, the results of the radiation pattern measurement show a directional radiation pattern. The measurement results of the three parameters can be seen in Fig. 10, Fig. 11, and Fig. 12, respectively.

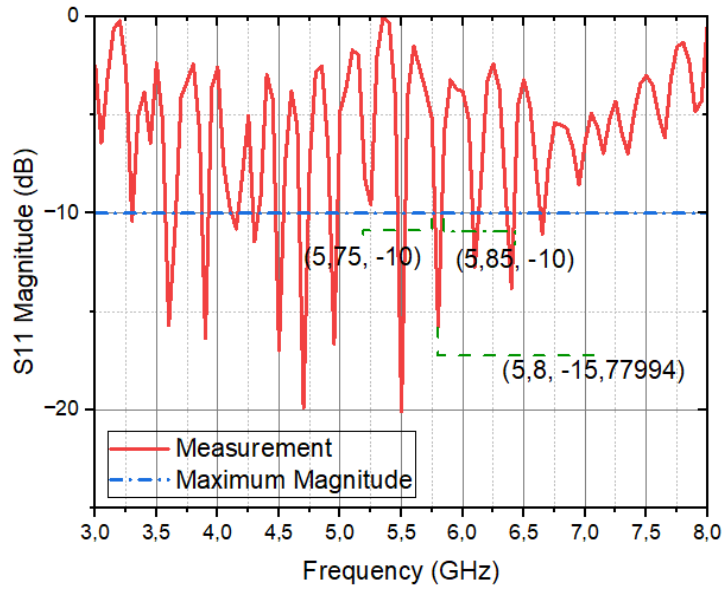


Fig. 10 Return loss measurement results

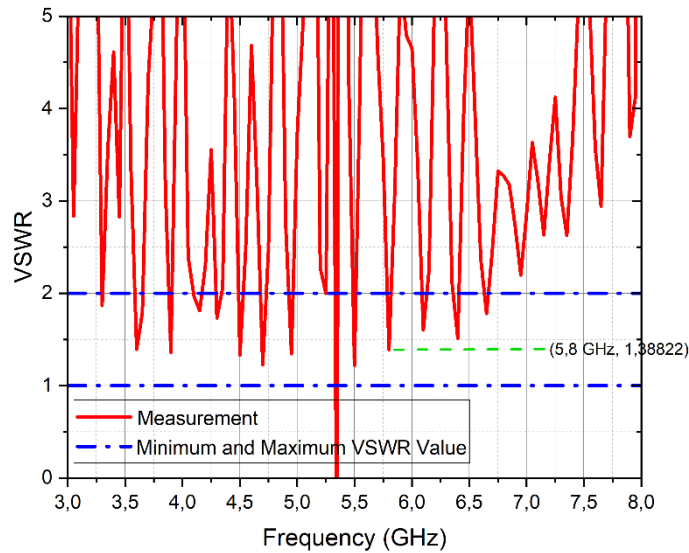


Fig. 11 VSWR measurement results

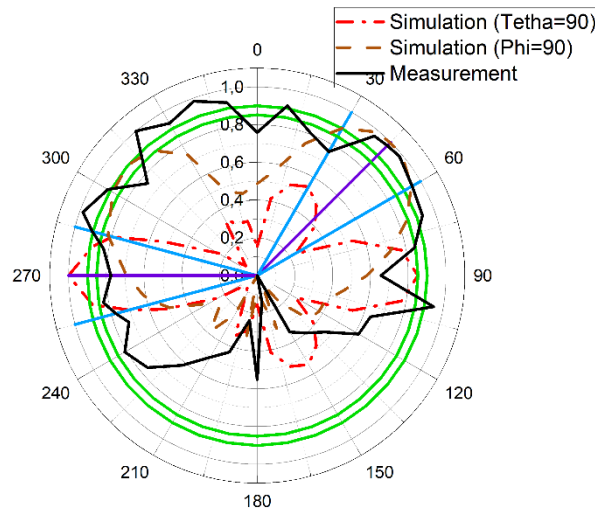


Fig. 12 Measurement results radiation pattern

Recently, the proposed antenna prototype was compared to the antenna prototype from the previous related research. The reference parameters used for comparison are gain, directivity, and radiation efficiency. Based on the results of the comparison, the proposed antenna excels in gain and directivity parameters. In detail, comparative data can be seen in Table 2.

Table 2 Comparison of proposed antenna with other research literature at 5.8 GHz of operational frequency

References	Peak Gain (dBi)	Directivity (degree)	Radiation Efficiency (%)
Proposed	5.65*	30*	96
[22]	Not mentioned	Not mentioned	Not mentioned
[20]	6.5	Not mentioned	99*
[19]	2.5	360	86
[18]	1	360	95
[17]	2.5	360	85

In this study, the system implementation analysis scheme can be represented in fig. 13. In the implementation analysis, the main component in the transmission is the distribution of the arrival and reception angles of the signal both at the receiver and the sender. So to analyze the scheme in figure 9, the most effective analysis is that we adopt the ULA system to solve the problem of estimating the Direction of arrival on the antenna transmission in the satellite communication system network system[37], [38], [39]. The system should have an N antenna, with a distance between d . As illustrated in Figure 1, the array receives K unknown signals, with the k -th signal ($k = 0, 1, \dots, K - 1$) having an angle of arrival θ_k .

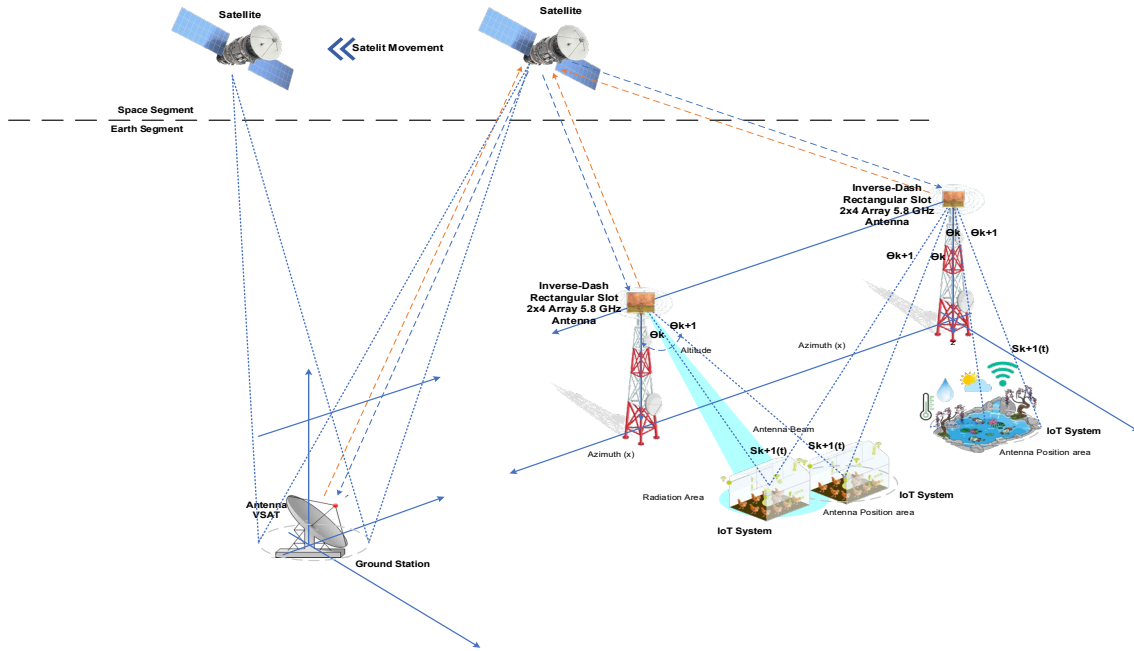


Fig. 13 Network architecture representation scheme

As depicted in Figure 9, the phase difference between two sequentially received signals is:

$$\Delta\varphi = \frac{2\pi d \sin \theta}{\lambda} \tag{5}$$

where λ is the wavelength of the signal.

First, pay attention to the situation of a single signal, where $s_n(t)$ it shows the signal received n at the time t

$$s_n(t) = s(t - n\tau) \tag{6}$$

where τ represents the time interval during which two antennas receive a signal. The received signal can alternatively be expressed as:

$$s(t) = z(t)e^{j2\pi f_0 t} \tag{7}$$

where f_0 is the signal frequency. So that

$$\begin{aligned} s(t - \tau) &= z(t - \tau)e^{j2\pi f_0 (t - \tau)} \\ &= s(t)e^{-j2\pi f_0 \tau} \\ &= s(t)e^{-j\Delta\varphi} \end{aligned} \tag{8}$$

Where $\Delta\varphi = 2\pi f_0 \tau$.

Substituting equations (8) to (6) is obtained

$$s_n(t) = s(t)e^{-jn\Delta\varphi} \tag{9}$$

From equations (7) and (9), the received signal array antennas follow the following equation

$$\begin{aligned}
 y(t) &= \begin{bmatrix} e^{-j2\pi f_0 \tau_0} \\ e^{-j2\pi f_0 \tau_1} \\ \vdots \\ e^{-j2\pi f_0 n} \end{bmatrix} s(t) \\
 &= \begin{bmatrix} 1 \\ e^{-j\frac{2\pi d \sin \theta}{\lambda}} \\ \vdots \\ e^{-j\frac{2\pi(N-1)d \sin \theta}{\lambda}} \end{bmatrix} s(t) \\
 &= As(t)
 \end{aligned} \tag{10}$$

Suppose there are two unknown signals namely $s_1(t)$ and $s_2(t)$, then the signal received by the n th antenna element can be expressed as follows:

$$\begin{aligned}
 y_n(t) &= e^{-j\frac{2\pi(n-1)d \sin \theta}{\lambda}} s_1(t) + e^{-j\frac{2\pi(n-1)d \sin \theta}{\lambda}} s_2(t) \\
 &= \begin{bmatrix} e^{-j\frac{2\pi(n-1)d \sin \theta_1}{\lambda}} & e^{-j\frac{2\pi(n-1)d \sin \theta_2}{\lambda}} \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix}'
 \end{aligned} \tag{11}$$

Therefore, the total received signal can be written as

$$Y = AS + N \tag{12}$$

Dengan

$A \cong [a(\theta_0), a(\theta_1), \dots, a(\theta_{\kappa-1})]$, $a(\theta_k) \cong [1, e^{-j2\pi\frac{d}{\lambda}\sin(\theta_k)}, \dots, e^{-j2\pi\frac{(N-1)d}{\lambda}\sin(\theta_k)}]$ denotes the steering vector for the k -th signal.

$S \cong [s_0, s_1, \dots, s_{M-1}] \in \mathbb{C}^{K \times M}$, $Y \cong [y_0, y_1, \dots, y_{M-1}] \in \mathbb{C}^{N \times M}$ and $N \in \mathbb{C}^{N \times M}$ denotes Additive White Gaussian Noise (AWGN) [41].

From the analysis that has been carried out, in order to validate the transmission model can be carried out efficiently, it is important to test the strength of the transmission signal using the signal analyzer spectrum to compare it with the reference antenna that has been developed in the previous study in fig. 14. The signal strength in the antenna implementation has a significantly better transmission efficiency value than the reference antenna with an average increase of 10dB in each sample experiment [42], which indicates that this antenna has a very significant innovation troboson to increase the expansion of the range of the satellite conconnection system.

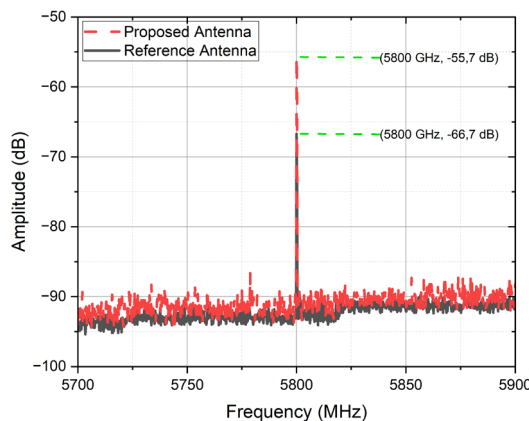


Fig. 14 Comparison of signal reinforcement between the reference antenna and the proposed antenna

4. Conclusion

This research highlights the importance of integration between wireless communication technology, Internet of Things (IoT) devices, and Low-Earth-Orbiting (LEO) satellite communication networks to overcome network access challenges in remote areas. With the increasing demand for fast and stable information and communication access technology, its success depends heavily on adequate communication networks, especially in underserved areas. To integrate the two systems, this study focuses on designing a microstrip antenna. The antenna design proposed in this study, namely a rectangular inverted-dash patch antenna with an operating frequency of 5.8 GHz, shows significant potential to extend the range of LEO satellite communication systems. The antenna is designed to improve gain and directivity, which is especially important in challenging environments in remote areas. The test results show that the prototype antenna has superior performance with a return loss of -15.78 dB, VSWR of 1.39, and radiation efficiency of 96%. The advantages of this antenna compared to other reference antennas, with an increase in average transmission efficiency of 10 dB, signify an innovative contribution in expanding the range and improving the performance of satellite communication systems. Overall, this study shows that the right antenna design is key to overcoming network challenges in remote areas and can support the provision of reliable connectivity for IoT devices. This solution not only increases the range but also ensures the availability and reliability of communications in systems that utilize LEO satellites.

Acknowledgement

The authors would like to express their sincere gratitude to the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia for providing financial support for this research. Special thanks are also extended to Semarang State Polytechnic for their invaluable support in terms of laboratory facilities and administrative assistance. The authors are equally grateful to the industrial partner CV. Maudy Network for their significant contributions in fostering innovation, providing testing equipment, and assisting in the commercialization of the developed technology.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

Irfan Mujahidin served as the principal investigator, leading the overall research activities and coordinating the development of the study. He was responsible for formulating the research objectives, directing the methodological framework, and preparing as well as finalizing the manuscript for journal submission. Budi Basuki Subagio contributed extensively to the technical aspect of the work, particularly in the design and measurement of the proposed antenna, ensuring that the parameters met the targeted specifications and were accurately presented in the article. Roni Apriantoro played a crucial role in the integration of the IoT network system with the LEO satellite communication architecture, bridging the hardware and communication protocols to achieve seamless interoperability, and documenting the results for inclusion in the manuscript. Muhlasah Novitasari Mara handled the data processing and optimization stages, analyzing experimental results, refining performance parameters, and ensuring that the reported findings were supported by robust statistical and computational validation. Siti Hasanah contributed by performing detailed calculations related to the testing mechanisms and overseeing the financial planning of both the research implementation and the publication process, ensuring resource allocation was efficient and in compliance with project guidelines. Akio Kitagawa provided expert supervision in both the design and testing phases, offering technical insights and guidance to maintain the quality and relevance of the research outcomes in line with current advancements in the field. All authors reviewed, edited, and approved the final manuscript, collectively ensuring that the research met the highest academic and technical standards.

References

- [1] E. Pasqua, "Satellite IoT connectivity: Three key developments to drive the market size beyond \$1 billion." Accessed: Jul. 01, 2024. [Online]. Available: <https://iot-analytics.com/satellite-iot-connectivity/>
- [2] I. Mujahidin, S. S. Hidayat, M. C. A. Prabowo, and A. Kitagawa, "C-Slot Circular Polarized Antenna for Hybrid Energy Harvesting and Wireless Sensing," *Pertanika J Sci Technol*, vol. 32, no. 3, pp. 1413–1425, Apr. 2024, doi: 10.47836/pjst.32.3.24.
- [3] R. Rudenko, I. M. Pires, P. Oliveira, J. Barroso, and A. Reis, "A Brief Review on Internet of Things, Industry 4.0 and Cybersecurity," *Electronics*, vol. 11, no. 11, 2022, doi: 10.3390/electronics11111742.
- [4] T. Kalsoom *et al.*, "Impact of IoT on Manufacturing Industry 4.0: A New Triangular Systematic Review," *Sustainability*, vol. 13, no. 22, 2021, doi: 10.3390/su132212506.

- [5] R. Chataut, A. Phoummalayvane, and R. Akl, "Unleashing the Power of IoT: A Comprehensive Review of IoT Applications and Future Prospects in Healthcare, Agriculture, Smart Homes, Smart Cities, and Industry 4.0," *Sensors*, vol. 23, no. 16, 2023, doi: 10.3390/s23167194.
- [6] A. Andreadis, G. Giambene, and R. Zambon, "Low-Power IoT for Monitoring Unconnected Remote Areas," *Sensors*, vol. 23, no. 9, 2023, doi: 10.3390/s23094481.
- [7] M. Mansour *et al.*, "Internet of Things: A Comprehensive Overview on Protocols, Architectures, Technologies, Simulation Tools, and Future Directions," *Energies*, vol. 16, no. 8, 2023, doi: 10.3390/en16083465.
- [8] D. Kanellopoulos, V. K. Sharma, T. Panagiotakopoulos, and A. Kameas, "Networking Architectures and Protocols for IoT Applications in Smart Cities: Recent Developments and Perspectives," *Electronics*, vol. 12, no. 11, 2023, doi: 10.3390/electronics12112490.
- [9] J. Kua, S. W. Loke, C. Arora, N. Fernando, and C. Ranaweera, "Internet of Things in Space: A Review of Opportunities and Challenges from Satellite-Aided Computing to Digitally-Enhanced Space Living," *Sensors*, vol. 21, no. 23, 2021, doi: 10.3390/s21238117.
- [10] I. Mujahidin, S. H. Pramono, and A. Muslim, "5.5 GHz Directional Antenna with 90 Degree Phase Difference Output," in *2018 Electrical Power, Electronics, Communications, Controls and Informatics Seminar, EECCIS 2018*, 2018. doi: 10.1109/EECCIS.2018.8692872.
- [11] Y. Wei, C. Arnold, and J. Hong, "Multiport Beamforming System Based on Reconfigurable Waveguide Phased Antenna Array for Satellite Communication Applications," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3261671.
- [12] O. Ledesma, P. Lamo, and J. A. Fraire, "Trends in LPWAN Technologies for LEO Satellite Constellations in the NewSpace Context," *Electronics*, vol. 13, no. 3, 2024, doi: 10.3390/electronics13030579.
- [13] G. Koukis and V. Tsaoussidis, "Satellite-Assisted Disrupted Communications: IoT Case Study," *Electronics*, vol. 13, no. 1, 2024, doi: 10.3390/electronics13010027.
- [14] I. A. Qureshi and S. Asghar, "A Systematic Review of the IEEE-802.11 Standard's Enhancements and Limitations," *Wireless Personal Communications*, vol. 131, no. 4, pp. 2539–2572, 2023, doi: 10.1007/s11277-023-10553-7.
- [15] L. Anchidin, A. Lavric, P.-M. Mutescu, A. I. Petrariu, and V. Popa, "The Design and Development of a Microstrip Antenna for Internet of Things Applications," *Sensors (Basel, Switzerland)*, vol. 23, no. 3, Jan. 2023, doi: 10.3390/s23031062.
- [16] H. Das, M. Sharma, and Q. Xu, "Microstrip Antenna: An Overview and Its Performance Parameter," in *Smart Antennas: Latest Trends in Design and Application*, P. K. Malik, J. Lu, B. T. P. Madhav, G. Kalkhambkar, and S. Amit, Eds., Cham: Springer International Publishing, 2022, pp. 3–14. doi: 10.1007/978-3-030-76636-8_1.
- [17] Z. Wang, M. Wang, and W. Nie, "Design of a Dual-Band WiFi Antenna Using the Theory of Characteristic Modes and Nested Chinese Characters," *Electronics (Switzerland)*, vol. 12, no. 16, 2023, doi: 10.3390/electronics12163465.
- [18] Z. Chen, B. Lu, Y. Zhu, and H. Lv, "A compact printed monopole antenna for WiMAX/WLAN and UWB applications," *Future Internet*, vol. 10, no. 12, 2018, doi: 10.3390/fi10120122.
- [19] A. U. Fakhridinovich, M. A. Sufian, W. A. Awan, N. Hussain, and N. Kim, "A Compact Antenna With Multiple Stubs for ISM, 5G Sub-6-GHz, and WLAN," *IEEE Access*, vol. 11, pp. 130418–130425, 2023, doi: 10.1109/ACCESS.2023.3333881.
- [20] K. N. Olan-núñez and R. S. Murphy-Arteaga, "Dual-Band Antenna on 3D-Printed Substrate for 2.4/5.8 GHz ISM-Band Applications," *Electronics*, vol. 12, no. 11, 2023, doi: <https://doi.org/10.3390/electronics12112368>.
- [21] I. Mujahidin, D. A. Prasetya, A. B. Setywan, and P. S. Arinda, "Circular Polarization 5.5 GHz Double Square Margin Antenna in the Metal Framed Smartphone for SIL Wireless Sensor," in *Proceedings - 2019 International Seminar on Intelligent Technology and Its Application, ISITIA 2019*, 2019. doi: 10.1109/ISITIA.2019.8937257.
- [22] M. A. Jamlos *et al.*, "5.8 GHz Circularly Polarized Rectangular Microstrip Antenna Arrays simulation for Point-to-Point Application," *Journal of Advanced Research in Applied Sciences and Engineering Technology*, vol. 28, no. 3, pp. 209–220, 2022, doi: 10.37934/araset.28.3.209220.
- [23] A. Sattarzadeh *et al.*, "Satellite-Based Non-Terrestrial Networks in 5G: Insights and Challenges," *IEEE Access*, vol. 10, 2022, doi: 10.1109/ACCESS.2021.3137560.

- [24] I. Mujahidin, D. A. Prasetya, Nachrowie, S. A. Sena, and P. S. Arinda, "Performance tuning of spade card antenna using mean average loss of backpropagation neural network," *International Journal of Advanced Computer Science and Applications*, 2020, doi: 10.14569/ijacsa.2020.0110280.
- [25] G. Adhitya, V. Abishek, R. M. Sundaram, and P. Jothilakshmi, "Design of Microstrip Antenna for X Band Satellite Communications," *International Journal of Research and Analytical Reviews (IJRAR)*, vol. 6, no. 2, 2019.
- [26] I. Mujahidin and A. Kitagawa, "CP Antenna with 2×4 Hybrid Coupler for Wireless Sensing and Hybrid RF Solar Energy Harvesting," *Sensors (Switzerland)*, vol. 21, pp. 1–20, 2021, doi: 10.3390/s21227721.
- [27] P. Angeletti and R. De Gaudenzi, "Optimizing Massive MIMO Design for Non Uniform Traffic in Broadband Telecommunication Satellites Networks," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3322445.
- [28] I. Mujahidin and A. Kitagawa, "The Novel CPW 2.4 GHz Antenna with Parallel Hybrid Electromagnetic Solar for IoT Energy Harvesting and Wireless Sensors," *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 8, 2021, doi: 10.14569/IJACSA.2021.0120845.
- [29] H. N. Al-Anbagi and I. Vertat, "Embracing Small Satellites Into Future 6G Inclusive IoT Coverage: A Deployment of Diversity-Based Theoretical Framework," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3324890.
- [30] I. Mujahidin and A. Kitagawa, "Ring slot CP antenna for the hybrid electromagnetic solar energy harvesting and IoT application," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 21, no. 2, pp. 290–301, 2023, doi: 10.12928/TELKOMNIKA.v21i2.24739
- [31] A. J. Rubio, A. S. Kaddour, H. Pruett, S. Magleby, L. L. Howell, and S. V. Georgakopoulos, "A Deployable Volume-Efficient Miura-Ori Reflectarray Antenna for Small Satellite Applications," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3327057.
- [32] D. A. Prasetya, A. Sanusi, G. Chandrarin, E. Roikhah, I. Mujahidin, and R. Arifuddin, "Small and Medium Enterprises Problem and Potential Solutions for Waste Management," *Journal of Southwest Jiaotong University*, 2019, doi: 10.35741/issn.0258-2724.54.6.21.
- [33] J. S. Roper and A. F. Peterson, "Modeling and Mitigation of Time Delay Error for Non-Timed Arrays in Satellite Communications," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3311753.
- [34] N. J. G. Fonseca, "Very Compact Waveguide Orthomode Transducer in the K-Band for Broadband Communication Satellite Array Antennas," *Sensors*, vol. 23, no. 2, 2023, doi: 10.3390/s23020735.
- [35] J. H. Lee, J. S. Joo, P. Kim, and J. G. Ryu, "Random Beam-Based Non-Orthogonal Multiple Access for Massive MIMO Low Earth Orbit Satellite Networks," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3296788.
- [36] N. Supreeyatitikul, A. Boonpoonga, and C. Phongcharoenpanich, "Z-Shaped Metasurface-Based Wideband Circularly Polarized Fabry-Pérot Antenna for C-Band Satellite Technology," *IEEE Access*, vol. 10, 2022, doi: 10.1109/ACCESS.2022.3179360.
- [37] M. Hasib, S. Kandeepan, W. S. T. Rowe, and A. Al-Hourani, "Direction-of-Arrival (DoA) Estimation Performance for Satellite Applications in a Multipath Environment with Rician Fading and Spatial Correlation," *Sensors*, vol. 23, no. 12, 2023, doi: 10.3390/s23125458.
- [38] J. Cho, Y. Seo, W. Shin, E. Lee, and S. Kahng, "Channel Selectivity of Satellite Transponders with the Antenna Combined with a Size-Reduced Metallic Waveguide Bandpass Filter Having Thin Metamaterial Resonators," *Sensors*, vol. 23, no. 4, 2023, doi: 10.3390/s23041948.
- [39] Y. Jiang, J. Fu, B. Li, and P. Jiang, "Distributed Sensitivity and Critical Interference Power Analysis of Multi-Degree-of-Freedom Navigation Interference for Global Navigation Satellite System Array Antennas," *Sensors*, vol. 24, no. 2, 2024, doi: 10.3390/s24020650.
- [40] M. Ikram, K. Sultan, A. T. Mobashsher, M. Moosazadeh, and A. Abbosh, "Wide-Angle Beam Steering Closed-Form Pillbox Antenna Fed by Substrate-Integrated Waveguide Horn for On-the-Move Satellite Communications," *Sensors*, vol. 24, no. 3, 2024, doi: 10.3390/s24030732.
- [41] A. M. Al-Saegh *et al.*, "AI-Based Investigation and Mitigation of Rain Effect on Channel Performance With Aid of a Novel 3D Slot Array Antenna Design for High Throughput Satellite System," *IEEE Access*, vol. 12, 2024, doi: 10.1109/ACCESS.2024.3368829.
- [42] D. Caratelli, R. Cicchetti, V. Cicchetti, and O. Testa, "A Wideband High-Gain Circularly-Polarized Dielectric Horn Antenna Equipped With Lamé-Axicon Stacked-Disk Lens for Remote Sensing, Air Traffic Control and Satellite Communications," *IEEE Access*, vol. 11, 2023, doi: 10.1109/ACCESS.2023.3249114.