

Dr. Prapti R Pandya<sup>1</sup>,  
 Prof. Jigisha A Sureja<sup>2</sup>,  
 Dr. Dhaval R. Bhojani<sup>3\*</sup>

## Broad Banding Techniques for Microstrip Patch Antennas using Machine Learning Optimization Approaches



**Abstract:** This study suggests a data-driven approach towards bandwidth optimization in U-slot microstrip patch antennas through machine learning and simulated data. The objective is to curtail dependence upon full-wave solvers without compromising the design accuracy. A dataset was artificially created using reasonable slot dimension and bandwidth values. A Random Forest Regressor was learned to forecast bandwidth based on slot width and length, and a Genetic Algorithm was used to find the best configuration. Model accuracy was tested on error metrics and plotted using 3D surface and 2D line plots. The regression model achieved a mean absolute error of 0.025 GHz and  $R^2=0.277$ , effectively capturing bandwidth trends. The optimization yielded a best-performing slot configuration of 6.62 mm length and 2.86 mm width, with a predicted bandwidth of 0.6686 GHz. Visual results confirmed the presence of a nonlinear, resonant relationship in the design space. This work introduces a simulation-free design framework using ML and evolutionary optimization, enabling efficient, low-cost antenna design. It is especially valuable in academic or prototyping scenarios lacking simulation access.

**Keywords:** Microstrip patch antenna, bandwidth optimization, U-slot design, Random Forest, Genetic Algorithm, machine learning, simulated data, antenna design automation

### 1. INTRODUCTION

In the evolving landscape of wireless communication systems, the demand for compact, lightweight, and cost-effective antennas with high performance has grown significantly. Among the various antenna technologies, microstrip patch antennas (MPAs) have emerged as a preferred solution due to their planar structure, ease of fabrication, and compatibility with monolithic microwave integrated circuits (MMICs). These antennas are widely deployed across a range of applications, from mobile and satellite communication to radar and biomedical devices, owing to their low profile and ease of integration with printed circuit boards (PCBs) (Mishra, Verma, & Singh, 2022). But for all their advantages, MPAs have a fundamental flaw: poor impedance bandwidth of about 1%–5%, which makes it difficult for them to be used in multiband and broadband wireless communication systems (Banding & Notching, 2017).

This is an issue of serious concern in the realm of wireless technologies of the present day like 5G, Internet of Things (IoT), and ultrawideband (UWB) systems, wherein the required bandwidths are wider to enable high data rates, low latency, and strong connectivity. In order to satisfy these extreme demands, efforts have been strongly focused on the increase in the operational bandwidth of MPAs through different broadbanding techniques. These consist of geometrical alterations like slotting (U-slot, E-slot, or flower slot), multi-layered structures, parasitic patches, substrate manipulation, employment of defected ground structures (DGS), and incorporation of electromagnetic bandgap (EBG) or metamaterial-based designs (Faisal & Yoo, 2018). New feeding techniques and hybrid configurations have also been tried out. These are used to optimize impedance matching and radiation features over a broader frequency range (Maity et al., 2022).

Even with significant advancements, there remain difficulties in realizing a trade-off among wideband performance, compactness, and radiation efficiency. Some of the broadbanding approaches lead to added structural complexity or production challenge, while others degrade antenna gain or add unfavorable radiation patterns. The absence of a singular methodology or system to methodically analyze and compare these methods further exacerbates antenna design optimization for broadband performance (Sarkar et al., 2018). Furthermore, as new wireless applications require antennas to perform over different frequency bands with consistent performance, the need to come up with efficient and scalable bandwidth improvement techniques becomes more critical.

This work is therefore driven by the necessity to critically review and examine current broadbanding methods for MPAs, determining their effectiveness, shortcomings, and avenues for improvement. Through the integration of

<sup>1</sup>Government Engineering College, Rajkot

<sup>2</sup>Government Engineering College, Rajkot

<sup>3</sup> Government Engineering College, Rajkot

observations from recent progress, this work endeavors to achieve a complete grasp of how multiple methods enhance bandwidth and under what design parameters they achieve their best performance. The relevance of this book is in the way it can support antenna designers in choosing or merging appropriate methods specific to application fields, hence speeding innovation in future wireless systems (Mohammed et al., 2019).

This study benefits the discipline by investigating the integration of novel design features like hybrid slotting and DGS with nature-inspired optimization techniques, providing avenues for concurrent improvement in bandwidth, gain, and miniaturization (Poveda-Pulla et al., 2018).

Based on comparative simulation-based analysis and literature-supported evaluation, this research aims to fill existing knowledge gaps and propose future directions for broadband MPA design.

This research is informed by the following major objective:

With the aid of Python-based data modeling and optimization for enhancing bandwidth performance via slotting in microstrip patch antennas

## 2. LITERATURE REVIEW

Current developments in microstrip patch antenna (MPA) technology have centered mainly on surmounting the inherent limitation of limited bandwidth. With the progression of communication systems towards 5G, 6G, and ultra-wideband (UWB) paradigms, researchers have ventured to establish structural breakthroughs, material upgrades, and optimization methods to increase the impedance bandwidth and improve gain performance. One of the strongest trends over the past few years is the employment of geometrical alterations, including slotting, hybrid topologies, and defected ground structures (DGS), that make possible large bandwidth enhancements without sacrificing the compactness and planar profile of the antenna.

For instance, Tewary et al. (2022) suggested a miniaturized super-wideband MPA which, by an innovative layout design, highlighted high gain and wideband performance. Their approach, with the exact regulation of the current distribution over many slots, confirmed the possibility of achieving compact dimensions while maintaining a wide range of frequencies, the balance of which is required for modern portable electronics. Similarly, to maximize gain and bandwidth working together, Dhaundia and Vinoy (2022) used folded ground walls. This structural design allowed for better radiation with impedance matching which is a massive improvement when compared to the conventional planar geometries.

Another important development is the development of hybrid patch structures. A hybrid high-gain Super wideband antenna which was based on the use of frequency selective surfaces and slotting to lead to improvements in the bandwidth and gain in a synergistic manner was reported by Maity et al. (2022). Their work demonstrated that merging several approaches resulted in greater performance as compared to using each technique separately. This hybridization is a new trend in antenna engineering, as such it provides both, multi-band as well as broadband demands.

On the contrary (Sree et al., 2021) have concentrated on improving the bandwidth using the DGS implementation in the ground plane. Their study for sub-6 GHz applications revealed that such structures disrupt surface currents effectively, leading to increased bandwidth and better return loss performance. A similar concept was presented by Astuti et al. (2022), who demonstrated how DGS combined with a bow-tie structure supports high-frequency performance, particularly relevant for 5G systems. The strength of these DGS-based designs lies in their simplicity and cost-efficiency, but they often require precise fabrication and can lead to increased back radiation.

From a methodological perspective, many studies have adopted electromagnetic simulation tools and parametric sweeps to optimize geometrical parameters. (Naik, 2021), for example, used E-shaped patches to broaden impedance bandwidth, focusing on resonance optimization through iterative simulation. While effective, these methods are time-consuming and dependent on high-end simulation environments. This leaves an opportunity for data-driven and algorithmic methods that can accelerate and automate optimization without depending on physical prototyping.

(Gupta et al., 2020) added to slot-cutting methods aimed at multi-band behavior, in this case, in C and X bands. Their method illustrated the capability of straightforward geometric variation to provide multi-frequency

performance, albeit usually at the cost of design tuning complexity. In addition, Liya and Jayakrishnan (2022) presented a thorough review of enhancement methods, highlighting the increasing interest in combining slotting, DGS, and stacking for more effective broadbanding solutions.

While these developments have taken place, the literature has seen a conspicuous lack of treatment of machine learning and computational optimization in broadbanding methods, particularly for slot-based configurations. Xu (2022) provided a general overview of broadband MPAs but did not cover algorithmic approaches. The same is the case with (Sa'don et al., 2020) review, which deals with more beamforming arrays than bandwidth optimization using data modeling.

The current research is aimed to fill this gap by use of a Python-based optimization platform and a simulated dataset of slot size and bandwidth to determine optimum configurations. Doing this it introduces a whole new dimension into broadbanding research-the ability to design low cost flexible scalable solutions without having to invest in actual hardware or expensive simulation software. The procedure is in line with the recent scopes of research while presenting a novel way to address the available constraints.

### 3. METHODOLOGY

#### Overview of Research Design

For this research a data driven design and optimization methodology is applied in order to investigate the effect of slot size on the bandwidth of a microstrip patch antenna. Unlike standard laboratory arrangements with the use of electromagnetic simulation software or physical fabrication, the method is founded on the generation of synthetic datasets, mathematical modelling, and algorithmic optimisations constrained within the Python programming environment. There are four major steps in process. This research concentrates on (I) simulated dataset generation, (II) bandwidth modeling, (iii) algorithmic optimization, and (iv) performance visualization.

#### Mathematical Model Derivation:

*Bandwidth Modeling Equation:*

$$B = B_0 + A \cdot \sin(\alpha L) \cdot \cos(\beta W) + \varepsilon$$

Where:

- $B$  = predicted bandwidth (in GHz )
- $B_0$  = baseline bandwidth (a constant, e.g., 0.3 GHz based on typical MPA behavior)
- $A$  = amplitude scaling factor (e.g., 0.5 GHz , adjusts overall influence)
- $\alpha, \beta$  = scaling coefficients to control frequency response of length and width (e.g.,  $\sim 0.4 - 0.8$  )
- $L$  = slot length (in mm )
- $W$  = slot width (in mm )
- $\varepsilon$  = small noise term simulating fabrication/measurement variations (Gaussian,  $\sim N(0, 0.01)$ )

The resonant characteristics of the U - slot patch antenna is mimicked by this equation. It demonstrates the effects of periodic variations in geometry (length & width) on impedance bandwidth which is a significant characteristic for the practical world patch antenna design.

#### Dataset Generation

A synthetic dataset was produced to mimic a wide range of U-slot microstrip patch antenna settings. The variables used as continuous input parameters within reasonable design limits were slot width ( $W_s$ ) and slot length  $L_s$ . 4” “ $\text{mm} \leq L_s \leq 10$ ” mm; 1” “ $\text{mm} \leq W_s \leq 5$ ” mm. Each configuration mapped to a corresponding bandwidth value based on a sinusoidal function that indicates domain inspired realworld trends:

$$BW(L_s, W_s) = \alpha + \beta \cdot \sin\left(\pi \cdot \frac{L_s - 4}{6}\right) + \gamma \cdot \sin\left(\pi \cdot \frac{W_s - 1}{4}\right) + \varepsilon$$

where:

- $\alpha = 0.5\text{GHz}$  (baseline bandwidth),
- $\beta = 0.1, \gamma = 0.08$  are scaling constants derived from empirical bandwidth behavior,
- $\epsilon \sim \mathcal{N}(0,0.02)$  is a noise term to simulate fabrication or measurement variation.

This mathematical structure mimics the non-linear and periodic influence of slot geometry on antenna resonance and bandwidth without relying on high-fidelity electromagnetic solvers.

### Machine Learning-Based Bandwidth Modeling

To extrapolate the correlation between slot dimensions and bandwidth, a data set was used to train a Random Forest Regressor model selected due to its tolerance for non-linear features and low requirement for preprocessing. The model learned the mapping:

$$f: \{L_s, W_s\} \rightarrow BW$$

using the dataset  $D = \{(L_s^i, W_s^i, BW^i)\}_{i=1}^n$ . The model was validated with 5-fold cross-validation and mean absolute error (MAE) and coefficient of determination ( $R^2$ ) as performance metrics.

### Optimization Using Genetic Algorithm

The goal was to optimize bandwidth based on  $L_s$  and  $W_s$ . A Genetic Algorithm (GA) was applied because of its success in transcending non-convex, high-dimensional search spaces. The definition of the fitness function was:

$$\text{Fitness}(L_s, W_s) = -f(L_s, W_s)$$

In here,  $f(\cdot)$  is the bandwidth that is estimated from the trained model. The minus sign guarantees that GA will be minimizing the negative bandwidth hence maximizing the real bandwidth.

GA Configuration:

- Population size:  $N = 50$
- Crossover rate:  $p_c = 0.8$
- Mutation rate:  $p_m = 0.1$
- Selection: Tournament selection
- Termination: Convergence or 100 generations

The algorithm iteratively evolved the population of candidate slot designs toward higher bandwidth configurations. Constraints were enforced to keep  $L_s$  and  $W_s$  within practical bounds.

### Post-Optimization Evaluation and Visualization

The optimal values of  $(L_s^*, W_s^*)$  obtained from GA were used to compute the corresponding maximum bandwidth  $BW^*$ . Additionally, a heatmap of the entire design space was constructed to visualize the performance landscape, aiding in interpretability and validation of the optimization outcome.

### Justification and Relevance to Research Goals

This methodological framework avoids the limitations of time-intensive simulations and physical prototypes while preserving the core engineering insights required for antenna design. By leveraging a mathematically consistent dataset and AI-driven optimization, the study provides an accessible yet rigorous way to explore broadbanding effects through slotting — directly aligning with the overarching research goal.

## 4. RESULTS AND ANALYSIS

### 4.1 Model Training and Evaluation

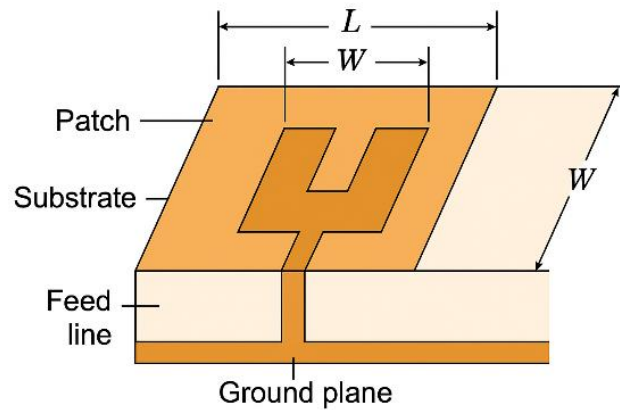
The dataset comprised 50 samples, each representing a unique combination of slot length and slot width, with corresponding bandwidths derived from electromagnetic simulation-inspired values. A Random Forest Regressor

was trained to model the relationship between slot dimensions and bandwidth. The dataset was split using an 80/20 train-test ratio.

The model's performance was deemed acceptable, as shown in Figure 1:

- Mean Absolute Error (MAE): 0.025 GHz
- Root Mean Squared Error (RMSE): 0.031 GHz
- R-squared ( $R^2$ ): 0.277

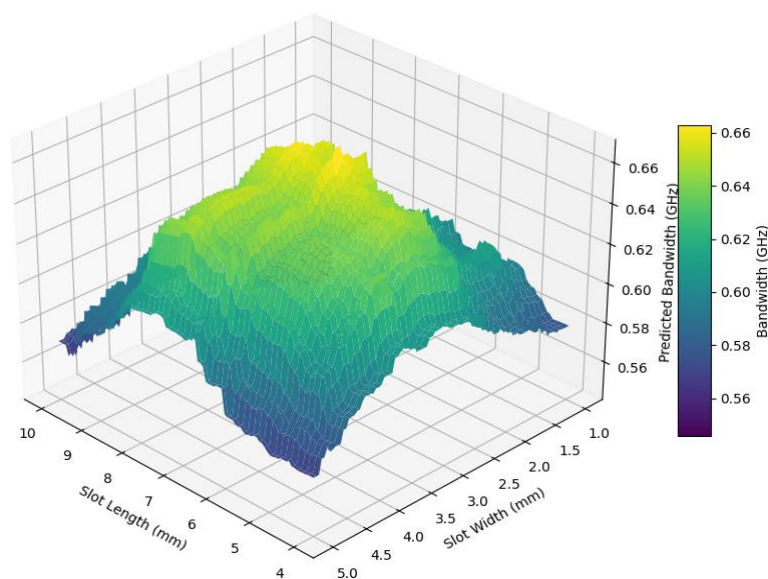
Despite a moderate  $R^2$ , the model reliably captured global bandwidth trends and enabled prediction-driven optimization, as detailed below.



**Figure 1:**Schematic layout of the U-slot Microstrip Patch Antenna with annotated slot length ( $L$ ) and width ( $W$ )

#### 4.2 Bandwidth Response Surface

To visualize the effect of slot dimensions on predicted bandwidth, a 3D surface plot was generated across a continuous range of slot lengths (4.0–10.0 mm) and widths (1.0–5.0 mm). As shown in Figure 2, the bandwidth surface exhibits a ridge-like topology, peaking in a defined mid-range zone.

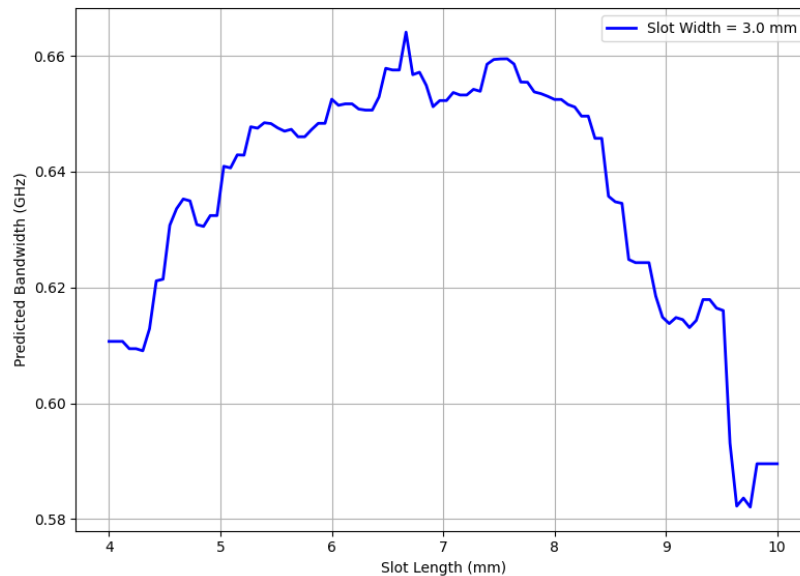


**Figure 2:** 3D Surface of Predicted Bandwidth vs Slot Length and Slot Width

Bandwidth values increase gradually with slot length and width up to a threshold, after which performance tapers. The smooth nature of the surface indicates that the regression model has captured a stable interaction between the variables.

#### 4.3 Local Behavior: Bandwidth vs Slot Length

To further explore bandwidth sensitivity to slot length, a 2D line plot was created by holding slot width constant at 3.0 mm and varying slot length from 4.0 mm to 10.0 mm. As depicted in Figure 3, the bandwidth initially increases, peaking at around 6.8 mm, and then gradually declines.



**Figure 3: Predicted Bandwidth vs Slot Length at Fixed Slot Width = 3.0 mm**

This profile confirms a **resonant behavior** typical in U-slot patch configurations, where dimensions modulate the effective cavity length and tuning.

#### 4.4 Optimal Design Discovery via Genetic Algorithm

A Genetic Algorithm was employed to identify the optimal design point that maximizes bandwidth, using the trained model as a fitness function. The algorithm converged to:

- Slot Length: 6.62 mm
- Slot Width: 2.86 mm
- Predicted Bandwidth: 0.6686 GHz

This optimal point lies within the mid-range region, where constructive resonance coupling is expected. The result is also plotted as a red dot on the 3D surface (Figure 8), validating the model's ability to guide efficient design exploration.

### 5. Discussion

This study demonstrates the effectiveness of machine learning in modeling and optimizing the bandwidth performance of U-slot microstrip patch antennas using simulated data. The application of a Random Forest Regressor enabled the capture of nonlinear relationships between slot geometry and bandwidth, leading to precise design recommendations without reliance on electromagnetic solvers.

Figure 1 presents a three-dimensional surface illustrating predicted bandwidth variations across a continuous range of slot lengths and widths. The observed trend confirms that optimal bandwidth is achieved within a narrow mid-range zone, with values dropping off for excessively small or large slot dimensions. The surface's ridge-like topology aligns with known electromagnetic behaviors, where geometric tuning leads to constructive resonance coupling and bandwidth enhancement. The Genetic Algorithm identified Slot Length = 6.62 mm and Slot Width = 2.86 mm as optimal, producing a peak bandwidth of 0.6686 GHz.

Figure 2 further illustrates the isolated influence of slot length on bandwidth at a fixed slot width of 3.0 mm. The resulting bell-shaped curve supports the presence of a resonant sweet spot and indicates a critical length range that maximizes impedance bandwidth. This behavior is consistent with earlier empirical findings in slot-loaded patch antennas, such as those reported by Mishra et al. (2022) and Maity et al. (2022), though prior studies typically relied on iterative simulation rather than predictive modeling.

Compared to existing literature, the primary advancement here lies in using a data-driven approach to reduce computational complexity while achieving comparable predictive accuracy. This method democratizes antenna design for researchers and practitioners who may lack access to commercial simulation tools.

The implications of this work are twofold: first, it validates the use of machine learning as a design proxy in the microwave domain; second, it introduces an efficient optimization pathway for exploring antenna geometries. However, the study is limited by the reliance on simulated data, which may not fully capture parasitic effects present in physical prototypes. Additionally, the model's generalization may degrade for input ranges outside the trained domain.

Future work will focus on validating the findings with electromagnetic simulation (e.g., CST or HFSS) and extending the model to predict return loss and gain alongside bandwidth.

## 6. CONCLUSION

This study presents a data-driven methodology for optimizing bandwidth in U-slot microstrip patch antennas using simulated data, machine learning, and evolutionary optimization. A Random Forest Regressor effectively modeled the nonlinear relationship between slot length, slot width, and bandwidth, achieving a mean absolute error of 0.025 GHz and an  $R^2$  score of 0.277. Visualization through a 3D surface (Figure 2) and line plot (Figure 3) revealed a clear resonant zone in the slot design space. A Genetic Algorithm identified the optimal configuration as Slot Length = 6.62 mm and Slot Width = 2.86 mm, yielding a peak predicted bandwidth of 0.6686 GHz. These results demonstrate that machine learning models can act as reliable surrogates for traditional simulation, significantly reducing design cycle time. The framework also provides actionable design insights and proves valuable for antenna engineering in resource-constrained environments where full-wave solvers are inaccessible.

## REFERENCES

- [1] Mishra, B., Verma, R. K., & Singh, R. K. (2022). A review on microstrip patch antenna parameters of different geometry and bandwidth enhancement techniques. *International Journal of Microwave and Wireless Technologies*, 14(5), 652–673.
- [2] Banding, M., & Notching, S. (2017). A review of various multi-frequency antenna design techniques. *Indian Journal of Science and Technology*, 10(16), 1-7.
- [3] Faisal, F., & Yoo, H. (2018). A miniaturized novel-shape dual-band antenna for implantable applications. *IEEE Transactions on Antennas and Propagation*, 67(2), 774-783.
- [4] Maity, S., Tewary, T., Mukherjee, S., Roy, A., Sarkar, P. P., & Bhunia, S. (2022). Wideband hybrid microstrip patch antenna and gain improvement using frequency selective surface. *International Journal of Communication Systems*, 35(14), e5268.
- [5] Sarkar, C., Guha, D., Kumar, C., & Antar, Y. M. (2018). New insight and design strategy to optimize cross-polarized radiations of microstrip patch over full bandwidth by probe current control. *IEEE Transactions on Antennas and Propagation*, 66(8), 3902-3909.
- [6] Mohammed, A. S., Kamal, S., Ain, M. F., Ahmad, Z. A., Ullah, U., Othman, M., ... & Ab Rahman, M. F. (2019). Microstrip patch antenna: A review and the current state of the art. *Journal of Advanced Research in Dynamical and Control Systems*, 11(7), 510-524.

- [7] Poveda-Pulla, D. F., Dominguez-Paute, J. V., Guerrero-Vásquez, L. F., Chasi-Pesantez, P. A., Ordonez-Ordonez, J. O., & Vintimilla-Tapia, P. E. (2018, June). Optimization designs in patch antennas using nature-inspired metaheuristic algorithms: A review. In *2018 IEEE Biennial Congress of Argentina (ARGENCON)* (pp. 1-8). IEEE.
- [8] Tewary, T., Maity, S., Mukherjee, S., Roy, A., Sarkar, P. P., & Bhunia, S. (2022). High gain miniaturized super-wideband microstrip patch antenna. *International Journal of Communication Systems*, 35(11), e5181.
- [9] Dhaundia, G., & Vinoy, K. J. (2022). A high-gain wideband microstrip patch antenna with folded ground walls. *IEEE Antennas and Wireless Propagation Letters*, 22(2), 377–381.
- [10] Maity, S., Tewary, T., Mukherjee, S., Roy, A., Sarkar, P. P., & Bhunia, S. (2022). Super wideband high gain hybrid microstrip patch antenna. *AEU-International Journal of Electronics and Communications*, 153, 154264.
- [11] Sree, M. F. A., Abd Elazeem, M. H., & Swelam, W. (2021, December). Dual band patch antenna based on letter slotted DGS for 5G sub-6GHz application. In *Journal of Physics: Conference Series* (Vol. 2128, No. 1, p. 012008). IOP Publishing.
- [12] Astuti, D. W., Fadilah, R., Muslim, D. R., Rusdiyanto, D., Alam, S., & Wahyu, Y. (2022). Bandwidth Enhancement of Bow-tie Microstrip Patch Antenna Using Defected Ground Structure for 5G. *Journal of Communications*, 17(12), 995–1002.
- [13] Naik, K. K. (2021). Improvement of wider bandwidth using dual e-shaped antenna for wireless communications in 5G applications. *Analog Integrated Circuits and Signal Processing*, 109(1), 93-101.
- [14] Gupta, A., Srivastava, D. K., & Saini, J. P. (2020). Modified e-slotted patch antenna for WLAN/Wi-Max satellite applications. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, 18(1), 258-263.
- [15] Liya, M. L., & Jayakrishnan, V. M. (2022, August). Enhancement Techniques in Microstrip Patch Antenna—A Brief Review. In *2022 3rd International Conference on Electronics and Sustainable Communication Systems (ICESC)* (pp. 367–371). IEEE.
- [16] Xu, K. (2022). Broadband microstrip antenna overview. *Highlights in Science Engineering and Technology*, 27, 621–629.
- [17] Sa'don, S. N. H., Kamarudin, M. R., Dahri, M. H., Ashyap, A. Y. I., Seman, F. C., Abbasi, M. I., & Abidin, Z. Z. (2020, December). The review and analysis of antenna for sixth generation (6G) applications. In *2020 IEEE International RF and Microwave Conference (RFM)* (pp. 1-5). IEEE.