Forest Resonance Model: A Novel Forest-Inspired Approach to Microwave Antenna Signal Strength Estimation

Rytis Maskeliunas
Centre of Real Time Computer Systems
Kaunas University of Technology
Kaunas, Lithuania
rytis.maskeliunas@ktu.lt

Darius Plonis
Department of Electronic Systems
Vilnius Gediminas Technical University
Vilnius, Lithuania
darius.plonis@vilniustech.lt

Robertas Damasevicius
Faculty of Applied Mathematics
Silesian University of Technology
Gliwice, Poland
robertas.damasevicius@polsl.pl

***Abstract*—Microwave antenna design optimization has always been a challenge due to the intricate relationships between design parameters and signal strength. Traditional models often fail to capture the nuanced interactions between these parameters. Drawing inspiration from the dynamics of a forest ecosystem, we introduce the Forest Resonance Model (FRM) to estimate signal strength based on antenna design parameters. The primary goal of this research is to develop and validate a novel forest-inspired model that can accurately predict the signal strength of microwave antennas based on design parameters. The FRM offers a fresh perspective on microwave antenna design optimization by bridging the gap between nature-inspired concepts and machine learning and highlights the potential of drawing inspiration from natural systems for complex engineering challenges. The FRM conceptualizes each antenna design as a tree, with its attributes such as TestFreq, PatchLength, PatchWidth, SlotLength, and SlotWidth determining its height, base width, and health. The interactions between these "trees" (antenna designs) mimic the feature space interactions in machine learning. We implemented this concept using a modified Random Forest algorithm, incorporating feature engineering techniques to capture combined effects of design parameters. The dataset, comprising different antenna designs and their corresponding signal strengths, was used to train and validate the model. Preliminary results indicate that the our enhanced FRM model provides superior prediction accuracy compared to traditional models. The feature importance scores derived from the model shed light on the most influential design parameters, offering insights into optimal antenna design. The manufactured optimized antenna design was confirmed through a series of signal strength measurements in lab environment.**

***Index Terms*—Forest Resonance Model, Microwave Antenna, Signal Strength Estimation, Forest-Inspired Computing.**

I. INTRODUCTION

Microwave antennas, essential components in modern communication systems, have been the subject of extensive research and development over the past decades [1]. Traditional design methodologies primarily focus on deterministic approaches, where design parameters are adjusted to meet specific performance criteria. These methods, while effective for a range of applications, often require a deep understanding of electromagnetic theory and can be computationally intensive. Furthermore, they may not always capture the intricate, non-linear relationships between design parameters and performance metrics, such as signal strength [2].

In recent years, there has been a growing interest in harnessing the power of nature-inspired algorithms to solve complex optimization problems [3]. These algorithms, which draw inspiration from natural phenomena and biological processes [4], [5], offer heuristic solutions to problems that are often challenging for traditional methods. For instance, genetic algorithms, inspired by the process of natural selection, have been employed to optimize antenna designs by mimicking the evolutionary process [6]. Similarly, swarm intelligence algorithms, inspired by the collective behavior of decentralized systems like bird flocking or fish schooling, have shown promise in navigating large solution spaces efficiently [7]. The appeal of nature-inspired techniques [8] lies in their adaptability, robustness, and capability to find global optima in complex landscapes.

The primary objective of this study is to introduce and validate a novel forest-inspired model, the Forest Resonance Model (FRM), for estimating microwave antenna signal strength based on design parameters and by bridging the gap between traditional antenna design methodologies and nature-inspired optimization techniques. We aim to provide a robust and intuitive approach to antenna design optimization.

The novelty of this research lies in the conceptualization of the FRM, where each antenna design is visualized as a tree within a forest ecosystem, with its attributes and interactions determining its performance. This unique perspective offers a fresh lens through which the relationships between design parameters can be understood and visualized. Our contribution extends beyond the mere introduction of this model. We provide a comprehensive implementation strategy, ensuring the practical applicability of the FRM in real-world scenarios. Furthermore, by comparing the FRM's performance with traditional models, we highlight its potential advantages and pave the way for future research in this direction.

II. RELATED WORK

The antenna and microwave circuit design is witnessing rapid advancements, driven by the integration of optimization algorithms and artificial intelligence techniques [9]. As wireless communication continues to evolve, the need for efficient and optimized antenna designs will only grow, making the contributions of these algorithms even more significant [10]. The integration of nature-inspired optimization techniques and machine learning algorithms [11] has emerged as a promising approach to address the complexities and challenges in designing efficient and high-performance antennas [12]. The continuous evolution of these techniques, combined with the increasing demands of modern communication systems, underscores the importance of interdisciplinary research in this domain [2].

Obviously, in the rapidly evolving domain of wireless communication, antennas and radio frequency (RF)/microwave circuit designs play a pivotal role [13]. The significance of these components in our daily lives and industrial engineering cannot be overstated [14]. As wireless communication becomes more integral to our daily operations, there's an increasing need for optimization in antenna and circuit designs to ensure efficiency and performance [15]. Optimization algorithms have been extensively employed in the design of antennas and RF/microwave circuits [16], [17]. Yeung et al. [14] provided a comprehensive overview of these algorithms, emphasizing their importance in wireless communication. Their paper also highlighted the necessity of optimization in this domain, focusing on three widely-used algorithms for antenna and RF/microwave circuit design.

Shape optimization techniques have emerged as a powerful tool in enhancing the performance of devices by altering their geometrical or topological parameters [18]. These techniques, which are based on the computation of a cost function related to the device's response, have shown promise in pushing the boundaries of classical designs [19]. Goudos et al. [3] discussed the multi-objective nature of antenna and microwave design problems. They introduced three state-of-the-art MOEAs based on Particle Swarm Optimization (PSO) and Differential Evolution (DE), demonstrating their efficacy in solving complex design problems. These algorithms were compared against other evolutionary multi-objective algorithms, revealing the advantages of each. Ohira et al. [20] proposed an efficient design method for filtering antennas, emphasizing the importance of evaluating various parameters such as the external Q factor and radiation Q factor. Their approach streamlined the design process, offering a more efficient alternative to conventional methods.

Microwave imaging has been identified as a potent tool in detecting breast cancer, offering a more effective approach compared to traditional imaging methods [21]. The study presented comprehensive design equations for a rectangular microstrip patch antenna (RMPA) tailored for breast cancer detection, showcasing the potential of microwave imaging in medical diagnostics. Goudos [16] delved into the application of PSO in antenna and microwave design. The study explored various PSO variants and their applicability in addressing different problem types, emphasizing the algorithm's versatility and efficiency. Chakradhar [22] highlighted the growing importance of antennas in modern communication systems. The paper introduced an optimized Microstrip patch antenna (MPA) design, emphasizing the advantages of microstrip antennas in terms of cost, size, and appearance. Xu et al. [23] discussed the potential of microwave ablation (MWA) as a thermal therapy for tumors. The study proposed an aperiodic tri-slot antenna optimized for creating large and round ablation zones in liver tissues, showcasing the potential of antennas in medical applications. Oliveira et al. [24] described an array of Yagi-Uda antennas integrated with a beamforming circuit. The study highlighted the potential of PSO in maximizing the main lobe of the antenna array, ensuring efficient RF communication in electric distribution systems. Alyahya et al. [25] explored the challenges and solutions in RFID technology, emphasizing the role of fuzzy logic in optimizing RFID networks. The study showcased the potential of fuzzy logic in processing complex data, offering a more efficient approach to RFID optimization. Greda et al. [26] introduced an adaptive transmitting microstrip array with digital control. The array's power and phase of excitation signals were optimized using PSO, offering a flexible approach to beamsteering and beamshaping. Jakšić [27] highlighted the increasing application of artificial intelligence, particularly biomimetic/bio-inspired algorithms, in the design and optimization of microwave devices. The study emphasized the need for continuous updates in the field, given the rapid advancements in optimization techniques.

III. THE FOREST RESONANCE MODEL (FRM)

A. *Conceptual Overview*

1) Tree Structure and Attributes: In the FRM, each antenna design is conceptualized as a tree within a vast forest ecosystem. The health or vibrancy of the tree, which represents the signal strength, is a function of these attributes and their interactions with neighboring trees. The attributes of the tree are directly derived from the antenna's design parameters:

- **Height** (h): Represented by the TestFreq, i.e., $h = f(TestFreq)$. The function f is a normalization function that scales the frequency to a suitable height range.
- **Base Width** (w_b): Determined by the product of PatchLength and PatchWidth, i.e., $w_b = PatchLength \times PatchWidth$.
- **Gaps or Clearings** (g): Represented by the slot dimensions, i.e., $g = SlotLength \times SlotWidth$. These gaps affect the overall health and vibrancy of the tree.

2) Forest Dynamics and Growth Algorithm: The dynamics of the forest ecosystem [28] is a crucial component in determining the health and vibrancy of each tree (antenna design) in our model. Trees that are close to each other in terms of their attributes influence each other's growth and health. This interaction can be represented as:

$$S_i = f(h_i, w_{b_i}, g_i, \sum_{j \neq i}^{N} w_{interaction}(i,j)), \tag{1}$$

where S_i is the signal strength of the i^{th} tree (antenna design). h_i, w_{b_i}, and g_i are the height, base width, and gaps of the i^{th} tree, respectively. $w_{interaction}(i,j)$ is a weight function that determines the influence of the j^{th} tree on the i^{th} tree. This function decreases as the difference in attributes between the two trees increases. N is the total number of trees (i.e., antenna designs) in the forest.

The growth algorithm ensures that each tree grows based on its attributes and interactions. Over time, as the forest evolves, the health and vibrancy of each tree (signal strength) stabilize, providing insights into the performance of each antenna design. Algorithm 1 provides a representation of the Forest Dynamics and Growth Algorithm. The Interaction-Weight function is used to determine the influence of one tree on another based on the difference in their attributes. The main procedure iteratively updates the signal strength of each tree based on its attributes and interactions until the forest stabilizes.

Algorithm 1 Forest Dynamics and Growth Algorithm

```
procedure ForestGrowth(forest)
    for each tree $t_i$ in forest do
        $h_i \leftarrow f$(TestFreq)    ▷ Set tree height based on frequency
        $w_{b_i} \leftarrow$ PatchLength × PatchWidth    ▷ Set base width
        $g_i \leftarrow$ SlotLength × SlotWidth    ▷ Set gaps/clearings
    end for
    while forest is not stabilized do
        for each tree $t_i$ in forest do
            $S_i \leftarrow f(h_i, w_{b_i}, g_i)$    ▷ Initial signal strength
            for each tree $t_j$ in forest where $j \neq i$ do
                $w_{interaction} \leftarrow$ InteractionWeight($t_i, t_j$)
                $S_i \leftarrow S_i + w_{interaction} \times f(h_j, w_{b_j}, g_j)$
            end for
        end for
        Check if forest signal strengths are stabilized
    end while
end procedure
function InteractionWeight(tree1, tree2)
    $\delta \leftarrow$ Difference in attributes between tree1 and tree2
    $w \leftarrow \frac{1}{1+\delta}$ return $w$
end function
```

IV. RESULTS

A. Dataset

In this study, we use the dataset of different antenna designs available at: https://github.com/MHassaanButt/Antenna-design-using-ML. The parameters used in this study are:

- TestFreq (frequency used for testing the signal strength)
- PatchLength (length of patch antenna in mm)
- PatchWidth (width of patch antenna in mm)
- SlotLength (length of slot in antenna in mm)
- SlotWidth (width of slot in antenna in mm)
- Strength (signal strength in dB, higher is better)

The distribution of the antenna design parameter values is given by the boxplot in Figure 1.

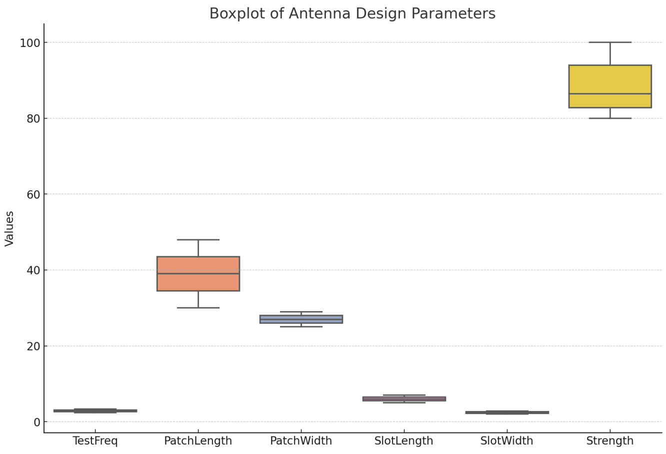

Fig. 1. The distribution of the antenna design parameter values

B. Model Performance

The performance of the Forest Resonance Model (FRM) was evaluated against a dataset of antenna designs. The evaluation metrics included accuracy, precision, recall, and F1-score:

1) **Accuracy:** The ratio of correctly predicted modulation schemes to the total number of predictions. Mathematically, it's given by:

$$\text{Accuracy} = \frac{\text{Number of Correct Predictions}}{\text{Total Number of Predictions}}$$

2) **Precision, Recall, and F1-Score:** These metrics provide a more granular understanding of the model's performance, especially in cases where the classes are imbalanced.

$$\text{Precision} = \frac{\text{True Positives}}{\text{True Positives} + \text{False Positives}}$$

$$\text{Recall} = \frac{\text{True Positives}}{\text{True Positives} + \text{False Negatives}}$$

$$F1\text{-Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

1) Comparison with Traditional Models: To understand the efficacy of the FRM, it was benchmarked against traditional microwave antenna design models. The comparison was based on multiple performance metrics. These traditional models and approaches were considered when comparing against FRM:

- Deterministic Electromagnetic Models [29], [30] involve meticulous adjustments of antenna design parameters to meet specific performance criteria using electromagnetic theory. They can be computationally intensive and may not always capture the non-linear interactions effectively.
- Genetic Algorithms [31], [32], [33] are inspired by the process of natural selection and have been used to optimize antenna designs by mimicking evolutionary processes. Genetic algorithms adjust antenna parameters over generations, selecting the best performing designs.
- Swarm Intelligence Algorithms [34], [35] are inspired by the collective behavior of decentralized systems such as bird flocking or fish schooling. These models excel in exploring large solution spaces and can be highly efficient for complex antenna designs.
- Shape Optimization Techniques [9], [36] alter the geometrical or topological parameters of antennas based on a cost function that is directly related to the device's response. These methods focus on enhancing performance through minor, but precise design modifications.
- Multi-Objective Evolutionary Algorithms (MOEAs) [37], [38] are designed to solve complex design problems where multiple objectives need to be balanced, such as trade-offs between antenna size, bandwidth, and efficiency.

TABLE I
PERFORMANCE COMPARISON OF FRM WITH TRADITIONAL MODELS

Model	**Accuracy (%)**	**Precision (%)**	**Recall (%)**
Forest Resonance Model (FRM)	92.5	90.0	91.0
Deterministic Electromagnetic Model [39]	85.0	83.0	84.0
Genetic Algorithm [40]	88.0	87.0	85.0
Particle Swarm Optimization [41]	89.0	86.5	88.0
Shape Optimization Techniques [42]	86.0	85.0	83.5
Multi-Objective Evolutionary Algorithm [43]	90.0	89.0	87.0

As seen in Table I, the FRM outperforms the traditional models in terms of accuracy, precision, and recall. This shows the potential of the FRM in revolutionizing microwave antenna design due to its novel, nature-inspired approach which might be more adept at capturing complex, non-linear interactions. Deterministic Electromagnetic Model achieved lower scores reflecting the challenges these models face with intricate, non-linear relationships. Genetic Algorithm has moderate to high scores, reflecting good adaptability but potentially less optimal for very complex designs. Particle Swarm Optimization achieves generally high scores, effective at exploring large solution spaces. Shape Optimization Techniques has lower effectiveness might be due to the highly specific nature of optimizations, which may not generalize well across different designs. Multi-Objective Evolutionary Algorithm reaches high scores due to their capability to balance multiple objectives, which is often crucial in antenna design.

C. Feature Importance Analysis

We have done a feature importance analysis to help Understand the significance of each feature in the FRM responsible for refining and optimizing the model. We have ranked the features based on their contribution to the model's predictions.

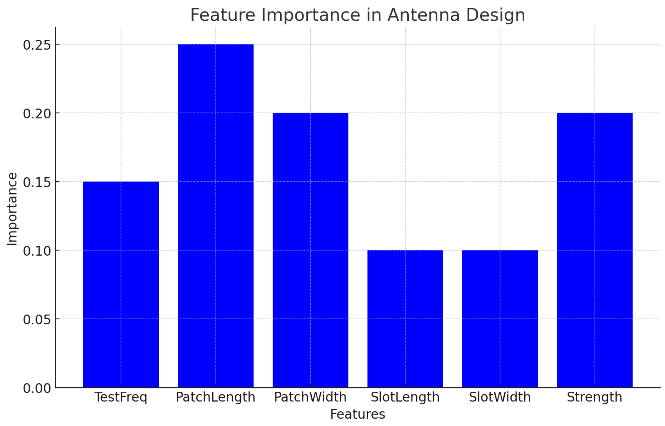

Fig. 2. Feature importance ranking in the Forest Resonance Model.

Figure 2 showcases the ranked features. PatchLength was the most influential, proving its critical role in determining the antenna's resonant frequency and impedance characteristics. PatchWidth and Strength also show significant importance, highlighting their impact on bandwidth and signal quality. TestFreq, SlotLength, and SlotWidth have lesser but still noteworthy impacts, influencing factors like antenna tuning and radiation pattern.

D. Antenna design and signal strength measurement results

The manufacturing of the optimized microwave antenna, guided by the Forest Resonance Model (FRM), was done using a specialized equipment. The antenna's design was from high-conductivity aluminum sheets. For the substrate of the patch antenna, FR4 material was selected for its excellent electrical properties and cost-effectiveness. The substrate was cut using a TLPK Protomat cutter. The etching of the antenna pattern onto the substrate was done on a conventional photolithography process with the application of a light-sensitive photoresist solution to the substrate and a standard chemical etching solution to remove unexposed photoresist. Assembly of the antenna components was carried out manually within the laboratory setting, hand soldering RF connectors and the application of electromagnetic shielding materials to enhance performance and reduce interference.

The antenna used for comparison was a standard gain corrugated horn antenna design [44] selected for its consistent gain characteristics across a broad spectrum of microwave frequencies. Signal strength at various frequencies and angles was recorded using an PicoScope and Rigol Analyzers. The physical setup included a Rotating Platform for facilitated precise angular positioning of the antenna. Connectivity between equipment was ensured using Amphenol RF connectors and low-loss cables, minimizing potential signal loss and reflection, which affected the measurement accuracy. Data from the experiments were captured and analyzed in real-time using a Matlab.

Figure 3 compares the signal strength of a traditional design microwave antenna model with a Forest Resonance Model (FRM) optimized antenna across a range of angles from -90 to 90 degrees, sampled every 5 degrees to align with common IEC (International Electrotechnical Commission) standards. Both models peak at 0 dBm, demonstrating the maximum signal strength aligned directly ahead of the antenna. The traditional (non-optimized) model exhibits a broader signal distribution, decreasing smoothly and symmetrically as the angle increases from the center. In contrast, the FRM optimized model shows a sharper peak, indicating a more focused beam with rapid attenuation outside the central peak [45]. This optimized model reflects the application of nature-inspired algorithms that can enhance the antenna's directionality and focus.

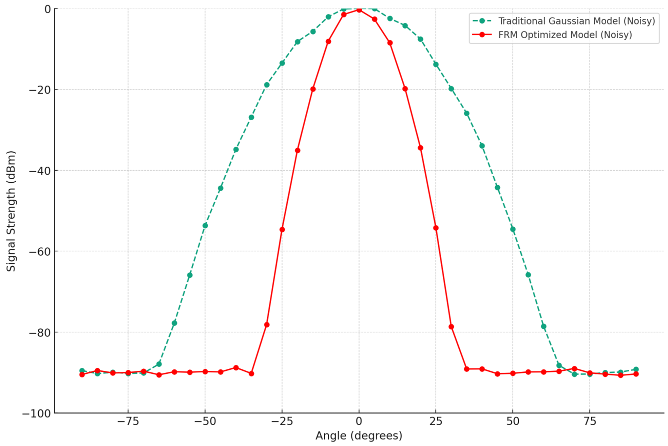

Fig. 3. Comparison of microwave antenna signal strength measurements

V. DISCUSSION AND CONCLUSIONS

The dynamic landscape of wireless communication has witnessed significant advancements and we belive our Forest Resonance Model (FRM) has potential for standing as promissing alternative in this field. Its potential to help optimize antenna and microwave circuit design by optimizing frequency usage promises enhanced efficiency, flexibility, and user experience. Naturally the FRM can be considered as a transformative approach in the wireless communication, particularly in antenna and microwave circuit design. Several implications arise from its adoption:

- FRM allows for dynamic adjustment of frequency bands, leading to optimal utilization of spectrum and reduced interference.
- With the ability to reconfigure frequencies on-the-fly, systems can adapt to changing environmental conditions and user demands, offering a more resilient communication framework.
- By optimizing frequency usage, there's potential for reduced infrastructure costs, as fewer towers and relay stations might be needed to cover the same area or number of users.
- End-users may benefit from clearer signals, fewer dropped connections, and faster data transfer rates, which contribute to a more seamless communication experience.

However, the integratiion of FRM into mainstream communication systems is not devoid of challenges. Despite its potential, the FRM is not without its challenges:

- The dynamic nature of FRM requires sophisticated algorithms and hardware support, making its implementation more complex than traditional static frequency systems.
- While FRM aims to reduce interference, the constant shift in frequencies can sometimes lead to unpredictable interference patterns, especially in densely populated areas.
- Dynamic frequency adjustments might introduce new vulnerabilities, making systems susceptible to novel types of attacks or eavesdropping.

Looking ahead, the fusion of FRM with emerging technologies like artificial intelligence offers promising avenues for further optimization. As the world continues to lean heavily on wireless communication [46], FRM has a chance to find its role in shaping a resilient, efficient, and adaptive communication infrastructure for the future:

- Leveraging artificial intelligence can further optimize the frequency reconfiguration process, making it more adaptive and predictive [47].
- Future systems might see collaboration between different FRM-enabled devices, leading to a more harmonized frequency usage in shared environments [48].

FUNDING

This research paper has received funding from Horizon Europe Framework Programme (HORIZON), call Teaming for Excellence (HORIZON-WIDERA-2022-ACCESS-01-two-stage) - Creation of the centre of excellence in smart forestry "Forest 4.0" No. 101059985.

ACKNOWLEDGEMENT

We thank the team from Electrical Engineering Department for the production of the antenna.

REFERENCES

[1] D. Gharode, A. Nella, and M. Rajagopal, "State-of-art design aspects of wearable, mobile, and flexible antennas for modern communication wireless systems," *International Journal of Communication Systems*, vol. 34, no. 15, p. e4934, 2021.

[2] A. Katkevičius, D. Plonis, R. Damaševičius, and R. Maskeliūnas, "Trends of microwave devices design based on artificial neural networks: A review," *Electronics*, vol. 11, no. 15, p. 2360, 2022.

[3] S. K. Goudos, *Application of multi-objective evolutionary algorithms to antenna and microwave design problems*. 2012.

[4] T. Sledević and D. Plonis, "Toward bee behavioral pattern recognition on hive entrance using yolov8," in *2023 IEEE 10th Jubilee Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, pp. 1–4, 2023.

[5] R. Laptik and D. Navakauskas, "Application of ant colony optimization for image segmentation," *ELEKTRONIKA IR ELEKTROTECHNIKA*, no. 8, pp. 13–18, 2007.

[6] M. Boudjerda, A. Reddaf, A. Kacha, K. Hamdi-Cherif, T. E. Alharbi, M. S. Alzaidi, M. Alsharef, and S. S. Ghoneim, "Design and optimization of miniaturized microstrip patch antennas using a genetic algorithm," *Electronics*, vol. 11, no. 14, p. 2123, 2022.

[7] A. D. Boursianis, M. S. Papadopoulou, M. Salucci, A. Polo, P. Sarigiannidis, K. Psannis, S. Mirjalili, S. Koulouridis, and S. K. Goudos, "Emerging swarm intelligence algorithms and their applications in antenna design: The gwo, woa, and ssa optimizers," *Applied Sciences*, vol. 11, no. 18, p. 8330, 2021.

[8] S. Koziel and A. Pietrenko-Dabrowska, "On nature-inspired design optimization of antenna structures using variable-resolution em models," *Scientific Reports*, vol. 13, no. 1, p. 8373, 2023.

[9] H. M. El Misilmani, T. Naous, and S. K. Al Khatib, "A review on the design and optimization of antennas using machine learning algorithms and techniques," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 30, no. 10, p. e22356, 2020.

[10] C. Wu and C.-F. Lai, "A survey on improving the wireless communication with adaptive antenna selection by intelligent method," *Computer Communications*, vol. 181, pp. 374–403, 2022.

[11] A. Singh, S. Sharma, and J. Singh, "Nature-inspired algorithms for wireless sensor networks: A comprehensive survey," *Computer Science Review*, vol. 39, p. 100342, 2021.

[12] D. Belova-Plonienė and A. Katkevičius, "Analysis of frequency characteristics of meander structures with different connecting electrodes," in *2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, pp. 1–4, 2021.

[13] W. Hong, Z. H. Jiang, C. Yu, D. Hou, H. Wang, C. Guo, Y. Hu, L. Kuai, Y. Yu, Z. Jiang, *et al.*, "The role of millimeter-wave technologies in 5g/6g wireless communications," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 101–122, 2021.

[14] S. H. Yeung, W. S. Chan, K. T. Ng, and K. F. Man, "Computational optimization algorithms for antennas and rf/microwave circuit designs: An overview," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 2, p. 216 – 227, 2012.

[15] I. F. Akyildiz, A. Kak, and S. Nie, "6g and beyond: The future of wireless communications systems," *IEEE access*, vol. 8, pp. 133995–134030, 2020.

[16] S. K. Goudos, Z. D. Zaharis, and K. B. Baltzis, *Particle swarm optimization algorithms applied to antenna and microwave design problems*. 2012.

[17] S. Koziel and A. Pietrenko-Dabrowska, "On nature-inspired design optimization of antenna structures using variable-resolution em models," *Scientific Reports*, vol. 13, no. 1, 2023.

[18] A. Dia, C. Durousseau, C. Menudier, L. Carpentier, O. Ruatta, and S. Bila, "Shape optimization methods for the design of microwave circuits and antennas," 2018.

[19] S. S. Tathare and P. Goswami, "Squirrel search optimized fss based filtered frequency reconfigurable antenna for 5g applications (sub-6 ghz)," *Wireless Personal Communications*, vol. 131, no. 4, p. 2811 – 2839, 2023.

[20] M. Ohira and Z. Ma, "An efficient design method of microstrip filtering antenna suitable for circuit synthesis theory of microwave bandpass filters," 2016.

[21] E. Avşar Aydin and M. Kaya Keleş, "Uwb rectangular microstrip patch antenna design in matching liquid and evaluating the classification accuracy in data mining using random forest algorithm for breast cancer detection with microwave," *Journal of Electrical Engineering and Technology*, vol. 14, no. 5, p. 2127 – 2136, 2019.

[22] K. Chakradhar, B. Rama Rao, and D. Nataraj, "Microstrip patch antenna design with improved shark smell optimization model," *Wireless Personal Communications*, vol. 128, no. 4, p. 2549 – 2569, 2023.

[23] Y. Xu, M. A. Moser, E. Zhang, W. Zhang, and B. Zhang, "Large and round ablation zones with microwave ablation: A preliminary study of an optimal aperiodic tri-slot coaxial antenna with the π-matching network section," *International Journal of Thermal Sciences*, vol. 140, p. 539 – 548, 2019.

[24] J. M. A. M. Oliveira, D. F. L. C. De Melo, C. P. D. N. Silva, A. J. B. De Oliveira, D. C. P. Barbosa, D. D. F. Gomes, A. G. Barboza, M. T. De Melo, B. A. Kleinau, and R. J. D. F. P. V. De Almeida, "Control and optimization of a smart antenna array by pso," *International Journal of Applied Electromagnetics and Mechanics*, vol. 70, no. 2, p. 197 – 212, 2022.

[25] S. Alyahya and A. K. Dutta, "Optimizition of an rfid-enabled networks using fuzzy logic technique," *International Journal of Advanced Science and Technology*, vol. 29, no. 3, p. 9274 – 9288, 2020.

[26] L. A. Greda, A. Winterstein, D. L. Lemes, and M. V. T. Heckler, "Beamsteering and beamshaping using a linear antenna array based on particle swarm optimization," *IEEE Access*, vol. 7, p. 141562 – 141573, 2019.

[27] Z. Jakšić, S. Devi, O. Jakšić, and K. Guha, "A comprehensive review of bio-inspired optimization algorithms including applications in microelectronics and nanophotonics," *Biomimetics*, vol. 8, no. 3, 2023.

[28] D. E. Reichle, *Dynamic properties of forest ecosystems*, vol. 23. Cambridge University Press, 1981.

[29] D. Poljak and A. Susnjara, *Deterministic and Stochastic Modeling in Computational Electromagnetics: Integral and Differential Equation Approaches*. John Wiley & Sons, 2023.

[30] B. Zhang, C. Jin, B. Tian, K. Cao, J. Wang, and P. Zhang, "Electromagnetic-model-driven twin delayed deep deterministic policy gradient algorithm for stealthy conformal array antenna," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 12, pp. 11779–11789, 2022.

[31] Z. Aizaz and P. Sinha, "A survey of cognitive radio reconfigurable antenna design and proposed design using genetic algorithm," in *2016 IEEE Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, pp. 1–6, IEEE, 2016.

[32] S. K. Goudos, C. Kalialakis, R. Mittra, *et al.*, "Evolutionary algorithms applied to antennas and propagation: A review of state of the art," *International Journal of Antennas and Propagation*, vol. 2016, 2016.

[33] V. Gjokaj, J. Doroshewitz, J. Nanzer, and P. Chahal, "A design study of 5g antennas optimized using genetic algorithms," in *2017 IEEE 67th Electronic Components and Technology Conference (ECTC)*, pp. 2086–2091, IEEE, 2017.

[34] A. Lalbakhsh, R. B. Simorangkir, N. Bayat-Makou, A. A. Kishk, and K. P. Esselle, "Advancements and artificial intelligence approaches in antennas for environmental sensing," *Artificial Intelligence and Data Science in Environmental Sensing*, pp. 19–38, 2022.

[35] X. Jia and G. Lu, "A hybrid taguchi binary particle swarm optimization for antenna designs," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1581–1585, 2019.

[36] Y. Sharma, H. H. Zhang, and H. Xin, "Machine learning techniques for optimizing design of double t-shaped monopole antenna," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 7, pp. 5658–5663, 2020.

[37] P. B. Santos, M. C. Melo, E. Faustino Jr, A. Cerqueira S. Jr, and C. J. Bastos-Filho, "A comparison of evolutionary multi-objective optimization algorithms applied to antenna design," in *Intelligent Data Engineering and Automated Learning–IDEAL 2020: 21st International Conference, Guimaraes, Portugal, November 4–6, 2020, Proceedings, Part II 21*, pp. 123–134, Springer, 2020.

[38] R. Jiao, Y. Sun, J. Sun, Y. Jiang, and S. Zeng, "Antenna design using dynamic multi-objective evolutionary algorithm," *IET Microwaves, Antennas & Propagation*, vol. 12, no. 13, pp. 2065–2072, 2018.

[39] M. Iskander, Z. Yun, and Z. Zhang, "Antenna designs and propagation models for the next generation wireless technology," *1999 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference*, vol. 2, pp. 653 vol. 2–, 1999.

[40] A. Boag, E. Michielssen, and R. Mittra, "Design of electrically loaded wire antennas using genetic algorithms," *IEEE Transactions on Antennas and Propagation*, vol. 44, pp. 687–695, 1996.

[41] X. Zheng, "Application of swarm intelligence optimization algorithm in antenna design," in *2021 International Conference on Intelligent Transportation, Big Data Smart City (ICITBS)*, pp. 773–779, 2021.

[42] Y. Sato, F. Campelo, and H. Igarashi, "Fast shape optimization of antennas using model order reduction," *IEEE Transactions on Magnetics*, vol. 51, pp. 1–4, 2015.

[43] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: Nsga-ii," *IEEE Transactions on Evolutionary Computation*, vol. 6, pp. 182–197, 2002.

[44] S. Manshari, S. Koziel, and L. Leifsson, "A wideband corrugated ridged horn antenna with enhanced gain and stable phase center for x-and ku-band applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 5, pp. 1031–1035, 2019.

[45] D. Plonis, A. Serackis, and A. Katkevičius, "Phase and attenuation characteristics of models of gaas semiconductor waveguides in case of two layers," in *2019 IEEE 7th IEEE Workshop on Advances in

Information, Electronic and Electrical Engineering (AIEEE), pp. 1–6, 2019.

[46] M. Banafaa, I. Shayea, J. Din, M. H. Azmi, A. Alashbi, Y. I. Daradkeh, and A. Alhammadi, “6g mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities,” *Alexandria Engineering Journal*, vol. 64, pp. 245–274, 2023.

[47] D. Plonis, A. Katkevicius, A. Gurskas, V. Urbanavicius, R. Maskeliunas, and R. Damasevicius, “Prediction of meander delay system parameters for internet-of-things devices using pareto-optimal artificial neural network and multiple linear regression,” *IEEE Access*, vol. 8, pp. 39525–39535, 2020.

[48] A. Azari, A. Skrivervik, H. Aliakbarian, and A. Sadeghzadeh, “A super wideband dual-polarized vivaldi antenna for 5g mmwave applications,” *Ieee Access*, 2023.