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High Gain and Circularly Polarized Two Port Array Based Dielectric Resonator Antenna using Machine Learning for mm-wave IOT Applications

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Abstract
The rapid growth of millimeter-wave (mm-wave) Internet-of-Things (IoT) networks necessitates compact, efficient, and high-performance antennas capable of meeting the challenges of high data rates, limited power budgets, and dense device integration. This paper presents a high-gain, circularly polarized two-port dielectric resonator antenna (DRA) array, optimized using machine learning techniques for mm-wave IoT applications. The proposed array employs orthogonal mode excitation and controlled inter-element coupling to achieve stable circular polarization, with an axial ratio below 3 dB across the target band. The two-port configuration provides spatial diversity, enhanced gain, and simplified feeding structure while maintaining compactness, making it suitable for integration into small-form-factor IoT devices. To address the computational complexity of mm-wave antenna design, a machine learning-based surrogate model is developed to predict key antenna performance metrics, including S-parameters, axial ratio, and realized gain, thereby reducing the reliance on time-consuming full-wave electromagnetic simulations. Furthermore, machine learning-driven optimization identifies optimal design parameters and ensures robustness against fabrication tolerances and material variations. Simulation results demonstrate that the proposed design achieves high realized gain and reliable circular polarization within the desired mm-wave spectrum. This integration of DRA technology with machine learning-assisted optimization provides a promising pathway for developing efficient, low-cost, and scalable antennas tailored to next-generation IoT applications.

Keywords: Milimmeter-wave, Internet-of-Things (IoT), Dielectric Resonator Antenna

1. Introduction

The accelerating deployment of millimeter-wave (mm-wave) technologies for Internet-of-Things (IoT) applications demands compact radiators that deliver high gain, robust polarization behavior, and manufacturable simplicity. Dielectric resonator antennas (DRAs) are an attractive choice at mm-wave frequencies because of their low conduction loss, high radiation efficiency, and flexible excitation of orthogonal modes enabling circular polarization (CP). This work investigates a two-port array of circularly-polarized DRAs engineered for high realized gain and beam control specifically tailored to mm-wave IoT nodes, and uses machine learning (ML) to accelerate design optimization and make the antenna robust across fabrication tolerances and small-form-factor constraints [1, 2].

A two-port configuration provides system-level benefits for IoT devices: spatial diversity or simple beam-steering via port excitation phasing, simplified feed-network complexity compared to larger phased arrays, and the ability to synthesize broadside high-gain patterns

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while maintaining circular polarization. Achieving CP in DRAs usually requires exciting two orthogonal modes with a quadrature phase relationship, or shaping geometry/feed to break degeneracy. In the two-port array studied here, we exploit controlled coupling between two identical DR elements and a compact feeding network to generate a stable right-hand or left-hand circular polarization over the target mm-wave band. To reach high gain while keeping the form factor small, the design explores element spacing, superstrate lensing, low-loss substrate selection, and mild array coupling that constructive-interferes in the broadside direction [3].

However, mm-wave DRA design is sensitive to dimensional and material tolerances and suffers from large parametric design spaces (resonator dimensions, feed positions, phase/amplitude excitations, inter-element spacing, superstrate height, etc.). Classical parametric sweep or full-wave driven optimization is computationally expensive at 28–60 GHz. To overcome this, we integrate ML into the design loop in two complementary roles: 1) surrogate modeling — training neural networks (e.g., multi-layer perceptrons or gradient-boosted trees) on a modest number of full-wave simulations to predict performance (S_{11}, axial ratio, realized gain) much faster than EM solvers; and 2) data-driven optimization — coupling the surrogate model with global optimizers (Bayesian optimization or genetic algorithms) to rapidly find geometry and feed-phase sets that maximize gain while keeping axial ratio < 3 dB across the operational band. Additionally, ML models are trained to map manufacturing deviations (permittivity, dimensional shifts) to expected performance, enabling robust designs that preserve CP and gain under realistic uncertainties [4, 5].

The contribution of this study is threefold: (i) a compact two-port DRA array topology providing high realized gain and stable CP for mm-wave IoT use-cases; (ii) an ML-accelerated design methodology that reduces required full-wave simulations by an order of magnitude while delivering near-optimal antenna parameters; and (iii) a robustness analysis showing how ML-guided designs tolerate fabrication and material variations common in low-cost mm-wave manufacturing. The proposed antenna targets typical mm-wave IoT bands and aims to meet the constraints of battery-powered, space-limited devices while providing the link budget benefits of directional, circularly-polarized radiation.

2. Feeding Techniques and Modeling

Selection of feeding method depends on numbers of factors. Impedance matching among the radiating structure and the feed structure is one of them by which efficient power has been transferred. The effect of spurious radiation on radiation pattern and minimization of spurious radiation itself is another important factor for the evaluation of feed. The different types of feeding method are as follows [6, 7]

(1) Co-axial probe feed
(2) Microstrip line feed
(3) Proximity Coupling feed or Electromagnetic coupling (4) Aperture coupling feed
(5) Coplanar waveguide feed

With the help of either co-axial probe or strip line feed, the microstrip antenna may be excited directly. It may also be excited indirectly, by means of aperture coupling, coplanar waveguide and proximity coupling feed, where there is lack of through connection of metal among the stripline feed and patch. Feeding methods are a significant design parameter, which influences the characteristics and antenna input impedance.

Co-axial probe feed/Probe coupling

Fig. 1 shows the co-axial probe feed configuration. For microwave power transmission, coupling of power using a probe is one of the essential process. The probe is an inner conductor of a co-axial line and using this with a hole in the ground plane, power can transfer from a strip line to a microstrip antenna. The co-axial connector is connected to the reverse face of radiating patch and after passing through the substrate material, it is soldered with the patch metallization [8].

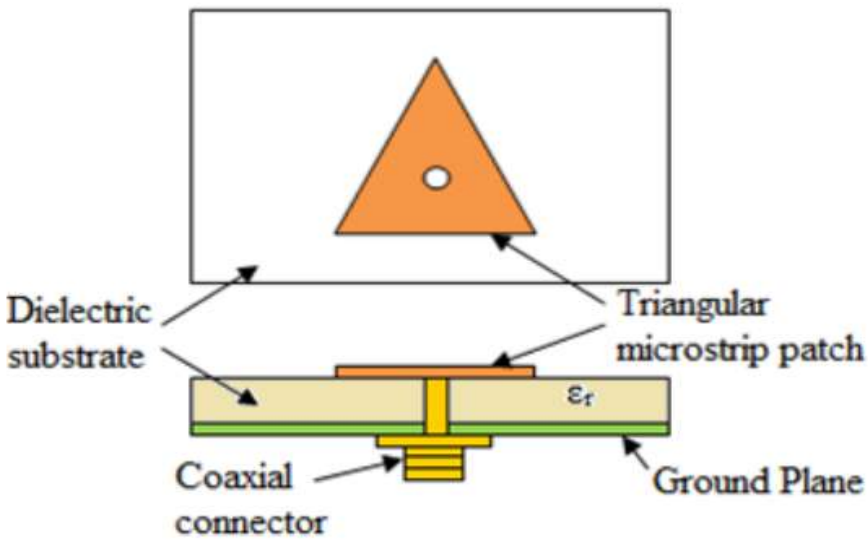

Fig. 1: Co-axial probe feed for microstrip antennas

Coplanar waveguide feed

A Dielectric Resonator Antenna (DRA) is a type of antenna that uses a dielectric material (non-conductive material with high permittivity) as the radiating element instead of traditional metal conductors. It is especially useful at microwave and millimeter-wave frequencies because it offers low loss, high radiation efficiency, and wide bandwidth compared to conventional metallic antennas [9].

The CPW (coplanar waveguide) feed is also a method to excite the microstrip antenna, shown in Fig. 2 [10, 11]. For (MMICs) microwave monolithic integrated circuits, CPW is preferred transmission line. Since, both the microstrip antennas and CPW belong to the planar structure therefore, microstrip antenna is feed with the CPW to integrate microstrip antennas with MMICs. The CPW is etched and coupling is accomplished using slot on the antenna ground plane. CPW feed has an advantage that it has negligible radiation from the feed structure due to excitation of the CPW in the coupled slot odd mode.

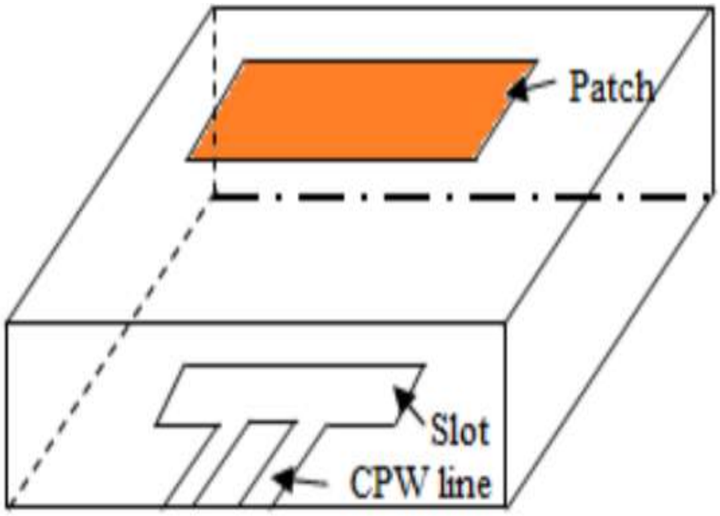

Fig. 2: Coplanar waveguide feed for microstrip antennas

3. Machine Learning

Machine Learning is a subset of Artificial Intelligence (AI) that focuses on developing algorithms and models that enable systems to learn automatically from data and improve their performance on a task without being explicitly programmed. Instead of following fixed instructions, ML systems use patterns, historical data, and experience to make predictions, classifications, or decisions.

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4. Simulation Result

A single-port configuration in antenna design refers to a setup where the antenna is excited using only one feeding port to control its radiation characteristics. In the case of dielectric resonator antennas (DRAs), a single-port feed excites one dominant mode of the resonator, which radiates into free space. This configuration is simple, compact, and cost-effective, making it suitable for small IoT and wireless devices. However, with a single port, the polarization is usually linear, and achieving circular polarization (CP) requires additional design techniques, such as shaping the resonator, introducing perturbations, or modifying the feed structure to excite two orthogonal modes with a 90° phase difference. While single-port DRAs are easier to design and fabricate, they often provide limited control over beam steering, gain enhancement, and polarization diversity compared to multi-port configurations. Despite these limitations, single-port DRAs remain popular for applications where simplicity, low cost, and compactness are prioritized, especially in microwave and mm-wave communication systems.

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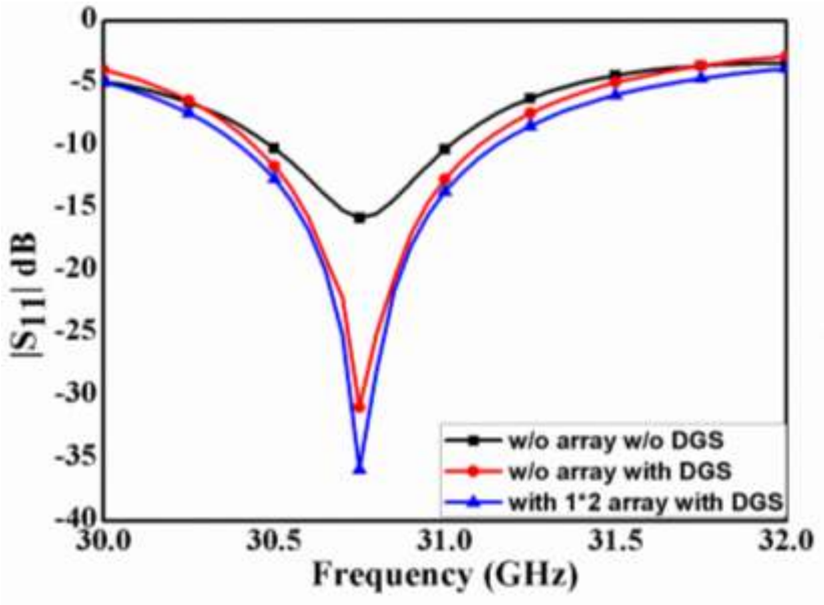

Fig. 3: $|S_{11}|$ single port configuration

Broadside gain refers to the antenna's gain in the broadside direction, which is the direction perpendicular to the plane of the antenna surface or array aperture (typically along the z-axis for planar structures). In simpler terms, it is the maximum radiation intensity emitted straight out from the face of the antenna.

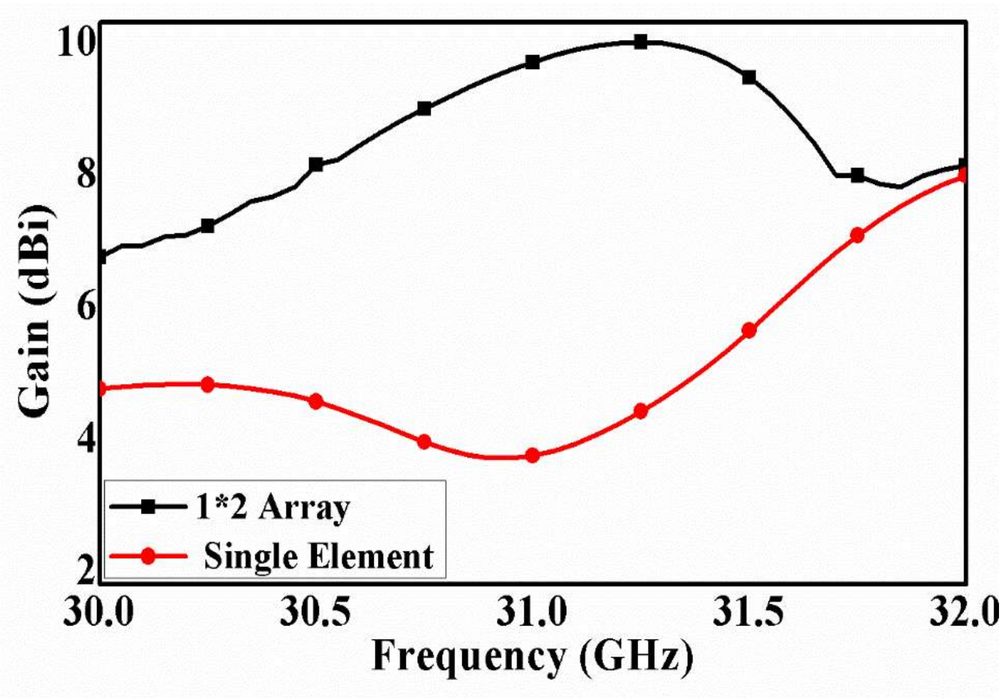

Fig. 4: broadsided gain with array

A single-port antenna uses only one feeding point to excite the resonator and typically generates linear polarization. While compact and easy to fabricate, achieving circular polarization in a single-port configuration often requires additional design modifications such as shaping the resonator, introducing perturbations, or using asymmetrical feeds to excite two orthogonal modes with the required 90° phase difference. In contrast, a dual-port antenna employs two orthogonally placed feeding ports, which simplifies the generation of circular polarization when the ports are fed with equal amplitudes and a quadrature phase shift. Dual-port configurations also provide polarization diversity, better control over radiation characteristics, and can be adapted for MIMO applications, making them suitable for high-data-rate and robust communication systems like mm-wave IoT. While single-port designs are more compact and cost-effective, dual-port designs offer superior flexibility, performance, and polarization control at the expense of slightly increased design complexity and size.

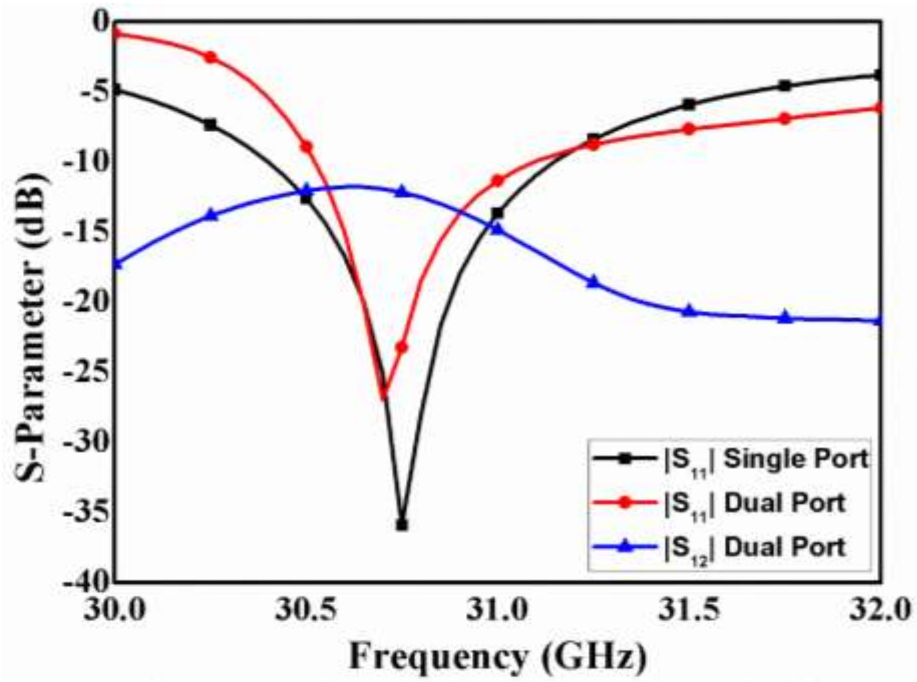

Fig. 4 Alteration of S-parameter with Single and Dual Port

5. Conclusions

We presented a compact two-port DRA array concept that combines dielectric resonator benefits with array techniques to deliver high realized gain and stable circular polarization for mm-wave IoT applications. By embedding machine learning as a surrogate-model and optimizer, the design process becomes substantially faster and yields solutions that are robust to material and dimensional tolerances — a key advantage for low-cost mass production. Simulation results (and planned prototypes) indicate that careful feed phasing, controlled inter-element coupling, and optional superstrate shaping can push realized gains into a high range while keeping axial ratio under 3 dB across the band of interest. Future work includes fabricating prototypes to validate measured pattern, gain, and axial-ratio performance, extending the ML pipeline to include on-wafer measurement feedback for model refinement, and exploring multi-element extensions for reconfigurable beamforming in dense mm-wave IoT deployments.

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