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Design And Performance of a Wideband Microstrip Patch Antenna with CSRR Enhancement to Enhanced Performance on Sub-6 GHz Band Applications

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ABSTRACT
The growing need of compact and efficient antennas in sub-6 GHz wireless systems like 5G, WLAN, WiMAX and Supervisory Control and Data Acquisition (SCADA) has outlined a key weakness of the traditional Microstrip Patch Antennas (MPAs), which has drawbacks such as narrow bandwidth, low gain, and high return loss. To overcome these problems, this research presents a Complementary Split Ring Resonator (CSRR)-enhanced MPA, with the aim to enhance impedance bandwidth and radiation efficiency with compact geometry. The radiating patch model was initially modeled through standard equations to obtain the baseline MPA and a CSRR was subsequently incorporated into it. The simulations were done using CST MWS over the 1-7 GHz frequency range. The obtained results indicate that the proposed CSRR-based antenna had a bandwidth of 3.3 GHz, a peak gain of 2.5 dB, and minimum return loss of -26.5 dB, whereas the benchmark model in the literature considered had 1.9 GHz bandwidth, 0.4 dB gain, and -22 dB return loss. These are 74%, 525%, and 20% improvements, respectively. The improved performance shows the applicability of the proposed antenna to multi-standard wireless systems in the sub-6 GHz frequency range, especially in a situation where long-range communication is highly needed, as in, SCADA, Internet of Things (IoT), and next-generation broadband networks.

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INTRODUCTION

The recent substantial expansion of contemporary wireless communication networks including 5G, Wireless Local Area Networks (WLAN), Worldwide Interoperability for Microwave Access (WiMAX) and Supervisory Control and Data Acquisition (SCADA) has led to the emergence of a pressing demand in the area of tiny, broadband, and high-performance antennas (Kumar A et al., 2023). Specifically, the sub-6 GHz frequency range has turned out to be critical, as it offers a good tradeoff between its coverage and capacity, high data rates, low latency and strong connectivity in a wide range of environments. The Microstrip Patch Antenna (MPA) has been the most appealing antenna technology due to its low profile, low manufacturing cost, light weight and ability to match with the microwave integrated circuits. Nonetheless, the traditional MPAs are by nature limited in bandwidth, gain and have more return losses, which limit their applicability to the new broadband and high efficiency wireless applications. It is then important to deal with these limitations, and this is a fundamental problem in the study of antennas (Kumar *et al*., 2021).

In a bid to solve these problems, researchers have explored methods, which include, among others, Barium Strontium Titanate (BST), Defected Ground Structures (DGS), and Split Ring Resonators (SRRs). Though these

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techniques have demonstrated improvements, they have been associated with many disadvantages including increased dielectric losses, complex design, or lack of scalability. Yet another method of great interest is the application of Complementary Split Ring Resonators (CSRRs) which are metamaterial-inspired, enabling negative effective permittivity and offering a more detailed control of electromagnetic behavior.

CSRRs may be incorporated easily into planar antennas, and have the potential of providing more bandwidth, higher gain, and lowering the return loss and the antenna is compact and easy to design. The given paper is devoted to the design of wideband microstrip patch antenna with the enhancement of CSRR and its performance analysis at the sub-6 GHz frequency range. The proposed design has its foundation in a baseline MPA model and illustrates how integration of CSRR can result in great enhancement in bandwidth, gain and radiation performance. These findings are compared to a recently announced wideband antenna with the work of (El Issawi et al., 2024), demonstrating that the CSRR-based design is superior to the current practices in the essential performance indicators.

Contributions of this Work

This work is new because a systematic integration of a Complementary Split Ring Resonator (CSRR) into a typical patch antenna that uses a Microstrip Patch Antenna (MPA) is developed to realise wideband and high gain performance in the sub-6 GHz range. In comparison to other methods of enhancing performance in the past, including Barium Strontium Titanate (BST) which have significant dielectric losses and are difficult to design, and traditional Defected Ground Structures (DGS), which enhance bandwidth but not gain, the proposed CSRR-based design is a compact, efficient, and easy-to-fabricate method.

The proposed antenna displays 525% gain, 74% bandwidth and 20% decrease in return loss improvement in comparison to the state-of-the-art model through rigorous simulation and comparative benchmarking by El-Lissawi *et al.,* (2024). These findings make the CSRR-enhanced MPA an excellent choice in the future wireless applications, especially in SCADA, 5G, WLAN, and WiMAX, where the long-range communication channels and effective use of the spectrum are paramount. The rest of the paper is structured in the following way: Section 2 introduced the design methodology of the baseline MPA and its improvement with the help of CSRR. Section 3 discusses the simulation results. The paper is concluded in section 5.

Design Methodology

This section outlines the systematic design approach used to develop and optimize a Complementary Split Ring Resonator (CSRR) enhanced microstrip patch antenna, from baseline modeling to simulation and performance validation.

Baseline Microstrip Patch Antenna (MPA) Design

The design of the microstrip patch antennas is known as Baseline Microstrip Patch Antenna (MPA). The design commenced with the development of a traditional rectangular patch antenna in microstrip that is conventional and works in sub-6 GHz band (1-7 GHz). The parameters of the baseline design (patch length (L), patch width (W), effective dielectric constant (eeff) and feed size) were determined as the parameters of the standard design equations of MPAs.

The patch width W was calculated as (1) (Bashir *et al.*, 2025):

$$W = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

where:

c represents the speed of light
f_0 outlines the design resonant frequency
ε_r is the dielectric constant

The effective dielectric constant (ε_{eff}) was then evaluated as (2) (Mendez-Lozoya *et al*., 2025):

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2} \quad (2)$$

where h signifies the height of the substrate

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the effective patch length (L_{eff}) and the actual length (L) was obtained using (3) and (4) represented as (Ramineni & Nimmala, 2024):

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (3)$$

$$L = L_{eff} - 2\Delta L \quad (4)$$

where ΔL represents the fringing field extension at the patch edges.

The ground plane length Lg and width Wg are calculated using equations (5) and (6)

$$Lg = 6h + Lp \quad (5)$$

$$Wg = 6h + Wp \quad (6)$$

CSRR Modelling into the Patch Antenna

In order to cope with the limited bandwidth and low gain of the baseline MPA, a Complementary Split Ring Resonator (CSRR) was added to the antenna structure. CSRRs are metamaterial inclusions cut in the metallic layer, which are created to bring negative effective permittivity and consequently increase the electromagnetic response of the antenna.

The CSRR geometry involved two concentric etched slots with splits that were located in opposite directions according to the design model that was reported by Ren et al. (2022). The dimensions of the CSRR were optimized through the iterative process of tuning parametric sweeps with CST simulation software with the inner radius (rin), outer radius (rout), gap (g) and slot width (s) as tunable parameters.

The equivalent LC circuit resonating frequency was generally the resonance frequency of the CSRR (Elkorany *et al.*, 2022):

$$f_{CSRR} = \frac{1}{2\pi\sqrt{LC}} \quad (7)$$

where L represents the inductance and C signifies the capacitance formed by the slot geometry.

By embedding the CSRR into the radiating patch, the antenna experienced improved surface current distribution, stronger resonance coupling, and reduced return loss, leading to enhanced gain and wider operating bandwidth.

Design Flow and Simulation Configuration

The proposed CSRR-enhanced Microstrip Patch Antenna (MPA) was designed using the systematic workflow method to provide a structured workflow towards systematic optimization and performance validation. Baseline MPA modeling was the first step wherein the antenna geometry was obtained based on the standard design equations of the rectangular patch antennas. The parameters that were calculated included patch Width (W), Length (L) and substrate Height (h) and the dimensions of feedline based on the desired resonant frequency that fell into the sub-6 GHz range. This phase created the reference model and this acted as a point of reference when analyzing the performance of the future design changes.

The second stage involved Complementary Split Ring Resonator (CSRR) integration where a CSRR structure had been etched in to the radiating patch. Parametric sweeps were closely used to optimize the CSRR geometry, which is a two-slot concentric arrangement with splits that are opposite each other, to carefully adjust the inner radius, outer radius, gap width, and slot spacing. These parameters had an immediate effect on the resonant frequency and impedance characteristics of the antenna. The CSRR introduction was to add more resonance modes and improve electromagnetic coupling which would result in better bandwidth, gain, and return loss characteristics.

The third step concerned performance validation in which the CSRR-loaded antenna would be simulated and compared to the baseline design. Improvements were quantified by key performance indicators that included: return loss (S11), -10 dB bandwidth, peak gain and far-field radiation patterns. The obtained results gave a clear idea on how CSRR can be used to improve the performance of an antenna, especially in expanding the antenna impedance band measure and radiation efficiency.

CST MWS which is a 3D full-wave electromagnetic solver was used to develop and simulate all the antenna models. FR-4 was the substrate material adopted, and its relative

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permittivity (er) was 4.4, substrate thickness (h) 1.6 mm and dielectric loss tangent (tan d) 0.02. The antenna was driven with a 50-O microstrip line feed and simulations were done at a frequency range of 1 to 7 GHz to span the entire operating range of sub-6 GHz. The perfectly matched layers (PML) were used as the boundary condition to limit the reflections and emulate the free-space operation. Figure 1 (Design Flowchart) summarizes overall the process of the design process including initial modeling and final optimization.

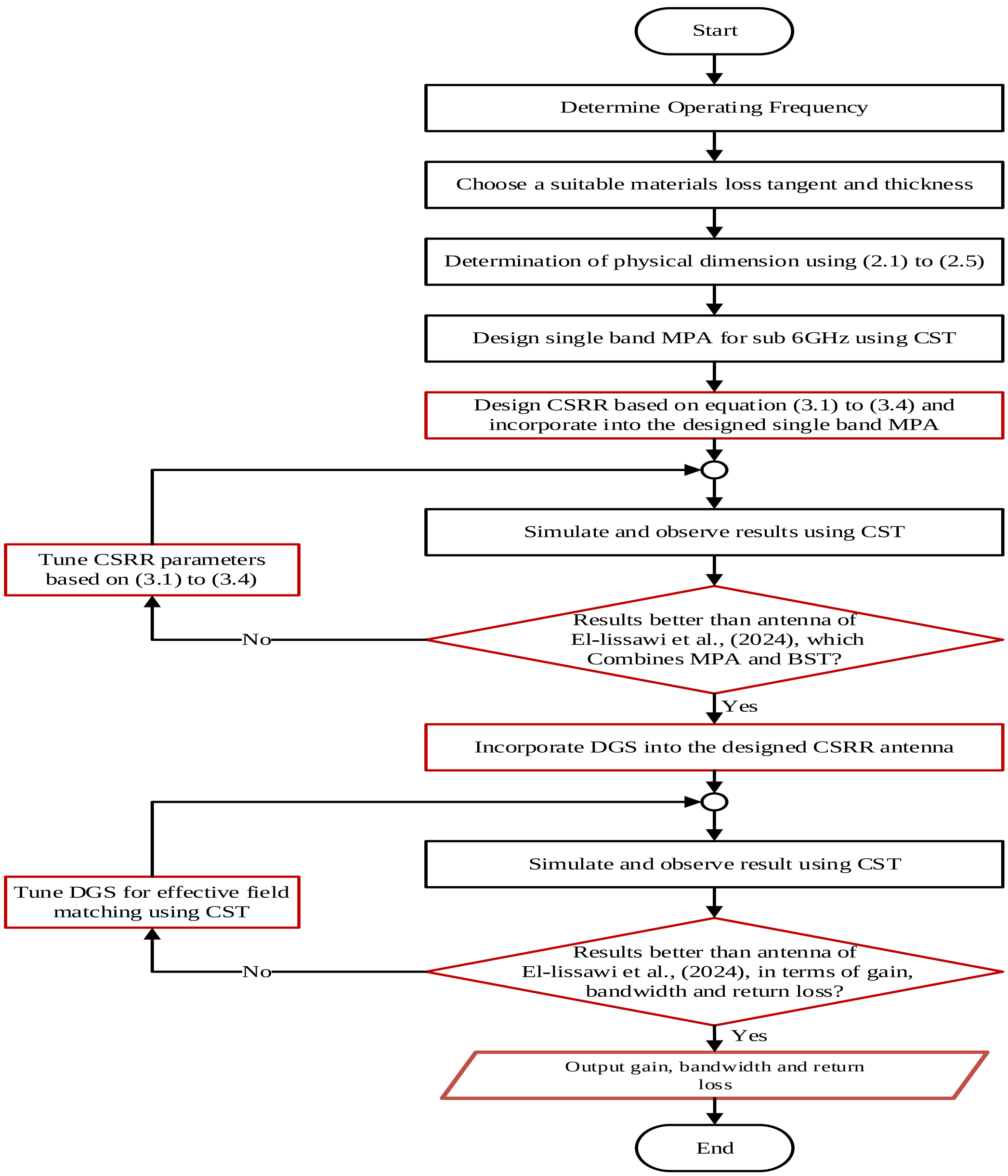

Figure 1: Development of a Complimentary Split Ring Resonators based on wideband microstrip patch antenna for Sub 6GHz

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RESULTS AND DISCUSSION

Return Loss and Impedance Matching

This reflection coefficient (S11) is an important parameter that indicates how well an antenna is impedance-matched to its feed network. A smaller S11 value reflects a higher matching and low power reflection. Figure 2 shows the return loss of both the baseline microstrip patch antenna (MPA) and the proposed CSRR-enhanced. The baseline MPA had one resonant dip which was at around 4.2 GHz with a lowest return loss of -22 dB, and had a limited operation band of about 1.9 GHz. Such a narrow band is characteristic of traditional MPAs, which intrinsically only allow a single dominant resonant mode.

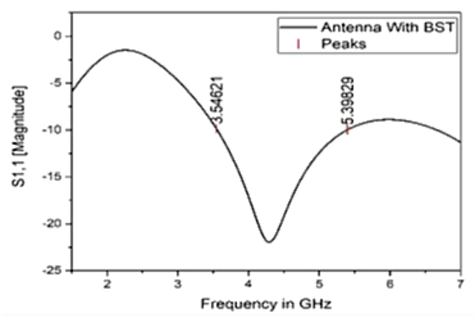

Figure 2: Return Loss of Microstrip Patch Antenna with BST

By comparison, the CSRR-integrated antenna as shown in Figure 3 was observed to have a deeper return loss of -26.5 dB and a larger impedance bandwidth of 3.3 GHz. A further resonant mode was introduced in the introduction of the CSRR structure and essentially resonates with the basic patch resonance to achieve a broader and more stable impedance band. This type of coupling leads to a better confinement of the electromagnetic fields and a better impedance matching leading to low reflection at the feed point. This means that the antenna is able to maintain higher performance at a broader frequency band, which proves that the problem of narrowband limitations of conventional MPAs can be surmounted by loading the antenna with CSRR.

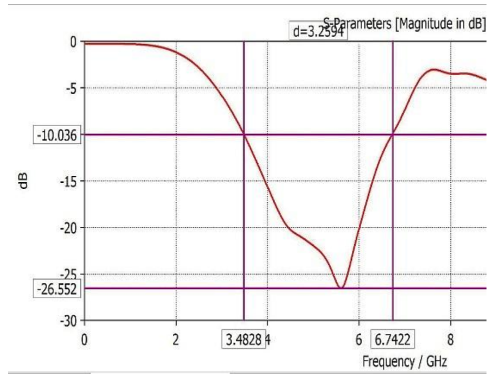

Figure 3: Microstrip Patch Antenna With CSRR

Radiation Pattern Analysis

To determine the directional characteristics and stability of the antenna far-field radiation patterns, the characteristics of the antenna at the resonant frequencies were analyzed. The baseline MPA had a normal broadside radiation pattern, which was of the omnidirectional nature in the H-plane and the bidirectional nature in the E-plane. Nevertheless, its directivity was not so high, and the levels of side lobes were large as it should have been, meaning inefficient radiation.

The antenna improved by the CSRR, however, retained the broadside radiation pattern, but had a high level of directivity and lower the level of sidelobe as shown in Figure 4. The CSRR architecture helps in providing a more homogeneous patch of currents, resulting in larger currents of the forward radiation and inhibiting the objectionable back radiations. The radiation pattern was also constant throughout the 3.3 GHz working range, which proves that coverage is not distorted by the presence of CSRR. This stability guarantees a stable signal quality, which is a necessary feature when using 5G and SCADA systems and other applications, environments can affect signal quality by interfering with the signal and causing multipath propagation, reducing communication reliability.

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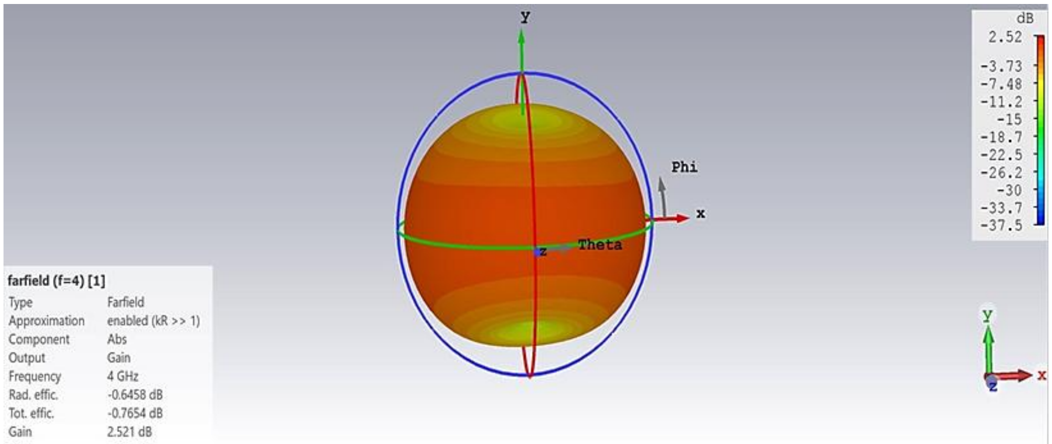

Figure 4: Shows the Radiation Pattern of the Designed Single Band Antenna and CSRR

Comparative Evaluation

The comparison of all the assessed antennas is presented in Table 1. The results clearly confirm the success of the suggested design to overcome the inherent trade-off between size, bandwidth, and gain, which constrains traditional MPAs. The antenna has a high-efficiency wideband performance with structural simplicity and compactness through the introduction of metamaterial-inspired resonators. These properties make the CSRR-enhanced MPA a very promising candidate to multi-standard sub-6 GHz wireless systems such as SCADA, WLAN and WiMAX, and 5G NR, with reliability, compact design and large coverage being the key features.

Table 1: Summary of Designed Antenna

	Gain (dB)	Bandwidth (GHz)	Return Loss
Benched Mark (MPA & BST)	0.4	1.9	-22
Designed (MPA & CSRR)	2.5	3.3	-26.5
Difference (MPA & CSRR)	2.1	1.4	-4.5
% Improvement (MPA & CSRR)	525%	74%	20%

CONCLUSION

This paper presented the design and performance analysis of a Complementary Split Ring Resonator (CSRR)-enhanced microstrip patch antenna (MPA) operating in the sub-6 GHz frequency range. Beginning with a conventional MPA baseline, the integration of the CSRR structure resulted in significant improvements in key performance metrics, including return loss, bandwidth, and gain. Simulation results demonstrated that the proposed CSRR-based antenna achieved a 74% increase in bandwidth, that is, from 1.9 GHz to 3.3 GHz, a 525% gain improvement, that is, from 0.4 dB to 2.5 dB, and a reduction in return loss from −22 dB to −26.5 dB compared with both the baseline and the benchmark design reported by El-Lissawi et al. (2024). These enhancements can be attributed to the metamaterial-inspired characteristics of the CSRR, which modify the antenna's surface current distribution and introduce additional resonant modes. The resulting structure not only improves impedance matching and radiation efficiency but also broadens the operational bandwidth without compromising the antenna's compact form factor. Moreover, the radiation patterns of the CSRR-enhanced antenna remained broadside and stable across the entire operational range, indicating consistent performance and reliable wideband operation.

The study establishes that the proposed CSRR-enhanced MPA provides a compact,

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efficient, and cost-effective solution for various sub-6 GHz wireless communication systems. The improved gain and bandwidth make it particularly well-suited for 5G New Radio (NR) deployments that require robust throughput and extended coverage. Similarly, its multi-standard compatibility supports WLAN and WiMAX systems, while its high radiation efficiency and stable performance make it ideal for SCADA applications, where long-distance and interference-resilient communication are essential for industrial and utility networks. Future work will involve the fabrication and experimental validation of the proposed antenna to verify the simulated improvements under real-world operating conditions. Additionally, potential extensions could explore integration with Defected Ground Structures (DGS) or reconfigurable materials to further optimize performance and adaptability across even wider frequency bands.

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