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TOWARD ROBUST IN-CAR CONNECTIVITY: SIMULATIVE INSIGHTS INTO THE BEHAVIOUR OF SINGLE PATCH AND 2x2 ARRAY ANTENNAS FOR 2.4 GHZ WI-FI APPLICATIONS

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Abstract: The incessant demand for reliable and robust in-car connectivity drives the evolution of automotive wireless communication. In this pivotal research, we ventured into the realm of 2.4 GHz Wi-Fi applications, emphasising refining antenna designs that focused specifically on the Bio-composite material single patch and the 2x2 array configurations. Our simulations, executed meticulously in CST Microwave Studio, yielded noteworthy findings. The single patch antenna, fortified with a quarter-wave feeding line, delivered an efficiency of 51% and a gain of 2.83 dBi. While promising, its bandwidth limitations beckoned a deeper dive into alternative configurations. Subsequently, our exploration of the 2 x 2 array antenna, enriched with a power divider, stood out as a beacon of improvement. Notably, it exhibited a significant gain elevation, registering at 5.79 dBi. This uptick underscores the 2 x 2 array's superiority over its single-patch counterpart in amplifying in-car Wi-Fi strength and hints at its potential to set a new benchmark in automotive wireless solutions. In synthesis, this research does more than just present empirical data; it offers a roadmap for automotive manufacturers and Wi-Fi solution providers, leading them towards more efficient and robust in-car wireless ecosystems. Beyond its immediate implications, our study lays a strong foundation for future explorations, potentially steering the discourse towards more intricate array antenna designs tailored for vehicular environments.

Keywords: antenna, material antenna, leucaenna leucochephala, embedded antenna, bio-composite antenna

1. INTRODUCTION

In the rapidly evolving landscape of vehicular, biocomposite antenna and industrial Wi-Fi applications, the quest for enhanced connectivity and sustainability propels research towards innovative antenna designs and materials. This paper aims to advance this frontier by comparing the performance of single patch antennas with 2 x 2 array patch antennas, utilising a novel bio-composite substrate, PB7030, a blend of 70% polypropylene and 30% Leucaena leucocephala wood sawdust at 500 µm. The shift towards bio-composite materials underscores a commitment to environmental sustainability and poses distinct challenges due to their unique dielectric properties and loss tangents, which are crucial in shaping antenna characteristics and, consequently, their performance in wireless applications [1], [2].
The adoption of PB7030 introduces a paradigm shift in antenna design, particularly for automotive and industrial wireless systems, where the demand for reliable and efficient connectivity is juxtaposed with the imperative for sustainable practices. The specific dielectric constant and loss tangent of bio-composites like PB7030 necessitate a thorough simulation-driven analysis to fully comprehend their impact on antenna performance, encompassing gain, bandwidth, and radiation patterns [3], [4]. Our research fills a crucial gap by systematically evaluating these antennas' performance, thereby providing insights into bio-composite substrates feasibility and potential benefits in wireless communication systems [5].
By focusing on simulation comparisons between single patch and 2 x 2 array antennas on PB7030 substrates, this study delves into the core of antenna performance metrics, offering a granular analysis of how bio-composite materials influence design outcomes. Such a comparison is pivotal for advancing antenna technology and guiding the sustainable evolution of vehicular and industrial wireless networks [6], [7]. The transition from traditional by using Fire retardant type-4 (FR4) material to bio-composite materials in antenna design reflects a broader trend

towards sustainability in the telecommunications industry, necessitating rigorous evaluation to ensure that environmental gains are not offset by compromised performance [8], [9].

The implications of this research are multifaceted, benefiting automotive manufacturers, industrial Wi-Fi solution providers, and the broader research community. By elucidating the performance dynamics of antennas crafted from bio-composite materials, the findings contribute to the dual objectives of enhancing wireless communication and promoting environmental sustainability [10], [11]. Moreover, the study's insights into the specific challenges and opportunities presented by bio-composite materials in antenna design serve as a valuable resource for future research [12].

In summary, this paper addresses a significant knowledge gap by rigorously comparing single patch antennas to 2 x 2 array antennas using a bio-composite substrate, thereby shedding light on sustainable materials' viability and performance implications in wireless antenna applications. Through this investigation, we aim to foster a deeper understanding of bio-composite substrates' potential to revolutionise antenna design for the betterment of both the environment and wireless communication technology [13], [14].

2. METHODOLOGY AND ANTENNA DESIGN

Designing and analysing antennas for vehicular Wi-Fi applications, particularly focusing on the 2.4 GHz frequency range, necessitates a meticulous approach. In this section, we detail the methodology and intricacies involved in designing a single patch antenna with quarter-wave feeding and a 2x2 array antenna equipped with a power divider.

2.1. Single Patch Quarter-Wave Feeding Technique

The single-patch antenna design, predominantly utilised for Wi-Fi, typically operates on the resonant frequency determined by the patch's dimensions. The primary dimension that plays a pivotal role in the resonant frequency is the length (L). For a rectangular patch antenna operating in its fundamental mode, L can be approximated using the following Equation 1:

$$\boldsymbol{L} = \frac{C}{2f_r\sqrt{\varepsilon_r+1}} \tag{1}$$

where: C represents the speed of light (approximately 3×10^8 m/s); f_r is the resonant frequency (in Hz) and ε_r is the relative permittivity of the substrate of biomaterial.

The quarter-wave feeding technique is often selected due to its simplicity and decent impedance-matching capabilities [4]. A quarter-wave transformer's length, Lt, can be represented as Equation 2:

$$L_t = \frac{\lambda_g}{4} \tag{2}$$

where λ_g is the guided wavelength.

2.2. A 2x2 Array Antenna with Power Divider

Constructing a 2x2 array involves the combination of four single-patch antennas. This arrangement boosts the gain, focusing the radiated energy in a specific direction. For the array to function as a cohesive unit, a power divider is implemented to ensure that the signal is evenly distributed amongst the individual patches. Typically, a 4-way power divider can be modelled with multiple quarter-wave transformers, each designed to match the antenna impedance to the source impedance. The characteristic impedance of the main feed is Z_{main}, and each branch is Z_{branch}. Considering the array's need to split power among the four patches equally, the relationship between these impedances can be established as Equation 3:

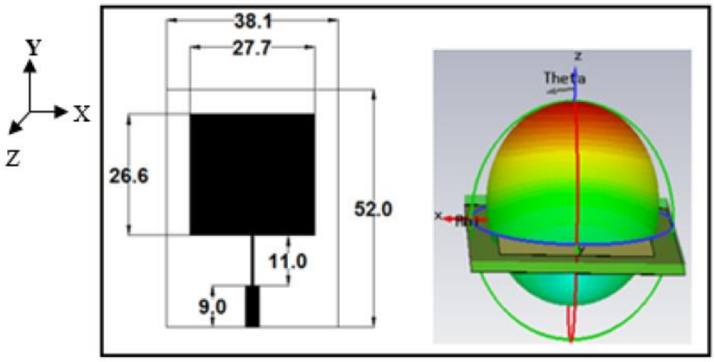
$$Z_{branch} = \sqrt{Z_{main} \times Z_{in}} \tag{3}$$

whew Z_{in} represents the input impedance of the individual antenna patches.

The design process ensures that the distance between each element in the array is selected to minimise side lobes, typically settling for half the operating wavelength. Combining the single-patch quarter-wave feeding technique and the power-divided 2 x 2 array design, this methodology aims to develop an optimal antenna design for vehicular Wi-Fi applications in the 2.4 GHz range. The ensuing simulations and evaluations, as delineated in subsequent sections, will validate the performance efficacy of these designs.

2.3. Single patch quarter wave feed line antenna discussion

The single patch antenna is simulated using the quarter wave feeding line method. The technique was chosen due to its low profile and miniature size compared to the previous single patch introduced earlier, as indicated by Figure 1.



(a) (b)

Fig. 1. Quarter wave antenna (a) dimension (b) 3D view radiation

As depicted in Figure 1, the substrate's dimensions span 52 mm x 39 mm, utilizing a UPB7030 (biomaterial with 70 Polypropylene and 30% Leucaenna Leucochephala sawdust wood) substrate. This substrate boasts a dielectric constant (*Dk*) of 3.05 and a loss tangent (*Tan δ*) of 0.0082, accompanied by a copper sheet thickness of 0.5 mm. Our simulation initiated with an examination of the radiation pattern's polar plot, focusing on the E-Plane (Phi-90°) and H-Plane (Phi 0°) of the single patch antenna. This analysis holds significance, as it lays the groundwork for determining polarization—whether vertical or horizontal—using this polar pattern as a foundational reference.

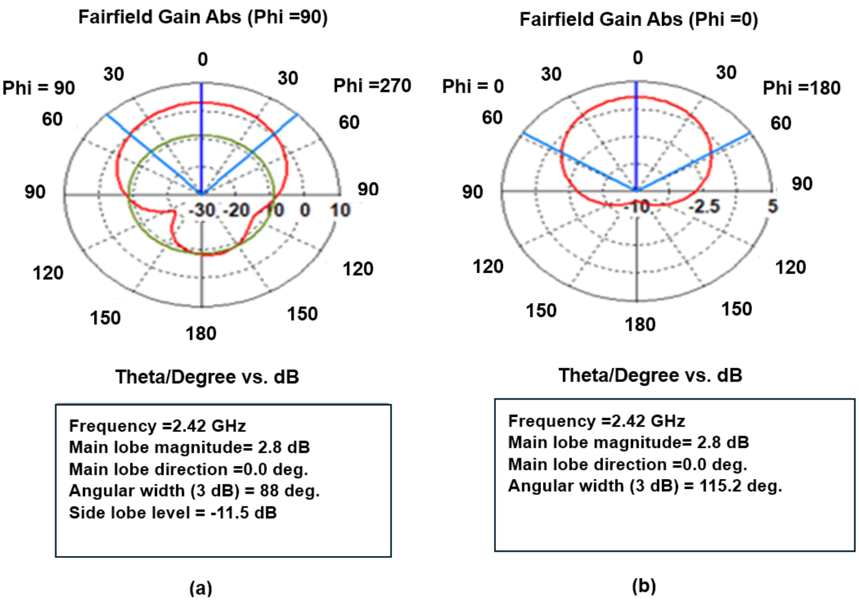


Fig. 2. Polar plot (a) Phi 90° (b) Phi 0°

The radiation pattern demonstrates a gain of 2.8 dBi at a central frequency (CF) of 2.42 GHz. As illustrated in Figure 2, both the E-Plane and H-Plane are directed towards the 0° angle. Figure 2(a) specifically showcases the E-Plane's -3 dB beamwidth pointing at 88°. Conversely, the H-Plane's -3 dB beamwidth, as presented in Figure 2(b), is observed to be 115.2°. These findings align seamlessly with extant literature, particularly with researchers who have previously fabricated a similar design (Park & Kwak, 2013). The antenna's polarisation is determined to be linear and vertically oriented. Figure 3(a) validates this assertion, indicating a dominant radiation pattern in the Phi 90° (E-Plane) for the vertical as seen in Figure 2(a), in stark contrast to the radiation pattern presented in Figure 3(b).

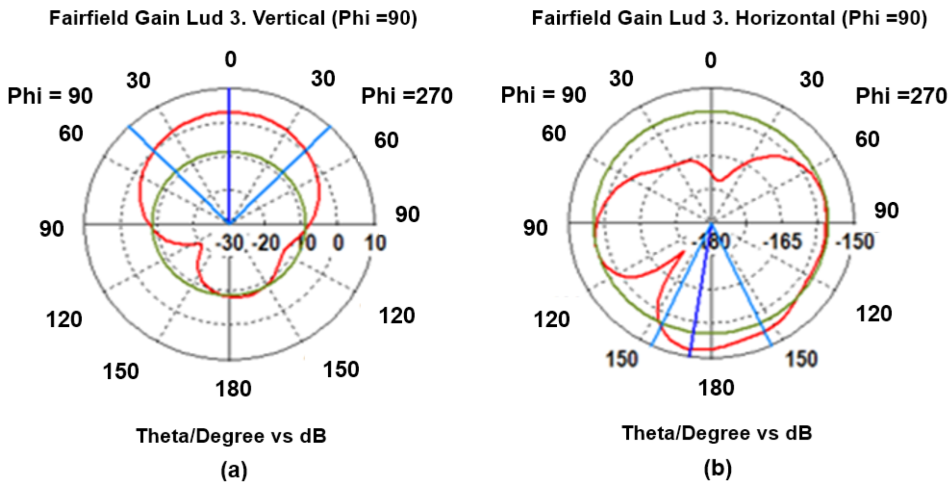


Fig. 3. Simulation Co and cross Phi 90° polarisation: (a) Vertical (b) Horizontal

The antenna's central frequency (CF) is resonant at 2.42 GHz, achieving a magnitude of -40.6 dB. Although the bandwidth of this antenna is limited to 70 MHz, it remains within the standard frequency spectrum for Access Points (WLAN). The operational frequency, delineated by values below -10 dB, spans 2.39 to 2.46 GHz. This performance is graphically represented in Figure 4, which employs the UPB7030 substrate chosen as the preliminary substrate for this study.

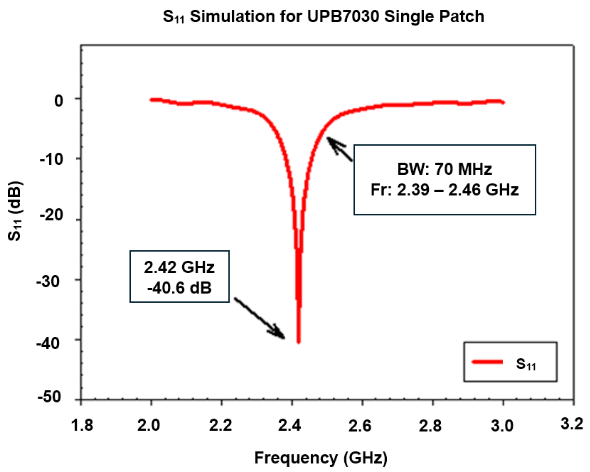


Fig. 4. S-Parameter magnitude plotting for quarter wave single patch

The comprehensive simulation results for the single patch quarter-wave feed antenna are detailed in Table 1 below.

Table 1. UPB7030 single patch quarter-wave antenna performance

Parameters	Simulation
Gain (dBi)	2.83
Efficiency (%, dB)	51 %, -2.926
Directivity (dBi)	5.8
Front to back (dB)	10
-3dB Beam width (degree)	88
Centre frequency (CF)	2.42 GHz
Operating frequency (Fr)	2.39 – 2.46 GHz
Bandwidth	70 MHz
S-Parameter magnitude	-40.6 dB
VSWR	1.02

The single patch antenna, utilising the quarter-wave feed technique, underwent extensive simulation and analysis. The results indicated an optimal performance at the 2.42 GHz frequency, registering an efficiency of 51%. Although this efficiency might appear modest, it is noteworthy that it surpasses the 50% threshold, marking it as viable for specific applications. The recorded gain stands at 2.83, aligning with results from prior studies on the single patch quarter-wave antenna. An impressive directivity of 10 dBi underscores this design's capacity to concentrate signals effectively in a particular direction.

Additionally, with a voltage standing wave ratio (VSWR) value of 1.02, minimal reflections are evidenced at the 2.42 GHz frequency. Drawing parallels with earlier designs (Aziz et al., 2018), this antenna model exhibits a remarkable size reduction: 42% in width, 21% in height, and 44% in the physical patch size, as illustrated in Figure 2. Such reductions accentuate the advantages of the single patch quarter-wave antenna over its air-gap counterpart in compactness. However, this compactness comes at the expense of bandwidth and efficiency. The analysis indicates a bandwidth reduction from 150 MHz (using the air-gap technique) to 70 MHz (with the quarter-wave technique). Similarly, efficiency dwindles from 96% (air-gap method) to 51% (quarter-wave method). To counter these limitations while preserving a low-profile design, the paper will explore using an array method to amplify the antenna's gain.

2.4. 2 X 2 Array antenna discussion

Integrating the single patch with a 2 x 2 array results in the formation of the OCFA antenna. Before progressing to an OCFA antenna structure with a 3 x 3 orientation, it is pivotal to scrutinise the enhancements offered by the 2 x 2 array. Given that the single patch quarter-wave feed antenna, as depicted in Figure 5, exhibits diminished gain and efficiency, the introduction of the array technique seeks to rectify these shortcomings. The array's design retains the quarter-wave feed configuration, incorporating a power divider to channel the energy from the four patches into a singular feed, all while maintaining a compact profile. Consistent parameters are employed, such as a dielectric constant (Dk) of 3.05 and a loss tangent (Tan δ) of 0.0082 for the UPB7030 substrate. The copper sheet's thickness remains at 0.5 mm. A detailed representation of the array antenna, which integrates the quarter-wave feed technique alongside its 3D visualisation, is provided in Figure 5. All dimensions are denoted in millimeters (mm).

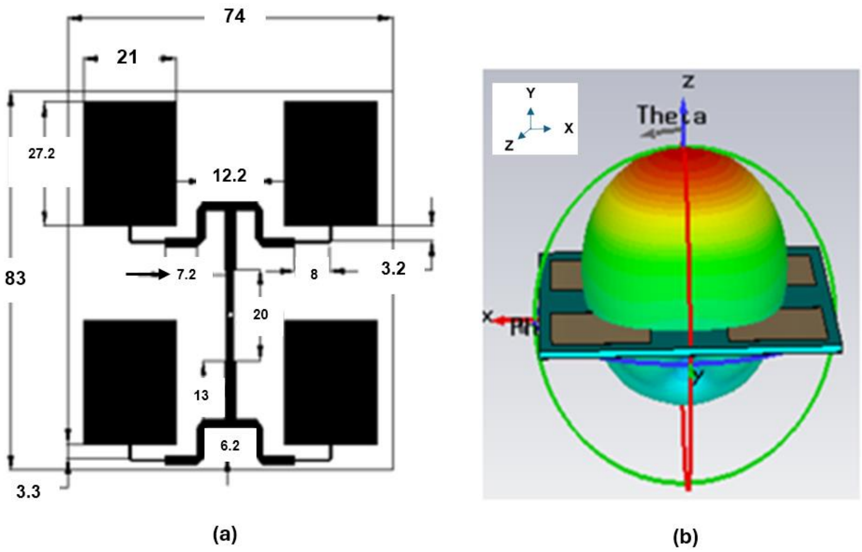


Fig. 5. 2 by 2 array antenna (a) dimension in mm (b) 3D radiation pattern for array

The 2 x 2 array antenna showcases a notable gain increase, escalating from 2.83 dBi (0.69 dB) observed in the single patch design to 5.79 dBi (3.65 dB) in the 2x2 array setup. This represents an impressive gain enhancement of 3 dB (0.86 dB) compared to the single patch. This observed improvement aligns with the theoretical assertion that every incremental deployment in the array configuration leads to an added 3 dBi (0.86 dB) gain [2]. The corresponding polar plots for Phi 90° (E-Plane) and Phi 0° (H-Plane) are graphically represented in Figure 6.

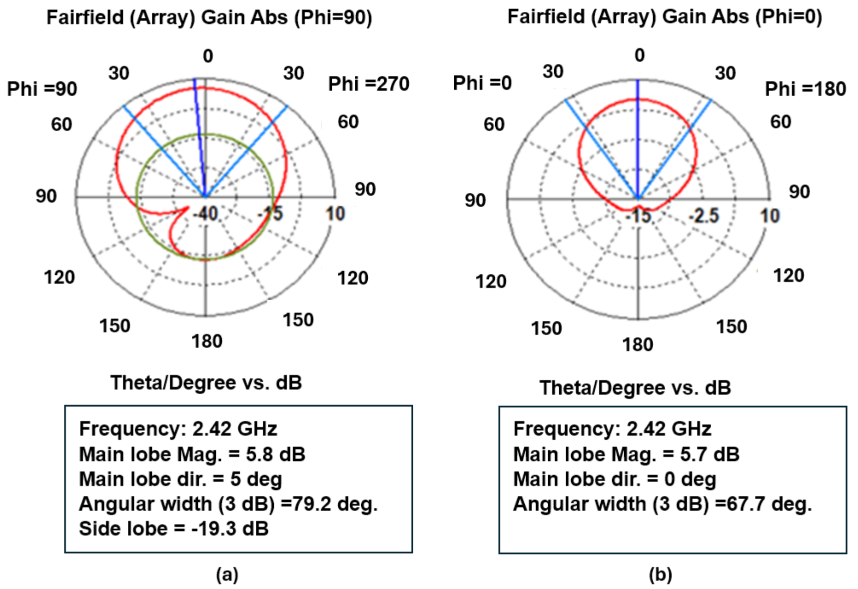


Fig. 6. 2 by 2 polar plot (a) Phi 90° (b) Phi 0°

The antenna employs a coaxial feed-through method, so achieving impedance matching becomes imperative, especially in low-profile configurations. The power divider transmission line is meticulously designed to ensure the antenna's impedance characteristics hover around 50 ±10 Ω, aiming for a Voltage standing wave ratio (VSWR) less than 2. This critical impedance feature for the 2 x 2 array antenna is depicted in Figure 7.

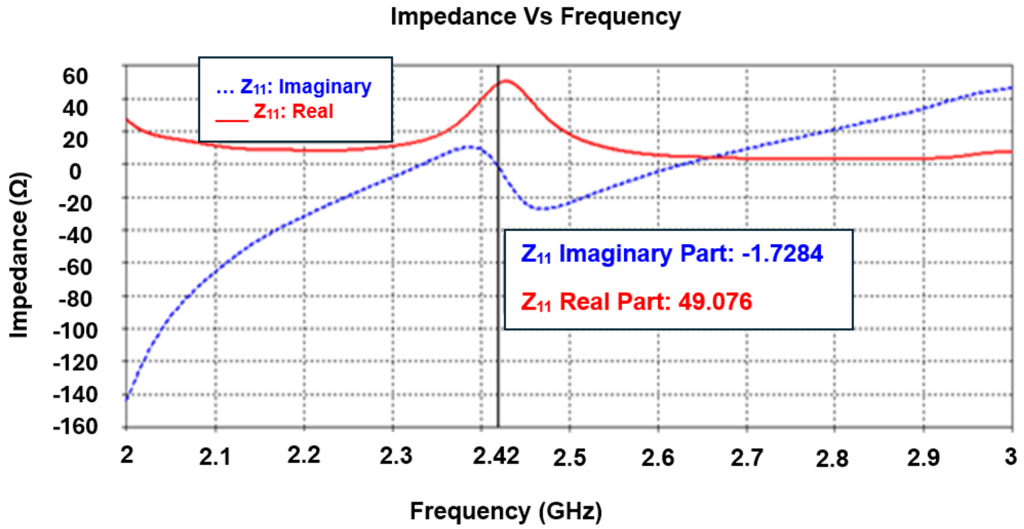


Fig. 7. Impedance characteristic of 2 by two array antenna

The antenna's complex impedance is measured to be 49.1-j1.73 Ω, signifying its capacitive nature due to the imaginary value of –j1.73 Ω. Given this capacitive characteristic, the current leads the voltage by a phase angle of 2°, as calculated using the relationship Tan-1 (-1.73/49.1). Such a value indicates that the S_{11} output is sharpened, and there's a slight reduction in both the physical size of the antenna and its ground plane, leading to its low-profile structure. The magnitude of the S_{11} for the antenna is depicted in Figure 8, registering a value of -34.8 dB at a center frequency (CF) of 2.42 GHz. Notably, capacitive-type antennas typically do not exhibit a significant increase in bandwidth compared to their inductive counterparts. A modest bandwidth increment of 10 MHz was observed when transitioning from the single patch antenna's 70 MHz to the array's 80 MHz. The operational frequency range of the array antenna spans from 2.38 GHz to 2.46 GHz, aptly covering the entire WLAN spectrum.

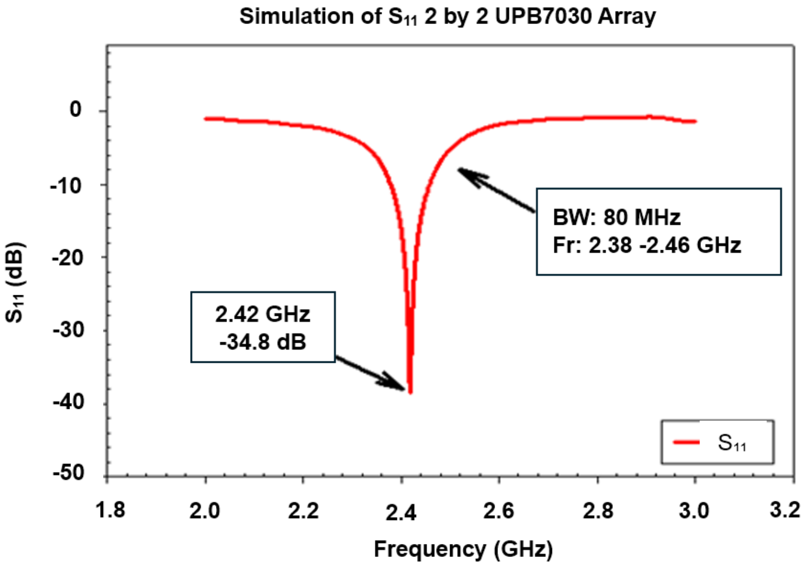


Fig. 8. S-parameter magnitude of 2 by 2 Array antenna

The observed increase in antenna gain aligns with established theory, suggesting that for each additional element in an array, there is an enhancement of approximately 3 dBi (ranging from 0.66 to 3.66 dB) compared to a single patch antenna. This gain progression across frequencies is illustrated in Figure 9, with the peak gain prominently identified at 2.42 GHz, registering a value of 3.66 dB.

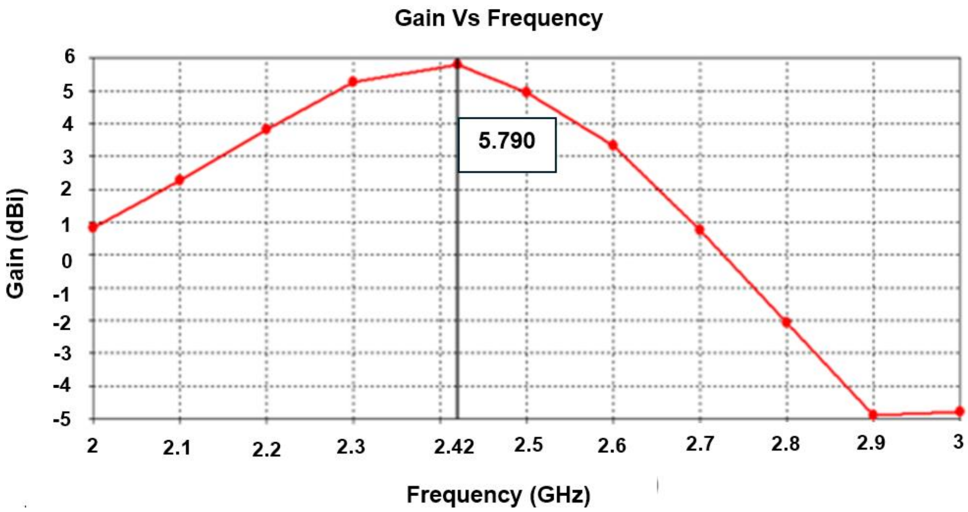


Fig. 9. 2 by two array gain over versus frequency

The transmission line associated with the 2 x 2 power divider is pivotal for optimal antenna performance. A primary challenge faced is impedance mismatch, leading to significant reflection in the antenna. Ensuring an even power distribution is essential to attain the desired peak directivity and gain. Interestingly, the current per section (A/m) for the array antenna, designed using the quarter-wave methodology, yields a lower current flow than the single patch, as evidenced in Figure 10 (air gap design). Specifically, while the air gap design registers 24.8 A/m, the array antenna under discussion delivers only 24.6 A/m. This discrepancy is expected: the air gap patch operates inductively, while the quarter-wave works capacitively. Capacitive antennas typically manifest lower current but higher voltage conduction. In contrast, inductive antennas follow the opposite trend. Figure 10 depicts the surface current distribution, underscoring how the current is most concentrated at the power divider. This concentration reduces surface current relative to the previous inductive single patch designed with an air gap.
The overall performance of the two-by-two (2 x 2) array antenna tabulated as indicated in Table 2.
As presented in Table 2, the antenna gain witnessed a significant increase of 51.2%, rising from 2.83 dBi (for the single patch) to 5.8 dBi (for the 2 x 2 array). Similarly, efficiency improved from 51% (with the single patch) to 52.1% (with the 2 x 2 array). An efficiency boost of 2% aligns with expectations; capacitive antennas typically do not present substantial efficiency improvements, and this marginal increase sufficiently meets the design objectives of the array.

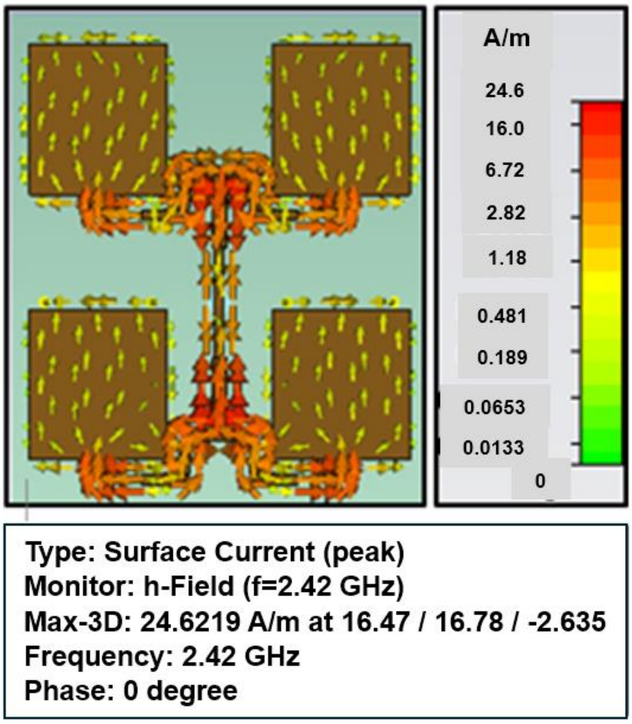


Fig. 10. Surface current distribution for two-by-two array (2 x 2)

Table 2. Overall simulation 2 x 2 array antenna UPB7030 performance

Parameters	Simulation	% of deviation
Gain (dBi)	5.8	51.2%
Efficiency (%, dB)	52.1%, -2.835	2%
Directivity (dBi)	8.6	33%
Front to back (dB)	13.5	26%
-3dB Beam width (degree)	79.2	Decrease 10%
Centre frequency (CF)	2.42	Same frequency
Operating frequency (Fr)	2.38-2.46GHz	0.4%
Bandwidth	80MHz	12.5%
S-Parameter magnitude	-34.8dB	14.2%
VSWR	1.04	1.92%

Note: % deviation indicated the difference between single patch quarter wave and two by two array

Moreover, with the transition to an array configuration, the directivity exhibited a remarkable ascent, going from a mere 5.6 dBi (single) to a notable 8.6 dBi (array). This shift underscores the array's enhanced capability to focus the antenna's radiative power. The comparative percentage deviation between the single patch and the array antenna is detailed in Table 2. In summation, the 2 x 2 array meets and exceeds the design objectives when juxtaposed with its predecessor while maintaining the desired low-profile array antenna configuration.

3. CONCLUSION

In addressing the pressing need for enhanced Wi-Fi vehicular connectivity, this research paper presents a comprehensive solution by evaluating single patches versus the 2 x 2 array antenna configurations. The 2 x 2 array emerges as the optimal choice, delivering a remarkable gain improvement of 51.2% and an elevated directivity from 5.6 dBi to 8.6 dBi. Despite the inherent capacitive characteristics of the array, which typically pose challenges to efficiency enhancement, a commendable 2% increase in efficiency was documented. Importantly, these advancements have been integrated without undermining the antenna's low-profile design, a paramount feature for vehicular applications. In conclusion, this research furnishes promising simulation results that could substantially bolster Wi-Fi vehicular connectivity. The 2 x 2 array configuration not only fulfils the set objectives but does so harmoniously, balancing performance and design, thereby paving the way for the next generation of vehicular communication systems.

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