

A Systematic Workflow for the Design and System-Level Integration of a 2.1 GHz PIFA Antenna Using AWR

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Abstract: The increasing complexity of modern wireless communication systems necessitates the accurate evaluation of antenna performance at the system level. A key challenge in the design workflow, however, is the high-fidelity integration of antenna models from three-dimensional (3D) electromagnetic (EM) simulations into system-level platforms. To address this issue, this paper presents a systematic workflow for the complete process from component design to system-level integration of a 2.1 GHz Planar Inverted-F Antenna (PIFA) within the AWR Design Environment. Initially, the antenna's physical dimensions are estimated based on quarter-wavelength ($\lambda/4$) resonance theory. Subsequently, the PIFA is modeled in the 3D EM simulator, AnalystTM, where its performance is optimized through parametric sweeps of the radiating arm length and feed point position to achieve precise frequency tuning and impedance matching. The simulation results demonstrate that the optimized PIFA exhibits excellent performance. Finally, this paper elaborates on the method for integrating the optimized antenna's S-parameters and far-field radiation pattern data into the Visual System Simulator (VSS) to create a high-fidelity behavioral model. This comprehensive workflow effectively bridges the gap between component-level EM simulation and system-level link analysis, providing a clear and practical paradigm for antenna-system co-design.

Keywords: AWR; Analyst; VSS; PIFA; S-parameters; Radiation Pattern.

1. Introduction

The rapid evolution of modern wireless communication technologies, driven by the proliferation of Fifth Generation (5G) and Internet of Things (IoT) applications, has imposed unprecedented challenges on the design of terminal device antennas. Stringent requirements for miniaturization, multi-band operation, and high efficiency have become paramount [1]. Among the various antenna solutions, the Planar Inverted-F Antenna (PIFA) (Fig.1) has emerged as a mainstream choice for mobile handheld devices, prized for its inherently low profile, compact structure, and ease of integration [2, 3]. A key advantage of the PIFA is its ability to resonate at a physical length of a quarter-wavelength ($\lambda/4$), significantly smaller than traditional half-wavelength antennas, thereby satisfying the demand for miniaturization [4, 5]. Moreover, its integrated ground plane effectively reduces backward radiation, lowering the Specific Absorption Rate (SAR) and enhancing user safety, a critical consideration in modern electronics [6, 7]. The flexibility of the PIFA structure allows for various techniques, such as etching slots on the radiating patch, to achieve multi-band or wideband performance to cover diverse communication standards like GSM, LTE, and WLAN [8, 9, 10].

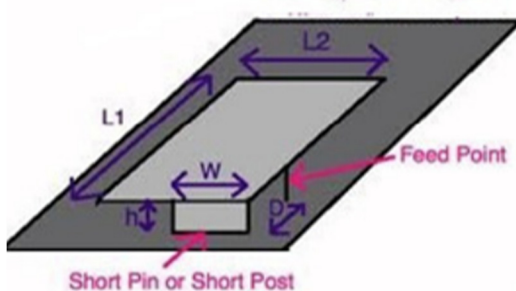


Fig 1. basic PIFA antenna

While extensive parametric studies have provided clear guidelines for optimizing PIFA performance by adjusting physical dimensions [2], a significant gap often persists between component-level design and its real-world application within a complete system. In conventional system-level simulations, the antenna is frequently oversimplified as an ideal component with a fixed gain. This approach neglects the antenna's true frequency-dependent characteristics, such as impedance mismatch and complex, non-isotropic radiation patterns [11]. Such simplifications can lead to substantial inaccuracies in predicting the overall system performance, highlighting an urgent need for a robust co-simulation methodology that integrates a high-fidelity antenna model [1].

To bridge this gap, this paper presents a systematic workflow executed entirely within the AWR Design Environment. It demonstrates the complete process from the theoretical design and 3D electromagnetic (EM) optimization of a 2.1 GHz PIFA to its high-fidelity integration into the Visual System Simulator (VSS). This work aims to provide a clear and reproducible paradigm for antenna-system co-design, ultimately enhancing the accuracy and efficiency of the entire development cycle. The remainder of this paper is organized to detail this workflow, presenting the antenna design methodology, the system integration procedure, and an analysis of the final performance results.

2. PIFA Antenna Design and Optimization

This section presents the detailed design methodology for the 2.1 GHz PIFA antenna, encompassing theoretical analysis, Simulation Setup, and the subsequent optimization process performed within the AWR Design Environment.

2.1. Theoretical Formula for PIFA Antennas

The PIFA not only features a smaller size, but its structure, backed by a ground plane, can also effectively reduce backward electromagnetic radiation towards the user's head, thereby lowering the Specific Absorption Rate (SAR) [4]. Meanwhile, its $\lambda/4$ resonance mode and the flexible positioning of its feeding and shorting points provide it with superior advantages in both impedance matching and multi-band design.

For a basic PIFA antenna, resonance occurs when the average electrical path length from the open radiating edge to the shorting structure is a quarter-wavelength. A widely accepted approximate formula (Eq.1-3) for the resonant length of a PIFA, which combines the effects of the radiating arm's length L_1 , width L_2 , and the shorting wall's width W , is given by [2]:

$$L_1 + L_2 - W = \frac{\lambda}{4} \quad (1)$$

This equation clearly indicates that increasing the width of the shorting structure, W , can effectively shorten the resonant length of antenna, thereby increasing its resonant frequency. This principle provides crucial theoretical guidance for the miniaturization and frequency tuning of PIFA antennas. To apply this theory to our design, we also need to incorporate the fundamental formula for electromagnetic wave propagation in a dielectric medium:

$$\lambda = \frac{c}{f\sqrt{\epsilon_r}} \quad (2)$$

where c is the speed of light in free space, f is the frequency, and ϵ_r is the relative permittivity of the substrate. By substituting (Eq. 2) into (Eq. 1), we can derive an estimation equation that directly relates the physical dimensions to the resonant frequency

$$L_1 + L_2 - W \approx \frac{c}{4f\sqrt{\epsilon_r}} \quad (3)$$

For the designated center frequency of 2.1 GHz, the free-space wavelength is approximately 142.8 mm. According to Equation (1), the required $\lambda/4$ resonant length is about 35.7 mm. However, this formula neglects significant factors such as the inductive effect of the shorting structure and strong fringing fields from the patch edges [6]; which can alter the effective electrical length. Therefore, for the initial design, a set of dimensions slightly larger than the theoretical estimate was chosen to account for these effects. The initial dimensions for the radiating patch were set to 45 mm and 20 mm, respectively. The shorting arm width (W) was chosen as 18 mm.

2.2. Antenna Configuration and Simulation Setup

The proposed PIFA was designed on a standard FR-4 substrate with a thickness of 1.6 mm and ϵ_r of 4.4. To ensure sufficient radiation efficiency while mimicking a typical mobile terminal layout, the radiating element was suspended at a height (H) of 5 mm above the ground plane. To accurately analyze and optimize this structure, a full-wave 3D electromagnetic simulation was performed using AWR Analyst™, a solver based on the Finite Element Method (FEM). This choice is critical as Analyst™ can precisely model the inherently 3D structure of the PIFA, including the vertical shorting wall and suspended patch, capturing complex current distributions and radiation behaviors that 2.5D planar solvers might miss. The simulation model was constructed with the following configuration. A three-layer

dielectric stackup was defined, consisting of the 1.6 mm FR-4 base, upon which a 5 mm thick air layer was placed to create the suspension. The initial 45 mm \times 20 mm radiating patch was drawn as a copper conductor on the top surface of the air layer. The grounding was implemented via a 1 mm \times 18 mm shorting wall, modeled as a via structure extending from a short edge of the patch down through both the air and FR-4 layers to connect to the ground plane below. To simulate radiation into free space, the bottom boundary ($-Z$ direction) was set as a Perfect Electric Conductor (PEC), while the remaining five faces of the simulation domain were configured as Perfectly Matched Layers (PML) to absorb outgoing waves. A wave port, representing a 50-ohm coaxial feed, was used for excitation. This was implemented by a 3 mm wide microstrip feed line on the patch, extending from a position near the shorting wall to the simulation boundary. The simulation was performed over a frequency range of 1.5 GHz to 3.0 GHz, with the center frequency explicitly set to 2.1 GHz.

2.3. Optimization and Final Design

Preliminary simulations based on estimated dimensions indicate that the antenna exhibits a resonance point at approximately 1.95 GHz. This frequency is below the target value, suggesting that the antenna's equivalent electrical length is excessively long. The optimization began with frequency tuning by systematically shortening the physical length of the radiating arm. This iterative process, monitored via the S11 parameter, continued until the resonant frequency was precisely shifted to 2.1 GHz, resulting in a final optimized length of 39.5 mm. Subsequently, to further refine the antenna's characteristics, a slotting technique was employed. A rectangular slot of 5 mm \times 10 mm was etched onto the radiating patch. This forces the surface currents to meander around the opening, effectively increasing the antenna's electrical length without altering its physical footprint—a valuable technique for miniaturization. The introduction of this slot necessitated minor re-adjustments of the patch dimensions to maintain the 2.1 GHz resonance. The final slotted geometry is depicted in Fig.2 and Fig.3. The final and most critical step was impedance matching. With the geometry correctly tuned for frequency, the S11 depth was only -8 dB, indicating a significant mismatch. As the input impedance of a PIFA is highly sensitive to the feed position relative to the shorting wall, a parametric sweep of the feed point location was performed. By translating the feed point, an optimal position was identified at 4.5 mm from the edge of the shorting wall. This adjustment resulted in an excellent return loss of -19.19 dB at 2.1 GHz, signifying a near-perfect match to the 50-ohm system impedance.

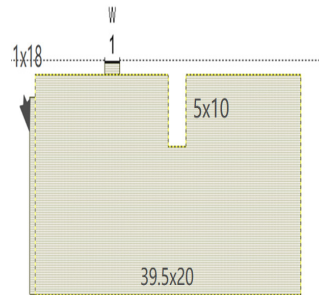


Fig 2. 2D antenna view

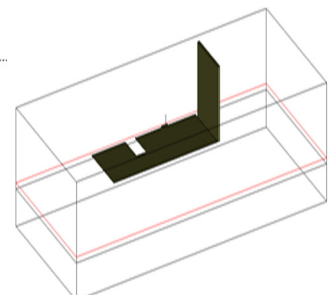


Fig 3. 3D antenna view

3. Results and Discussion

The simulated performance of the final, optimized 2.1 GHz

PIFA antenna validates the effectiveness of the design and optimization workflow. The key performance metrics are presented and analyzed cohesively in this section. The impedance matching characteristics of the antenna were evaluated first. As shown in Fig.4, the antenna achieves an excellent return loss of -19.19 dB at the 2.1 GHz center frequency. This value, significantly below the -10 dB threshold, indicates that over 98% of the input power is efficiently delivered to the antenna. The effective operational bandwidth, defined by $S_{11} < -10$ dB, spans from 1.5 GHz to 2.6 GHz, fully satisfying the design requirements. This strong matching performance is corroborated by the Voltage Standing Wave Ratio (VSWR) of 1.247 at 2.1 GHz, a value exceptionally close to the ideal of 1 (Fig.5). The Smith chart in Fig.6 further reveals that the input impedance at resonance is $54 + j11 \Omega$ (normalized to $1.08 + j0.22$), confirming a near-

perfect match to the 50Ω system and validating the success of the feed point optimization. The far-field radiation characteristics at 2.1 GHz were then analyzed. Fig.7 provides a comprehensive visualization of the antenna's 3D radiation pattern. The pattern is clearly directional, with a prominent main lobe achieving a peak directivity of approximately 5.22 dBi and a deep null in the backward direction. This excellent front-to-back ratio is highly desirable for mobile terminals, as it minimizes radiation towards the user, contributing to a lower SAR. A detailed examination of the 2D planar cuts of this pattern reveals a maximum co-polarization (E-Theta) gain of 6.45 dBi in the direction of $\Phi = -54^\circ$ (Fig.8). In the same direction, the cross-polarization (E-Phi) gain is suppressed to -4.6 dBi, resulting in a Cross-Polarization Discrimination (XPD) of 11.05 dB (Fig.9).

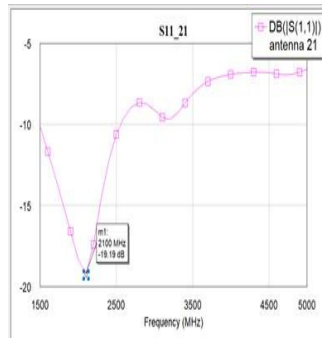


Fig 4. S11

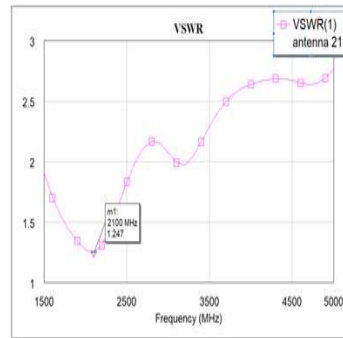


Fig 5. VSWR

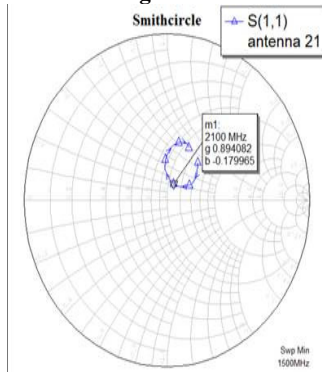


Fig 6. Smithcircle

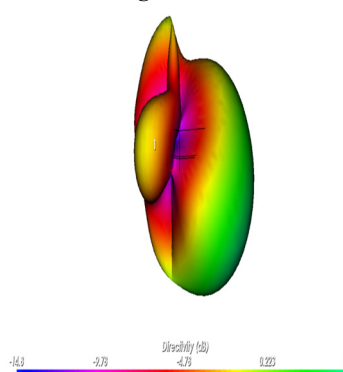


Fig 7. 3D pattern

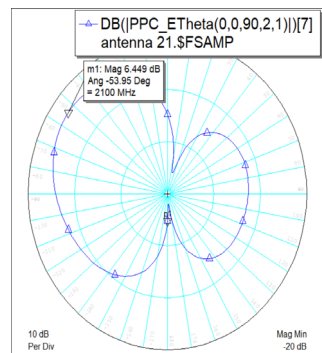


Fig 8. EPhi

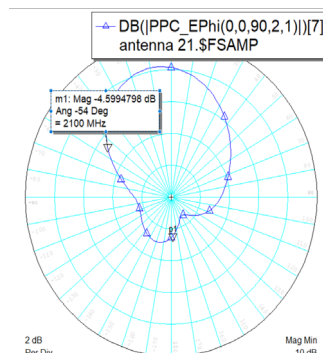


Fig 9. ETheta

The overall performance metrics are summarized in Table 1, collectively demonstrating that the proposed PIFA is well-matched, provides high gain with good polarization purity,

and exhibits a radiation pattern suitable for mobile applications.

Table 1. Summary of Simulated Performance for the Optimized 2.1 GHz PIFA

Parameter	Return Loss	VSWR	Input Impedance	ETheta	EPhi	XPD
2.1GHz PIFA	-19.19 dB	1.247	(1.08,0.22)	6.45dBi ($\Phi = -54^\circ$)	-4.6 dBi	11.05 dB

4. System-Level Integration and Modeling in VSS

While the electromagnetic simulations in Section III confirm the high performance of the designed PIFA as a standalone component, its true impact can only be evaluated within a complete communication system. To bridge the gap between component-level design and system-level analysis, a high-fidelity behavioral model of the optimized antenna was created and integrated into the Visual System Simulator (VSS) to create a "digital twin" for co-simulation [12]. This integration process leverages the ANTENNA block within VSS and consists of two key steps using the simulation data obtained from EM. First, the antenna's circuit matching characteristics were defined by configuring the "Circuit port mismatch" parameter of the ANTENNA block to the "Return Loss, dB" mode and entering the precise simulated value (-19.19 dB at 2.1 GHz). This ensures that the system-level simulation accurately accounts for any power loss due to impedance mismatch, providing a much more realistic model than an ideal antenna. Second, the antenna's spatial radiation characteristics were incorporated by exporting the far-field radiation pattern data into a standard text data file and directing the "Radiation pattern (RADPAT)" parameter within the VSS ANTENNA block to this file. This step endows the system-level model with the antenna's true directional gain and pattern shape. The complete configuration of the ANTENNA block, as shown in Table 2, encapsulates all key performance aspects of the designed PIFA. Through these two steps, a comprehensive behavioral model is established, enabling realistic end-to-end system simulations for metrics such as link budget or EVM while fully accounting for the real-world performance of the antenna component. This procedure provides a reliable and systematic workflow for antenna-system co-design.

Table 2. data file

THETA (°)	PHI (°)	Gain (dB)
90	-180	-2.3754
90	-178	-2.1791
90	-176	-1.9843
90	-174	-1.7908
90	-172	-1.5967
...
90	172	-3.4085
90	174	-3.1928
90	176	-2.9821
90	178	-2.7762
90	180	-2.5736

5. Conclusion

In this paper, a systematic workflow for the design, optimization, and system-level integration of a 2.1 GHz Planar Inverted-F Antenna was successfully demonstrated within the AWR Design Environment. Through a methodical process of theoretical estimation, 3D EM modeling, and parametric optimization, a high-performance PIFA was realized, achieving an excellent return loss of -19.19 dB and a maximum co-polarization gain of 6.45 dBi. More

significantly, this work detailed the critical step of creating a high-fidelity "digital twin" of the antenna in the Visual System Simulator (VSS) by integrating its simulated S-parameters and far-field radiation data. This comprehensive procedure bridges the crucial gap between component design and system analysis, providing a clear, practical, and reproducible paradigm for antenna-system co-design. The presented methodology enhances the accuracy of system-level predictions and serves as a valuable template for the development of a wide range of antenna-integrated wireless systems. Future work could focus on fabrication and measurement to experimentally validate these findings.

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