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Application and Validation of the Wave Concept Iterative Process for a 5-Shaped Patch Antenna for 5G Applications

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Abstract. The design, development and validation of a new 5-shaped patch antenna at 3.5 GHz designed to be used in mid-band 5G was done in this paper. We first designed the antenna with the Wave Concept Iterative Process (WCIP) MATLAB implementation. The project was later validated with CST Microwave Studio simulation. We discuss the theory of WCIP and numerical results. The good agreement between the two methods indicates that WCIP is very good for planar structure analysis with a reflection coefficient of -25 dB at 3.5 GHz and much faster computation.

1 Introduction

5G networks will need compact, high-performance antennas that can run efficiently at mid-band frequencies. Microstrip patch antennas are ideal for 5G since they are planar, cost-effective and easy to integrate into various electronic devices. While microstrip patch antennas have many benefits, the standard calculation methods for them like Method of Moments, Finite Element Method and Finite Difference Time Domain method can take a lot of memory and processing power to perform effectively [1]; this challenge highlights the need for more efficient techniques. WCIP [2] is one of the most important approaches in the efficient and accurate modeling of planar structures for advanced wireless technologies. This work shows that using WCIP on a new five-shaped antenna could achieve the high performance required for 5G in 3.5 GHz with speed and precision that are the most important breakthroughs for antenna design of next generation.

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2 WCIP Theoretical Background

Figure 1, adapted from [3], shows the iterative procedure we employ to analyze the circuit. We start by applying an excitation source on the interface plane, thereby defining the initial incident-wave distribution.

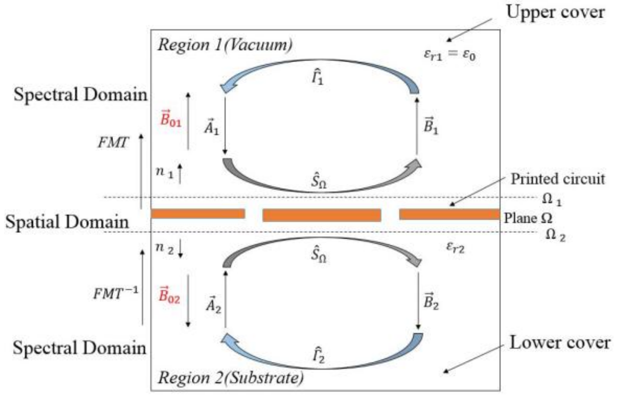

Fig. 1. Methodology of the rigorous iterative procedure

The iterative process is represented analytically by a system of two equations. The first equation, formulated in the spatial domain, describes the geometry under investigation. The second equation, expressed in the modal domain, assumes mode independence. The fast modal transform (FMT) converts data from the spatial domain to the modal domain for mode-based analysis. The inverse fast modal transform (FMT^{-1}) subsequently returns the results to the spatial domain for further evaluation. This process enables efficient analysis and promotes convergence of solutions.

2.1 Basic Equations

The WCIP method operates in both the spatial and spectral domains and utilizes two fundamental relations as described in [4]:

$$\vec{A} = \hat{S}_{int}\vec{B} + \vec{A}_0 \quad (1)$$

$$\vec{B} = \hat{\Gamma}\vec{A} \quad (2)$$

Where:
$\vec{A}$: incident wave,
$\vec{B}$: reflected wave,
$\hat{S}_{int}$: scattering operator,
$\hat{\Gamma}$: reflection operator,
$\vec{A}_0$: source excitation.

The incident and reflected electromagnetic waves exhibit a defined relationship with the tangential components of the electromagnetic field [5].

$$\vec{A_i} = \frac{1}{2\sqrt{Z_{0i}}}(\vec{E_{0i}} + Z_{0i}\vec{J_i}) \quad (3)$$

$$\overrightarrow{A_i} = \frac{1}{2\sqrt{Z_{0i}}}(\overrightarrow{E_{0i}} + Z_{0i}\overrightarrow{J_i}) \quad (4)$$

Where Z_{0i} is the characteristic impedance and $\overrightarrow{J_i} = \vec{n} \times \overrightarrow{H_i}$

2.2 Reflection and Diffraction Operators

The reflection operator, as defined within the spectral domain, is expressed as follows:

$$\Gamma_{mn}^{\alpha} = \langle f_{mn}^{\alpha} \left| \frac{1 - Z_{0i} Y_{mn}^{\alpha}}{1 + Z_{0i} Y_{mn}^{\alpha}} \right| f_{mn}^{\alpha} \rangle \quad (5)$$

With modal admittances [6]:

$$Y_{mn}^{TE} = \frac{\gamma_{mn}}{j\omega\mu_0} \quad (6)$$

$$Y_{mn}^{TM} = \frac{j\omega\varepsilon_0\varepsilon_r}{\gamma_{mn}} \quad (7)$$

The boundary conditions define the scattering operator [6], [7]:

On metals: $\overrightarrow{E_1} = \overrightarrow{E_2} = 0$ (8)

On dielectrics: $\overrightarrow{E_1} = \overrightarrow{E_2}, \overrightarrow{J_1} + \overrightarrow{J_2} = 0$ (9)

On source: $\overrightarrow{E_1} = \overrightarrow{E_0} - Z_0\left(\overrightarrow{J_1} + \overrightarrow{J_2}\right) = 0$ (10)

2.3 Fast Modal Transform

Spatial data are transformed into the spectral domain using FFT expansions.

$$|A_x(x,y)\rangle \sum_{m,n} A_{xmn} e^{-j\beta_{xm}x} e^{-j\beta_{ym}y} \quad (11)$$

$$|A_x(x,y)\rangle \sum_{m,n} A_{xmn} e^{-j\beta_{xm}x} e^{-j\beta_{ym}y} \quad (12)$$

Where $\beta_{xm} = \frac{2\pi m}{a}$ and $\beta_{yn} = \frac{2\pi n}{b}$

3 Antenna design description

The proposed 5-shaped patch is printed on a Rogers RT5880 dielectric substrate. In the numerical model, the substrate is given by a relative permittivity of $\varepsilon_r = 2.2$, a loss tangent of $tan\delta = 0.02$, and a thickness of $h = 1.57mm$. These parameters determine the electromagnetic load on the radiating element and the size of the microstrip. The antenna is dimensioned for operation at 3.5 GHz. The substrate has a length of 44.3 mm and a width of 45 mm, which is enough area for the patch and ground plane. The radiating patch is 29.9 mm wide, 25.2 mm long, and 0.035 mm thick. A 14 mm long microstrip feed line of width 5.2 mm is used to create the resonant impedance of close to 50 Ω. This setup will drive the power from the source to the radiating patch and is in line with the standard impedance matching method for slotted microstrip designs [8, 9, 10]. The 5-shaped contour will make the surface current path longer and redistribute that current path, so that the antenna resonates near 3.5 GHz and does not get too large in general.

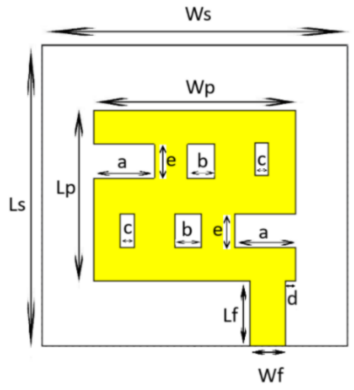

Fig. 2. Antenna geometry

In Fig. 2, we show the main geometric variables of the antenna. The numerical values of these are collected in Table 1..

Table 1. Antenna Dimensions

Parameter	Value (mm)
W_s	45
L_s	44.3
W_f	5.2
L_f	14
W_p	29.9
L_p	25.2
a	9
b	4
c	2
d	1.5

4 Simulation Methodology

4.1 WCIP Implementation

The electromagnetic response of the 5-shaped antenna was first calculated with a MATLAB implementation of WCIP. The analysis region of the antenna and the computational space around it were sampled on a uniform 256×256pixel grid [11]. Each pixel represents a constant size, so the grid directly controls the geometric resolution of the model. The incident and reflected fields are updated at each grid location over 7000 iterations [12], and the algorithm is able to track the evolution of the solution over the whole structure. The frequency sweep was from 2 GHz to 5 GHz, covering the intended 5G mid-band resonance [11]. Convergence was measured by the variation of input impedance between subsequent iterations. The calculation was considered converged when the variation reached 0.001, which was chosen to make the calculation stable and repeatable [13]. At each step, the FFT was used to make the changes between the spatial and spectral domains, which reduces the cost of multiple modal conversions and still retains the field information needed for WCIP [14].

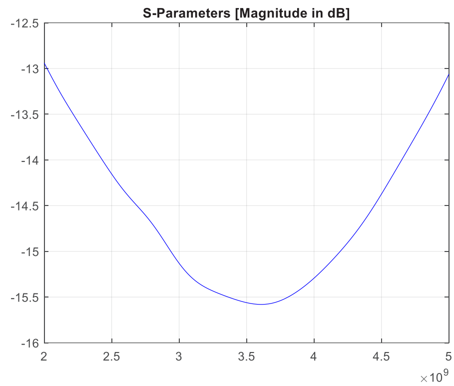

Fig. 3. Reflection coefficient obtained with WCIP

4.2 Simulation Setup

CST Microwave Studio was used as the independent full-wave model. We used open boundaries with the Add Space option and used the finite simulation region to simulate an unbounded environment and thus avoid reflections from the domain limits [15]. The antenna was excited with a waveguide port. The mesh density was at least 20 cells per wavelength, and the mesh was refined near the feed and the discontinuities of the 5-shaped patch, where the electromagnetic field varies most rapidly. The time-domain solver was used to cover the 3-4 GHz region, with the target resonance. Return loss and input impedance were extracted after the mesh quality and accuracy of the solver had been adjusted for comparison with the WCIP results.

5 Results and Discussion

The geometry shown in Figure 2 is a compact planar configuration tuned to the 3.5 GHz band. Its reflection coefficient S_{11} is calculated using the MATLAB WCIP model shown in Figure 3 and CST Microwave Studio in Figure

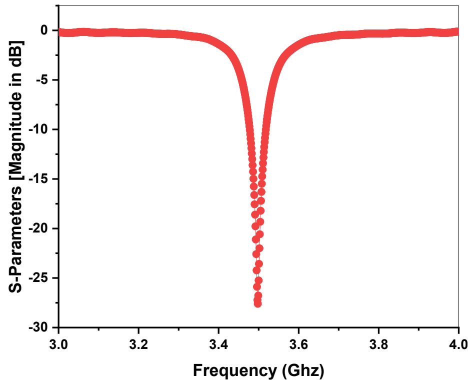

Fig. 4. Reflection coefficient obtained with CST

Both simulations show the resonance at around 3.5 GHz, confirming agreement in the predicted operating frequency. The matching depth is not identical: WCIP gives a reflection coefficient of -15.6 dB, whereas CST predicts -25 dB. Both values remain below the conventional -10 dB matching criterion, but the 9.4 dB difference shows that the agreement is stronger for resonant frequency than for the exact S_{11} magnitude.

5.1 Convergence and Stability

Figures 5 and 6 show the numerical behavior of the WCIP calculation. After a brief transient, the input impedance quantity and the reflection coefficient stay relatively stable and almost unchanged. For this reason, the iterative exchange between the spatial and modal domains is approaching a numerically stable solution.

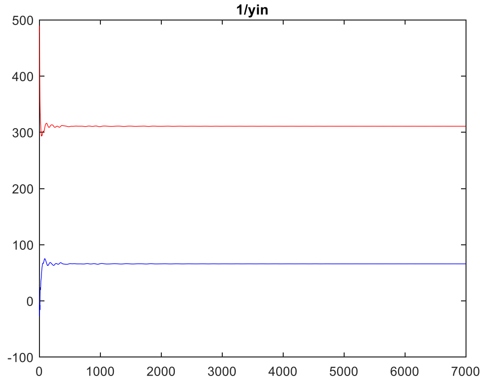

Fig. 5. Input impedance convergence

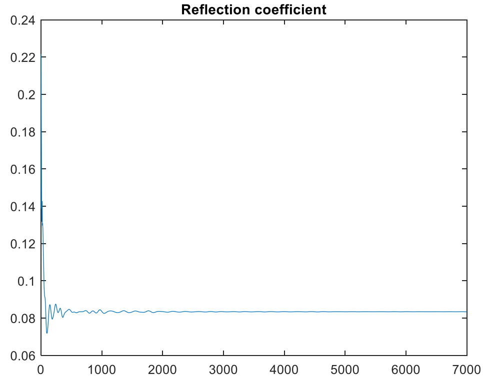

Fig. 6. Reflection coefficient convergence

5.2 Comparison between WCIP and CST

Table 2 summarizes the primary performance parameters obtained from both WCIP and CST simulations.

Table 2. Comparison between WCIP and CST Simulation Results.

	WCIP (MATLAB)	CST Microwave Studio	Observation
Resonant Frequency (GHz)	3.5	3.5	Excellent agreement between both methods.
Reflection coefficient (dB)	-15.6	-25	CST shows deeper matching.

Moreover, the computation time with the WCIP approach was approximately 43 seconds, significantly faster than the 251 seconds required by CST, resulting in a computational speed-up factor of approximately 5.8.

The results indicate that the WCIP achieves high accuracy and substantially improves computational efficiency compared to conventional full-wave solvers.

6 Conclusion

We have applied a MATLAB based WCIP formulation to the analysis of a small 5-shaped patch antenna designed for mid-band 5G operation. The antenna resonates at 3.5 GHz, both in WCIP and CST Microwave Studio. The WCIP prediction is $S_{11} = -15.6\ dB$, while CST is $S_{11} = -25\ dB$, so the two approaches are comparable in the operating frequency, although CST produces a deeper matched response. The main advantage for WCIP is that the analysis is completed in only 43 seconds compared to 251 seconds in CST, which is a speed-up of about 5.8. This reduction in the execution time makes WCIP suitable for rapid iterative design and preliminary optimization of planar microwave structures. Future work will expand the formulation to multilayer antennas, array configurations, and reconfigurable structures, where repeated full-wave simulations can be particularly expensive. In these studies, we will be able to clarify the range of geometries for which WCIP can still be used without compromising the accuracy needed for the prediction.

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