Advanced Transverse Wave Approach for MM-Wave Analysis of Planar Antennas applied in 5G-Technology

Mohamed Ayari [1†], Yamen El Touati [1††] and Saleh Altowaijri [1]
Mohamed.ayari@nbu.edu.sa Yamen.Touati@nbu.edu.sa Saleh.Altowaijri@nbu.edu.sa
[1] Faculty of Computing and Information Technology, Northern Border University –Kingdom of Saudi Arabia;
[†] Syscom Laboratory, National Engineering School of Tunis, Tunis El-Manar University, Tunisia
[††]Institut Supérieur des Arts Multimédia de la Manouba (ISAMM), University of Manouba, Tunisia

Abstract
In this paper, a fast numerical electromagnetic (EM) method based on the transverse wave formulation called-up Advanced Transverse Wave Approach (A-TWA) is presented. An appropriate 5G antenna is designed, simulated and investigated in the context of Millimeter-Wave Wireless Communication Systems. The obtained simulation results are found in good agreement with literature. Such a method can provide for the simulators a great library integrating the most complexly and sensitively geometry elements that can have a huge impact on the applications supported by new wireless technologies.

Keywords: *Advanced transverse wave approach; Wireless Communication Systems; 5G-planar structure; Simulation results*

1. Introduction

The design and analysis of 5G antennas with different kind from large to very thin in terms of size, are the subject of many recent publications. Also, the 5G antennas can be constructed in different shapes such as rectangle [1-2] which is considered as the conventional one, circle or pseudo-circle [3-4], cross [5], or hexagon [6] and have a relative impact on the radiation patterns [7]. Indeed, patch antennas have played an important role in communication through wireless connections [8-9] and improved the radiation properties through the variations in antenna parameters [10-11]. A new capacitive coupled patch antenna array providing 360° coverage has been developed in [12] to cover the frequency band of 24-28 GHz used for 5G based smartphone services. In [13], a mm-Wave phased array 5G antenna which is running in the frequency range of 25 to 40 GHz has been designed and analyzed in the context of multiple-input multiple-output (MIMO) applications. The frequency allocation undergoes difficulties in terms of increasing which impel Federal Communication Committee (FCC) to add more than 18 GHz of spectrum encompassing Millimeter-Wave frequencies [14] in order to provide an expanded framework for development and research in Millimeter-Wave 5G.

Manuscript received December 5, 2021
Manuscript revised December 20, 2021
https://doi.org/10.22937/IJCSNS.2022.22.1.41

Additionally, Finite element method (FEM) [15-20], method of moments (MOM) [21-23], and the iterative multilevel fast multipole method (MLFMM) [24] are intercepted in the full-wave-investigation of 5G antennas requiring a high level of accuracy or geometrical complexity. These numerical methods presented certain shortcomings in the mm-wave investigation of planar antennas used in wireless communication [25]. The Advanced Transverse Wave Approach (ATWA) with its novel version which is developed by our research team presents several advantages setting it apart from other numerical EM methods, in terms of speed, compactness and memory in the context of wireless applications. Towards this end, we present our efficient method ATWA for mm-Wave 5G antenna simulations and we quantify its efficiency and stability in this circumstance. Referring to aforementioned works, an appropriate 5G antenna is selected and designed as an adequate prototype through respectable specific characteristics so as to validate our approach in mm-wave 5G applications as well as to investigate smart and advanced antennas for new generation of cellular technology.

This paper is organized as follows: section 2 presents the theoretical foundation of the two-dimensional transverse wave approach (2D- ATWA) for EM- analysis of mm-wave structures. The design of the proposed 5G-antenna is the subject of section 3. The subsequent section (section4) sets out to present and analyze the different obtained simulations results and compare them with literature. Section 5 concludes our work and opens a new trend for ongoing research.

2. Theory

Defining $\hat{S}$ as the spatial diffraction operator describing the boundary conditions from the discontinuity surface Ω. It depends hence on the configuration of studied structure. The air-dielectric interface (Ω) is divided into cells and can include three sub-domains: dielectric (Di), metal (Me) and source (Sce).

$\hat{S}$ can be expressed as:

$$\hat{S} = \sum_{SUB} S_{\Omega_{SUB}} \hat{H}_{\Omega_{SUB}} \quad (1)$$

where $\hat{H}_{\Omega_{SUB}}$ is the projection operator given in Dirac notation:

$$\hat{H}_{\Omega_{SUB}} = |H_{\Omega_{SUB}}(u,v)\rangle\langle H_{\Omega_{SUB}}(u,v)| \quad (2)$$

$H_{\Omega_{SUB}}$ stands for the indicator function of the sub-domain Ω_{SUB} (SUB refers to the nature of sub-domain: *Di*, *Me*, *or Sce*) defined by:

$$H_{\Omega_{SUB}}(u,v) = 1_{\Omega_{SUB}}(u,v) = \begin{cases} 1 & if (u,v) \in \Omega_{SUB} \\ 0 & Otherwise \end{cases} \quad (3)$$

So, the air-dielectric interface Ω is characterized by the following relation:

$H_{\Omega_{SUB=Sce}} + H_{\Omega_{SUB=Di}} + H_{\Omega_{SUB=Me}} = 1$ (4)

In Ω_{SUB} sub-domain, the waves A and B are connected by $S_{\Omega_{SUB}}$ as follows:

$$\underbrace{\begin{bmatrix} B_1^x \\ B_1^y \\ B_2^x \\ B_2^y \end{bmatrix}}_{B} = S_{\Omega_{SUB}} \underbrace{\begin{bmatrix} A_1^x \\ A_1^y \\ A_2^x \\ A_2^y \end{bmatrix}}_{A} \quad (5)$$

The detailed expressions of $S_{\Omega_{SUB}}$ for different domains are given in [27-28].

We infer therefore that the diffraction operator $\hat{S}$ is the responsible to link the incident and reflected waves in spatial domain. This relation can be translated as:

$$B = \hat{S}A \quad (6)$$

By the way in the modal domain, $\hat{\Gamma}$ represents the reflection operator ensuring the connection between incident and reflected waves. This can be ensured by the following equation:

$$A = \hat{\Gamma}B \quad (7)$$

Indeed, the modal expansion of the reflection operator $\hat{\Gamma}$ can be written following the Dirac notation as:

$$\hat{\Gamma} = \sum_{\alpha=TE,TM} \sum_m^M \sum_n^N |f_{mn}^\alpha\rangle \Gamma_{mn}^\alpha \langle f_{mn}^\alpha| \quad (8)$$

Where:

$\{|f_{mn}^\alpha\rangle\}$are Transverse TE and TM Eigen-functions of $\hat{\Gamma}$ verifying $\langle f_{p,q}^\alpha | f_{p',q'}^\alpha\rangle = \delta_{q,q'}^{p,p'}$.

Overall, the mutual coupling between incident (***A***) and reflected (***B***) waves leads to the following scheme:

$$\begin{cases} A = \hat{\Gamma}B & \text{In modal domain} \\ B = \hat{S}A + \overset{(0)}{B} & \text{In spatial domain} \end{cases} \quad (9)$$

Where:

$\overset{(0)}{B}$ stands for the global excitation wave on the source.

The transition between spatial and modal spaces is established by the intermediary of spectral space. Indeed, the transformation from spatial to spectral domains is guaranteed by two-dimensional fast Fourier transform (2D-FFT) [26-28] for uniform and non-uniform distribution on discontinuity space.

3. Design of Elliptical Antenna for 5G

We propose as 5G antenna the elliptical patch already studied and investigated in [20] as depicted in Fig. 1. This antenna can be used in 5G wireless mobile applications. The design parameters are given in Table1 which are closed to the one given in [20] in order to make a judicious comparison between the different simulation results. The modeling parameters chosen for the proposed antenna based on our A-TWA approach are defined and detailed in Table2.

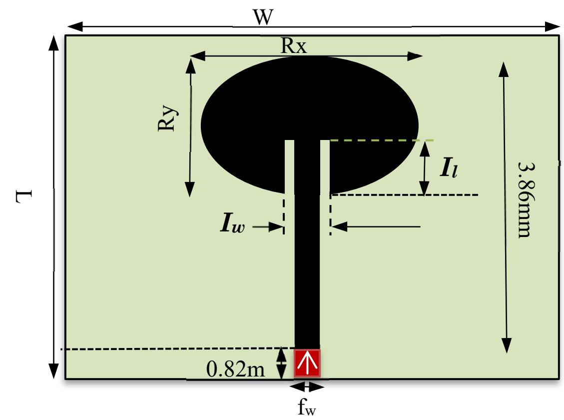

Fig.1 Design of 5G elliptical antenna

Table1. Design parameters

Parameters (mm)	W	L	R_x	R_y	f_w
Our approach	5.12	5.12	1.64	1.44	0.82
Ref [20]	5.00	5.00	1.60	1.40	0.80
Parameters (mm)	h	g_1	I_1	I_w	δ
Our approach	5.2	1.82	0.78	0.72	0.05
Ref [20]	1.6	1.8	0.75	0.7	0.035

Table2. Modeling parameters

Parameters	**Mesh grid**	**Waveband**	**Permittivity of regions**	**Polarization**
Our approach	256 × 256	F_min=50GHz F_max=70GHz Step_Frq=0.5GHz	$\varepsilon_{r_1} = 1$ $\varepsilon_{r_2} = 4.4$	Unilateral in y-direction
Parameters	**Box nature**	**Iteration Number**	**Surface impedance**	**Layers number**
Our approach	Periodic walls	300	$Z_S = 0$	monolayer

4. Simulation results and Discussions

The simulation examination was carried out by our electromagnetic simulator which is developed under C++ environment and built on ATWA approach. The admittance observed by the excitation source named Yin is computed to each iteration from the electromagnetic quantities, and it is pertinent for the validation of the stability or no of the system. Fig.2 demonstrates the convergence of the system for less than 100 iterations at 25GHz which confirm the stability of our A-TWA approach for mm-wave investigation of 5G antennas.

We notice that the reference 28 GHz antenna [20] is simulated using the Finite-Element Method (FEM) based high-frequency structure simulator (HFSS) of ANSYS, Inc. Or, the computational complexity for both the forward and backward of the 2D-ATWA process is guaranteed at $O(N_T log N_T)$ where N_T represents the meshing density applied to the structure to be analyzed. Our approach is much faster than FEM method in the context of EM simulations of planar antennas. This has been well-proved in the previous work presented in [22].

The proposed elliptical antenna is designed on a compact Fr-4 substrate [29] with relative permittivity $\varepsilon_{r_2} = 4.4$.

The simulation results as shown in Fig.3 displays the evolution of S11 parameter of the proposed antenna obtained based on our approach and compared to the one investigated in [20]. The resonance frequency obtained by our approach is depicted at 28.7 GHz which is in good similitude and better performance with the reference antenna [20] resonated at 28 GHz. The return losses are respectively -42.7 dB and-43.3 dB and the impedance bandwidth is attained from 26.2 to 32.8 GHz by the way from 26.6 to 32.1 GHz for antenna reference. This proves the efficiency and accuracy of our advanced approach in the investigation process of 5G antennas in low computation time.

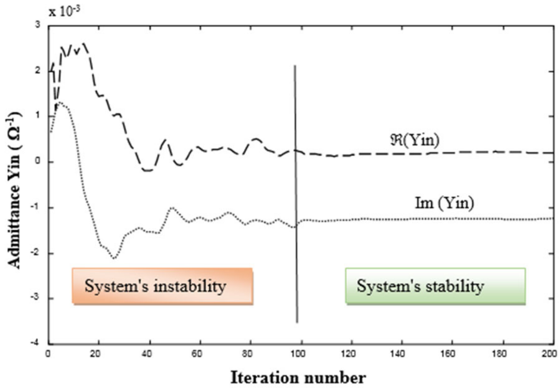

Fig.2 Evolution of both imaginary (R(Yin)) and real (Im(Yin)) parts of Yin as function of iteration number at 28 GHz

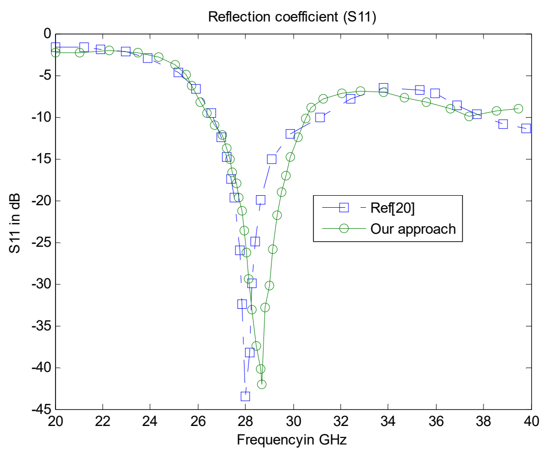

Fig.3 Insertion parameter (reflection coefficient) S11

5. Conclusions

A rapid Advanced Transverse Wave Approach (ATWA) has been well presented and developed in the context of mm-wave wireless communication systems. An elliptical 5G compact patch antenna has been successfully designed, simulated, and validated by our approach which proves again its stability and fastness in terms of time complexity and accuracy contrasted with the commercial simulator HFSS based on Finite-Element Method. The Simulation results show that the proposed 5G antenna resonates at 28.7GHz and achieved the impedance bandwidth of 26.2-32.8 GHz which are in satisfactory agreement with references. This approach can be improved and extended to investigate the unlicensed mm-wave ISM-band applications.

Acknowledgements

The authors gratefully acknowledge the approval and the financial support of this research from the Deanship of Scientific Research study by the grant number 7427-CIT-2017-8-F, Northern Border University, Arar, KSA

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Mohamed Ayari received the Dipl.-Ing., M.S., and Ph.D. degrees in Telecommunications in 2003, 2004, and 2009, respectively, from the National Engineering School of Tunis (ENIT), Tunisia, in collaboration with the National Polytechnic Institute of Toulouse, France, and Virginia Tech, USA. He has been a teacher at several universities since 2003. He has been a permanent research member at the 6'COM laboratory at ENIT from 2003. In 2005 he joined RCEM-Inc. in Toulouse, France. Since 2010, he has been a tenure-track associate professor at the National Engineering School of Carthage (ENICAR), Carthage University, Tunisia. In 2015, he is joined the IT Department of the Faculty of Computing and Information Technology, Northern Border University (NBU), Kingdom of Saudi Arabia, as an assistant professor. His current research interests are electromagnetic (EM) fields, numerical EM methods, and computer-aided design of microwave circuits and antennas. His research interests also include information security, image processing and wireless applications.

Yamen El Touati received his Engineering, M.S. and Ph.D. degrees in computer science from the National School of Computer Science (ENSI), University of Manouba in 2003, 2005, and 2014, respectively. He is an assistant professor at ISAMM, University of Manouba, Tunisia, and a permanent research member of the OASIS laboratory at the National School of Engineers of Tunis, University of Tunis El Manar, Tunis, Tunisia. Currently, he is on secondment as an assistant professor in computer science in the Department of Computer Science, Faculty of Computing and Information Technology, NBU, Kingdom of Saudi Arabia. His research interests include modeling, diagnosis, and control supervision of dynamic hybrid systems and timed systems, with various automata-based and Petri-net-based models. His research also, focuses on security and opacity issues for composed web services.

Saleh Altowaijri obtained his PhD from Swansea University in the area of cloud computing. Currently he is an Associate Professor at the Department of Information Systems, Faculty of Computing and Information Technology, Northern Border University, Rafha, Kingdom of Saudi Arabia. He has over 10 years of research experience and has published several book chapters, conference, and journal papers. He is a reviewer of several international conferences and journals. His research interests include grid and cloud computing, database management systems, data mining, information systems, information technology risk management, IoT, and emerging ICT systems in healthcare and transportation sectors.