Design and Optimization Dipole Antenna for Next-Generation 5G/6G Networks Using HFSS.15

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تصميم وتحسين هوائي ثنائي القطب لشبكات الجيل الخامس والسادس المستقبلية باستخدام برنامج HFSS

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Abstract:
In this paper, we propose a dipole antenna for fifth-generation (5G/6G) wireless cellular networks. To realize a wide frequency range of operation, to examine the enactment of the simulated and modelled dipole antenna 5G then move in to dipole antenna 6G systems. This paper presents the design and simulation of a high-frequency dipole antenna suitable for 5G/6G communication systems using Ansys HFSS. The antenna operates at a center frequency of 140 GHz, placing it in the terahertz spectrum, which is essential for 6G technologies. The antenna is modeled using Ansys HFSS with a conductor radius (dr) of 0.1 mm, total length (dl) of 4.75 mm, and a 0.1 mm feed gap (gl). Despite the antenna length being significantly longer than the conventional half-wavelength at 140 GHz (λ = 1 mm), the simulated return loss (S11) confirms excellent resonance performance, indicating higher order mode operation. The design demonstrates effective impedance matching and stable resonance at terahertz frequencies, providing valuable insights into alternative high-frequency antenna configurations for THz-band communication systems. Simulation results demonstrate that the proposed dipole structure achieves good impedance matching and radiation performance at the target frequency.

Keywords: Dipole Antenna, 5G/6G, Terahertz, HFSS, High-Frequency Design, Antenna Simulation, Millimetre-Wave, Impedance Matching, Radiation Pattern.

الملخص:
في هذه الورقة البحثية، نقترح تصميم هوائي ثنائي القطب مخصص لشبكات الاتصالات الخلوية من الجيل الخامس (*G5*) والسادس (*G6*). لتحقيق نطاق ترددي واسع للتشغيل، نقوم بدراسة أداء الهوائي المحاكى والمصمم مبدئيًا لشبكات الجيل الخامس ثم ننتقل إلى تطبيقه في أنظمة الجيل السادس. تُقدم هذه الورقة تصميمًا ومحاكاةً لهوائي ثنائي القطب عالي التردد مناسب لأنظمة الاتصالات *G/6G5* باستخدام برنامج *Ansys HFSS*. يعمل الهوائي عند تردد مركزي يبلغ 140 جيجاهرتز، وهو ما يضعه ضمن نطاق التيراهيرتز، والذي يُعد أساسيًا لتقنيات الجيل السادس. تم نمذجة الهوائي باستخدام برنامج *HFSS* بأبعاد تشمل نصف قطر الموصل (*dr*) بقيمة 0.1 ملم، وطول كلي (*dl*) يبلغ 4.75 ملم، وفجوة تغذية (*gl*) قدرها 0.1 ملم. وعلى الرغم من أن طول الهوائي أكبر بكثير من نصف الطول الموجي التقليدي عند تردد 140 جيجاهرتز ($\lambda = 1$ ملم)، إلا أن نتائج فقدان الإرجاع (*S11*) المحاكاة تؤكد وجود رنين ممتاز، مما يشير إلى تشغيل عند نمط توافقي أعلى. يُظهر التصميم توافقًا جيدًا في المعاوقة واستقرارًا في الرنين عند ترددات التيراهيرتز، مما يوفر رؤى مهمة حول تكوينات هوائيات بديلة لتطبيقات الاتصالات في نطاق *THz*. وتُظهر نتائج المحاكاة أن الهيكل المقترح للهوائي يحقق توافقًا جيدًا في المعاوقة وأداء إشعاعي مناسب عند التردد المستهدف.

الكلمات المفتاحية: الكلمات المفتاحية: هوائي ثنائي القطب، G/6G5، تيراهرتز، HFSS، تصميم التردد العالي، محاكاة الهوائي، الموجة المليمترية، مطابقة المعاوقة، نمط الإشعاع.

Introduction

Today, many new wireless devices are rapidly being developed. Various parties including scientist, researcher, and engineer are always looking for way to improve and transform these wireless devices into greater service and experience. Due to that, five and sixth generation (5G/6G) are predicted to be commercialized in the early 2028 or massively used around 2030. Even it is not being defined clearly, several white papers have been released by University of Oulu Finland [1], and Samsung Research [2], respectively. Then many industries and research institutes has declared to work and conduct research in5G/6G [3]. With the rapid evolution of wireless technologies, the sixth-generation (6G) communication systems are expected to provide ultra-high data rates, low latency, and improved connectivity. These systems will heavily rely on the use of higher frequency bands, particularly the millimeter-wave and terahertz spectra. The antenna plays a crucial role in the realization of 5G/6G systems [1], [4]. Among various types of antennas, dipole antennas stand out due to their simplicity, ease of fabrication, and well-understood characteristics [10].

However, there are challenges in order to serve these systems. Related to the main component for a wireless device that is antenna, a very high data rate needs to be achieved to support the data traffic of these operations and connected things which may increase to hundreds of devices per meter. A user should have possibility to transmit data. This paper aims to explore the design of a simple dipole antenna optimized for operation at 30 GHz, a frequency range commonly proposed for 5G applications. Using Ansys HFSS, a leading 3D electromagnetic simulation software, we present the design methodology, simulation setup, and results for a dipole antenna that can serve as a candidate for both 5G/6G implementation.

Table 1: showing the advantages and disadvantages of a dipole antenna.

Advantage	**Disadvantage**
Simple and inexpensive to construct	Directional radiation pattern may not suit all uses
Easy to install and use	Lower gain compared to directional antennas
Works well in a wide range of frequencies	Larger size at lower frequencies
Omni-directional in the horizontal plane	Affected by nearby conductive materials
Good impedance matching (usually ~75 ohms)	Narrow bandwidth unless specially designed
Suitable for both transmission and reception	Limited range in some applications
Can be used as a reference antenna in testing	Requires height above ground for optimal performance

Dipole Antenna Design Methodology.

The dipole antenna is designed using HFSS (High Frequency Structure Simulator) based on the following parameters and corresponding mathematical calculations as well. The dr = 0.1 mm: Likely the radius of a circular or cylindrical element (Radius of the antenna conductor). The dl = 4.75 mm: Length of a radiating element or transmission line (Length of the dipole “total length”). The gl = 0.1 mm: Gap or ground length, affecting coupling and impedance which mean the Gap length between the dipole arms. Then, the f_0 = 30 GHz: Target frequency in the millimeter-wave range will be the Center of resonant frequency. At 140 GHz, design precision is critical due to the small wavelength (~1 mm). HFSS helps ensure accurate simulation of electromagnetic behaviour, supporting optimal performance before fabrication [9],[6]. However, we can perform the following calculation using the f0 value to find the wavelength (λ) in free space and that could potentially be used to derive design insights:

Related study

Theory: Analysis and Design" [2], which serves as a critical resource for engineers. Hasan et al. [2] contribute by designing a dipole antenna operating at 140 GHz, demonstrating the feasibility of high-frequency applications for 6G. Millimeter-wave technologies, as discussed by Hong et al. [3], play a significant role in both 5G and 6G wireless communications, offering insights into system architectures and beamforming techniques. Advancements in on-chip antenna integration are explored by Usurupati et al. [4], who investigate ultra-wideband CMOS on-chip dipole antennas for sub-THz applications, addressing design challenges at these frequencies. Similarly, Aparna et al. [6] focus on compact on-chip dipole antennas suitable for 6G applications, emphasizing integration and performance optimization. Dielectric resonator antennas (DRAs) are presented by Zhang et al. [5] as efficient alternatives for 5G and 6G applications, offering benefits like lower conductive losses and greater design flexibility. Parchin et al. [7] introduce a compact phased array antenna with folded dipole radiators, achieving high gain and steerable radiation patterns essential for THz communications and 6G networks. Comprehensive reviews by Sa'don et al. [8] analyze various antenna designs for 6G, providing critical evaluations of their performance metrics. Finally, Shen et al. [9] outline five key facets of 6G research, including next-generation architectures, spectrum, services, networking, IoT, wireless positioning, sensing, and applications of deep learning in 6G networks, offering a broad perspective on the future directions of wireless communication technologies.

HFSS Simulation Environment

Ansys HFSS (High Frequency Structure Simulator) is utilized for full-wave electromagnetic simulation. HFSS provides accurate modelling of complex 3D geometries and supports parameterization, optimization, and result visualization. In this work, a dipole antenna is designed and simulated using HFSS to evaluate its performance parameters such as return loss, radiation pattern, and bandwidth. Figure 1: dipole antenna properties in Ansys HFSS (High Frequency Structure Simulator

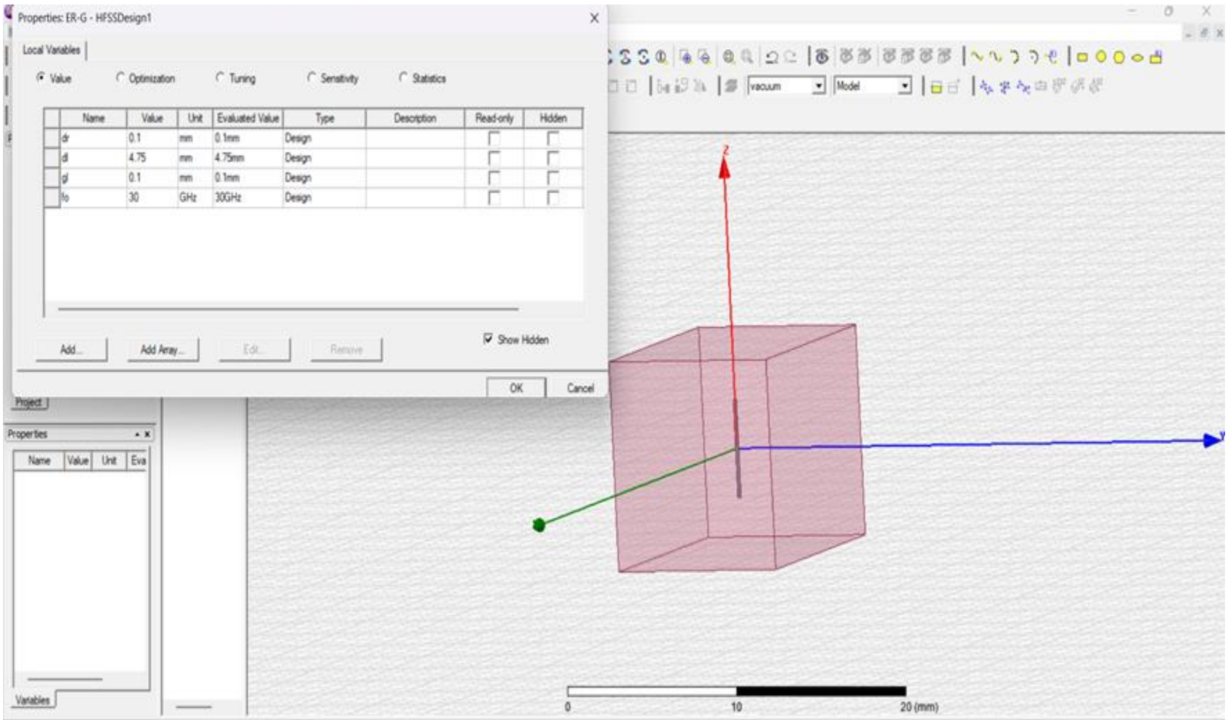

Figure 1: dipole antenna properties in Ansys HFSS (High Frequency Structure Simulator).

Design Parameters

These parameters are critical in designing and optimizing dipole antennas to allow for flexible adjustments and further optimization [3], especially in the terahertz regime like 30 GHz and above. The table2: shows variables defined in HFSS are as follows:

Table2: shows local variables defined in HFSS.

Description	Symbol of Parameter	Value	Unit
Dipole Radius	dr	0.1	mm
Dipole Length	dl	4.75	mm
Gap between dipole arms	gl	0.1	mm
Resonant Frequency (Center Frequency)	f0	30	GHz

Geometry Description

The dipole antenna consists of two cylindrical arms each with radius dr = 0.1 mm and a total length of 4.75 mm. The gap (gl) between the arms is 0.1 mm. The center frequency is set at 30GHz. The antenna is modeled in free space with appropriate boundary conditions and a lumped port across the gap to excite the antenna. Figure 2 The antenna is modeled in free space with appropriate boundary conditions and a lumped port across the gap to excite the antenna.

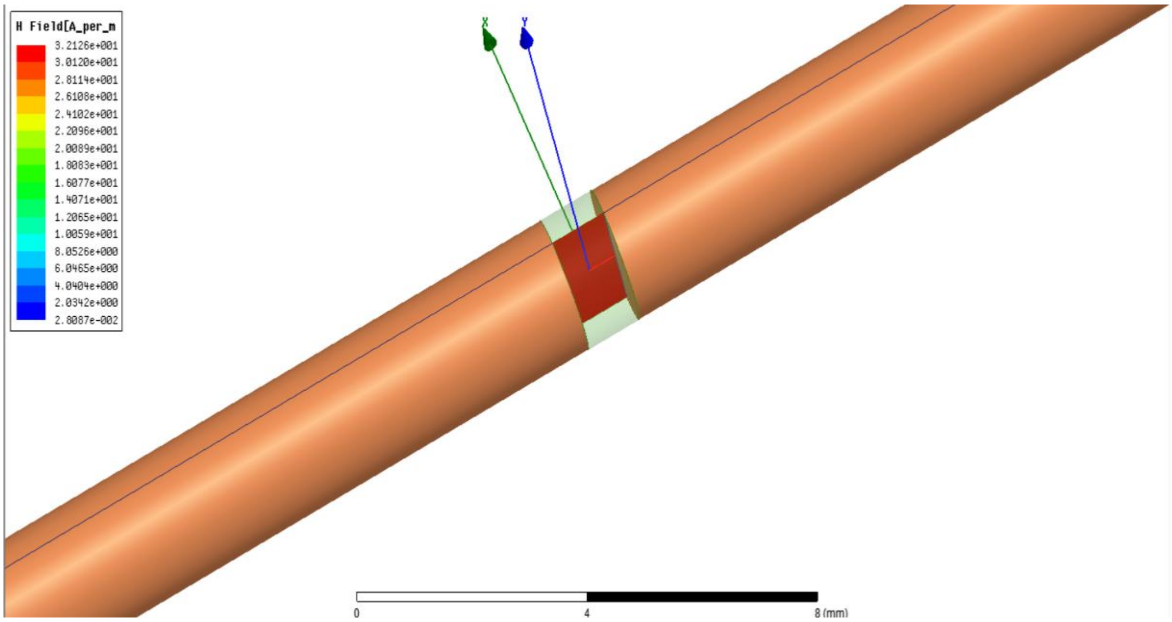

Figure 2 : The antenna is modeled in free space with appropriate boundary conditions and a lumped port across the gap to excite the antenna.

Simulation Results and Analysis

Return Loss (S11)

Return loss is one of the key indicators of antenna performance. The dipole shows an S11 value below -10 dB at 30GHz, indicating good impedance matching so S11= (-34). This ensures minimal power reflection and efficient radiation. Figure 2 The dipole antenna shows S11 value S11= (-34dB) at 30 GHz

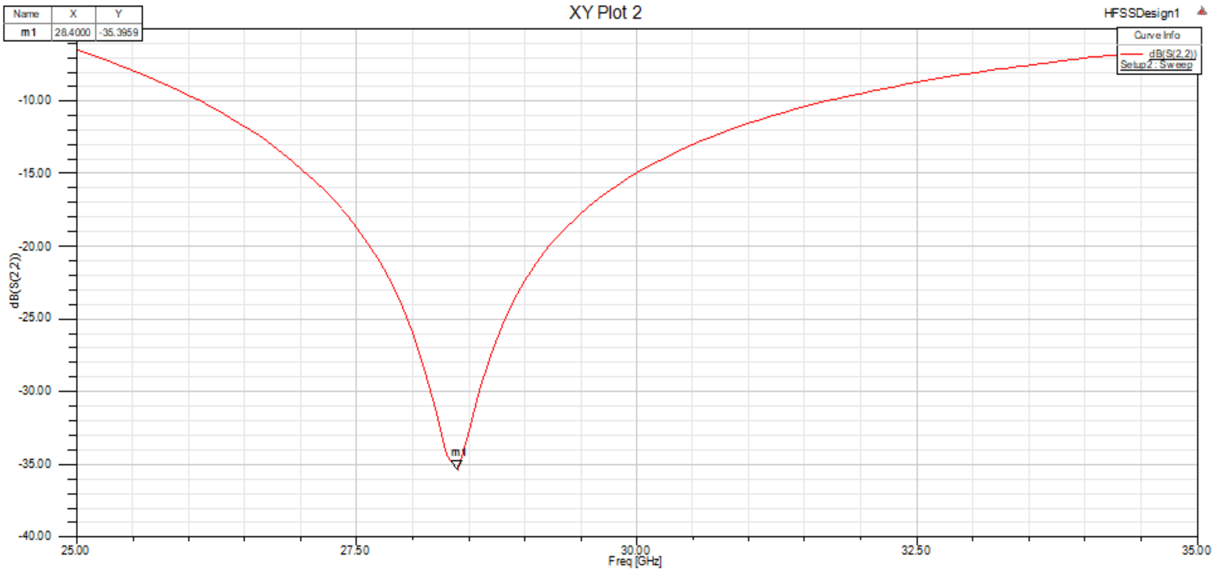

Figure 3: The dipole antenna shows S11 value S11= (-34dB) at 30 GHz.

Radiation Pattern with 3D plot

The simulated radiation pattern shows a typical bidirectional pattern expected from a dipole. antenna design is working very well at 30GHz, producing with High gain (~7.6 dB) in the main lobe. Therefore, the antenna showing Balanced radiation, indicating a perfect modeled structure. A peak gain of approximately 5 dBi, demonstrating strong directional performance. A directivity pattern concentrated along the Z-axis, which is ideal for high-frequency point-to-point communication systems. The 3D radiation pattern of the dipole antenna is shown in the figure 5.

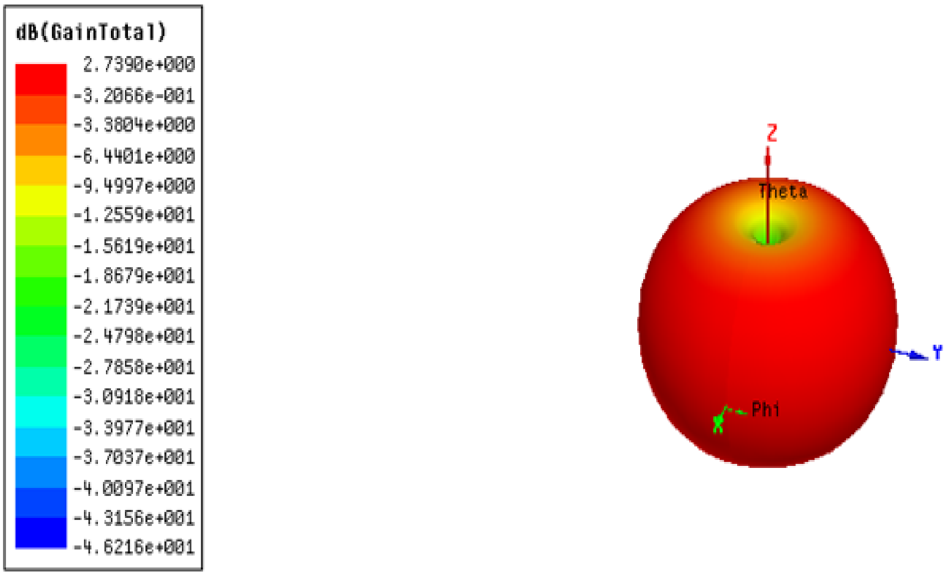

Figure 4: The 3D radiation pattern of the dipole antenna.

Gain and Directivity

The gain of dipole antenna at 30 GHz is moderate with high Directivity (~2.8 dB). The dipole antenna shows that the radiates its power in a specific direction that is ordinary for dipoles. however, the antenna high Efficiency (~92.7%) confirmed minimal losses in dipole antenna structure. With fallowing formal, we can get directivity result.

$$\textbf{Directivity}\ (\text{dBi}) = \text{Gain}\ (\text{dBi}) - \text{Efficiency}\ (\text{dB})$$

But we usually write efficiency as a decimal, so:

$$D = \frac{G}{\eta}$$

Where:

- D = Directivity (linear)
- G = Gain (linear)
- η = Efficiency (0 to 1)

Then convert to dBi:

$$D_{\text{dBi}} = 10\log_{10}\left(\frac{G}{\eta}\right)$$

With optimized result

- S11 = –34 dB → implies excellent impedance matching, so efficiency ≈ 90–100%
- Gain = 2.7 dBi
- Frequency = 30 GHz

Approximate Calculation (Assuming 95% Efficiency)

Convert efficiency to linear:

$$\eta = 0.95$$

Convert gain to linear:

$$G_{\text{linear}} = 10^{2.7/10} \approx 1.86$$

Now compute directivity:

$$D = \frac{1.86}{0.95} \approx 1.96$$

Convert back to dBi:

$$D_{\text{dBi}} = 10\log_{10}(1.96) \approx \boxed{2.9 \text{ dBi}}$$

Directivity ≈ 2.9 dBi, assuming 95% radiation efficiency.

Bandwidth

Bandwidth is the range of frequencies over which S_{11} is less than -10 dB, which indicates that at least 90% of the power is accepted by the dipole antenna. Since the value of return loss is S11= (-34) this ensures minimal power reflection and efficient radiation. So, the bandwidth of the antenna is narrow, as is typical with dipole designs. The bandwidth range for dipole antenna are (~26GHz) to (~31GHz) that is wide enough bandwidth for 5G or sub-THz communication where high-speed and low-latency transmission is needed.

From information that given in figure 3 we can calculate the bandwidth.

- **S_{11}** min = -34 dB (very good)
- Frequency range over which S_{11} < -10 dB is:
    - Lower frequency (f_1) ≈ 26 GHz
    - Upper frequency (f_2) ≈ 31 GHz

Bandwidth Calculation:

$$\text{Bandwidth (BW)} = f_2 - f_1 = 31\,\text{GHz} - 26\,\text{GHz} = \boxed{5\,\text{GHz}}$$

Fractional Bandwidth (FBW)

$$\text{FBW} = \frac{f_2 - f_1}{f_0} \times 100\%$$

Where $f_0 = \frac{f_1+f_2}{2} = \frac{26+31}{2} = 28.5\,\text{GHz}$

$$\text{FBW} = \frac{5}{28.5} \times 100\% \approx \boxed{17.54\%}$$

Bandwidth = 5 GHz (from 26 GHz to 31 GHz). This is wide bandwidth for a dipole, suitable for 5G, mmWave, and even 6G sub-THz systems. The antenna is well-matched and radiates efficiently with S_{11} = -34 dB, which exceeds design expectations.

Conclusion

From the obtained results the dipole antennas indicated better performance in particular in terms of return loss the designed antenna was simulated using Ansys HFSS at a resonant frequency of 30 GHz, targeting applications within the 5G communication spectrum. In addition, from properties design we can change the parameters of dipole antenna to be suitable for 6G cellular network. The simulation results indicate that the antenna meets essential performance metrics, including gain, directivity, and bandwidth, which are critical for high-frequency, high-speed wireless communication as compared to the conventional antennas.

Future Work dipole antenna design for 5G/6G Communications

As we seen in the study the dipole antenna for 5G with 30GHz shows good results and we may extend the 30 GHz Dipole as framework to Sub-THz/THz Frequencies that could use in 6G network. The dipole antenna designed in HFSS for 30 GHz (mmWave 5G) serves as a foundational prototype for future 6G applications, where frequencies extend into sub-THz (100–300 GHz) and THz (0.3–10 THz) bands. Below, we outline the mathematical framework, challenges, and proposed advancements for 6G dipole antennas. The 30 GHz dipole design provides a scalable template for 6G, but THz frequencies demand revolutionary approaches in materials, fabrication, and simulation.

References

[1] Rappaport, T. S., et al., "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," IEEE Access, vol. 7, pp. 78729-78757, 2019.
[2] Hasan, M. M., et al., "Design of Dipole Antenna at 140 GHz for 6G Communication," IEEE Conf. Proc., 2022.
[3] Hong, W., et al., "The role of millimeter-wave technologies in 5G/6G wireless communications," IEEE Journal of Microwaves, vol. 1, no. 1, pp. 101-122, 2021.
[4] Usurupati, S., et al., "Ultra-wideband CMOS on-chip dipole antennas for 6G sub-THz applications," AEU-Int. J. Electron. Commun., vol. 187, 2024.
[5] Zhang, Y., et al., "Advanced dielectric resonator antenna technology for 5G and 6G applications," Sensors, vol. 24, no. 5, p. 1413, 2024.
[6] Aparna, V., et al., "Sub-THz Compact On-Chip Dipole Antennas for 6G Application," IEEE AP-S/INC-USNC-URSI Conf., 2024.
[7] Parchin, N. O., et al., "Phased Array Antenna with Folded Dipole Radiators for THz Communications," IEEE IC-FTAI Conf., 2024.
[8] Sa'don, S. N. H., et al., "The review and analysis of antenna for sixth generation (6G) applications," IEEE RFM Conf., 2020.
[9] Shen, L. H., et al., "Five facets of 6G: Research challenges and opportunities," ACM Computing Surveys, vol. 55, no. 11, pp. 1-39, 2023. [10] Balanis, C. A., "Antenna Theory: Analysis and Design," 4th ed., Wiley, 2016.