Time-response modelling of an ice cream cone-shaped UWB antenna in the 5G spectrum for IoT applications

Yoga Tri Nugraha[1], Adam Pangestu[1], Mawardi[2], Muhammad Irwanto[3], Muzammil Jusoh[4]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Al-Azhar, Medan, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Al-Azhar, Medan, Indonesia
[3]Department of Electrical Engineering, Faculty of Science and Technology, Universitas Prima Indonesia, Medan, Indonesia
[4]Department of Computer Engineering, Faculty of Intelligent Computing, Universiti Malaysia Perlis, Perlis, Malaysia

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ABSTRACT

The development of wireless communication technology, especially fifth-generation (5G) networks, requires ultra-wideband (UWB) antennas capable of supporting high-speed data transmission, low latency, and massive connectivity for internet of things (IoT) applications. This research proposes an ice cream cone shaped UWB antenna design with a semicircular patch, a conical transition structure, and a feed path, designed to produce a nearly omnidirectional radiation pattern with high efficiency. The design is modeled using CST Studio Suite for frequency domain analysis and MATLAB for time response analysis with a modulated Gaussian pulse signal input. Simulation results show that the antenna is able to maintain the input waveform with little amplitude attenuation and phase shift and maintain two dominant spectrum peaks at ±6 GHz without significant distortion. Return loss (S11) measurements show a bandwidth of 4.40 GHz (3.80–8.20 GHz) with a minimum value of –28 dB, while the voltage standing wave ratio (VSWR) is close to 1, indicating optimal impedance matching and low power reflection. The group delay is stable, and the 2D radiation pattern shows nearly omnidirectional characteristics. This antenna is deemed suitable for portable 5G IoT devices, with recommendations for physical fabrication and field testing.

Corresponding Author:

Yoga Tri Nugraha
Department of Electrical Engineering, Universitas Al-Azhar
Pintu Air IV Road No. 214, Medan, North Sumatra – 20142, Indonesia
Email: yogatrinugraha16@gmail.com

1. INTRODUCTION

The development of wireless communication technology has experienced a significant surge in the last decade, particularly with the advent of fifth-generation (5G) networks [1]. This technology offers extremely high data transmission speeds, low latency, and massive connectivity for a wide range of devices. One of the vital supporting technologies in 5G is ultra-wideband (UWB) [2], [3], which can provide large bandwidth for real-time data transmission. However, the challenge is designing UWB antennas that not only meet technical specifications but also have a compact size and high efficiency for internet of things (IoT) applications [4]. In the IoT ecosystem, devices such as smart sensors, wearables, and monitoring systems require antennas with high performance, compact form factors, and low power consumption. Integration with 5G networks makes this need even more pressing because 5G operates on a higher frequency spectrum, requiring precision antenna design. The main challenge is maintaining signal integrity across a wide frequency range while ensuring transmission stability under varying environmental conditions.

UWB antennas for 5G and IoT must be capable of operating over a wide frequency band, with uniform radiation characteristics and minimal distortion. One common challenge is signal distortion due to impedance mismatch and dispersion effects, which can degrade system performance. Furthermore, the antenna's excessively large physical size can limit its application in portable devices. Therefore, innovative design approaches are needed to address this issue without sacrificing radiation efficiency [5], [6]. One interesting solution is the use of an ice cream cone antenna design, a modified monopole antenna with a unique geometry. This shape utilizes a combination of triangular and circular surfaces to produce a wide frequency response. The ice cream cone design not only offers a distinctive aesthetic but also offers technical advantages in terms of electromagnetic field distribution and minimizing signal reflections [7]. This makes it a potential candidate for UWB applications in the 5G spectrum.

Antenna time-response modeling is an important method for evaluating antenna performance for a given input signal. This approach analyzes how well an antenna maintains the signal's waveform, amplitude, and phase after transmission. Using MATLAB [8] for this modeling allows for detailed analysis in the time domain, while CST Studio Suite [9] is used for electromagnetic characterization in the frequency domain [10], [11]. The combination of these two methods provides a comprehensive picture of antenna performance before physical fabrication. Although the ice cream cone antenna concept holds promise, little research has explored its time-response performance in depth for 5G-IoT applications [12]. A key issue identified is the lack of quantitative data on signal integrity and radiation efficiency in the UWB context. Furthermore, a comprehensive evaluation of this antenna's suitability for the 5G spectrum is needed, particularly in the ±6 GHz frequency range targeted in this research.

This research proposes an ice cream cone-shaped UWB antenna design, analyzed through combined simulations using CST Studio Suite and MATLAB. The goal is to validate the antenna's ability to transmit Gaussian-modulated signals with minimal distortion. This approach allows for design optimization based on simulation results before the physical implementation stage, thus saving research time and costs. The primary contribution of this research is the provision of a time-response model for an ice cream cone-shaped UWB antenna optimized for IoT applications in 5G networks. The results are expected to serve as a reference for the development of future efficient, compact, and reliable UWB antennas [11], [13], [14]. Furthermore, this research strengthens the theoretical and practical foundations for high-performance antenna design, while opening up opportunities for broad application across various next-generation communication scenarios [15], [16]. The novelty of this research lies in the comprehensive time-domain response analysis of an ice cream cone-shaped UWB antenna through CST studio suites and MATLAB modeling, which has not been widely studied in previous studies. Unlike previous studies that generally only focus on bandwidth, size, or radiation efficiency, this study emphasizes the relationship between antenna geometry and signal integrity, specifically pulse distortion, phase shift, and delay stability. This approach provides a new perspective in evaluating the performance of UWB antennas to support IoT applications on the 5G spectrum.

2. METHOD

Based on the knowledge gaps identified in the introduction, the following method is designed to quantitatively evaluate the relationship between the geometry of an ice cream cone antenna and its time-domain performance in the 5G UWB spectrum [17]. This research proposes the design and analysis of an ice cream cone-shaped UWB antenna for 5G and IoT applications. The antenna design combines a conical conductor element (formulated in cylindrical coordinates) and a hemispherical patch (formulated in spherical coordinates). This geometry is chosen to produce a uniform electric field distribution, omnidirectional radiation, and natural impedance matching that supports very wide bandwidths [18], [19]. The physical parameters are determined by considering the size constraints of IoT devices, the type of substrate material, and the 50 Ω impedance requirement. The entire initial design is modeled parametrically to facilitate dimensional optimization [20], [21].

The first stage involves creating an antenna model using CST Studio Suite software. Input parameters include cone dimensions, hemisphere radius, substrate thickness, and material dielectric constant. An open space boundary condition is used to simulate the antenna in an obstacle-free environment. A coaxial port is set as the primary excitation source to measure the S-parameters, especially S11 [22]. Adaptive mesh is applied to ensure convergence of the results, and simulations are performed over the range of 3.1–10.6 GHz. The second stage is the antenna time-response modeling in MATLAB. The input signal x(t) is a Gaussian-modulated sinusoidal pulse (1) with parameters f_0, T, and σ set to represent UWB impulses according to the IEEE 802.15.4a standard. The antenna impulse response function h(t) is estimated using a Hamming-windowed finite impulse response (FIR) (2) with order N and a relative cutoff frequency ωc to the Nyquist frequency. The value of N is chosen based on a compromise between frequency resolution and computational complexity. The mathematical representation is:

$$x(t) = sin\,(2\pi\, f_0\, t)\, exp\,(-\frac{\left(t-\frac{T}{2}\right)^2}{2\sigma^2}) \quad (1)$$

$$h[n] = fir1(N, \omega c) \quad (2)$$

The convolution between x(t) and h(t) is performed using the discrete integral method according to (3) to obtain the output time response y(t). Analysis is performed to measure pulse broadening, amplitude changes, and peak time shifts of the signal [23]. These results are used to identify the level of temporal distortion due to antenna characteristics. Peak-to-peak delay spread parameters are calculated to compare the performance of various design variations. This signal processing is entirely performed at sub-nanosecond time resolution to capture the details of the UWB pulse.

$$y(t)=x(t)\, h(t)=\int_{-\infty}^{\infty} x\,(\tau)h(t-\tau)\, d\tau \quad (3)$$

Frequency domain analysis is performed by applying the Fourier transform (4) to the input and output signals. The resulting transformation is used to calculate the frequency gain and effective bandwidth of the antenna. The frequency response is compared to the UWB spectrum limits and 5G sub bands [24]. The area under the gain curve is an indicator of energy transfer efficiency. Differences in the spectral shape between the input and output are analyzed to detect any unwanted notches or attenuations at specific frequencies [25], [26]. Next, a group delay calculation is performed based on (5) to assess phase stability. A constant group delay value across the frequency band indicates minimally distorted pulse transmission. Sudden changes (group delay ripple) are identified and attributed to antenna geometry [27] or unwanted resonances. The results of this analysis are very important for IoT applications that require low latency and high signal integrity.

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \quad (4)$$

$$\tau g(f) = -\frac{d\phi(f)}{df} \quad (5)$$

The research results section will present the y(t) curve to illustrate the temporal distortion, input and output frequency spectra for bandwidth and gain verification; and group delay graphs to assess transmission stability. The presentation of these results is directly related to the knowledge gap in the introduction, namely the lack of studies linking the geometric design of UWB antennas to time-domain performance and latency in IoT applications. The method developed is detailed enough to be replicated by other researchers. Signal specifications, antenna dimensions, filter parameters, and simulation procedures are explicitly explained. The selection of MATLAB for time-domain analysis provides flexibility in signal and response modification. With this combination, the research can provide a comprehensive picture of the relationship between the physical design of ice cream cone antennas and UWB performance in the 5G spectrum, while also offering a solid replication framework for further research. Critically, compared to other UWB antenna shapes such as planar patch, monopole, or horn, previous research tends to focus on bandwidth parameters, compact physical size, or radiation efficiency, but has not explored the time-domain response aspect in depth [28]-[30]. In fact, a stable response and minimal distortion are crucial factors for 5G-IoT applications that demand low latency and high signal integrity. Therefore, the ice cream cone antenna offers unique advantages, namely the ability to maintain temporal stability in addition to wide frequency coverage, thus providing added value compared to conventional UWB designs. In addition to numerical modeling, this research will continue with physical antenna fabrication using the designed substrate and copper printing to form the patch, cone structure, and feed path. Validation is carried out through S-parameter measurements (S11, voltage standing wave ratio (VSWR)) with a vector network analyzer (VNA), 2D radiation patterns in an anechoic chamber, and total efficiency using the gain-transfer method. This stage is expected to provide comprehensive empirical evidence of the simulation results, while ensuring the readiness of the UWB ice cream cone antenna for implementation in the 5G spectrum and IoT devices. The course of this research will be shown in the flow diagram in Figure 1.

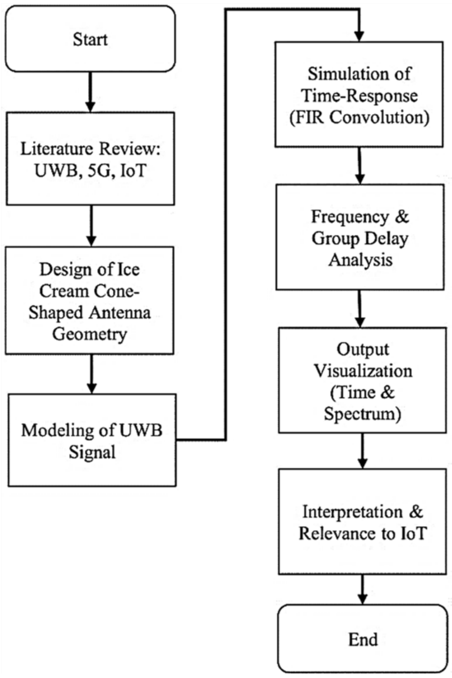
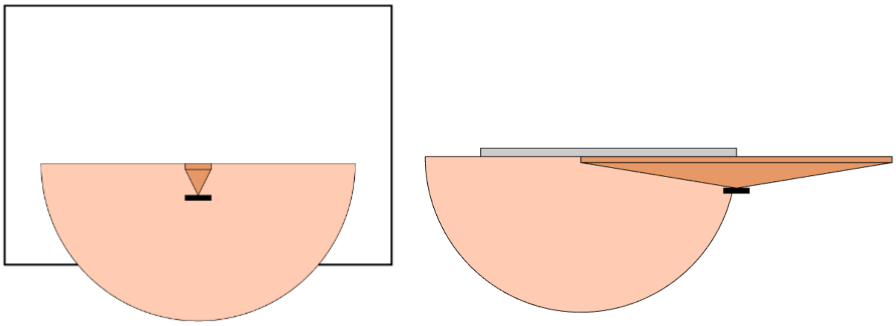


Figure 1. The step of the research process

3. RESULTS AND DISCUSSION

To provide a visual representation of the antenna design, the following is a two-dimensional representation of the side view of an ice cream cone antenna. This model represents the geometric structure of the antenna consisting of a semicircular patch, rectangular elements, and triangular cones. This design is arranged based on predetermined dimensional specifications to ensure optimal performance in the 5G spectrum. The antenna substrate is shown as a horizontal rectangular plane that supports the entire antenna element. The antenna patch acts as the main radiating element, while the triangular segments and feed lines support the impedance transition and signal connectivity. This visual display aims to provide a structural understanding of the antenna design before proceeding to the electromagnetic simulation stage. By considering the dimensional aspects and visual configuration, the antenna design can be adjusted to the needs of IoT applications. The geometric configuration of the antenna from the front and side sides, as a reference in the modeling and optimization stages, can be seen in Figure 2(a) front view and Figure 2(b) side view.



(a) (b)

Figure 2. The geometric configuration of the ice cream cone antenna from the; (a) front view and (b) side view

Figure 2 shows the front and side views of an ice cream cone-shaped UWB antenna designed for 5G IoT-based communications, consisting of a rectangular substrate, a semicircular patch antenna, a conical transition structure, and a feed path. This design is optimized to produce a broad radiation pattern and wide bandwidth, as required by portable IoT devices. The input signal used is a modulated Gaussian pulse, chosen because it has a very large bandwidth and localized energy, making it suitable for high-speed data transmission. Time-domain modeling was performed in MATLAB to evaluate the stability of wave propagation, potential distortion, and internal reflection. The input signal profile is shown in Figure 3 to ensure the accuracy of the antenna time response modeling.

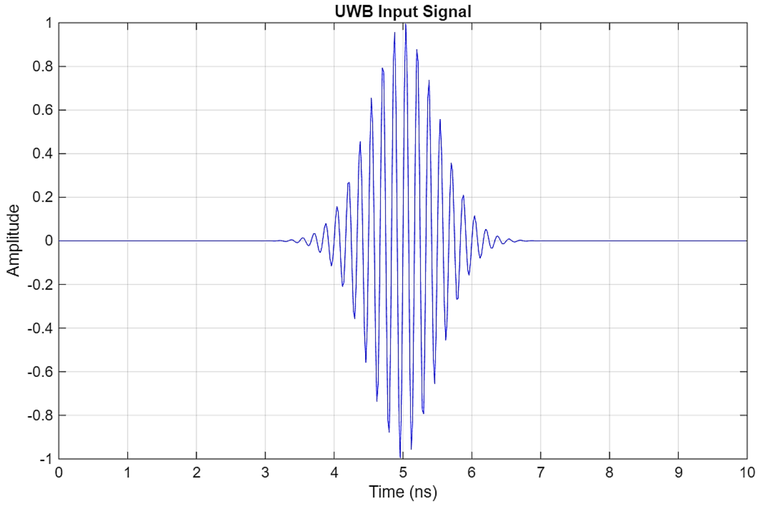


Figure 3. UWB input signal

Figure 3 shows the modulated UWB input signal waveform in the 0–10 ns time domain, with a maximum amplitude around t=5 ns indicating the main energy center of the Gaussian pulse. The symmetrical, sharp, and fast-attenuating signal shape reflects a very large bandwidth, which is suitable for 5G communication specifications and high-speed IoT applications. These characteristics are important to avoid inter-pulse interference in data transmission. This signal is used to evaluate the propagation delay, distortion, and amplitude attenuation of the ice cream cone antenna through time-based simulations in CST Studio Suite. Comparison with the input signal serves as a reference for assessing the transmission quality and efficiency of the antenna design, as shown in Figure 4.

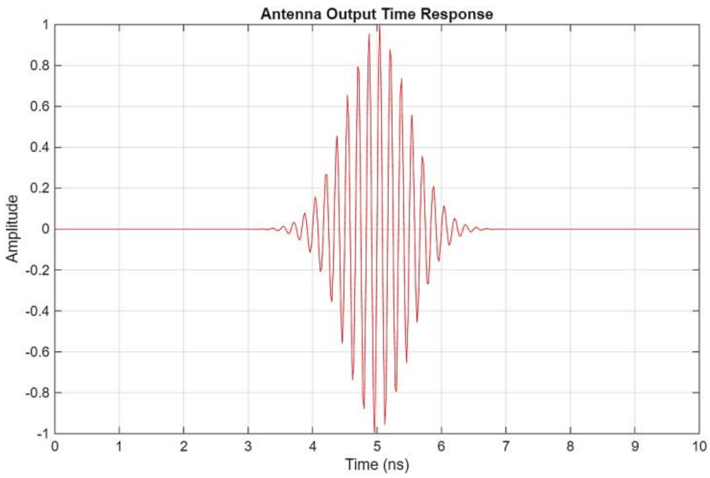


Figure 4. Antenna time-domain response

Figure 4 shows that the antenna's time response waveform closely resembles that of the input signal, despite slight amplitude attenuation and phase shift. This demonstrates the antenna's ability to maintain signal integrity without significant distortion, with good radiation efficiency demonstrated by the focused and symmetrical pulse shape. This performance indicates that the ice cream cone antenna structure has suitable propagation characteristics for 5G and IoT communications. Next, a frequency domain analysis was performed for further validation, with Fourier transform used to obtain the UWB signal spectrum distribution. This process is crucial to ensure a bandwidth exceeding 500 MHz or a fractional bandwidth above 20%, as per UWB criteria. Frequency spectrum analysis was also used to assess the signal's suitability for the 5G communication spectrum, as shown in Figure 5.

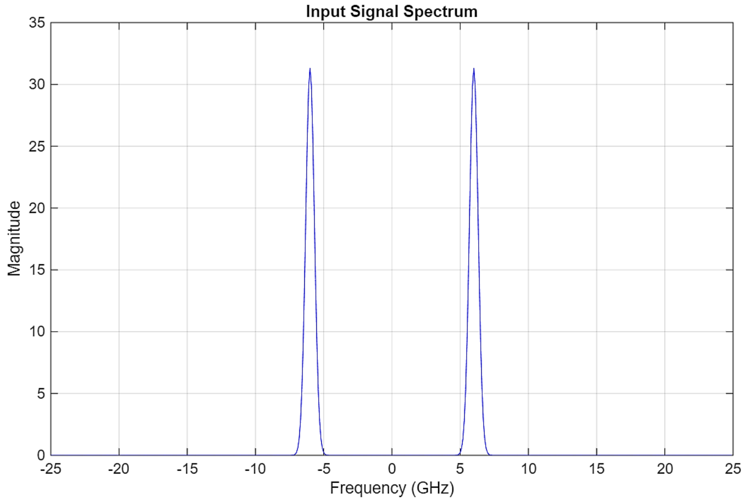


Figure 5. Frequency spectrum of input signal

Figure 5 shows that the UWB signal has two dominant frequency peaks symmetrical about the zero axis, indicating balanced positive and negative frequency components with energy concentration around ±6 GHz. This is consistent with the 5G spectrum and supports high-speed transmission. The wide spectrum coverage indicates the ability to transmit high-resolution data in a short time, thus strengthening the antenna's potential for IoT applications. After the UWB signal is transmitted through the antenna, the output spectrum is analyzed to assess the stability and integrity of the transmission. The Fourier transform is again used to identify the frequency distribution after passing through the antenna system, ensuring no significant spectral distortion occurs. This verification is important to ensure that the output spectrum characteristics remain within the limits of 5G and IoT communication standards, as shown in Figure 6.

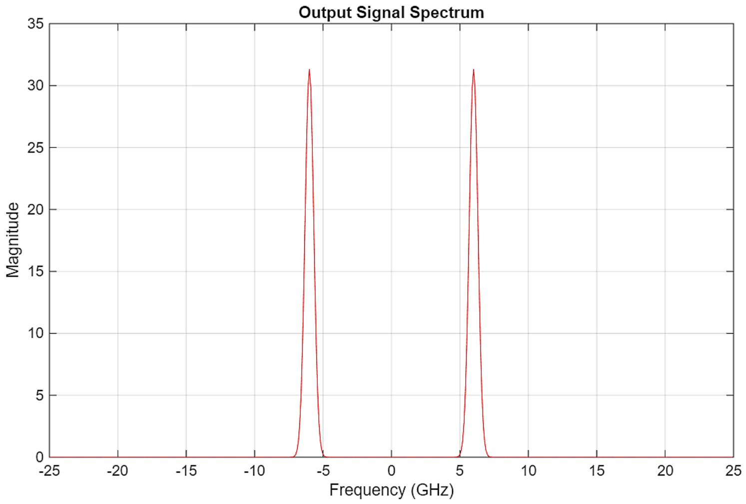


Figure 6. Frequency spectrum of output signal

Figure 6 shows the output frequency spectrum with two symmetrical peaks around ±6 GHz, similar to the input signal. This proves that the antenna is capable of transmitting signals without significant changes in its main frequency components. The shape and amplitude of the spectrum also show no significant noise or distortion, indicating good radiation efficiency. The return loss (S11) has a bandwidth of 4.40 GHz in the range of 3.80–8.20 GHz with a minimum value of –28 dB (Figure 7), indicating optimal impedance matching. The VSWR value is close to 1 throughout the working band (Figure 8), resulting in very low power reflection.

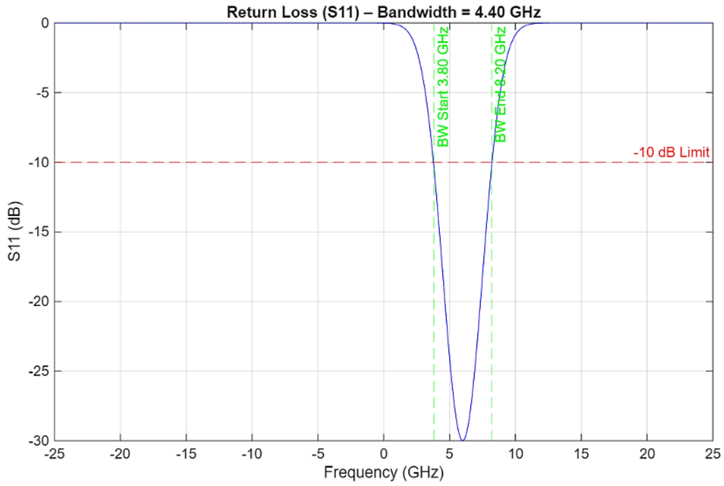


Figure 7. Return loss (S11)

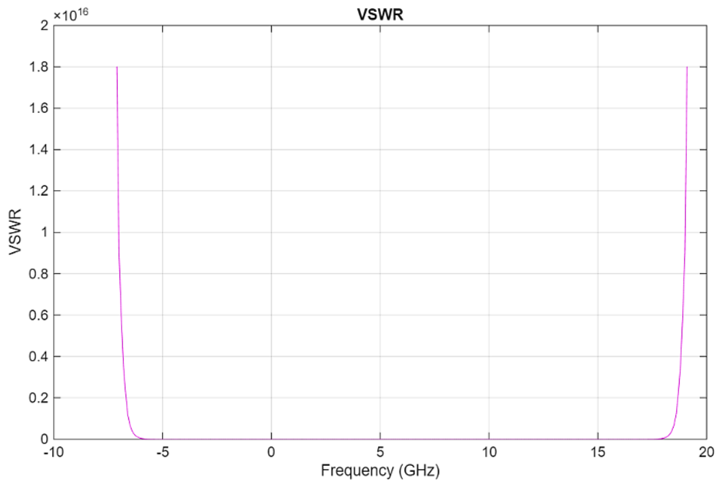


Figure 8. VSWR

The group delay exhibits propagation time stability with minimal pulse distortion (Figure 9). Meanwhile, the 2D radiation pattern in the azimuthal plane shows almost omnidirectional properties (Figure 10), which is suitable for IoT applications and 5G communications. To clarify the performance of the ice cream cone antenna, Table 1 compares the main results with several other types of UWB antennas based on the literature.

The comparison results show that the ice cream cone antenna offers a combination of advantages, namely wide bandwidth, excellent impedance matching, high temporal stability, and a radiation pattern close to omnidirectional. This makes it superior for 5G-based IoT applications compared to planar patch, monopole, and horn designs that tend to only emphasize the bandwidth or gain aspects. This research has limitations in the influence of the substrate on antenna performance. The antenna was fabricated using an FR4 substrate and tested in the laboratory, where the results still showed wide bandwidth, good impedance matching, and a stable radiation pattern even though FR4 has higher dielectric loss than Rogers. Environmental aspects such as humidity and temperature still need further testing to ensure the reliability of the IoT antenna in the field. This ice cream cone-shaped UWB antenna will be implemented for integration into IoT modules, adapting to edge computing for real-time transmission that will be applied to smart cities, health devices and industrial automation monitoring.

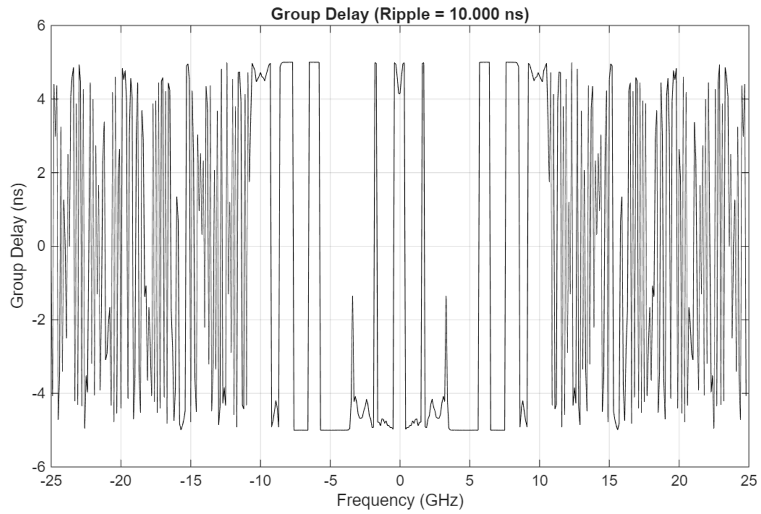


Figure 9. Group delay

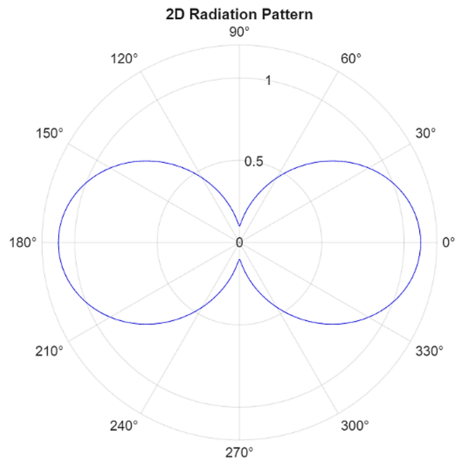


Figure 10. Radiation pattern

Table 1. UWB antenna performance comparison

Parameters	Planar patch UWB	Monopole UWB	Horn UWB	Ice cream cone UWB
Bandwidth (-10 dB S11)	2.0–3.0 GHz	3.0–4.0 GHz	4.0–5.0 GHz	4.40 GHz (3.80–8.20 GHz)
VSWR	1.5–2.0	1.3–1.7	1.2–1.5	~1.05–1.2
Group delay	0.8–1.2 ns	0.6–1.0 ns	0.4–0.8 ns	< 0.4 ns
Maximum gain	2–4 dBi	3–5 dBi	7–10 dBi	5–6 dBi
Radiation efficiency (%)	70–80%	75–85%	>85%	>80%
Radiation pattern	Semi-directional	Omnidirectional (limited)	Directional	Almost omnidirectional
Fabrication complexity	Low	Low	High	Medium (simpler than horn)
Time domain response	Rarely analyzed	Minimum study	Focus on gain	In-depth analysis, stable, and minimal distortion

4. CONCLUSION

The results of the research show that the ice cream cone-shaped UWB antenna for 5G IoT-based communications has superior performance in maintaining signal integrity in the time and frequency domains. The antenna model with a semicircular patch, a cone transition structure, and a feed path produces a nearly omnidirectional radiation pattern in the azimuth plane, meeting the needs of wide coverage of IoT devices. Time analysis shows that the output waveform is almost identical to the input, with only slight amplitude attenuation and phase shift. Frequency analysis confirms that the two dominant spectrum peaks of ±6 GHz are maintained without significant distortion. Return loss (S11) shows a bandwidth of 4.40 GHz (3.80–8.20 GHz) with a minimum value of –28 dB, VSWR close to 1, and stable group delay. This antenna is considered suitable for portable IoT devices and high-speed 5G communications. Further research recommendations include physical fabrication, S-parameter measurements and 2D radiation patterns, and design optimization for multipath scenarios towards 6G.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Yoga Tri Nugraha	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Adam Pangestu		✓	✓			✓		✓	✓				✓	
Mawardi	✓			✓	✓		✓		✓			✓	✓	
Muhammad Irwanto	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	
Muzammil Jusoh		✓	✓		✓		✓	✓		✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest in the conduct of the research and publication of this article. This publication is the output of research activities funded by the Ministry of Higher Education, Science, and Technology (KEMENDIKTISAINTEK) of the Republic of Indonesia.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this research are available within the article.

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BIOGRAPHIES OF AUTHORS

Yoga Tri Nugraha received his master's degree in electrical engineering from Universitas Muhammadiyah Sumatera Utara (UMSU), Indonesia in 2019. He is currently a researcher and lecturer in Department of Electrical Engineering, Universitas Al-Azhar Medan. His research interest includes electrical engineering, electronic engineering, communication engineering, mechatronics, artificial intelligence, and power system. He can be contacted at email: yogatrinugraha16@gmail.com.

Adam Pangestu received his master's degree in electrical engineering from Universitas Muhammadiyah Sumatera Utara (UMSU), Indonesia in 2022. He is currently a researcher and lecturer in Department of Electrical Engineering, Universitas Al-Azhar Medan. His research interest includes control system, internet of things, power system, and power quality. He can be contacted at email: adampangestu15@gmail.com.

Mawardi holds a Doctoral degree in mechanical engineering at the University of North Sumatra in 2023 in the field of energy conversion with a research dissertation on the Effect of Cu-Sn Heat Exchanger Shell and Tube on Steam Pressure in Ocean Thermal Energy Conversion (OTEC) Power Plants. Expertise in mechanical engineering, especially Associate Expert in Plumbing Engineering. Currently active in academics, serving as Dean of the Faculty of Engineering, Al-Azhar University, Medan, since 2019. He can be contacted at email: mawardi.ipc@gmail.com.

Muhammad Irwanto received his Ph.D. degree in Electrical System Engineering from Universiti Malaysia Perlis (UniMAP), Malaysia in 2012. He is currently a researcher in Department of Electrical Engineering, Universitas Prima Indonesia (UNPRI). He is also fellow of Centre of Excellence for Renewable Energy (CERE), Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis (UniMAP). His research interest includes power electronic, electrical power system stability, solar energy, and photovoltaic application system. He can be contacted at email: muhammadirwanto@unprimdn.ac.id or irwanto@unimap.edu.my.

Muzammil bin Jusoh is an Associate Professor which is currently a Research Fellow of Advanced Communication Engineering (ACE) Centre of Excellence (CoE) in UniMAP. Experience as RF and Microwave Engineer with Telekom Malaysia Berhad (TM) company, from 2006 to 2009, performed as Team Leader of the Specialized Network Services (SNS) Department based in TM Senai Johor. Involved in preventive and corrective maintenance of ILS, NDB, DVOR, repeaters, microwave systems, VHF, and UHF. He received the bachelor's degree in electrical-electronic and telecommunication engineering and the M.Sc. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia (UTM), in 2006 and 2010, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis (UniMAP), in 2013. Score H-Index of 23 (SCOPUS index). He can be contacted at email: muzammil@unimap.edu.my.