SCIENTIFIC OASIS

Decision Making: Applications in Management and Engineering

Journal homepage: www.dmame-journal.org
ISSN: 2560-6018, eISSN: 2620-0104

Carbon Nanotube-Titanium Composites-based Antennas for 6G Wireless Networks: Performance Evaluation

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ARTICLE INFO

Article history:
Received 15 April 2025
Received in revised form 20 July2025
Accepted 07 August 2025
Available online 15 September 2025

Keywords:
CNT-Ti Composite Antennas, 6G Wireless Networks, Radio Frequency Antennas, and Communication Systems

ABSTRACT

The development of innovative communication systems employing carbon nanotube–titanium (CNT–Ti) composite-based antennas remains a challenging task, particularly with regard to optimising their performance. Consequently, the design phase assumes a critical role in advancing these antennas. In this context, the performance of CNT–Ti composite antennas was assessed for their potential application in future 6G wireless communication networks. These antennas exhibited notable characteristics, including high efficiency, wide bandwidth, considerable flexibility, and improved impedance features, rendering them well-suited for 6G networks and high-speed data transmission. Furthermore, the analysis of CNT–Ti composite antennas revealed superior properties relative to conventional antennas, such as enhanced electrical conductivity, low loss tangent, minimal energy dissipation, high signal efficacy, broad bandwidth, and reduced voltage standing wave ratio (VSWR). Although antennas with specialised directional patterns, such as those used in satellite communications, may face constraints in widespread application due to their large size and high manufacturing costs, the study emphasised that further research should focus on optimising the production processes, cost-efficiency, design scalability, and long-term reliability of these antennas. Such investigations would facilitate their sustainable integration into large-scale wireless network technologies.

1. Introduction

The global halal industry has evolved into a major economic sector encompassing food and beverage, cosmetics, pharmaceuticals, tourism, and finance. Its expansion is fuelled by the growing global Muslim population, alongside increasing demand from non-Muslim consumers for products aligned with hygienic, high-quality, and ethically sound production standards. Estimates indicate the industry's value at approximately USD 1.4 trillion in 2017, with projections reaching USD 2.6 trillion by 2024 [1]. Technological advancements, particularly blockchain and e-commerce, have significantly enhanced transparency and trust throughout halal supply chains [2]. Nonetheless, the sector remains

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https://doi.org/10.31181/dmame8220251555

subject to complex regulatory and certification requirements, which necessitate strict compliance with halal and thayyib standards to safeguard product integrity and ensure international market access [3]).

Sixth-generation (6G) networks represent the next evolution in wireless communication technologies, offering extremely high data transfer rates, near-zero latency, and extended coverage through the utilisation of frequencies approaching the terahertz range [13]. However, achieving optimal performance at such high frequencies presents significant challenges, particularly in antenna design, where conventional materials often suffer from radiation inefficiencies, material losses, and mechanical limitations. To overcome these constraints, composite materials have emerged as effective alternatives. Among them, CNT–Ti composites have attracted renewed attention. CNTs provide excellent electrical conductivity, thermal resistance, and low weight, while Ti contributes enhanced durability and mechanical strength. Together, these materials improve both the structural and electrical properties of CNT–Ti composites, making them highly suitable for 6G antenna applications.

Over recent decades, mobile networks have evolved through successive generations, each offering improvements in speed, capacity, and latency. By 2030, 6G networks are projected to deliver data rates of up to 1 Tbps with high efficiency. Nonetheless, challenges such as device synchronisation and radiofrequency modelling must be addressed to realise this goal. Antennas, as critical components of 6G infrastructure, are essential for providing the required conductivity, structural stability, and performance needed to develop compact, high-performance antennas suitable for terahertz applications, wearable technologies, and advanced sensing, thereby enhancing the capabilities of next-generation communication systems [4].

The progression from 1G to the anticipated 6G has transformed global communication, moving from the rudimentary analogue phones of the past to high-speed, sophisticated networks capable of supporting modern applications [25]. The first 1G network, launched in Japan in 1979, operated using analogue technology at 800–900 MHz, enabling mobile communication but offering poor signal quality, limited security, and short battery life. The transition to 2G in 1991 introduced digital communication through GSM and CDMA technologies, improving security, energy efficiency, and support for services such as SMS and multimedia messaging, despite low data rates [27]. With the introduction of 3G in 2001, mobile broadband speeds reached up to 2 Mbps, enabling video calls, internet browsing, and media streaming, although high deployment costs and capacity limitations persisted. The 4G network further advanced mobile broadband through LTE and LTE-Advanced technologies, providing bandwidths up to 1 Gbps and enabling HD streaming, online gaming, and extensive application ecosystems, despite urban network congestion issues. The 5G network, launched in 2019, facilitated ultra-reliable low-latency communication with speeds up to 10 Gbps, supporting smart cities, IoT, and AR/VR applications; however, challenges related to coverage and high infrastructure costs remained [10].

Looking forward, 6G networks are expected to leverage terahertz communications and AI-enhanced networking to achieve data rates up to 1 Tbps with sub-millisecond latency, supporting applications such as holographic communications and brain-computer interfaces by 2030 [12]. Nevertheless, challenges concerning terahertz-compatible hardware, energy efficiency, and regulatory frameworks must be addressed before full-scale deployment. In summary, the development of wireless communication has consistently focused on higher speeds, improved efficiency, and expanded functionality. Each successive generation has advanced further than its predecessor. The 6G era is expected to overcome existing limitations through AI-driven automation, immersive technologies, and unprecedented data rates, fundamentally transforming the landscape of network connectivity [22].

2. Attributes of Carbon Nanotube-Titanium (CNT-Ti) Composites

The CNT–Ti composite is created by integrating the exceptional properties of CNTs and Ti, producing a high-performance material suitable for advanced technological applications [26]. CNTs are formed by rolling sheets of graphene into tubular structures, which confer outstanding electrical conductivity, tensile strength surpassing that of steel, low density, and thermal conductivity reaching up to 3500 W m^{-1} K^{-1}. Their high aspect ratio allows for efficient load distribution, making CNTs ideal reinforcing agents in composite materials. CNTs are categorised as single-walled (SWCNTs) and multi-walled (MWCNTs); SWCNTs exhibit superior electrical conductivity, whereas MWCNTs demonstrate enhanced mechanical strength due to their multiple-wall configuration [9]. Consequently, CNT–Ti composites combine high strength, low density, and favourable thermal properties, rendering them highly advantageous for engineering applications.

3. Essential Features of Radio Antennas

Radio antennas operating within the frequency range of 30 Hz to 300 GHz play a critical role in wireless communication by enabling the transmission and reception of electromagnetic waves. The operational principle of antennas relies on electromagnetic radiation, where alternating currents generate propagating waves for transmission, while incoming waves induce currents for reception. Antenna performance is influenced by several parameters, including frequency, wavelength, radiation pattern, gain, and polarization [25]. Various types of antennas serve distinct functions: dipole antennas are commonly used for internet broadcasting, parabolic antennas for satellite communication, and patch antennas for Wi-Fi and GPS applications. Impedance matching reduces power loss, and bandwidth defines the usable frequency range. Advanced systems often employ antenna arrays and beamforming techniques to enhance signal directionality and overall efficiency. These antennas are integral to broadcasting, cellular networks, radar systems, and wireless technologies such as Wi-Fi 2 and Bluetooth [7]. Over time, the development of intelligent antennas, metamaterials, and multiband capabilities has improved adaptability and performance. Looking ahead, 6G networks are expected to incorporate advanced antennas to ensure ubiquitous connectivity and support AI-based applications in autonomous vehicles, drones, and the Internet of Things, thereby fostering a highly interconnected digital environment, as illustrated in Figure 1.

Fig.1: An Artistic View of 6G Wireless Communication Technology in Smart Cities

Although wireless communication and CNT–Ti composites are advancing in manufacturing, several challenges remain, providing opportunities for further research. The design and performance optimisation of CNT–Ti antennas is particularly complex; integrating CNTs and Ti to enhance bandwidth and radiation characteristics continues to be a sophisticated problem. The alignment, dispersion, and interaction of CNTs with Ti require more detailed investigation, as these factors directly influence the electrical and mechanical properties of the composites [11]. Achieving high durability under extreme conditions, including radiation exposure, temperature fluctuations, and mechanical stress, represents a major challenge, especially in aerospace, maritime, and space applications. Furthermore, issues related to scalability and production, such as high costs and inconsistent manufacturing methods, limit the widespread deployment of CNT–Ti composites. Ensuring consistent quality and understanding the electromagnetic behaviour of CNT–Ti composites, particularly regarding electromagnetic compatibility, is essential [14].

The potential of CNT–Ti composites in future networks, including 5G and terahertz 6G systems, remains underexplored. Their performance must be optimized to enable rapid data transmission with minimal latency. Environmental responsibility also necessitates attention to sustainability and recyclability. Addressing these challenges is central to advancing communication systems; CNT–Ti composites can significantly improve antenna efficiency, bandwidth, and longevity. Their lightweight structure and high performance make them ideal for high-frequency applications, particularly in 5G and 6G networks, where rapid and reliable data transmission is critical. Their mechanical strength and low mass have already benefited aerospace applications, including satellites, drones, and deep-space missions [5]. The growing demand for compact, high-performance antennas in the Internet of Things (IoT) and smart technologies highlights the potential of CNT–Ti composites. Their lightweight nature contributes to energy-efficient communication, supporting sustainability. Further development of CNT–Ti composites promises advancements in telecommunications, nanotechnology, and intelligent systems, shaping the future of wireless networks. The use of CNT–Ti composites in antenna design is advantageous, combining the mechanical, electrical, and thermal properties of the constituent materials.

CNTs enhance antenna efficiency by reducing resistive losses, increasing conductivity, and enabling operation at millimetre-wave frequencies. Studies indicate that CNT-based antennas achieve higher gain and lower energy loss than conventional materials such as copper. Ti provides thermal stability, corrosion resistance, and structural strength, making CNT–Ti composites suitable for industrial and aerospace applications in harsh environments [9]. The incorporation of CNTs into Ti further increases mechanical strength and conductivity, improving efficiency and bandwidth beyond what conventional copper antennas can achieve. Techniques such as chemical vapour deposition allow uniform CNT coating on Ti substrates, optimising performance across a broad frequency range, particularly for 5G and 6G networks. Nonetheless, challenges regarding cost-effectiveness, scalability, and versatility across applications persist. Further research is needed to design wearable and IoT devices capable of reliable operation under severe conditions. The exploration of CNT–Ti composites has significant potential to advance antenna technology and realise its capabilities in next-generation communication systems [23].

Optimally combining CNTs with Ti can substantially enhance the mechanical strength and conductivity of composite-based antennas, enabling them to outperform traditional copper antennas in both efficiency and bandwidth [32]. The present research aims to develop CNT–Ti composite antennas optimised for contemporary 5G and 6G networks. The primary goal is to produce antennas with wider bandwidth, improved efficiency, better VSWR, minimal power loss, and structural integrity. By leveraging the superior mechanical and electrical properties of CNT–Ti composites, these antennas exhibit enhanced design performance. CNTs improve conductivity, reduce electrical losses, and increase radiation efficiency compared to conventional materials, while Ti ensures durability and stable operation under demanding conditions. Additionally, CNT–Ti antennas offer increased bandwidth, making them highly suitable for high-frequency applications in future communication systems [31].

4. Materials and Methods

As previously noted, the design of antennas for 6G networks remains highly challenging, prompting scientists and engineers to develop a range of composite structures exhibiting ultra-wide bandwidth, high efficiency, compact form factors, and stable performance across millimetre-wave frequencies. Conventional materials are limited in their ability to reduce propagation losses and maintain stability in densely populated communication environments, thereby necessitating advanced technological solutions [35]. Composites incorporating CNTs have attracted considerable attention due to their exceptional electrical conductivity, low density, and capability to transmit high-frequency signals. Numerous studies have demonstrated that CNTs effectively reduce resistive losses and enhance antenna performance; however, large-scale manufacturing and integration continue to present significant challenges [34]. Ti is recognised for its unmatched mechanical strength, corrosion resistance, and stability under harsh environmental conditions, making it widely used in aerospace and high-performance applications. Nevertheless, its intrinsic electrical properties are insufficient for the design of advanced antennas, necessitating combination with other functional materials. In this context, CNT–Ti composites, forming hybrid structures, have been proposed as antenna materials for 6G wireless communication. These composites merge the high electrical conductivity of CNTs with the structural robustness and thermal stability of Ti. The primary objective is to advance next-generation communication systems while addressing integration challenges through optimisation of material performance and antenna design [6].

5. Material Selection and Characterizations

The development of CNT–Ti composite antennas for 6G network implementation necessitates a comprehensive evaluation of the material properties and overall performance. Integrating the exceptional electrical conductivity, thermal stability, and mechanical strength of CNTs, along with their low signal loss and high efficiency at terahertz frequencies [21], with the superior durability and corrosion resistance of Ti, offers significant advantages for antennas designed to operate under extreme conditions. Manufacturing techniques, such as chemical vapour deposition (CVD) and powder metallurgy, facilitate optimal integration of CNTs with Ti, thereby enhancing the composite properties.

To ensure the suitability of these composites for 6G applications, it is essential to thoroughly understand their electrical, mechanical, and thermal behavior. A critical challenge lies in optimizing CNT dispersion and bonding to maximize conductivity, mechanical strength, and energy dissipation within the composites. The cylindrical nanostructure and high aspect ratio of CNTs contribute to enhanced antenna performance. Their high electrical conductivity enables efficient electromagnetic wave transmission, while a tensile strength of up to 200 GPa ensures structural endurance without adding weight. With thermal conductivity reaching 3,500 W m^{-1} K^{-1}, CNTs surpass most conventional materials in heat dissipation, maintaining stability under demanding conditions. The flexibility and fracture toughness of both SWCNTs and MWCNTs further improve the composite's resistance to mechanical stress, as illustrated in Figure 2. Chemical modification of CNTs can enhance their dispersion within the composite, extending their applicability in advanced communication technologies. By combining CNTs with Ti, it is possible to produce a high-performance material specifically engineered for next-generation wireless systems [19]. This combination improves the conductivity, durability, and efficiency of CNT–Ti composites, making them highly desirable for future antenna development.

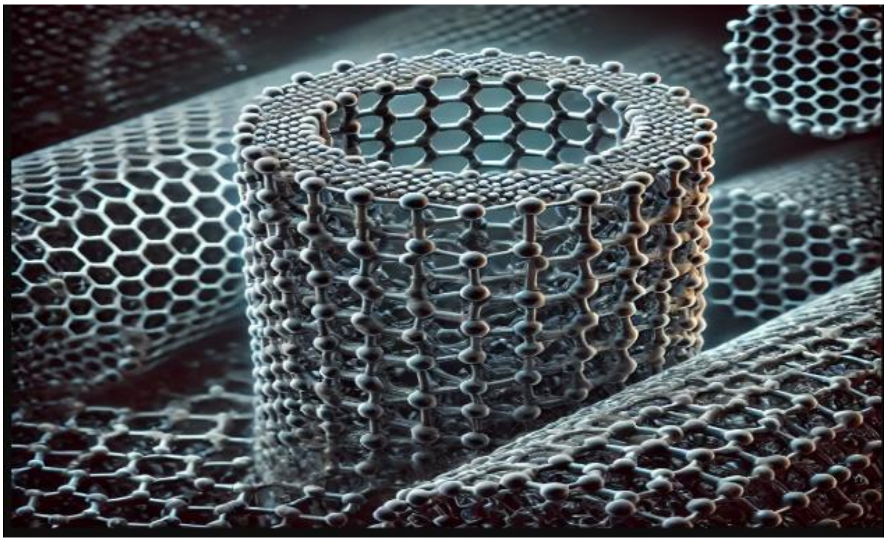

Fig.2: Appearance of Single and Multi-Walled CNT

Ti has long been valued for its combination of low density and corrosion-resistant properties, particularly in aerospace, biomedical, and industrial applications, owing to its strength, durability, and versatility. Its high strength-to-weight ratio renders it suitable for demanding environments that require mechanical resilience and tolerance [18]. Ti exhibits tensile strengths ranging from 400 to 1,400 MPa and demonstrates resistance to cyclic loading, making it well-suited for aerospace and medical applications. Its thermal conductivity ($22\ W\ m^{-1}\ K^{-1}$) is moderate, favouring applications where structural integrity takes precedence over electrical conductivity ($2.38 \times 10^{6}\ S\ m^{-1}$). The naturally forming titanium oxide (TiO_2) layer is self-repairing, enhancing its corrosion resistance and providing flexibility to withstand harsh environments such as seawater and carbonic acid-containing media. Although Ti has relatively low electrical conductivity, its thermal stability, mechanical strength, and corrosion resistance make it indispensable for applications requiring long-term performance under stringent conditions. Additionally, its biocompatibility has expanded its use in medical technologies, significantly contributing to advances in both medicine and engineering [16].

6. Working Principle of CNT-Ti Composites

Various fabrication techniques, including spark plasma sintering, CVD, and powder metallurgy, are employed to produce CNT–Ti composites with tailored properties. By controlling the orientation and distribution of CNTs during synthesis, both the overall composite performance and its functional behaviour can be significantly enhanced. The resulting composites are highly advantageous for applications such as sensors, antennas, and energy systems, offering improved thermal dissipation, excellent electrical conductivity, mechanical reinforcement, and long-term durability [30]. Next-generation 6G wireless networks utilise CNT–Ti composites in ways comparable to conventional copper antennas in terms of electrical properties and lightweight characteristics. However, CNT–Ti composites substantially reduce mass, which is critical for wearable and aerospace applications. Titanium-based materials, such as titanium carbide (Ti_3C_2), further enhance flexibility, performance, and reliability of antennas across wide frequency ranges and under mechanical stress, making them highly suitable for adaptive communication systems. The integration of CNTs with Ti in composite antennas offers a promising route for 6G networks, combining lightweight structures, mechanical flexibility, and high-frequency performance. Although research in this domain remains at an early stage, the demonstrated potential of CNTs and Ti-based materials indicates their suitability for diverse wireless communication applications. Addressing challenges related to material production, interface engineering, and structural design is essential to optimise gain, bandwidth, and radiation efficiency.

Continued experimental investigation and computational modelling are expected to drive innovation, enabling the seamless integration of CNT–Ti composites into next-generation communication technologies [28; 33].

7. Advantages of CNT-Ti Composites-based Antennas

As previously discussed, CNT–Ti composite antennas exhibit superior electrical conductivity and enhanced electromagnetic wave propagation compared with conventional materials. These properties enable significant reductions in power loss and expansion of the operating frequency range, rendering them highly suitable for high-frequency applications, including 5G and millimetre-wave communications [23]. Their lightweight structure considerably reduces the overall mass of antennas, improving efficiency in aerospace and satellite systems while extending operational range in wearable and portable electronic devices. CNT–Ti composites demonstrate exceptional durability, resisting extreme temperatures, mechanical stress, and corrosive conditions, which ensures reliable performance in demanding environments such as space missions, marine operations, and industrial settings. Their resistance to radiation, vacuum, seawater, and chemical corrosion further enhances longevity and functional stability. The adaptability of these composites allows for the production of compact and lightweight antenna designs, suitable for applications such as the Internet of Things and nanosatellites, thereby improving signal transmission and overall antenna performance [38].

CNT–Ti composites also contribute to sustainable communication technologies by enhancing signal efficiency and reducing energy consumption [31]. Their durability minimizes replacement frequency, lowers material waste, and supports the sustainable development of wireless systems. The combination of high strength, longevity, and low mass makes CNT–Ti antennas highly applicable in aerospace, defense, telecommunications, and wearable electronics, offering high-performance solutions for satellites, drones, autonomous vehicle sensor systems, and next-generation networks. The robustness of CNT–Ti antennas positions them as an ideal choice for space applications, ensuring reliable communication under extreme conditions.

8. CNT-Ti Integration Strategy

Combining Ti with CNTs produces advanced composites exhibiting superior mechanical, electrical, and thermal properties. The synergistic interaction between CNTs and Ti presents significant industrial potential, necessitating a detailed understanding of their interaction to maximise composite performance. High-quality CNTs are typically synthesized via CVD, after which the adhesion of Ti onto CNTs is modified through chemical oxidation or functionalisation. Both nanoparticle- and micrometre-scale Ti powders are employed to ensure effective interaction with CNTs. Maintaining uniform CNT dispersion within the Ti matrix is essential, as agglomeration can compromise the mechanical properties of the resulting composites [25]. Techniques such as ultrasonic agitation and ball milling can facilitate consistent incorporation of CNTs into the Ti matrix, ensuring uniform reinforcement. The interfacial bond between CNTs and Ti is critical for optimising electrical conductivity, load transfer, and thermal performance. Strategies such as thermal densification or the use of adhesion-enhancing coupling agents can strengthen this interface. While CVD enables direct deposition of CNTs onto Ti surfaces, methods like spark plasma sintering (SPS) promote densification and preserve structural integrity [38]. Complex Ti–CNT architectures can also be fabricated using techniques such as 3D printing. CNTs contribute to increased stiffness, tensile strength, and durability, whereas Ti enhances corrosion resistance, resulting in composites with exceptional overall performance.

The enhanced thermal conductivity of CNT–Ti composites supports efficient heat dissipation in high-performance electronics and aerospace components, while their superior electrical conductivity makes them suitable for antennas and sensors. Their remarkable strength-to-weight ratio renders them ideal for lightweight structural applications. CNT–Ti composites have diverse applications in cutting-edge technologies: they are particularly advantageous for 6G antenna development due to their reduced weight and high conductivity. In aerospace, these composites enable the creation of lightweight, robust aircraft components, while in biomedical contexts, they provide durable, biocompatible materials for medical implants. The integration of nanomaterials and metals exemplifies innovative solutions across industry, technology, and healthcare [8].

9. Electrical Conductivity of CNT-Ti Composites

The electrical conductivity of CNT–Ti composites can be evaluated using approaches such as effective medium theory (EMT) or percolation models, expressed by the following relationship:

$$\boldsymbol{\sigma} CNT\ Ti = \sigma Ti(1 + \beta \frac{fCNT}{fC - fcnt}) \quad (1)$$

In this expression, σCNT–Ti represents the effective electrical conductivity of the CNT–Ti composite, σTi denotes the electrical conductivity of pure Ti, fCNT is the volume fraction of CNTs within the composite, Fc corresponds to the critical percolation threshold of CNTs (typically ranging from 0.1 % to 5 % depending on dispersion), and β is a fitting parameter influenced by CNT alignment and dispersion. Alternatively, when CNTs are uniformly dispersed and randomly oriented within the Ti matrix, a simplified mixing rule may be applied:

$$\sigma CNT - Ti = fCNT\sigma CNT + (1 - fCNT)\sigma Ti \quad (2)$$

In this context, σCNT denotes the electrical conductivity of CNTs (approximately 10^6 S/m for metallic CNTs), while fCNT and 1 − fCNT represent the respective volume fractions of CNTs and Ti. When the CNT content falls below the percolation threshold, the composite's conductivity approaches that of Ti. Consequently, achieving uniform CNT dispersion is crucial to maximise electrical performance and minimise signal loss in 6G antennas fabricated from CNT–Ti composites.

10. Characteristic Impedance of CNT-Ti Composite

The characteristic impedance of a CNT–Ti composite within an antenna system can be represented by the following expression:

$$ZCNT - Ti = \frac{\mathbf{1}}{\boldsymbol{\sigma CNT - Ti.A}} \quad (3)$$

In this expression, ZCNT–Ti and σCNT–Ti denotes the characteristic impedance and electrical conductivity of the CNT–Ti composite, respectively, while A represents the cross-sectional area of the conducting path. Increasing the CNT content enhances signal transmission by reducing impedance and boosting conductivity. Optimal CNT dispersion ensures effective impedance matching, which is critical for 6G applications. CNT–Ti composite antennas leverage the mechanical stability of Ti and the high electrical conductivity of CNTs to improve signal integrity and overall performance in next-generation wireless networks [15; 20; 25]. At this stage, the key properties of various antennas fabricated from CNT–Ti composites are typically analyzed.

11. CNT-Ti Composites-based Antenna Design

11.1 Patch Antenna

Because CNT–Ti composites enhance mechanical strength, electrical conductivity, and radiation efficiency, antennas based on these materials are widely employed in high-frequency applications, including 6G. In this design, a CNT–Ti patch on a dielectric substrate serves as the radiating element [4]. The primary components of a patch antenna are as follows:

- Patch: A rectangular or square conductive element responsible for emitting electromagnetic waves. When CNT–Ti composites replace conventional materials such as copper, the patch benefits from reduced weight, improved thermal stability, and enhanced conductivity.
- Substrate: A dielectric layer, for example FR4 or Rogers RT (εr = 4.4), provides both insulation and structural support, ensuring efficient signal propagation.

- Feed Line: The microstrip feed delivers energy to the patch. The use of CNT–Ti composites reduces resistive losses, thereby increasing overall antenna efficiency.

11.2 Microstrip Antenna

This type of antenna demonstrates optimised energy transfer with minimal signal loss. Microstrip antennas utilise CNT–Ti-based feed lines to achieve enhanced performance in high-frequency applications. The inclusion of CNT–Ti reduces skin-effect losses and improves signal transmission, as illustrated in Figure 3. The main components of this antenna are as follows:

- Microstrip Line: A conductive strip fabricated from CNT–Ti and placed on a dielectric substrate. Its high conductivity and smoother surface contribute to increased signal efficiency.
- Dielectric Layer: An insulating substrate, such as FR4 or Rogers RT, provides structural support to the microstrip line while minimising transmission losses.
- Top Conductor Layer: An optional upper conductive layer that further enhances signal propagation.

12. Advantages of CNT-Ti Composites in Antenna Design

Some of the key advantages of CNT–Ti composite antennas include:

- High Electrical Conductivity: Improves radiation efficiency and minimizes power loss.
- Lightweight Structure: Suitable for advanced applications, including 6G and satellite communications.
- Improved Thermal Stability: Maintains reliability under extreme environmental conditions.
- Enhanced Mechanical Strength: Ensures durability for flexible and wearable antenna technologies.

The combination of CNTs with Ti enhances overall efficiency, bandwidth, and radiation performance, positioning CNT–Ti antennas as a highly promising solution for next-generation 6G wireless network communications [17; 36].

The radiation pattern of an antenna describes the spatial distribution of its radiated power, which can be omnidirectional or directional, and includes key features such as the main lobe, side lobes, and nulls. In CNT–Ti composite antennas designed for 6G networks, this pattern is affected by the high electrical conductivity and low mass of CNTs, as well as the structural stability provided by Ti. The normalized radiation pattern for this type of antenna can be represented as follows:

$$P(\theta,\emptyset) = \left|E_\theta(\theta,\emptyset)\hat{\theta} + E_\emptyset(\theta,\emptyset)\hat{\emptyset}\right|^2 \quad (4)$$

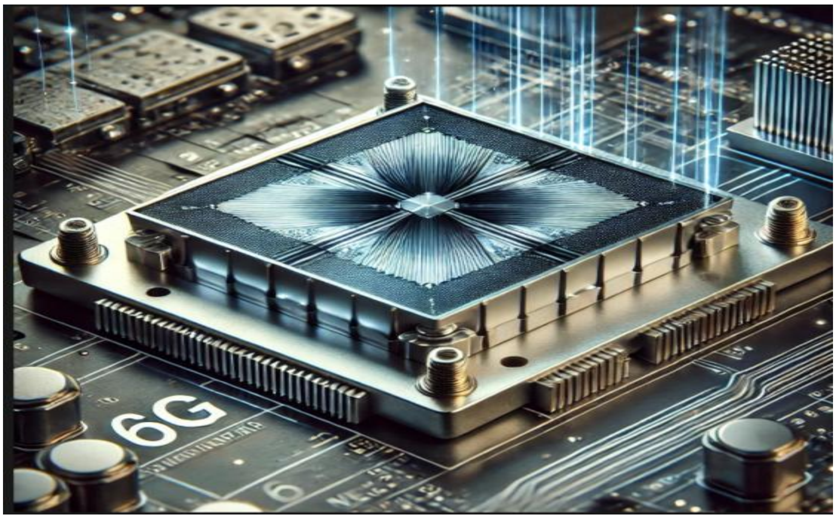

Fig.3: 6G Patch Microstrip Antenna Design using CNT-Ti Composites

In this expression, P(θ,ϕ) represents the radiated power density as a function of elevation (θ) and azimuth (ϕ), while Eθ and Eϕ correspond to the electric field components in their respective directions. For array configurations, the array factor, AF(θ,ϕ), is commonly considered in 6G systems. The resulting modified radiation pattern can be expressed as follows:

$$AF(\theta,\emptyset) = \sum_{n=1}^{N} I_n e^{j(\vec{k}.\vec{n})} \quad (5)$$

In this expression, N denotes the number of antenna elements, In represents the current at each element, k is the wavevector, and n⃗ indicates the position vector of each element. For 6G applications, beamforming techniques are employed to dynamically adjust the radiation pattern:

$$P_{6G}(\theta,\emptyset) = P(\theta,\emptyset).BF(\theta,\emptyset) \quad (6)$$

In this context, BF(θ,ϕ) represents adaptive beamforming, which optimises coverage and overall performance. The intrinsic properties of CNT–Ti composites have a significant effect on the radiation characteristics. The electrical conductivity (σCNT) and permittivity (ϵCNT–Ti) directly influence the electric field components, requiring careful integration into the feed network to achieve efficient signal transmission and enhanced antenna performance. The gain of an antenna quantifies the radiated power in a specific direction relative to an isotropic source, whereas directivity measures the concentration of energy in that direction. For CNT–Ti composite antennas in 6G networks, these properties are shaped by the high conductivity of CNTs and the structural stability of Ti. The directivity (D) can be calculated as follows:

$$D(\theta,\emptyset) = \frac{4\pi U(\theta,\emptyset)}{Prad} \quad (7)$$

In this expression, D(θ,ϕ) represents directivity as a function of elevation (θ) and azimuth (ϕ) angles. U(θ,ϕ) denotes the radiation intensity in the specified direction, defined as U(θ,ϕ) = r^2 P(θ,ϕ), where P(θ,ϕ) is the power density. The total radiated power, Prad, is then calculated using the following relation:

$$Prad = \int_0^{2\pi}\int_0^{\pi} P(\theta,\emptyset) r^2 sin\theta d\theta d\emptyset \quad (8)$$

It is important to note that CNT–Ti composites can enhance directivity by reducing energy dissipation through their improved electrical conductivity (σCNT). The antenna gain (G) is related to its efficiency (η) according to the following relationship:

$$G(\theta,\emptyset) = \eta * D(\theta,\emptyset) \quad (9)$$

In this expression, G(θ,ϕ) denotes the antenna gain, while η represents the efficiency, which is affected by the low resistivity of CNTs and the structural robustness of Ti. Efficiency encompasses material loss (ηm), mismatch loss (ηmismatch), and surface wave loss (ηs). The efficiency (η) of CNT–Ti composite antennas can be determined using the following formula:

$$\eta = \eta m.\eta mismatch.\eta s \quad (10)$$

For 6G applications, the directivity is adjusted through dynamic beamforming and can be expressed as follows:

$$D_{6G}(\theta,\emptyset) = D(\theta,\emptyset).BF(\theta,\emptyset) \quad (11)$$

In this expression, BF(θ,ϕ) represents the beamforming function, which is dynamically optimised according to user location and network conditions to achieve adaptive directional radiation. Antenna efficiency (η) quantifies the ratio of radiated power to input power and is affected by resistive losses and impedance matching:

$$\eta = \eta rad.\eta mismatch \quad (12)$$

In this context, ηrad denotes the radiation efficiency, accounting for power losses arising from material resistivity and surface waves, while ηmismatch represents the impedance mismatch efficiency, which considers power losses caused by reflection or mismatch between the antenna and the feedline.

The radiation efficiency (ηrad) can be expressed as follows:

$$\eta rad = \frac{Prad}{Pinput} \quad (13)$$

In this expression, Prad represents the power radiated by the antenna, and Pinput denotes the total power supplied to the antenna.

For CNT–Ti composite antennas, the radiation efficiency can be affected by the following factors:

1. Material Conductivity (σCNT–Ti): The high electrical conductivity of CNTs reduces ohmic losses. The relationship between radiation resistance (Rrad) and loss resistance (Rloss) is given by:

$$\eta rad = \frac{Rrad}{Rrad+Rloss} \quad (14)$$

Ti contributes to the structural integrity of the composite and improves thermal dissipation by reducing resistive heating.

2. Surface and Dielectric Losses: The synergistic combination of CNTs and Ti reduces surface and dielectric losses owing to their superior surface characteristics and thermal stability. The mismatch efficiency (ηmismatch) can be determined using the following relation:

$$\eta mismatch = 1 - |\Gamma|^2 \quad (15)$$

In this expression, **Γ** represents the reflection coefficient at the feed point, which is defined as follows:

$$\Gamma = \frac{Zin-Zfeed}{Zin+Zfeed} \quad (16)$$

In this expression, Zin denotes the input impedance of the antenna, while Zfeed represents the impedance of the feedline.

For CNT–Ti composite antennas, effective impedance matching is achieved by adjusting the composite's properties, thereby minimising reflection and maximising power transfer. Frequency-dependent performance in 6G applications, operating at millimetre-wave or terahertz frequencies, is primarily influenced by the following factors:

1. Ohmic Losses: Due to the exceptional conductivity of CNTs, CNT–Ti composites reduce resistive losses that are more pronounced in conventional materials at high frequencies.

2. Dielectric Losses: Even within high-frequency ranges, CNT–Ti composites exhibit low dielectric losses, enhancing overall antenna efficiency.

The overall efficiency of CNT–Ti composite antennas can be determined using the following formula:

$$\eta = \frac{Rrad}{Rrad+Rloss}\left(1 - \left|\frac{Zin-Zfeed}{Zin-Zfeed}\right|^2\right) \quad (17)$$

This expression quantifies the total efficiency by accounting for both impedance matching and intrinsic material properties. Due to the low resistivity, high electrical conductivity, and thermal stability of CNT–Ti composites, antennas fabricated from these materials are capable of meeting the stringent performance requirements of 6G wireless networks with exceptional efficiency.

The principal factors influencing the efficiency of CNT–Ti composite antennas are directivity and gain. While gain reflects efficiency losses related to material and surface characteristics, directivity depends on the total radiated power and radiation intensity. Structural integrity, electrical conductivity, and integration with dynamic beamforming—which alters directivity—play significant roles in determining the efficiency of CNT–Ti composite antennas. Radiation resistance and impedance matching further affect efficiency by ensuring maximal power transfer and minimising losses. Moreover, the superior conductivity of CNT–Ti composites reduces resistive losses, while their low dielectric loss enhances performance, particularly at the high frequencies relevant to 6G systems. In summary, CNT–Ti composite antennas can achieve exceptional efficiency through the optimisation of these factors in conjunction with careful design, thereby fulfilling the rigorous requirements of next-generation wireless networks [7; 10; 23; 24; 27; 29].

13. Results and Discussion

A CST Studio Suite was employed to model a novel project aimed at evaluating the performance of the proposed CNT–Ti composite antennas. The Antenna Design module was initiated, and the Patch Antenna configuration was selected. The initial step involved defining the substrate by creating a rectangle measuring 2.89 mm in length and 2.5 mm in width, with a thickness of 0.254 mm. The chosen material for the substrate was a dielectric with a relative permittivity of 3 and a loss tangent of 0.002, representing the CNT component. The patch was subsequently created by overlaying a rectangle on the substrate. This material exhibited a conductivity of 10^6 S/m and a relative permittivity of 2.5. A ground plane was incorporated beneath the substrate by drawing another rectangle composed of titanium, which possesses a conductivity of 2.38 × 10^6 S/m. Simulations were performed using the Frequency Domain Solver over a frequency range of 100 GHz to 300 GHz, and a Waveguide Port I was included to allow signal input. This configuration demonstrated optimal antenna performance within the specified frequency range, utilising CNTs for the patch and titanium for the ground plane.

The effective conductivity of the CNT–Ti composite is dependent on the volume fraction of CNTs, which is determined by the percolation threshold; a higher concentration of CNTs enhances conductivity. In cases where CNTs are uniformly dispersed, a simplified mixing rule can be applied. Increasing the CNT fraction leads to improved composite conductivity, thereby enhancing antenna efficiency. When the CNT concentration falls below the percolation threshold, the conductivity approaches that of titanium. Proper dispersion of CNTs is essential to minimise signal loss in 6G antennas. The electrical conductivity of CNTs is inversely related to the characteristic impedance of CNT–Ti composites; lower CNT concentrations result in reduced impedance. Reduced impedance facilitates more efficient signal transmission, minimises power losses, and improves overall antenna performance. Optimised CNT dispersion ensures superior impedance matching, which is critical for 6G wireless communications.

Figure 4 illustrates the influence of varying CNT concentrations on the electrical conductivity of CNT–Ti composites. Both the simple mixing rule (dashed blue line) and the EMT model (solid red line) are presented. The findings indicate that increasing the CNT volume fraction (fCNT) enhances the composite's electrical conductivity. The EMT model offers a more accurate representation of conductivity behaviour as it incorporates the effects of CNT distribution. The high conductivity of CNTs (~10^6 S/m) reduces eddy current losses and allows for broader bandwidth. Additionally, the inclusion of titanium improves mechanical stiffness, ensuring stable performance across a wide frequency range. Reduction of the skin effect at millimetre-wave and terahertz frequencies further preserves signal quality in 6G applications.

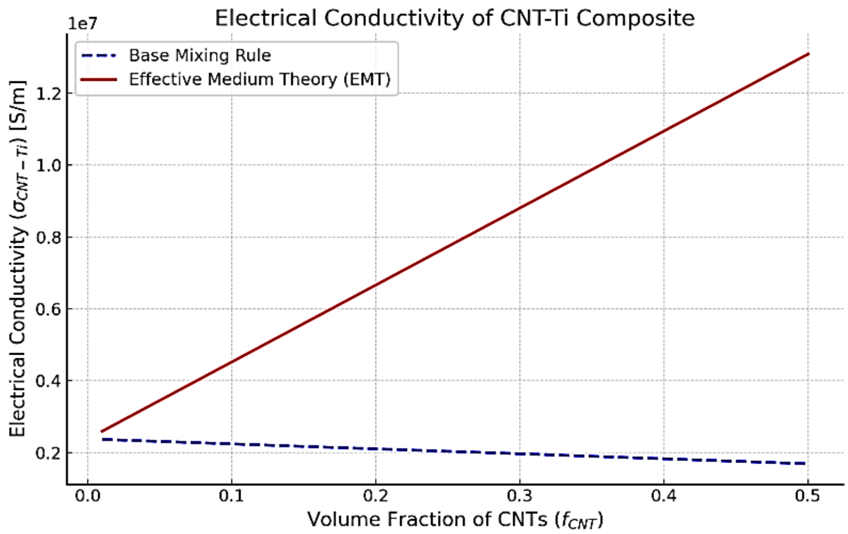

Fig.4: Electrical Conductivity of CNT-Ti Composite Against Volume Fraction of CNTs

Figure 5 depicts the variation of the S11 parameter (dB) with frequency, ranging from 100 GHz to 300 GHz, for a CNT–Ti composite antenna. The S11 parameter represents the fraction of power reflected by the antenna. Lower S11 values (approaching -10 dB or lower) indicate superior impedance matching with the feed line, which in turn enhances radiation efficiency. In the simulations, S11 was observed to remain below -10 dB across specific frequency bands, demonstrating effective antenna performance and high radiation efficiency.

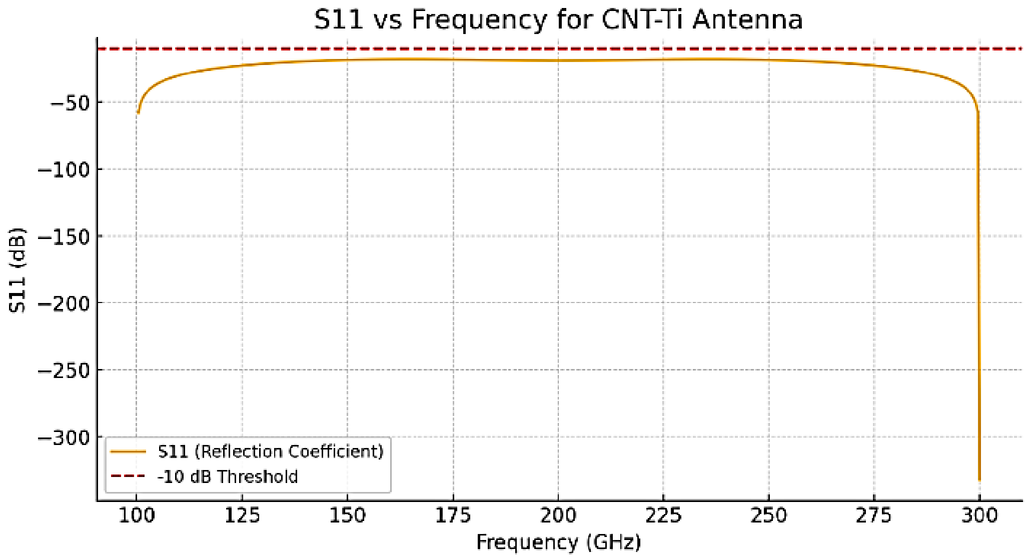

Fig.5: Frequency-Dependent Variation of S11 Parameter for CNT-Ti Composite

13.1 Effective Bandwidth Analysis

The operational bandwidth is often defined as the frequency range over which S11 remains below -10 dB, as indicated by the red threshold line. The graph demonstrates that the CNT–Ti composite antenna exhibits a comparatively wide range of operational frequencies, rendering it suitable for 6G applications and other high-frequency uses. This broad bandwidth can be attributed to the intrinsic material properties, where titanium ensures mechanical stability and CNTs provide high electrical conductivity, maintaining consistent antenna performance across the entire frequency spectrum.

13.2 Impact of Composite Material on Antenna Performance

CNTs contribute to reducing the quality factor (Q), thereby broadening the bandwidth, mitigating the skin effect at high frequencies, and enhancing both signal penetration and overall efficiency. Simultaneously, titanium reinforces the mechanical strength of the antenna, prevents long-term structural failure, and minimises impedance variations across frequencies, ensuring stable operational characteristics. In this study, S11 and VSWR analyses were employed to evaluate the performance of the proposed CNT–Ti composite antenna. A significant proportion of input power was radiated when S11 remained below -10 dB, confirming high radiation efficiency. The VSWR values were found to be below 2, indicating effective impedance matching with the feed line. Conversely, an S11 value higher than -10 dB would signify increased power reflection, thereby reducing radiation efficiency.

Observed increases in VSWR suggest potential impedance mismatches, necessitating the use of matching networks, such as LC circuits or optimised microstrip designs. Frequency-dependent variations in S11, particularly at higher frequencies, can be attributed to wave interference within the antenna geometry (Figure 5). Minor fluctuations in surface current distributions across the antenna layers may also contribute to these variations. These findings corroborate the suitability of CNT–Ti composite antennas for 6G and other high-frequency applications. The proposed antenna demonstrated a wide operational bandwidth, making it highly relevant for 6G wireless networks, which demand high radiation efficiency for effective signal transmission. Wide bandwidth is critical for supporting high data rates and minimising signal losses at millimetre-wave and terahertz frequencies. The low-loss CNT–Ti composite facilitates efficient impedance matching and ensures stable performance across most frequencies.

Nonetheless, further refinement, such as the application of quarter-wave transformers or LC matching networks, could improve impedance matching at specific frequencies. Advanced simulations in CST provide detailed performance modelling, and fine-tuning the microstrip geometry can further reduce S11 variations. Looking forward, CNT–Ti composite antennas are poised to support 6G networks, where AI-enabled systems can dynamically adjust impedance in response to changing operational conditions. To further enhance antenna surface quality and performance, advanced nanofabrication techniques, such as Nano-printing, may be employed, offering sustainable solutions for high-performance next-generation wireless communication systems.

13.3 Radiation Characteristics of CNT-Ti Composite-based Antenna for 6G Wireless Networks

CNT–Ti composite-based antennas for 6G wireless networks offer several notable advantages, including low mass and enhanced structural stability. Consequently, a detailed evaluation of their radiation characteristics, encompassing power distribution, gain, directivity, and beamforming, is essential and can be achieved through mathematical modelling. The radiation pattern derived from Equation 1 indicates that maximum radiation occurs at 90°, which effectively maximises horizontal energy propagation. Minimal radiation at 0° and 180° concurrently improves directivity by limiting vertical energy dispersion. Furthermore, variations in power distribution across different azimuth angles (ϕ) reveal a stable horizontal emission, highlighting the antenna's suitability for deployment in densely populated urban environments. The gain pattern aligns with the principal radiation direction, showing a peak gain of 9 dB at 90°, reflecting efficient energy concentration. The achieved efficiency ratio of $\eta = 0.9$ demonstrates the advantages of the high conductivity of CNTs combined with the mechanical stability of Ti, which reduces resistive losses. Gain reduction at 0° and 180° also attenuates unnecessary emissions (Figure 6). The observed gain enhancement further strengthens signal transmission at millimetre-wave and terahertz frequencies, mitigating significant path losses. Directional radiation additionally reduces interference, a critical factor in high-density network deployment. It is suggested that antenna elements can be multiplexed to further improve directivity by managing constructive interference, with optimal performance obtained through uniform current distribution.

Based on Figure 6, it can be inferred that the phase modulation term (ej(k r·n)) enables precise beam steering, which is a critical feature for adaptive transmission. Enhanced beam shaping improves coverage flexibility within dynamic environments, while reduced sidelobe levels decrease interference and enhance spatial resolution. Beamforming techniques are particularly advantageous in time-varying conditions, allowing radiation patterns to be directed towards active users, thereby maximising gain and coverage. The suppression of sidelobes contributes to overall efficiency by minimising wasted radiation.

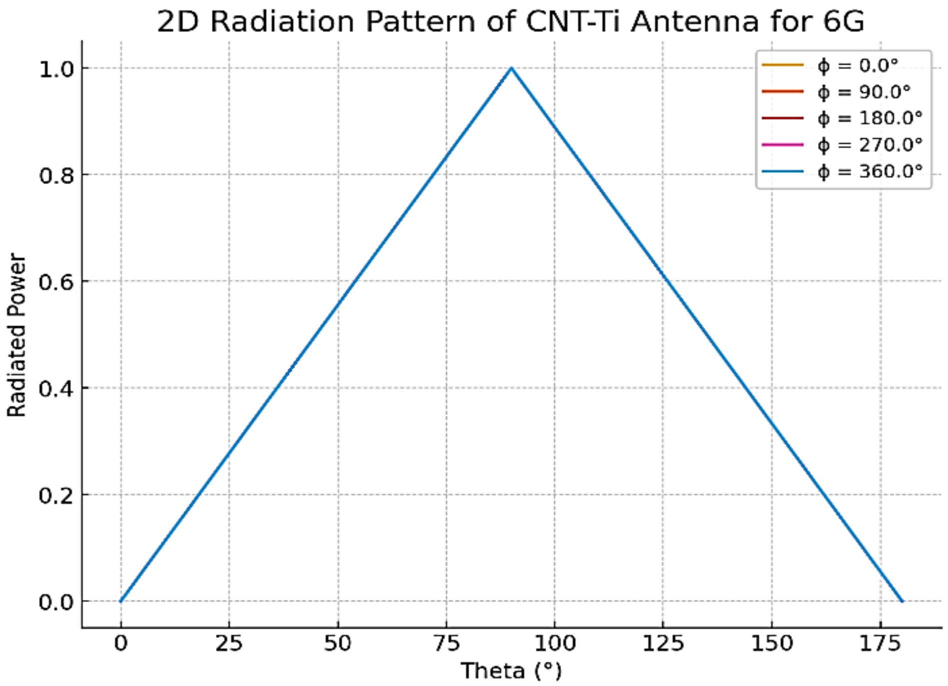

Fig.6: Radiation Characteristics of CNT-Ti Composite-Based Antenna for 6G Wireless Networks

For high-frequency bands, increasing the signal-to-noise ratio (SNR) is essential to ensure communication quality, while mobile platforms, including UAVs and autonomous vehicles, benefit from intelligent beam optimisation. Overall, this comprehensive evaluation confirms the suitability of CNT–Ti composite-based antennas for future wireless networks. They offer high-gain directional radiation for extended millimetre-wave and terahertz links, enable dynamic beamforming to improve connectivity, reduce energy consumption through efficient power distribution, and provide adaptive radiation control to support advanced applications such as massive MIMO, mobile edge computing, and the IOT. Mathematical and numerical analyses indicate that the proposed CNT–Ti composite antenna is a highly promising candidate for high-frequency 6G communications, delivering superior directivity, gain, real-time adaptive beamforming, and energy-efficient radiation patterns. Furthermore, these antennas can be seamlessly integrated into 6G networks, enhancing power efficiency, network flexibility, and signal reliability, establishing them as an essential component in the evolution of wireless communication technologies.

13.4 Gain and Directivity Analysis of CNT-Ti Composite Antennas for 6G Wireless Networks

Figure 7 illustrates the frequency-dependent behaviour of four principal performance parameters of the antenna, namely power density, wavelength, gain, and directivity. According to the wave relation ($\lambda = c / f$), where f denotes the frequency and c represents the speed of light, the analysis demonstrates that wavelength decreases as frequency increases. Higher frequencies concentrate more energy within a given area, which is particularly relevant for radar systems and wireless communication. This is reflected in the observation that power density rises moderately with frequency. Both directivity and gain exhibit upward trends as frequency increases, indicating enhanced antenna performance and greater focus of the radiated energy at higher frequencies. These findings corroborate fundamental principles of antenna design and electromagnetic wave propagation, offering essential insights for optimising high-frequency communication systems and improving the efficiency of CNT–Ti composite antennas across various applications.

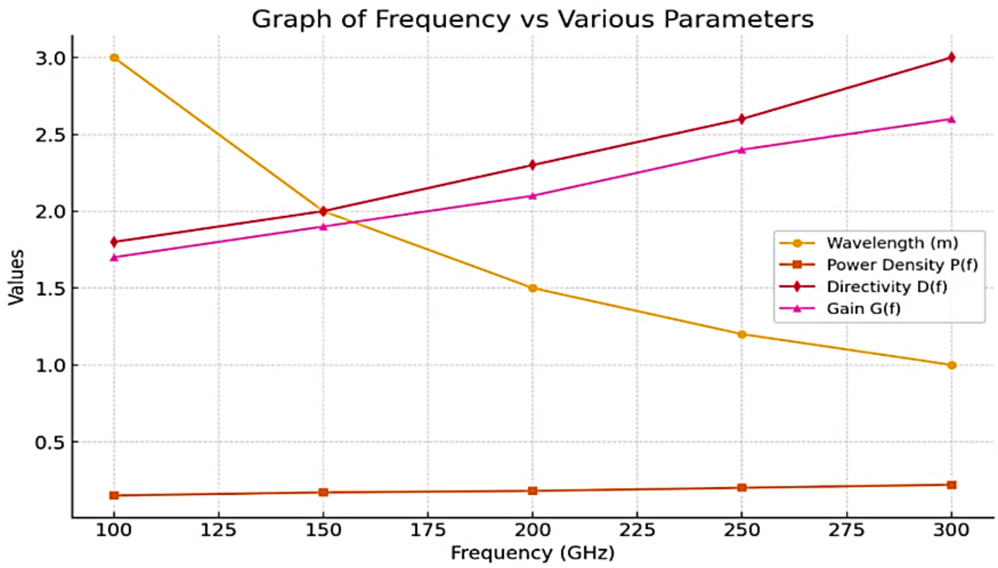

Fig.7: Wavelength, Power Density, Directivity, and Gain against Frequency

13.5 Efficiency Analysis of CNT-Ti Composite Antennas for 6G Wireless Networks

Figure 8 depicts the variation of efficiency with frequency for the CNT–Ti composite-based antenna, including radiation efficiency (η rad), mismatch efficiency (η mismatch), and total efficiency (η total). Radiation efficiency increases progressively with frequency, indicating enhanced capability for energy radiation at higher frequencies, likely attributable to improved material quality and reduced resistive losses. Across all frequencies, mismatch efficiency remains constant at a value of 1.00, signifying negligible power loss due to reflections or impedance mismatch. Consequently, the total efficiency, which is the product of radiation and mismatch efficiencies, follows the same trend as η rad, reaching a maximum of 0.90 at the highest frequency. This demonstrates that the antenna achieves optimal impedance matching, ensuring maximal power transfer (Figure 8). Moreover, the rise in frequency reduces conductor and dielectric losses, further enhancing radiation efficiency. Overall, the system's efficiency improves with increasing frequency, making it highly effective for high-frequency applications such as millimetre-wave communications, satellite links, and 5G networks, where efficient energy radiation is critical.

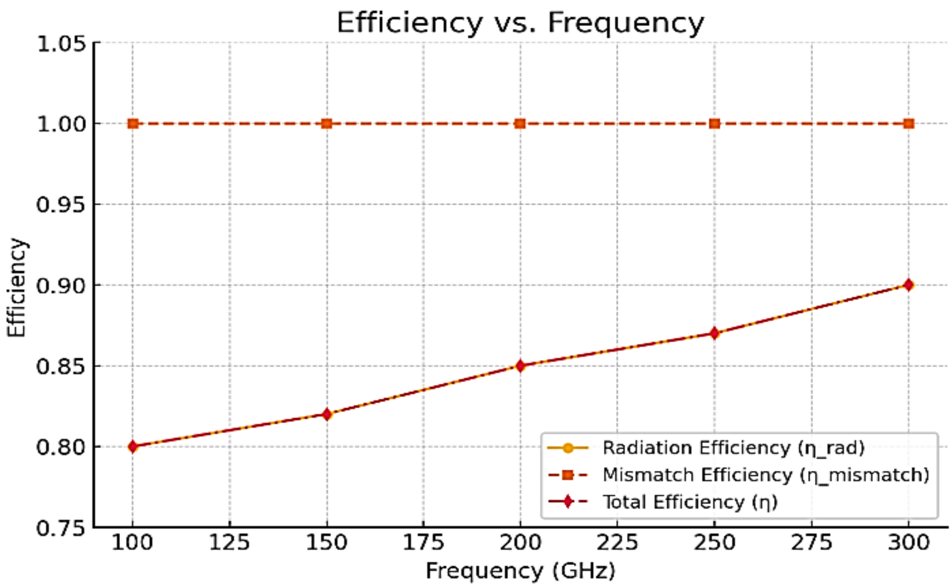

Fig.8: Frequency-Dependent Efficiency of CNT-Ti Composite-Based Antenna

Table 1 presents a comparative analysis of the performance of CNT–Ti composite-based antennas relative to other antennas reported in the literature. The CNT–Ti composite-based antenna demonstrates multiple notable advantages over traditional antenna types. Nevertheless, the extent of its superiority depends on the specific application and the performance criteria required for that use.

Table 1
Comparison of CNT-Ti Composites-Based Antenna's Performance with Other Types of Antennas Reported in the Literature

Property	**CNT-Ti Composite**	**Microstrip Patch**	**Horn Antenna**	**Dipole Antenna**	**Parabolic Dish**
Quality Factor (Q)	Low (2-20)	High (50-100)	Medium (20-50)	Low (10-30)	Very High (100+)
Bandwidth (GHz)	Wide (10-100)	Narrow (1-5)	Moderate (5-20)	Moderate (5-15)	Very Narrow (<1)
**Reflection Coefficient	Γ	)**	Low (0.10-0.30)	Moderate (0.20-0.50)	Low (0.10-0.20)
VSWR	1.22 - 1.85	1.5 - 3.0	1.2 - 1.5	1.3 - 2.5	~1.1
Impedance Matching	High	Moderate	High	Moderate	Very High
Application Areas	6G, Broadband, High-Speed Communication	Wireless LAN, RFID, Satellite	Radar, Microwave, Broadcasting	TV, FM Radio, Mobile Communication	Satellite Communication, Deep Space

13.6 Benefits of the CNT-Ti Composite Antenna: High Conductivity and Low Loss

Both CNTs and Ti are distinguished by their exceptional electrical conductivity, mechanical strength, durability, and low energy loss. Consequently, CNT–Ti composite-based antennas operate with minimal power dissipation, resulting in high efficiency, particularly in applications requiring low signal attenuation, such as high-speed or broadband communications. Key attributes of the proposed CNT–Ti composite-based antennas include:

- Wide Bandwidth: CNT–Ti composite antennas typically provide broader bandwidth than conventional antennas, capable of covering extensive frequency ranges (10 GHz to 100 GHz or higher). This renders them highly suitable for advanced applications, including 6G networks, IoT devices, and high-speed data transmission.
- Excellent Impedance Matching: These antennas generally exhibit reduced reflection coefficients, indicating superior impedance matching. This improves power transfer efficiency while minimising signal loss due to reflections. CNT–Ti antennas often demonstrate low VSWR values, confirming effective impedance alignment.
- Lightweight and Flexibility: The low density and inherent flexibility of CNTs make CNT–Ti antennas ideal for portable devices, wearable technologies, drones, and applications where minimal weight and compact form factor are essential.
- Durability and Strength: The integration of CNTs with Ti enhances mechanical robustness and longevity, making the antennas resistant to physical stress, harsh environmental conditions, and mechanical wear. Compared with conventional antenna types, such as microstrip patches, CNT–Ti antennas exhibit superior resilience and suitability for wearable and demanding applications.

14. Conclusion

Mathematical modelling and simulation were employed to evaluate the performance of antennas based on CNT–Ti composites for potential 6G wireless network applications. The results indicated that the proposed CNT–Ti composite-based antenna surpassed conventional antenna designs in terms of bandwidth, efficiency, flexibility, and impedance matching, confirming its suitability for high-speed, broadband communication and next-generation wireless systems, including 6G. In certain applications, such as satellite communications, where traditional antennas like parabolic dishes are still preferred, their inherent limitations may restrict widespread deployment. The choice of a CNT–Ti composite antenna ultimately depends on specific system requirements, including frequency range, dimensional constraints, and budget considerations. Applications demanding high performance and efficient power transfer at elevated frequencies are particularly suited to benefit from CNT–Ti composite antennas. The enhanced characteristics of these antennas can be attributed to their high electrical conductivity and low loss tangent, offering significant advantages over conventional materials. With respect to impedance matching, energy efficiency, signal propagation, and transmission effectiveness, CNT–Ti composite-based antennas outperform other designs. Moreover, they maintain lower VSWR values and broader bandwidth, facilitating compatibility across diverse communication systems. Advancements in CNT–Ti composite antenna technology present promising opportunities for next-generation communication systems. However, careful design and optimization are essential to address challenges related to cost and size. Further research is necessary to develop scalable manufacturing processes for CNT–Ti composite antennas and to evaluate their long-term reliability and economic feasibility before deployment in large-scale networks. Investigating additional nanomaterials and their integration with advanced technologies could yield innovative antenna architectures and enhance the capabilities and sustainability of next-generation wireless systems.

References

[1] Thomson Reuters and DinarStandard, State of the Global Islamic Economy Report 2018/19, Dubai: Dubai Islamic Economy Development Centre, 2018. [Online]. Available: https://www.zawya.com/en/press-release/state-of-the-global-islamic-economy-report-2018-19-islamic-economy-marks-steady-growth-ocw95h4a

[2] S. Secinaro, D. Calandra, A. Secinaro, V. Muthurangu, and P. P. Biancone, "The role of artificial intelligence in accounting: Machine learning and deep learning," Journal of Applied Accounting Research, vol. 22, no. 1, pp. 185–205, 2021, doi: 10.1108/JAAR-10-2019-0124.

[3] M. M. Chaudry and M. N. Riaz, Halal Food Production, 2nd ed., Boca Raton, FL: CRC Press, 2014, doi: 10.1201/b16768.

[4] Abbaoui, H., Aoud, S. E. E., Ali, S. U., Ghammaz, A., Belahrach, H., & Ibnyaich, S. (2025). Design, analysis and implementation of an optimized cost-effective octagonal patch antenna with UWB characteristics for 5G applications and beyond. *AEU-International Journal of Electronics and Communications*, *190*, 155655. https://doi.org/10.1016/j.aeue.2024.155655

[5] Ahammed, T. B., Patgiri, R., & Nayak, S. (2023). A vision on the artificial intelligence for 6G communication. *Ict Express*, *9*(2), 197-210. https://doi.org/10.1016/j.icte.2022.05.005

[6] Akbar, M. S., Hussain, Z., Ikram, M., Sheng, Q. Z., & Mukhopadhyay, S. (2022). 6G survey on challenges, requirements, applications, key enabling technologies, use cases, AI integration issues and security aspects. *arXiv preprint arXiv:2206.00868*. https://doi.org/10.48550/arXiv.2206.00868

[7] Akyildiz, I. F., Kak, A., & Nie, S. (2020). 6G and beyond: The future of wireless communications systems. *IEEE access*, *8*, 133995-134030. https://doi.org/10.1109/ACCESS.2020.3010896

[8] Ali, S. M., Sovuthy, C., Imran, M. A., Socheatra, S., Abbasi, Q. H., & Abidin, Z. Z. (2020). Recent advances of wearable antennas in materials, fabrication methods, designs, and their applications: State-of-the-art. *Micromachines*, *11*(10), 888. https://doi.org/10.3390/mi11100888

[9] Amram Bengio, E., Senic, D., Taylor, L. W., Headrick, R. J., King, M., Chen, P., Little, C. A., Ladbury, J., Long, C. J., & Holloway, C. L. (2019). Carbon nanotube thin film patch antennas for wireless communications. *Applied Physics Letters*, *114*(20). https://doi.org/10.1063/1.5093327

[10] Banafaa, M., Shayea, I., Din, J., Azmi, M. H., Alashbi, A., Daradkeh, Y. I., & Alhammadi, A. (2023). 6G mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities. *Alexandria Engineering Journal*, *64*, 245-274. https://doi.org/10.1016/j.aej.2022.08.017

[11] Burke, P., Rutherglen, C., & Yu, Z. (2006). Carbon nanotube antennas. Nanomodeling II, 41-45. https://doi.org/10.1117/12.678970

[12] Chaccour, C., Soorki, M. N., Saad, W., Bennis, M., Popovski, P., & Debbah, M. (2022). Seven defining features of terahertz (THz) wireless systems: A fellowship of communication and sensing. *IEEE Communications Surveys & Tutorials*, *24*(2), 967-993. https://doi.org/10.1109/COMST.2022.3143454

[13] Chakradhar, A., Kumar, S., Sristi, J., & Kumar, P. P. (2023). Evolution and Potential Application of 6G Wireless Communication in Smart Cities. 2023 10th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON), 9798350382471. https://doi.org/10.1109/UPCON59197.2023.10434562

[14] Dash, S., & Patnaik, A. (2024). Advancements in Terahertz Antenna Design. *arXiv preprint arXiv:2412.19156*. https://doi.org/10.48550/arXiv.2412.19156

[15] Douhi, S., Labihi, S., Eddiai, A., Lakrit, S., El Achaby, M., & Al-Gburi, A. J. A. (2025). Design, characterization, and electromagnetic performance of a flexible wideband RF antenna using composite materials. *Journal of Science: Advanced Materials and Devices*, *10*(1), 100847. https://doi.org/10.1016/j.jsamd.2024.100847

[16] Fung, C. K. M., Xi, N., & Balasubramaniam Shanker, K. W. C. L. (2008). Design and Experimental Testing of Nano Antenna for Carbon Nanotube (CNT) Based Infrared Sensors. IEEE SENSORS 2008 Conference. https://warwick.ac.uk/fac/sci/eng/research/grouplist/sensorsanddevices/mbl/database/ieeesensors08/PDFs/Papers/363_6379.pdf

[17] Fung, C. K. M., Xi, N., Shanker, B., Lai, K. W. C., Zhang, J., Chen, H., & Luo, Y. (2008). Design and fabrication of nano antenna for carbon nanotube infrared detector. 2008 8th IEEE Conference on Nanotechnology, 1424421047. https://doi.org/10.1109/NANO.2008.67

[18] Haque, M. A., Nirob, J. H., Nahin, K. H., Singh, N. S. S., Paul, L. C., Algarni, A. D., ElAffendi, M., & Ateya, A. A. (2024). Regression supervised model techniques THz MIMO antenna for 6G wireless communication and IoT application with isolation prediction. *Results in Engineering*, *24*, 103507. https://doi.org/10.1016/j.rineng.2024.103507

[19] Hasan, M. M., Islam, M. T., Alam, T., Kirawanich, P., Alamri, S., & Alshammari, A. S. (2024). Metamaterial loaded miniaturized extendable MIMO antenna with enhanced bandwidth, gain and isolation for 5G sub-6 GHz wireless communication systems. *Ain Shams Engineering Journal*, *15*(12), 103058. https://doi.org/10.1016/j.asej.2024.103058

[20] Hussein, M. M., Saafan, S. A., Abosheiasha, H., Abd El-Hameed, A. S., Zhou, D., Salem, M., & Darwish, M. A. (2023). Design, characterization, fabrication, and performance evaluation of ferroelectric dielectric resonator antenna for high-speed wireless communication applications. *Journal of Alloys and Compounds*, *968*, 172170. https://doi.org/10.1016/j.jallcom.2023.172170

[21] Jurn, Y. N., Malek, M. F., Liu, W.-W., & Rahim, H. A. (2015). Performance assessment of the simulation modeling approach of SWCNT at THz and GHz antenna applications. 2015 IEEE 12th

Malaysia International Conference on Communications (MICC), 1509000194. https://doi.org/10.1109/MICC.2015.7725442

[22] Kamath, S., Anand, S., Buchke, S., & Agnihotri, K. (2024). A review of recent developments in 6G communications systems. *Engineering Proceedings*, *59*(1), 167. https://doi.org/10.3390/engproc2023059167

[23] Krishna, K. G., & Singh, A. P. (2023). Wireless Networking for 5G And 6G using Millimeter-Wave Technological Innovation. 2023 International Conference on Power Energy, Environment & Intelligent Control (PEEIC), 9798350357769. https://doi.org/10.1109/PEEIC59336.2023.10450826

[24] Kumar, K., Vani, V. D., Raj, V. H., Dutt, A., Kunekar, P., & Sahu, D. N. (2024). Cutting-Edge Communication: Integrated Satellite-Aerial 6G Networks for Point-to-Point Connectivity. 2024 7th International Conference on Contemporary Computing and Informatics (IC3I), 9798350350067. https://doi.org/10.1109/IC3I61595.2024.10829221

[25] Lu, G., Wang, J., Xie, Z., & Yeow, J. T. (2021). Carbon-based THz microstrip antenna design: A review. *IEEE Open Journal of Nanotechnology*, *3*, 15-23. https://doi.org/10.1109/OJNANO.2021.3135478

[26] Moxley, M., & Kirkici, H. (2024). Multi-walled Carbon Nanotubes Patch Antenna. *Authorea Preprints*. https://www.techrxiv.org/doi/full/10.36227/techrxiv.172470814.40208925

[27] Oughton, E., Geraci, G., Polese, M., Shah, V., Bubley, D., & Blue, S. (2024). Reviewing wireless broadband technologies in the peak smartphone era: 6G versus Wi-Fi 7 and 8. *Telecommunications Policy*, *48*(6), 102766. https://doi.org/10.1016/j.telpol.2024.102766

[28] Pang, J., Bachmatiuk, A., Yang, F., Liu, H., Zhou, W., Rümmeli, M. H., & Cuniberti, G. (2021). Applications of carbon nanotubes in the internet of things era. *Nano-Micro Letters*, *13*(1), 191. https://doi.org/10.1007/s40820-021-00721-4

[29] Rawat, A., Yadav, D., & Tiwari, M. (2023). A review on mmWave antennas for wireless cellular communication. 2023 7th International Conference on Computing Methodologies and Communication (ICCMC), 1665464089. https://doi.org/10.1109/ICCMC56507.2023.10084024

[30] Sarycheva, A., Polemi, A., Liu, Y., Dandekar, K., Anasori, B., & Gogotsi, Y. (2023). 949 2D Titanium Carbide (MXene) for Wireless Communication. In *MXenes: From Discovery to Applications of Two-Dimensional Metal Carbides and Nitrides* (pp. 949-970). Jenny Stanford Publishing. http://doi.org/10.1201/9781003306511-48

[31] Serghiou, D., Khalily, M., Brown, T. W., & Tafazolli, R. (2022). Terahertz channel propagation phenomena, measurement techniques and modeling for 6G wireless communication applications: A survey, open challenges and future research directions. *IEEE Communications Surveys & Tutorials*, *24*(4), 1957-1996. https://doi.org/10.1109/COMST.2022.3205505

[32] Shin, H., Park, S., Kim, L., Kim, J., Kim, T., Song, Y., & Lee, S. (2024). The future service scenarios of 6G telecommunications technology. *Telecommunications Policy*, *48*(2), 102678. https://doi.org/10.1016/j.telpol.2023.102678

[33] Swetha, M., Muneshwara, M., Murali Manohara Hegde, A., & Lu, Z. (2023). 6G wireless communication systems and its applications. In *Machine Learning and Mechanics Based Soft Computing Applications* (pp. 271-288). Springer. https://doi.org/10.1007/978-981-19-6450-3_25

[34] Ticku, A., Sidana, S., Sinha, A., Sathesh, S., Uniyal, M., Kumar, B., Sinha, R. S., Raj, P., Al-Khayyat, A., & Sikarwar, M. (2024). Next-Gen IoT: 5G Realities and 6G Possibilities. 2024 15th International Conference on Computing Communication and Networking Technologies (ICCCNT), 9798350370249. https://doi.org/10.1109/ICCCNT61001.2024.10724540

[35] Vu, D.-N., Dao, N.-N., Won, D., & Cho, S. (2023). Potential enabling technologies for 6G mobile communication networks: A recent review. 2023 Fourteenth International Conference on Ubiquitous and Future Networks (ICUFN), 9798350335385. https://doi.org/10.1109/ICUFN57995.2023.10199909

[36] Wang, C., Zhang, N., Liu, C., Ma, B., Zhang, K., Li, R., Wang, Q., & Zhang, S. (2024). New advances in antenna design toward wearable devices based on nanomaterials. *Biosensors*, *14*(1), 35. https://doi.org/10.3390/bios14010035

[37] Yunus, N. A. M., Hanapi, Z. M., & Kamarudin, S. (2024). 6G on the Horizon: Technologies, Requirements, Trends, and Potential Techniques. 2024 International Conference on Electrical, Computer and Energy Technologies (ICECET), 9798350395914. https://doi.org/10.1109/ICECET61485.2024.10698610

[38] Zeydan, E., Arslan, S., & Turk, Y. (2024). 6G wireless communications for industrial automation: Scenarios, requirements and challenges. *Journal of Industrial Information Integration*, *42*, 100732. https://doi.org/10.1016/j.jii.2024.100732