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 July 2025
Accepted 07 August 2025
Available online 15 September 2025

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

ABSTRACT

Innovative communication systems based on advancement of the nanotube titanium (CNT -Ti) composites-based antennas are still difficult to design and optimize their performance, so the design could ultimately be crucial in development of these antennas. It is on this basis that the performance of these CNT -Ti CNT based composite antennas in the likely application in future wireless communication of the 6G networks was evaluated. The one that was shown by these antennas was high efficiency, large bandwidth, great flexibility, and enhanced attributes of improvement of impedance, which are appropriate in 6G wireless networks and high-speed communication. Besides, the analyzed CNT Ti composite-based antennas demonstrated a high conductivity, low loss tangent, low energy loss, high signal effectiveness, high bandwidth and low VSWR levels in comparison to conventional antennas. The proposed antennas with special directional patterns that are popular like the satellite communication might be constrained in the volume of their usage, however, with their large size and its expensive design. It was concluded that the enhancement of manufacturing process, price, design, scalability, and long-term reliability of the proposed antennas as the implementation in the large-scale technology of wireless networks should be the subject of the further studies allowing the sustainable expansion.

1. Introduction

Sixth generation (6G) networks represent the next level in the sphere of wireless communications technologies and represent the ability to transfer data with extremely high speeds, nearly no latency, as well as coverage which is extended thanks to the use of frequencies reaching to the terahertz range [1]. However, achieving a better performance at a high frequency is fraught with many problems particularly in the antenna design where traditional media faces radiation inefficiencies, material losses and mechanical constraints. As a way of addressing these limitations with traditionally available materials which were available to make antennas, various composite

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https://doi.org/10.31181/dmame8220251555

materials became solutions. Carbon nanotubes composites with titanium (CNT Ti) composites have cropped up in renewed interest among other composites. NT has better electrical conductivity, thermal resistance and lightweight capacity. Ti, on its part, offers improved endurance and strength. The two materials complement each other in terms of their contribution to the structural and electrical performance of CNT -Ti composites, which makes them the best material to use in 6G antennas.

Over the past decades, mobile networks have been developing with better speed, capacity, and latency each time with new generations. The 6G networks by the year 2030 are set to offer up to 1 Tbps of data speed and efficiency [2]. However, synchronization of devices and radiofrequency modelling are some of the issues that should be addressed to achieve this objective. Antennas, which are a necessary part of 6G network technologies, have the potential to grant the necessary conductivity, strength and stability to the development of compact and high-performance antennas suitable to terahertz applications, wearable technology, and high-performance senses, therefore enhancing the potential of next-generation communication systems [3].

Wireless networks today have experienced progress, which began progressing 1G to the expected 6G and thus the world has become communication leaders thanks to the development of superior high speed high-end networks, a factor beyond the embarrassing analogue phones of the past, but with even greater capabilities to support newer generation applications [4]. This continuous innovation has been driving the development of new and increasingly efficient and competent technologies. The 1G wireless network rolled out in 1979 (in Japan) used the analogue technology with frequency of 800-900MHz enabled mobile communication though its quality was poor and security was limited and battery life was short. The move to 2G network in 1991 marked the move to digital form of communication under GSM and CDMA which improved the security and energy conservation through this as well as supporting the various services like SMS and multimedia messaging despite the low data rates [5]. Mobile broadband Mobile broadband became available with the introduction of 3G in 2001 (in Japan) which enabled 3G speeds up to 2Mbps that supported video conversations, online surfing, and streaming media. Nevertheless, the expensive implementation cost and capacity were a challenge. Today, 4G network has transformed LTE and LTE-Advanced making the bandwidth up to 1Gbps and made it possible to stream HD, play games online, and utilize application ecosystems despite such obstacles as the congestion of networks in cities.

The emergence of 5G network in 2019 allowed supporting ultra-reliable low-latency communication with speeds up to 10 Gbps and smart cities, IoT, and AR/VR applications. However, it has been struggling with challenges of limited coverage and high infrastructure expenses [6]. By 2030, it was estimated that using the 6G network, with improved terahertz communication and AI-enhanced networks, may achieve data rates of up to 1 Tbps and sub-milliseconds latency, supporting a wide range of applications such as holographic communications and brain-computer interfaces. However, a host of challenges of THz-compatible hardware, energy efficiency and legal issues have to be overcome before complete operational deployment [7]. Concisely, the development of wireless communication has certainly shown the continuous use of higher speed, greater efficiency, and expanded functions. Successive generations have developed further than others. Nevertheless, the 6G network technologies hope to overcome the available limitations by using AI contributed automation, immersion technology, and unprecedented high-data speeds and will reshape the future of network connectivity [8].

1.1 Attributes of Carbon Nanotube-Titanium (CNT-Ti) Composites

The carbon nanotube titanium (CNT-Ti) composite is formed as a combination of the exhaustive characteristics of the carbon nanotube and titanium to create the high-performance materials that can be used in state of the art technology [9]. Carbon nanotubes (CNTs) are made by rolling pieces of graphene into a tube that gives it high electrical conductivity, tensile strength that is higher than those of steel, lightweight properties, and thermal conductivity with values up to 3500 Wm -1 K -1. They have a high aspect ratio and therefore, distribute their load efficiently making CNTs reinforcing agents of choice in composites. The CNTs are of the single (SWCNTs) and multi-walled (MWCNTs) type; single-walled ones are known to be the best electrical conductors and multi-walled (MWCNTs) ones are the best in mechanical strength due to their multi-wall structure [10]. Therefore, CNT-Ti composites have such properties as high strength and low density and good thermal characteristics, which make it beneficial to use in engineering.

1.2 Essential Features of Radio Antennas

Radio antennas that work on a frequency between 30 Hz to 300 GHZ are very important in communication through wireless transmission or reception of the electromagnetic waves. The mechanism of operation in antennas is based on electromagnetic radiation whereby the alternating currents produce propagating waves to be transmitted and incoming waves which produce receiving currents. The parameters of antenna efficiency vary with many factors such as the frequency, wavelength, radiation pattern, gain and polarization [11]. There are several realizations of antennas with each having distinct functions: the dipole antennas can be used on internet broadcast, the parabolic antennas on the satellite connection, and the patch on the Wi-Fi and GPS. Impedance matching minimizes the loss of power and bandwidth specifies the frequency range. More sophisticated systems use antenna arrays and beamforming to sharpen the signal direction and improve efficiency. These antennas serve in broadcasting, cellular systems, radar, and wireless systems like Wi 2 and Bluetooth among others [12]. The development of intelligent antennas, metamaterials and multiband capabilities has over the years enhanced adaptability and performance. It is anticipated that the 6G networks of the future will include superior antennas to facilitate ubiquitous connectivity and implement the AI-based tools in autonomous vehicles, drones, and the Internet of Things to promote an extremely connected digital world as shown in Figure 1.

Fig.1: an artistic view of 6G wireless communication technology in smart cities.

Although wireless communication and CNT-Ti are moving forward in terms of manufacturing as a composite, it still arranges several challenges which could be exploited in research. Design and performance optimization of CNT -Ti antennas is a challenging task: the incorporation of carbon nanotubes and titanium to boost bandwidth and radiation is still a sophisticated issue. The alignment of CNTs, dispersion, and interaction with titanium need more in-depth studying because the aforementioned affect electrical and mechanical characteristics of the composts [13,14]. The development of high levels of durability in the case of extreme environments, such as radiation levels, temperature variations and mechanical loads present a major challenge especially in the aerospace, maritime and space sectors. Existing scalability and production issues including expensive costs and lack of uniform production methods restrict the usage of CNT-ti composites on a considerable scale. This is because it is important to achieve consistent quality and explain how to act within the electromagnetic environment of CNT Ti composites particularly with respect to electromagnetic compatibility [15].

The future networks in terms of CNT-Ti composite and other credible materials that will be used include 5G and terahertz 6G are under-explored. Their performance should be optimized to transmit data as fast as possible and with low latency. If the technologies are to be environmentally responsible, great attention is also required with sustainability and recyclability. Feeling these hindrances is central to furthering the communication systems: It is possible to enhance the antenna efficiency, bandwidth and longevity with CNT-Ti composites to a great extent. Their portability and performance aspects qualify them to be deployed on high-frequency applications, especially in high-speed networks of 5G and 6G where fast and consistent data transmission is essential. Their low mass and strength have been used to benefit satellites, drones, and missions in deep space in aerospace and space applications [16]. The immense potential of compact, high-performance antennas is observed by the increasing need to have such antennas in the Internet of Things and smart technologies. In addition, they have the advantage of being lightweight, which helps to make communication energy-efficient, thereby encouraging sustainability. The further development of CNT -Ti composites have the potential of improving telecommunications but has the effect of improving nanotechnology and intelligent systems leading to the future of wireless networks. Succinctly, the use of CNT Ti composites in antenna design is very advantageous in that it presents a combination of the mechanical, electrical as well as thermal characteristics of the elemental materials.

CNTS enhances antenna efficiency through less resistive losses, increased antenna conductivity, and they work at millimeter-wave frequencies. Many works have shown that CNT-based antennas have a better gain and the lowest energy loss than antennas made of conventional materials like copper. The thermal stability, corrosion resistance and strength of titanium make it stable structurally. As a result, Ti-composites are interesting both in the industrial and aerospace applications when the requirements are to work in unfavorable conditions [17]. The addition of CNTs to Ti may also contribute to a significant increase in mechanical strength and conductivity, which, in turn, will result in the improvement of efficiency and bandwidth that copper antennas have no hopes of attaining. Synthesis processes, like chemical vapor deposition can allow the uniform CNTs to be coated on Ti substrates, which provides the best performance over a diverse range of frequencies, particularly at 6G and 5G networks. However, the cost-effectiveness, scalability and the flexibility of use across varied applications remain a problem. Therefore, more studies would be needed on how to design wearable and IoT technology and achieve credible work under severe conditions. The exploration of CNT- Ti composites has the potential to bring substantial advantages to the development of the antenna technology to enable the fulfillment of its potential in the next-generation communication systems [18]. The all-optimal combination of CNT with Ti has the potential of significantly improving the mechanical strength and conductivity of a specific product, which makes composite-based antennas surpass the conventional copper antennas in terms of efficiency and bandwidth [19].

The presented research aims to create CNT-Ti composites-based antennas that work better for modern 6G and 5G networks. This is because of the applied and fundamental interests in these antennas for future wireless communication. The major goal is to make composite-based antennas have a wider bandwidth, more efficient, and a better voltage standing wave ratio (VSWR) and keep the power losses to a minimum and the structure intact. Because of the combination of better mechanical and electrical properties, such composites have been demonstrated to improve antenna design. CNTs could make the composite even better by lowering electrical losses, enhancing its conductivity, and increasing the radiation efficiency in comparison with conventional materials. On the other hand, Ti in the composite-based antennas ensures their high durability as well as stable performance in tough conditions. Also, composites-based antennas could increase the bandwidth, which makes them very useful for high-frequency uses in future communication systems [20].

2. Materials and Methods

As mentioned above, the antenna design of sixth generation (6G) networks has proven very difficult due to which scientists and engineers have developed several composite structures that have ultra-wide bandwidth, high efficiencies, compact designs, and stable performances over the millimeter-wave frequencies. Traditional resources have restricted capabilities to reduce propagation losses and support stability in ways of overpopulated communication settings, thus requiring high-tech solutions [21]. The attractiveness of composites that contain carbon nanotubes (CNT) has been eliciting substantial interest due to its high electrical conductivity, low weight, and ability to transmit high-frequency data. Many studies have confirmed the utility of CNT in limit resistive losses and improving the antenna performance but large scale manufacturing and integration challenges are still present [22]. Titanium is known to be unmatched in terms of strength, resistance to corrosion and stability in harsh environmental conditions, and has wide use in aerospace and high performance. Nonetheless, its intrinsic electrical characteristics are not enough to design advanced antennas, but it needed to be mixed with other useful materials. We discuss in this respect the CNT-Ti composite making (hybrid structure) as a wireless communication antenna material in 6G. The suggested antennas combine the high conductivity of CNTs with the structural integrity and thermal stability of titanium. The first one is to further the next generation communication systems and work on integration issues through material performance measurement and design optimization [23].

2.1 Material Selection and Characterizations

Development of CNT-Ti composites-based antennas for 6G networks implementation requires a systematic assessment of the material properties and overall performance. The integration of exceptional electrical conductivity, thermal stability, and mechanical strength, low signal loss and high efficiency of CNTs at terahertz frequencies [24] with the excellent durability and corrosion resistance of Ti can be advantageous for making antennas suitable for operation under extreme conditions. In this case, manufacturing methods, such as CVD and powder metallurgy could help Ti and CNT integrate perfectly, which improves the properties regarding the composites. To make sure that the suggested composites are good for 6G applications, we need to fully understand how they behave electrically, mechanically, and thermally. One of the biggest problems is the optimization regarding dispersion of CNT as well as their bonding for maximizing the dissipation, strength, and conductivity of composites. CNTs with cylindrical nanostructures and high aspect ratios could increase the performance of antennas.

In addition, their high electrical conductivity can support efficient electromagnetic wave transmission, while a tensile strength as much as 200 GPa ensures the product's endurance without any added weight. With a thermal conductivity of 3,500 W/m·K, CNTs outperform most of the existing materials in heat dissipation, maintaining stability in demanding environments. The flexibility and fracture toughness of both SWCNTs and MWCNTs can considerably improve the composites resistance to mechanical stress (Figure 2). Chemical modifications of CNTs can further enhance their dispersion in the composite structures, broadening their applicability in communication technologies. By combining CNTs with titanium one can create a high-performance material tailored for next-generation wireless systems [25]. This combination enables us to enhance the conductivity, durability, and efficiency of the CNT-Ti composites that is desirable for future antenna development.

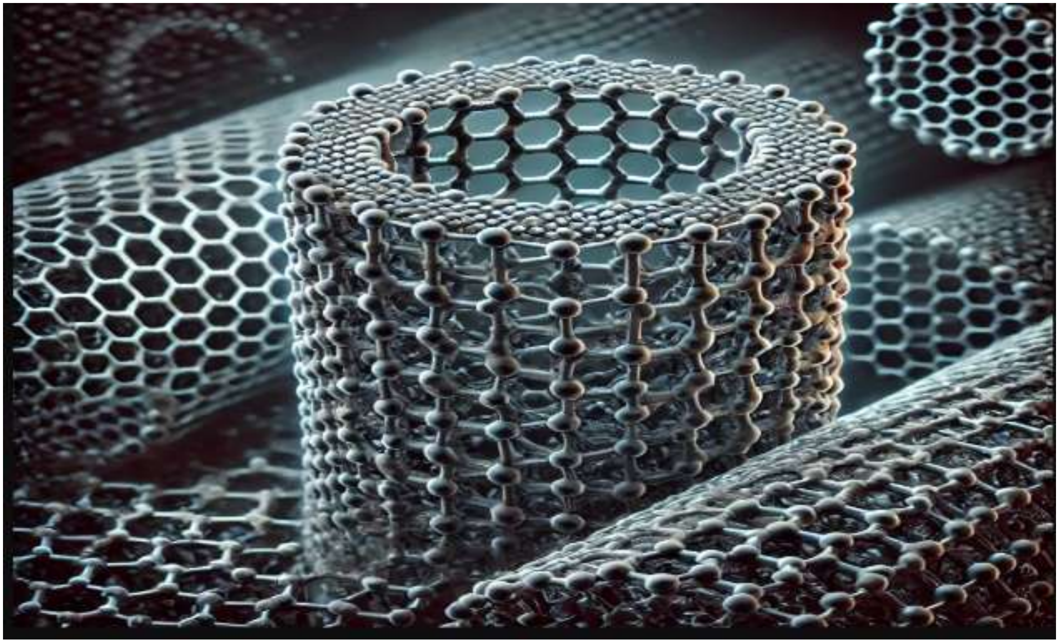

Fig.2: appearance of single- and multi-walled CNT.

Titanium has been an important element due to its lightweight property and corrosion resistance behavior particularly in the aerospace, biomedical and industrial applications due to its strength, durability and versatility. The fact that it has high strength to weight ratio makes it suitable in those rigorous environments that demand mechanical resilience and tolerance [26]. Titanium has tensile strengths of 400 to 1400 Mpa which are also resistant in cyclical stress load and is therefore suitable in the aerospace and medical world. Its thermal conductivity (22 W m -1 K -1) is medium, which makes it suitable for special purposes, where structural integrity is more important than the electrical conductivity (2.38 x 10 6 S m -1). The titanium oxide (TiO 2) layer is self-restoring to increase its resistance to corrosion, which gives it a high flexibility to withstand aggressive conditions like sea water and other carbonic acid-containing media. Although being low in electrical conductivity, the thermal stability, mechanical power, and corrosion inhibition of titanium makes it an inseparable element in applications that are susceptible to long-term use with high standards of performance. In addition to this, its biocompatibility has even heightened its application in the field of medicine technology thus its effect on the advances made in the field of medicine and engineering is significant [27].

2.2 Working Principle of CNT-Ti Composites

Different processes such as spark plasma sintering, chemical vapor deposition, and powder metallurgy are used to fabricate CNT -Ti composites with specific properties. With an ability to regulate the orientation and distribution of CNTs, not only is overall composite performance enhanced, but also the functional behavior is directly impacted using the techniques of synthesis.

The resultant composite is very favorable in the sensors, antennas and energy systems and offers improved thermal dissipation, superb electrical conductivity and durability besides the mechanical reinforcement [28]. These novel wireless networks of 6G are like standard copper antennas, which are similar in electrical features and weightlessness, but they significantly decrease mass, and it is a key consideration in wearable and aerospace applications. More titanium-based materials like titanium carbide (Ti_3C_2) will have particular benefit in flexibility, performance and reliability of antenna at a wide frequency and in the faces of mechanical loads, making it useful in the adaptable communication systems. Combinations of CNT and Ti in composite antennas are a promising way to 6G networks, providing lightweight constructions, flexibility, and high frequency performance. Even though the studies in this field are still preliminary, the evidenced potential of CNTs and titanium-based substances denotes a high potential in the usage of the materials in multiple possible wireless communication. However, the requirement to solve issues connected with material production, interface engineering, as well as structural design is critical to maximize gain, bandwidth, and radiation efficiency. Further experimental research and computer simulations would fuel further innovation as the processes will enable the smooth incorporation of CNT–Ti composites into the technologies of the new generation of communication systems [29;30].

2.3 Advantages of CNT-Ti Composites-based Antennas

As has been already mentioned, CNT Ti composite-based antennas have better electrical conductivity and electromagnetic wave propagation than traditional materials. Those characteristics allow making them very efficient in the reduction of power loss, and expanded the operating frequency band, thus making them suitable in high-frequency operations to 5G and millimeter-wave communications [18]. Their low mass structure significantly lowers the mass of the antennas, making them more efficient about load in aerospace and satellite systems as well as increasing range in wearable and portable electronics. These composites have extremely high durability and can resist the harsh temperatures, mechanical, and corrosion conditions thereby making them reliable in high-temperature conditions, like space flight, marine operations, and in-industrial applications. The fact that they resist radiation, vacuum, sea water, and corrosive chemicals also increase longevity and performance. Customization enables small and lightweight designs to be used in applications such as Internet-of- Things and nanosatellites that enhance the transmission of signals and the overall performance of the antenna [31]. CNT Ti composites facilitate sustainable communication technologies by improving the efficiency of signals and lowering the amount of energy produced [20]. Moreover, they are durable and, therefore, can minimize the rate of replacement, lessen the amount of material waste, and encourage sustainable development of wireless systems. Having these outstanding qualities of high durability and lightweight, CNT Ti compound antennas can be applied in aerospace, defense, telecommunications, and wearable electronics, and provide high performance solutions to satellites, drones, sensor systems on autonomous vehicles and next generation networks. The durability of CNT antennas with Ti, therefore, qualifies them as the best antenna in space travel that supports effective communication in the severe environments.

2.4 CNT-Ti Integration Strategy

When titanium is combined with CNTs, high-technology composites are produced which have superior mechanical, electrical and thermal properties. The synergistic interaction between CNTs and Ti has considerable industrial potential implying that a thorough insight into the interaction of the two is required to ensure maximum performance. The first method used to produce quality CNTs goes through the chemical vapor deposition process, then the adhesion of titanium on CNT is altered by the chemical oxidation or functionalization. Nanoparticles as well as micrometer-scale titanium powders are used to ensure that the CNTs interact effectively with nanoparticles. It is necessary to retain constant nanotube dispersions in the titanium matrix because agglomeration reduces mechanical characteristics of the obtained composites [11].

To provide consistent reinforcement regarding CNTs into Ti, methods such as ultrasonic agitation and ball milling could facilitate consistent distribution. In terms of electrical conductivity, load transfer, and thermal performance, the interfacial bond between CNTs and Ti is crucial. Thermal densification or adhesion-enhancing coupling agents could be used for strengthening such bonds. Whereas CVD permits direct CNT deposition onto Ti surfaces, fabrication methods like the spark plasma sintering (SPS) enhance densification and maintain structural integrity [32]. Complex Ti-CNT structures can also be produced using a variety of methods, including 3D printing. CNTs increase stiffness, tensile strength, and durability, whereas Ti improves corrosion resistance, leading to a material with excellent performance. Those composites enhanced thermal conductivity allows for effective heat dissipation in high-performance electronics as well as aerospace components, whereas their increased electrical conductivity makes them appropriate for antennas and sensors. CNT-Ti composites' exceptional strength-to-weight ratio makes them perfect for lightweight structural applications. In cutting-edge technology, Ti-CNT composites have several uses. They are ideal for 6G antenna development in wireless communication because of their decreased weight and conductivity. About the aerospace industry, composites help create lightweight, strong aircraft parts, and in the biomedical industry, they offer durable, biocompatible materials for medical implants. Innovative solutions in industry, technology, and healthcare are demonstrated by the fusion of nanomaterials and metals [33].

2.5 Electrical Conductivity of CNT-Ti Composites

The electrical conductivity of CNT-Ti composites can be estimated using effective medium theory (EMT) or percolation models via the relation:

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

where σCNT-Ti, σTi, fCNT, Fc, and β are the corresponding effective electrical conductivity of the CNT-Ti composite, electrical conductivity of pure titanium, volume fraction of CNTs in the composite, critical percolation threshold of CNTs (typically between 0.1–5% depending on the dispersion), and CNT alignment and dispersion-dependent fitting parameter.

Alternatively, if CNTs are well-dispersed and randomly oriented within the titanium matrix, a more simplified mixing rule can be used:

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

where σCNT is the electrical conductivity of carbon nanotubes (~10^6 S/m for metallic CNTs), fCNT and 1−fCNT are the corresponding volume fractions of CNTs and titanium. For CNT content below the percolation threshold, the conductivity is close to that of titanium. Thus, proper dispersion is essential for maximizing the electrical performance and minimizing the signal loss in 6G antennas made of CNT-Ti composites [34].

2.6 Characteristic Impedance of CNT-Ti Composite

The characteristic impedance of CNT-Ti composites in an antenna system can be expressed as:

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

In which ZCNT-Ti and σCNT-Ti are the corresponding characteristic impedance and electrical conductivity of CNT-Ti composite; A is the cross-sectional area of the conducting path. A higher concentration of CNT improves signal transmission through lowering impedance and increasing conductivity. Effective impedance matching is ensured by optimal CNT dispersion, which is crucial for 6G applications. CNT-Ti composite antennas provide enhanced signal integrity as well as overall performance in next-generation wireless networks through utilizing the mechanical stability regarding Ti as well as high conductivity of CNTs [35;11;36]. The major characteristics of different antennas manufactured of CNT-Ti composites are often discussed at this point.

2.7 CNT-Ti Composites-based Antenna Design

2.7.1 Patch Antenna

Because CNT-Ti composites improve mechanical strength, electrical conductivity, and radiation efficiency, such types of antennae is frequently used in high-frequency applications, such as 6G. A CNT-Ti-based patch on a dielectric substrate is used as the radiating element in the design regarding this type of antenna [3]. The next are the primary components of a patch antenna:

Patch: A rectangular or square conductive component that emits electromagnetic waves. CNT-Ti composites decrease weight, increase thermal stability, and enhance conductivity when used in place of traditional materials, such as copper.

Substrate: A dielectric layer, such as FR4 or Rogers RT ($\varepsilon r = 4.4$), provides insulation and structural support, ensuring efficient signal propagation.

Feed Line: A microstrip feed structure delivers energy to the patch, where the CNT-Ti composite minimizes resistive losses, increasing efficiency[34].

2.7.2 Microstrip Antenna

This type of antenna shows optimized energy transfer with minimum signal loss. The microstrip antennas employ CNT-Ti-based feed lines for enhanced performance in high-frequency applications. The material reduces the skin-effect losses and improves the signal transmission as shown in Figure 3. This type of antenna includes are following components:

- Microstrip Line: A conductive strip made from CNT-Ti, placed on a dielectric substrate. Its high conductivity and reduced surface roughness enhance signal efficiency.
- Dielectric Layer: An insulating substrate, such as FR4 or Rogers RT, supports the microstrip line while minimizing transmission losses.
- Top Conductor Layer: An optional upper conductive layer further refines signal propagation.

2.8 Advantages of CNT-Ti Composites in Antenna Design

Some of the main advantages of CNT-Ti composites-based antennas are the following:

- High Electrical Conductivity: Enhances radiation efficiency and reduces power loss.
- Lightweight Structure: Ideal for advanced applications like 6G and satellite communications.
- Improved Thermal Stability: Ensures reliability in extreme conditions.
- Enhanced Mechanical Strength: Provides durability for flexible and wearable antenna technologies.

The integration of carbon nanotubes with titanium enhances the efficiency, bandwidth, and radiation characteristics, establishing CNT-Ti antennas as a promising solution for next-generation 6G wireless networks communication [19;33].

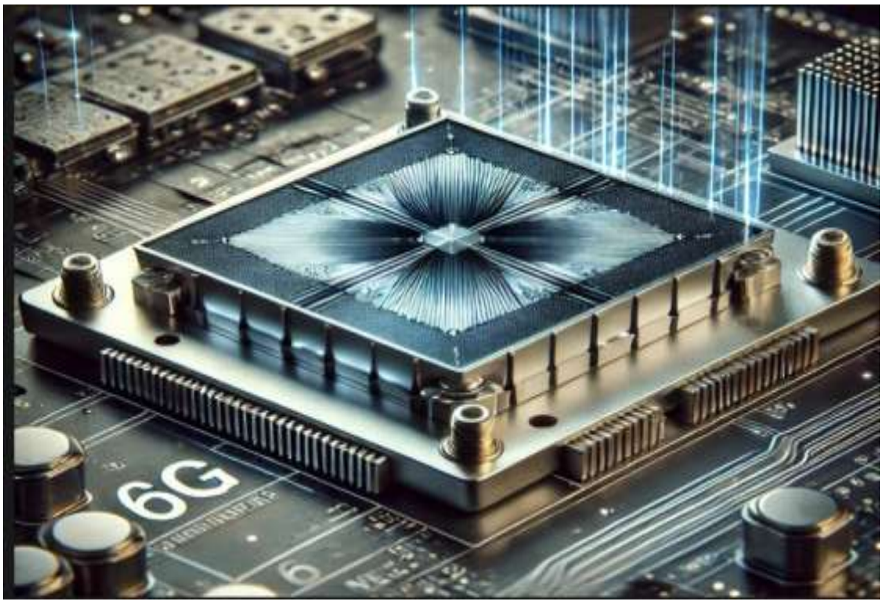

Fig.3: 6G patch microstrip antenna design using CNT-Ti composites

The radiation pattern of an antenna defines its spatial power distribution as omnidirectional or directional, with key components such as the main lobe, side lobes, and nulls. In CNT-Ti composites-based antennas in 6G networks this pattern is influenced by high conductivity and lightweight of CNTs, along with the structural stability of Ti. The normalized radiation pattern in this antenna can be expressed as:

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

where P(θ,ϕ) denotes radiated power density depending on elevation (θ) and azimuth (ϕ), whereas Eθ and Eϕ represent the electric field components in their respective directions. Array factor, AF(θ,ϕ) (if applicable) for array configurations is common in 6G systems. The modified radiation pattern takes the form:

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

where N denote the number of elements, In represent the current at each element, k represents the wavevector and $\vec{\boldsymbol{n}}$ represent the element's position vector. For 6G applications, beamforming methods adjust the pattern dynamically:

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

where BF(θ,ϕ) denotes adaptive beamforming, optimizing coverage and performance. CNT-Ti composite properties significantly impact radiation characteristics. Conductivity (σCNT) and permittivity (ϵCNT−Ti) directly influence field components, necessitating precise integration into the feed network to ensure efficient signal transmission and enhanced antenna performance.

The quantity gain of an antenna signifies the radiated power in a specific direction relative to an isotropic source, while directivity measures energy concentration in that direction. For CNT-Ti composites-based antennas in 6G networks, these properties are influenced by the CNTs' high conductivity and Ti's stability. Directivity (D) is calculated using:

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

where D(θ,ϕ) is the directivity as a function of elevation (θ) and azimuth (ϕ) angles. U(θ,ϕ) is the radiation intensity in the specified direction (θ,ϕ) given by $U(\theta,\emptyset) = r^2P(\theta,\emptyset)$, where P(θ,ϕ) is the power density and Prad is the total radiated power calculated via:

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

It is worth mentioning that CNT-Ti composites can improve the directivity by minimizing the energy dissipation through enhanced conductivity (σCNT). The gain (G) of the antenna is related to the efficiency (η) via:

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

where G(θ,ϕ) is the gain. η is the efficiency influenced by the low resistivity of CNTs and robustness of Ti that includes the material loss (ηm), mismatch loss (ηmismatch), and surface wave loss (ηs).

The efficiency (η) of CNT-Ti composite-based antennas can be calculated using:

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

For 6G applications, the directivity is modified by the dynamic beamforming and takes the form:

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

where BF(θ,ϕ) is the beamforming function, optimized dynamically for user location and network conditions (for adaptive directional radiation).

Antenna efficiency (η) measures the ratio of radiated power to input power, influenced by the resistive losses and impedance matching:

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

where ηrad radiation efficiency – accounts for power losses due to material resistivity and surface waves and $\eta mismatch$ impedance mismatch efficiency – account for power losses due to reflection or mismatch between the antenna and the feedline.

The radiation efficiency (η rad) can be written as:

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

where $Prad$ is the power radiated by the antenna and $Pinput$ Total input power delivered to the antenna.

For CNT –Ti composites-based antennas, the radiation efficiency can be influenced by the following factors:

1. Material conductivity ($\sigma CNT - Ti$), wherein high conductivity of CNTs reduces the ohmic losses. The radiation resistance (Rrad) and loss resistance (Rloss) are related via:

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

Ti provides the structural integrity and enhances the thermal dissipation by minimizing the resistive heating.

2. Surface and Dielectric Losses: The unique combination of CNTs and Ti mitigates these losses due to superior surface properties and thermal stability. The mismatch Efficiency ($\eta\boldsymbol{mismatch}$) can be obtained via:

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

Here, **Γ** is the reflection coefficient at the feed point given by:

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

where Zin is the input impedance of the antenna and $Zfeed$ is the impedance of the feedline.

For CNT-Ti composites-based antennas, efficient impedance matching is achieved by tuning the composite's properties, ensuring minimal reflection and maximum power transfer. Frequency dependence for 6G applications operating at millimeter – wave or terahertz frequencies can be appreciably affected mainly by the following factors:

1. Ohmic Losses: Because of CNTs' extraordinary conductivity, CNT-Ti composites reduce losses that are increased in traditional materials at high frequencies.

2. Dielectric Losses: Even at high frequency ranges, CNT-Ti composites show low dielectric loss, increasing overall efficiency.

The final efficiency value of CNT-Ti composites-based antennas can be calculated via:

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

This formula quantifies the total efficiency by combining impedance matching and material properties. Because of the low resistivity, high conductivity, and thermal stability regarding CNT-Ti composites, antennas composed of such materials could meet the demanding performance requirements related to 6G wireless networks with remarkable efficiency.

The primary determinants regarding composites-based antennas' efficiency are directivity and gain. While gain accounts for efficiency, such as material and surface losses, directivity is dependent on total radiated power as well as radiation intensity. The structural integrity, material conductivity, and integration regarding dynamic beamforming, which modifies directivity, have an impact on the efficiency of CNT-Ti composites-based antennas. Radiation resistance as well as impedance matching might have an impact on the antenna's efficiency, guaranteeing maximum transmission and less power loss. Additionally, the strong conductivity of CNT-Ti composites reduces such losses, and their low dielectric loss guarantees improved performance, especially at high frequencies, such as those found in 6G systems. In summary, CNT-Ti composites-based antennas could achieve remarkable efficiency through optimizing such factors in conjunction with the design, hence satisfying the rigorous demands of next-generation networks [6;12;18;30;34;36].

3. Results and Discussion

A CST studio suite had been used to model a new project, which was used to test the performance of the proposed CNT Ti composite-based antennas. Antenna Design module was opened, and the Patch Antenna option was picked. The first step was to place the substrate by drawing a rectangle with the size of 2.89 2.5 mm long and wide respectively and a thickness of 0.254mm. The selected material was a dielectric with a relative permittivity of 3, and loss tangent of 0.002, which was carbon nanotube (CNT). The patch was then adopted by tracing a rectangle over the substrate. The conductivity of this material is also 10 6 S /m 2 and the relative permittivity 2.5. It was equipped with a ground plane by designing another rectangle beneath the substrate with titanium as the material and it has conduction capacity of 2.38x10 6 S m -1. The Frequency Domain Solver was used in the simulation, a frequency range of 100GHz to 300GHz was used. Waveguide Port I was included to allow entry of signals. This design provided the best performance of the antenna at the given range of frequencies, and it utilised a combination of CNTs as the patch and titanium as the ground plane. Effective conductivity depends on the volume fraction of CNTs which depend on the percolation threshold in which high concentration of CNTs results in better conductivity. A simplified mixing rule is also assumed in the case when CNTs are well mixed. An increase in CNT fraction leads to an increase in the conductivity of the composite which increases the efficiency of the antenna. At lower values of percolation, the conductivity approaches that of titanium. To reduce signal loss in 6G antenna, proper dispersion of CNTs is necessary. The conductivity of the CNTs is negatively correlated with the characteristic impedance of the CNTTi composites and hence the lower the concentration of CNTs, the lower the impedance. Small impedances are better in transmitting a signal, minimized power loss, and improved antenna efficiency. Optimised dispersion guarantees greater impedance matching, which is paramount to the 6G wireless communication.

Figure 4 illustrates the effect of CNT concentrations variation on the electrical conductivity of CNT-Ti composite. Both the simple mixing rule (represented by the dashed blue line) and the EMT equation (represented by the solid red line) are included. The results revealed that with the increase of volume fraction of carbon nanotubes (fCNT) the electrical conductivity of the composite was improved. The EMT model provided a more accurate representation of the composite's conductivity behavior because it accounts for the effect of the nanotube distribution. This high conductivity of CNTs (~10^6S/m) is useful to reduce the eddy current losses, allowing for a wider bandwidth. Furthermore, the incorporation of titanium can enhance the mechanical stiffness, maintaining the performance across a broad frequency range. The reduction of the skin effect in the millimeter-wave and terahertz bands helps to preserve the signal quality in 6G applications.

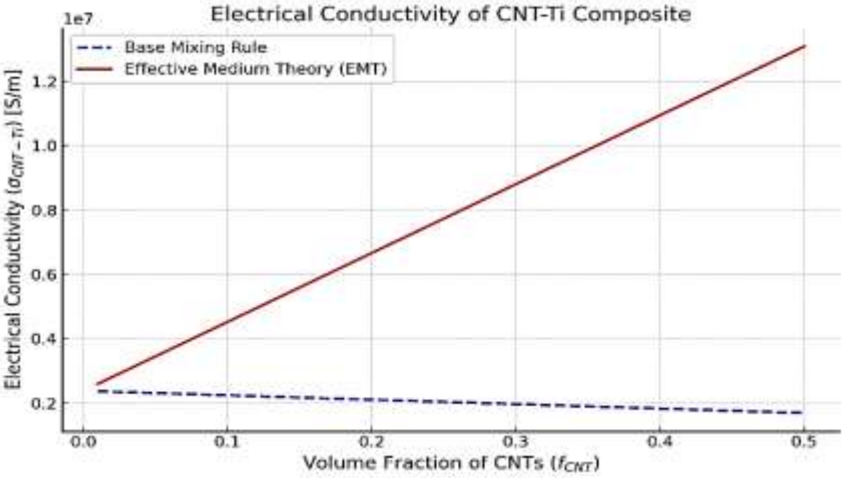

Fig.4: Electrical conductivity of CNT-Ti composite against volume fraction of CNTs.

Figure 5 illustrates how the S 11 parameter (dB) changes with frequency (100 GHz to 300 GHz) of a CNTti composite based antenna. S 11 parameter is the proportion of power that is reflected by the antenna. With a lower S S11 (nearer the -10 dB or worse) unit, this corresponds to the high-quality impedance matching the feed line, which will consequently increase the radiation efficiency. S 11 was also found to be less than -10 dB in certain frequency bands, indicating good antenna performance and efficiency of the radiation.

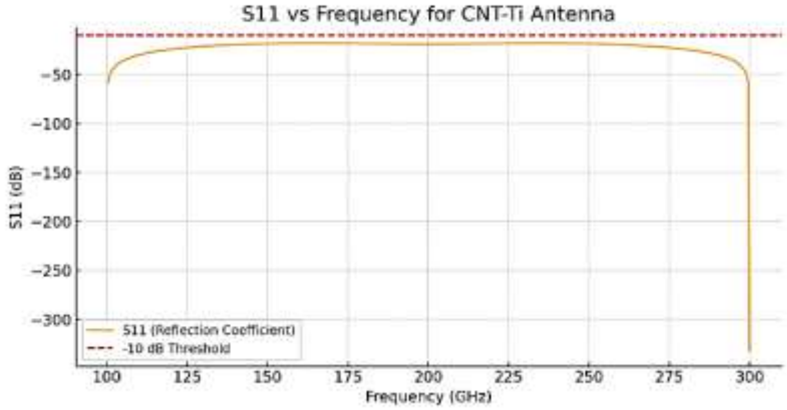

Fig. 5: Frequency-dependent variation of S11 parameter for CNT-Ti composite.

3.1 Effective Bandwidth Analysis

It is sometimes described as the frequency range between which the S 11 can be defined as less than -10 dB (as shown by the red threshold line). The graph shows that the CNT -Ti composite-based antenna has a relatively broad range of operational frequencies, making it acceptable that it can be used at 6 G as well as at high frequencies. The broadcasted wide bandwidth may be explained by the material characteristics, with titanium providing mechanical stability and CNTs high electrical conductivity to ensure the performance remains the same throughout the entire range of frequencies.

3.2 Impact of Composite Material on Antenna Performance

CNTs They assist in reducing the quality factor Q, hence extending the bandwidth, reducing the skin effect at high frequencies, and enhancing signal penetration and efficiency. In the meantime, Ti improvements in mechanical strength of the antenna, eliminates failure over time, and minimizes changes in impedance over frequencies, which gives the antenna constant characteristics of operation. The analysis of S11 and VSWR was used as the performance evaluation of the proposed composite-based antenna in the current study. A substantial amount of input power was radiated when S 11 was less than -10 dB, and this ensured high efficiency. VSWR was less than 2, which is an indication of appropriate impedance that is matched with the feed line. A negative S\(11) with a value greater than -10dB would be considered as greater power reflection, which reduces radiation efficiency. The VSWR values were found to be increasing, which means the possible occurrence of impedance mismatch, and thus matching network (ashing LC networks or optimised microstrip design) was necessary. The dependence of frequency and changes in S with frequency S S011 shows some slight deviations in S011 at higher frequencies which can be attributed to the interference in the wave at the antenna structure because of its geometrical structure (Figure⁻5). Some slight variations in performance can occur between surface current distributions within the antenna layers. This finding confirms the appropriateness of the proposed antennas to 6G and high frequency designs. Also, the CNT-Ti composite-based antenna had a wide band of operation, which makes it highly applicable to the 6 G wireless which needs a high level of radiation efficiency to transmit the signal successfully. High data rates, low signal loss at millimetre -wave frequencies and terahertz require wide bandwidth. The large bandwidth may ensure that the proposed antenna is applicable to high-frequency operations (THz & mm -Wave). The CNT Ti material composition has a low loss that promotes performance and impedance matching. Most of the frequencies allow stable operation which guarantees a reliable connection. But more effort is possible to enhance impedance matching at specific frequencies like applying quarter-wave transformers or LC matching networks. More specific performance modelling is provided with the advice of advanced simulations (CST). Tuning the microstrip geometry can reduce further variations in S 11. The proposed antennas found their way to 6 G networks in the future as the AI will be able to dynamically tune the impedance to remain in tune with the ever-changing environment. To strengthen the quality and performance of the antenna surfaces, more sophisticated methods of nanofabrication (e.g., nano-print) need to be employed to provide a sustainable solution to the high-performance network communication.

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

The antennas based on CNT-Ti composites 6G wireless networks have several salient benefits, including the fact that they are of minimal mass and exhibiting increased structural stability. Therefore, there is an urgent need to carefully evaluate the radiation features of this type of antennas as this includes power distribution, gain, directivity, and beamforming using mathematical modeling. The radiation pattern of equation derivative of equation1 shows the maximum emission of radiation to occur at 90 degrees which in essence provides the maximum propagation of horizontal energy. Minimal radiation at both 0 o and 180 o concurrently enhances directivity by reducing vertical dispersion. Moreover, the differences in the distribution of power of the antenna at different azimuth of the antenna (ϕ) indicate a stable distribution of horizontality which is important in highlighting its portability in populated urban areas. The gain pattern is consistent with the main direction of radiation such that the gain is 9db at 90 but this result supports the effective energy concentration. The acquired efficiency ratio of $\eta = 0.9$ justifies the benefits bestowed by the outstanding conductivity of CNTs and the resistance stability of Ti, thus, reducing the amount of resistive losses. Besides, the gain decreased at 0 degrees and 180 degrees of functionality attenuates the unnecessary emissions (Figure 6). The intuited gain improvement also helps to add to the strength of signals at the millimeter-wave and terahertz frequency bands, which overcome significant path losses. In addition, directional radiation suppresses the interference, a significant aspect when implementing high density networks. It has been argued that the elements of an antenna can be multiplexed to improve directivity due to constructing interference, and the optimal performance is achieved with uniform current distribution.

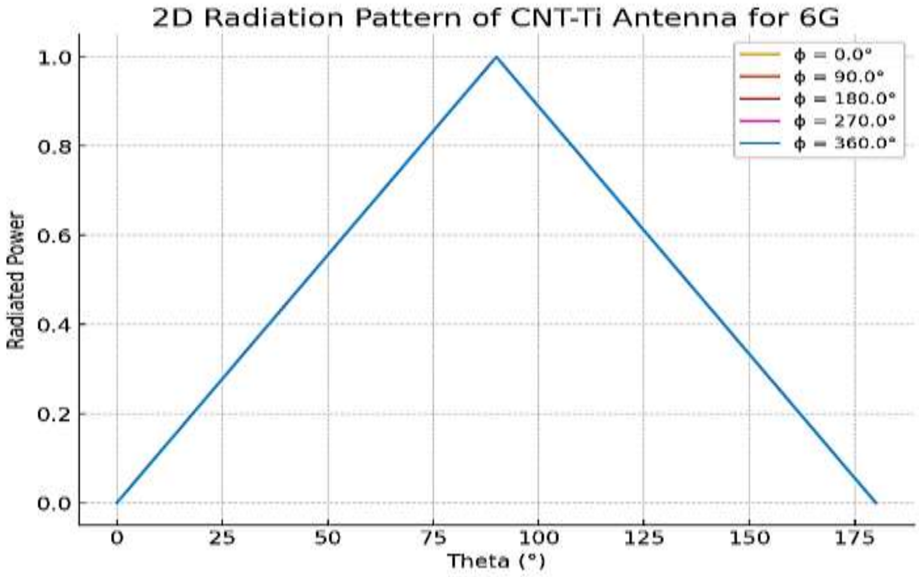

Fig. 6: Radiation characteristics of CNT-Ti composite-based antenna for 6G wireless networks.

Based on Figure 6, it is possible to assume that the phase modulation term (e Clevelandj(k r n) enables accurate beam steering, which is one of the most important aspects of adaptive transmission. The further beam shaping improves the coverage flexibility in the dynamic environment; at the same time, reduced sidelobe levels yield lesser interference and increase the spatial resolution. Beamforming methods are also extremely useful in time-varying dynamics to shape radiation fields to focus the energy on operational users with beamforming effect maximizing gain to maximize coverage. Sidelobes which were suppressed were found to enhance general efficiency because of reduction in wastage radiation. On the one hand, the signal-to-noise ratio (SNR) in high-frequency bands should increase to improve the quality of communication, and on the other hand, mobile applications, such as UAVs and autonomous cars, are supported by smart beam optimization. Concisely, the current holistic evaluation upholds the feasibility of CNT-Ti composite based antennas in future wireless network, as they have the capabilities of providing the user with the high gain directional radiation covering longer millimeter and terahertz communications, to implement or update beamforming as the basis of enhancing connectivity, to minimize energy usage through efficient power sharing, and to offer dynamic radiation control in availing advanced applications of massive MIMO networks, mobile edge computing networks, and the internet of things. According to the results obtained by mathematical and numerical analysis, it is claimed that the proposed CNT -Ti composite-based antenna is a promising solution to high-frequency 6G communications, which has better directivity, gain, real-time adaptive beamforming, and energy-saving radiation pattern that can be used to support sustainable network operation. Additionally, these antennas can be smoothly incorporated into 6G networks to increase power efficiency, network flexibility, and signal reliability by several degrees to make it an indispensable element in the development of wireless communication technology.

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

Figure 7 displays the frequency dependence of the four main performance parameters of the antenna, namely power density, wavelength, gain and directivity. Following wave equation (λ c) 1 /f, where f is the frequency and c is the speed of light, the analysis shows that there is a reduction in wavelength that is concurrent with an increase in the frequency. The higher frequencies put more energy in each area, and this is very important in radar systems and in wireless communication, this can be seen in the fact that power density increases more modestly with frequency. The directivity and gain parameters both have positive trends with increasing frequency indicating that antennas perform better with increase in frequency and they also become increasingly focused. Such observations support basic concepts of antenna design and electromagnetic wave propagation, which provide the insights necessary in improving the high-frequency communication systems and the enhancement of the efficiency of antennas in various applications.

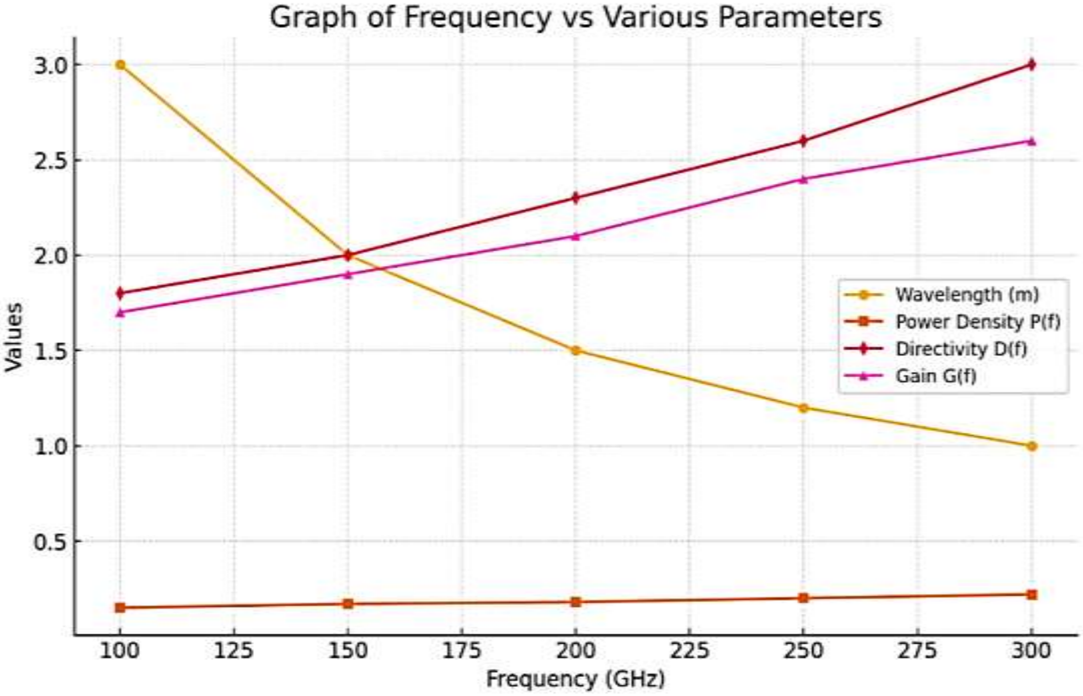

Fig.7: Wavelength, power density, directivity, and gain against frequency.

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

Figure 8 illustrates the frequency-dependent change in efficiency of the CNT- Ti composite-based antenna, i.e. radiation efficiency (η rad), mismatch efficiency (η mismatch) and the overall efficiency (η total). Radiation efficiency shows an incremental improvement with an increase in frequency, an attribute that suggests an increased capability in energy radiation at a higher frequency, perhaps due to an increase in the quality of the material and reduced resistive losses. At any frequency, mismatch efficiency is the same with value equal to 1.00, which indicates that there is no power lost in reflections or impedance mismatch. The reason is that, total efficiency is the product of the radiation and mismatch efficiencies, and therefore has same trend as η rad, with a peak of 0.90, also at the highest frequency. With this, the antenna reaches maximum impedance matching, which is why it guarantees the maximum power transfer (Figure 8). Furthermore, increased frequency leads to higher radiation efficiency due to less conductor loss as well as dielectric loss. Overall, the efficiency of the system increases with frequency making the system very efficient at higher frequencies. These findings also highlight that the system is appropriate in high-frequency users, including millimeter-wave communication systems, satellite communications, and 5G technology, where good energy radiations are a key element.

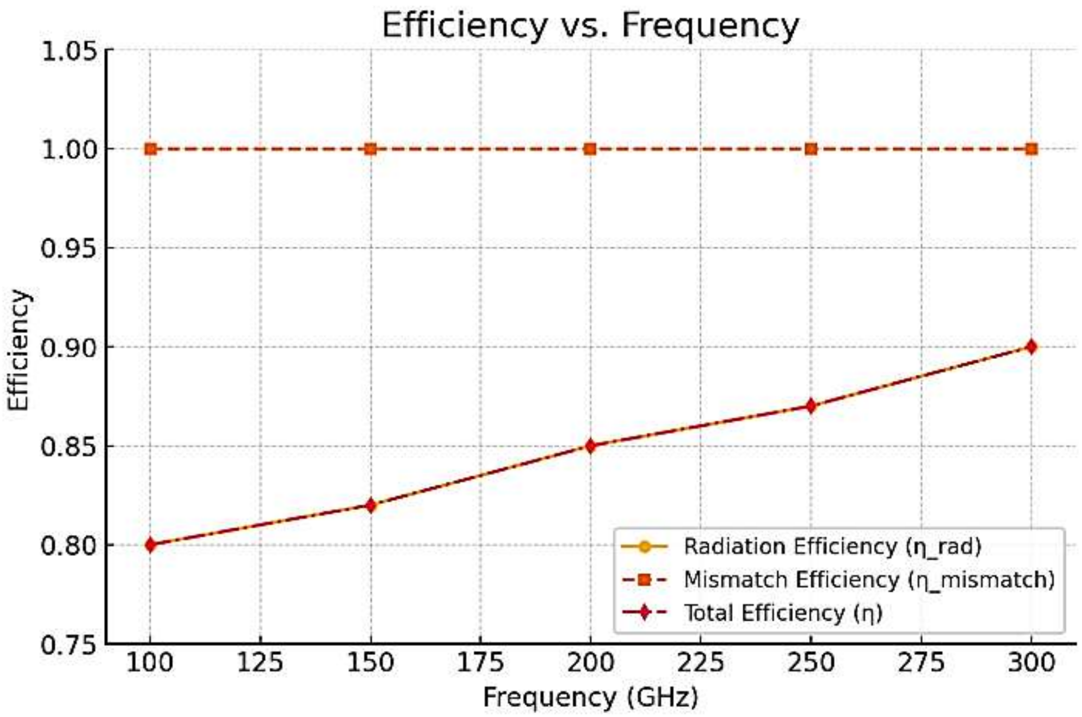

Fig.8: Frequency-dependent efficiency of CNT-Ti composite-based antenna.

Table 1 compares the performance of CNT-Ti composites-based antenna with other types of antennas reported in the literature. The CNT-Ti composite-based antenna presented several distinct advantages over conventional antennas. However, the superiority of CNT-Ti composite-based antenna is determined by its particular use and performance requirement.

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

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

Both CNTs and Ti are renowned for their exceptional electrical conductivity, high strength, durability, and low loss. Thus, CNT-Ti composites-based antennas can operate with minimal energy dissipation, enabling them highly efficient, especially in scenarios that require low signal loss, such as high-speed or broadband communication. Some salient features of the proposed CNT-Ti composites-based antennas are the following:

- Wide Bandwidth: CNT-Ti composite-based antennas generally offer a broader bandwidth compared to traditional antennas, with the ability to cover a wide frequency range (10 GHz to 100 GHz or higher). This makes them well-suited for cutting-edge applications like 6G networks, IoT devices, and fast data transmission.

- Excellent Impedance Matching: CNT-Ti composite-based antennas typically exhibit lower reflection coefficients, indicating superior impedance matching. This leads to improved power transfer efficiency and reduced signal loss due to reflection. CNT-based antennas often display low VSWR values, which are indicative of good impedance matching.
- Lightweight and Flexibility: The lightweight and flexible nature of carbon nanotubes makes CNT-Ti antennas ideal for use in portable devices, wearables, drones, or any application where minimizing weight and size is important.
- Durability and Strength: The combination of CNTs and Ti can enhance the mechanical strength and durability of these antennas, making them more resistant to physical stress, harsh conditions, and wear. In contrast to other types of antennas like microstrip patches that are more susceptible to damage, the proposed antenna has strong wearable resistance.

4. Conclusion

Mathematical modeling and simulation were used to assess the performance regarding antennas depending on CNT-Ti composites for possible 6G wireless network communication. Results showed that the suggested CNT-Ti composites-based antenna outperformed other types of antennas in terms of bandwidth, efficiency, flexibility, and improved impedance matching, confirming its suitability for high-speed, broadband communication, and next-generation wireless systems, such as 6G. In applications, like satellite communication, in which conventional antennas, such as parabolic dishes could still be favored, such drawbacks could frequently restrict the use of such antennas. The requirements regarding the system, such as frequency requirements, size limitations, and financial restraints, will ultimately determine if CNT-Ti composite antenna is the ideal option. Applications requiring great performance as well as effective power transfer at high frequencies have been found to benefit from such antennas. The increased properties regarding CNT-Ti composites-based antennas could be attributed to their low loss tangent and high conductivity, which provide notable advantages over conventional antenna materials. About impedance matching, reduced energy loss, signal transmission, and improved signal efficiency, the investigated CNT-Ti composites-based antenna performed better than the others. Additionally, such antennas maintain lower VSWR values as well as higher bandwidth, which improves interoperability with a range of communication systems. The advancement regarding such antennas could lead to fascinating opportunities for their application in cutting-edge communication technology. It has been claimed that careful design and performance optimization is necessary to address the problems with the cost and size of antennas depending on CNT-Ti composites. Additionally, studies should be conducted to develop and scale up different manufacturing techniques for antennas depending on CNT-Ti composites. Prior to using them in extensive communication networks, their cost-effectiveness and long-term reliability should be assessed. Investigating more nanomaterials and how they can be integrated with cutting-edge technologies is worthwhile since it could result in innovative antenna designs and increase the capability of next-generation wireless systems for long-term expansion.

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