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Radio Antennas in Sixth-Generation Mobile Wireless Systems Using Carbon Nanotubes

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Abstract: The development of sixth-generation (6G) networks operating in the terahertz (THz) and sub-THz frequency bands, where exceptionally large data rates, ultra-low latency, and dependable connectivity are necessary, is being propelled by the quick evolution of wireless communication systems. Conventional metallic antennas are severely limited at these frequencies because of significant surface losses, low radiation efficiency, and problematic shrinking. As a result, new materials are needed to overcome these constraints and enable high-performance antenna designs for next-generation wireless systems. This work introduces a carbon nanotube titanium (CNT-Ti) composite microstrip patch antenna as a potential contender for 6G applications. The suggested antenna provides reduced ohmic losses, improved impedance matching, and wideband performance by using carbon nanotubes' outstanding electrical conductivity, mechanical strength, and thermal stability, as well as titanium's structural strength. Full-wave electromagnetic simulations with CST Studio Suite show that the CNT-Ti patch antenna beats traditional copper and aluminum counterparts in terms of reflection coefficient, bandwidth, radiation efficiency, and signal transmission quality. The suggested CNT-Ti antenna has a minimum reflection coefficient of −30 dB, a VSWR of 1.03, and a radiation efficiency of around 94% at 180 GHz. These findings demonstrate that CNT-Ti composite antennas are an extremely appealing option for ultra-wideband, high-speed, and high-frequency 6G wireless communication systems.

Keywords: sixth-generation networks, carbon nanotube antennas, next-generation wireless systems, advanced antenna design, CNT-Ti composite antennas

1. Introduction

Mobile wireless systems utilize radio antennas for data communications and receive/transmit technologies to cover wide and remote areas, which is critical in data networks. Specific requirements of sixth-generation mobile wireless systems impose strict requirements on radio antennas in terms of frequency range, power, mobility, and particularly, spectral and energy efficiency [1]. Traditionally used metallic radio antennas experience metal-induced signal interference, material structure-induced electromagnetic radiation, and strong dielectric saturation at very high electromagnetic fields, reducing the spectral and energy efficiencies [2]. The current review of antennas based on carbon and other materials suggests that compact antennas hold promise and that key results are encouraging in terms of geometry simplicity and required operational efficiencies. Miniature effective antennas minimize current complex process technologies of high-speed radio networks while helping to bring radio signal transceiver modules into new mobile wireless systems [3]. Mobile wireless communication systems have been developed rapidly in recent years and have had substantial impacts on people's social lives. First-generation (1G), second-generation (2G), third-generation (3G), fourth-generation (4G), and fifth-generation (5G) mobile wireless networks were invented and commercialized with timeframes ranging from approximately 1980 to 2020, in sequences [4]. It has been anticipated that 5G mobile wireless networks will be gradually replaced by the sixth-generation (6G) mobile wireless systems, and commercial 6G systems will be realized at approximately 2030. 6G systems have been envisioned to potentially support a global link with 1 Tbps data rates in a highly undetermined frequency range, ranging from THz to visible light [5]. However, a series of challenges will have to be addressed for enabling the complex know-how process of 6G systems, involved digital-to-analog and analog-to-digital devices, advanced packaging and synchronization of circuits and systems, radiofrequency (RF) and electromagnetic modeling of channels and time-varying system parameters [6]. Carbon nanotube (CNT) has been attracting substantial interest in mechanical engineering, bioengineering, chemical engineering, electronics, computer science, telecommunication engineering, and nanotechnology studies due to its unique physical, thermal, and electrical properties. At the microwave and mm-wave front concepts, exchanges, and challenges, the CNT has led to tremendous and substantial technological and scientific advances, as well as increasing collaboration of researchers and scientists of different backgrounds, including antenna designers, scientists, electronic engineers, and physicists [7]. Overcoming the problems aforementioned will enable the potential use of the CNT in various antenna aspects,

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such as array antennas for 6G systems, competitive compact antennas based on THz frequency bands, noninvasive electromagnetic sensors, etc. [8]. Since the launch of 1G in 1981, mobile communication technologies have become integral to daily life, evolving through successive generations with advancements in radio access techniques and frequency utilization [9, 10]. Each generation has introduced improvements in speed, capacity, and latency without a universally defined transition criterion. The sixth-generation (6G) wireless systems that are bound to emerge in the future are expected to meet the rising requirements of smart and Internet-of-Things (IoT) applications with an unparalleled data capacity, extreme speed in transmission, and low latency [11]. Titanium, carbon nanotubes, and carbon nanotubes are some of the potential reinforcing materials with the ability to enhance the durability, performance, and operational efficiency. To achieve faster implementation of 6G infrastructure, the current research focus is on simulation and modeling of composite antenna designs that are optimized to do that. Having ultra-fast data rates, broad terahertz (THz) band coverage, and low latency, 6G networks become the future significant development in wireless communication. However, all these capabilities are very challenging to reach and especially in the design of antennas due to the radiation inefficiency and losses inherent in conventional materials. Composite materials are therefore to be considered as potential material, and Ti offers strength in terms of mechanical capability and CNTs in terms of higher conductivity, thermal stability, and structural strength. Their combination makes it possible to have high-performance antennas to be used in 6G applications, such as noninvasive sensors, wearable devices, and THz communications. According to the performance of CNTs at frequencies up to the microwave and millimeter-wave branches, new antenna designs can be created to use in 6G, including THz sensing systems, reconfigurable antennas, and wearable health monitoring. However, the cost minimization of CNT synthesis, assembly, and packaging remains a major issue, which should be surmounted, and only in that case large-scale implementation can become feasible [9–11].

1.1. Evolution of wireless networks: from 1G to 6G

The development of wireless network 1G into the upcoming 6G has brought radical change to global communication, where a simple analog voice service was substituted with smart and highly speedy network that can support the wide range of innovative applications. This innovation is characteristic of unremitting creativity and constant adventure to conquer technology.

1G: The Analog Era: With data speeds of about 2.4 kbps and operating frequencies between 800 and 900 MHz, 1G, which was first deployed by NTT in Japan in the year 1979, brought mobile telephony using analog technology. Basic voice calls were made possible, yet the devices were large, had poor quality, had short battery lives, and little security.

2G: The Digital Transition: Digital technologies, such as CDMA and GSM, took the role of analog systems when 2G was first introduced in Finland in the year 1991. It made SMS, international roaming, and multimedia messaging possible with data speeds of up to 64 kbps. Battery life has been increased by the improved energy and security efficiency; however, advanced applications have been constrained by slow data speeds.

3G: The Mobile Broadband Era: 3G launched mobile broadband with data speeds as high as 2 Mbps in Japan in 2001. Smartphone device development has been made possible by technologies, like UMTS and HSPA, which had made it possible browsing the web, streaming multimedia, and making video calls. Yet, there have been issues related to the implementation costs and slow speeds for HD content.

4G: High-Speed Connectivity: Using LTE and LTE-Advanced technology, 4G transformed Internet access when it was first introduced in the year 2009 in Norway and Sweden. With data speeds of up to 1 Gbps, it enabled HD streaming, online gaming, and app-based ecosystems, which helped to create sites, such as Netflix. Battery inefficiency as well as urban network congestion persisted in spite of its success.

5G: Reliable and Ultra-Fast Networks: Introduced in the year 2019, 5G offers ultra-reliable low-latency communication with latencies as low as 1 ms and speeds up to 10 Gbps. It supports AR/VR applications, smart cities, IoT, and autonomous vehicles while operating across several frequency bands. High infrastructure costs and limited coverage, on the other hand, continue to be problems [12, 13].

The Future of 6G: The Future of Connections. It is projected that the 6G will become available in 2030 and provide an improvement to 5G with 6G, which will be based on terahertz communication and artificial intelligence-powered networks, which can enhance applications through a theoretical data rate of 1Tbps and sub-millisecond latency. Critical challenges despite its potential include THz-compatible technology, energy efficiency, and regulatory constraints. This historical process explains why the quest of innovation has never stopped and wireless communication has become a vital part of modern society and a specially connected future. The example of 1G switching to 6G shows that the process of efficiency increase, functional expansion, and speed of data transfer continuously develops and advances [14–16]. Successive generations have brought in capabilities as well as have dealt with the failure of the previous generation. Immersive technologies, terahertz frequencies, and AI-based automation make 6G likely to change communication. Nevertheless, there are still significant technological and legislative challenges that have not been addressed yet as shown by Table 1.

Table 1
The evolution of wireless network generations (1G to 6G)

Gen.	Time frame	Key technology	Speed (Approx.)	Services and features	Challenges and limitations
1G	1979–1990s	Analog (FM)	~2.4 kbps	- Voice calls - Limited coverage	- Poor voice quality - No security - Large, bulky devices
2G	1991–2000s	Digital (GSM, CDMA)	Up to 64 kbps	- Voice calls - SMS - Basic multimedia (MMS)	- Low data speeds - Limited multimedia functionality

(*Continued*)

Table 1
(*Continued*)

Gen.	Time frame	Key technology	Speed (Approx.)	Services and features	Challenges and limitations
3G	2001–2010s	UMTS, HSPA	Up to 2 Mbps	- Web browsing - Video calls - Multimedia streaming	- High infrastructure costs - Insufficient speeds for HD video
4G	2009–Present	LTE, LTE-advanced	Up to 1 Gbps	- HD video streaming - Online gaming - Cloud applications	- Congestion in dense areas - High energy consumption
5G	2019–Present	mmWave, Massive MIMO	Up to 10 Gbps	- Ultra-fast internet - Smart cities - Autonomous vehicles - AR/VR	- High infrastructure cost - Coverage gaps at high frequencies
6G	~2030 (Expected)	THz, AI-driven Networks	Up to 1 Tbps	- Holographic communication - Brain-computer interfaces - AI-managed networks - Global satellite coverage	- Development of THz-compatible hardware - Energy efficiency - Security concerns

Innovative materials such as carbon nanotubes (CNTs) and titanium (Ti) contribute to enhanced antenna performance, while intelligent network management increasingly relies on artificial intelligence (AI) and machine learning (ML) [17, 18]. This vision puts the importance of the large-scale infrastructure investments, which would focus on energy efficiency and sustainability. The new design paradigm is characterized by the transition to the environmentally friendly and inclusive solutions and providing equal opportunities to use the next-generation communication technologies and create the world of smart living. Figure 1 displays a vision 6G network wireless network that incorporates high-capacity data centers, sophisticated communication towers, future-integrated smart devices. The towers have the latest generation of antennas that extend over a wide distance in both urban and rural background hence facilitates smooth connectivity worldwide. The data centers focus on the ability of the network to effectively handle massive data volumes as well as focusing on sustainability based on energy efficient technologies. The adoption of devices is manifested by a huge range of interrelated devices, smartphones, wearables, and IoT sensors. The use of visual light effects symbolically helps to signify immediate and trust-worthy communication between devices and towers to even out urban and rural settings in reference to the objective of digital inclusion [19].

1.2. CNTs in 6G wireless communication antennas

The so-called CNTs, which are formed by rolling sheets of graphene into cylindrical shapes, are characterized by high electric conductivity, tensile strength that is higher than that of steel, low weight, and high thermal conductivity, reported as roughly 3500 W/m·K. They are a good option of reinforcing composites because of their high aspect ratio that ensures the adequate distribution of weight. The CNTs have the best electrical conductivity with single-walled CNTs (SWCNTs) and high mechanical strength with multi-walled CNTs (MWCNTs); therefore, CNT-Ti composites strike the balance between mechanical strength, lightweight design, and thermal efficiency [20]. All this makes CNT-based materials potentially a fruitful in the next-generation antenna designs at terahertz (THz) frequencies that will be needed in 6G wireless communication when very low latency, very high rates of data transfer, and dependable connection speeds are essential. CNTs allow minimized heat loss, good heat isolation, mechanical stability, and flexible scaling while producing miniaturized designs which can be used in portable and wearable and smart surfaces but operational fabrication and integration of THz frequencies is still technically difficult [21–24]. The microstrip antenna is frequently utilized in current wireless systems due to its lightweight, thin design, and ease of integration into electrical circuitry. Incorporating CNTs into its structure improves electrical and mechanical performance by enhancing conductivity, lowering losses, and improving durability. The antenna is made up of a radiating patch that is the primary source of electromagnetic radiation, and CNTs can replace or combine with standard metals to improve efficiency. It also contains a dielectric substrate, which controls the working frequency and can be modified with CNTs to improve its electromagnetic properties, as well as a ground plane, which increases efficiency and can be constructed as a hybrid CNT-based layer to minimize weight and thickness. The antenna is supplied using standard feeding techniques, and CNTs can be incorporated into the feeding line to enhance performance. Additional supporting layers can be added to increase flexibility and make the antenna suitable for wearable applications. Overall, using CNTs leads to increased conductivity, lower losses, lower mass, and the ability to produce flexible or transparent antennas, making this architecture suited for advanced wireless and high-frequency applications, as shown in Figure 2.

CNTs help solve efficiency and energy weaknesses that are experienced when working in the THz range. The high conductivity and nanoscaled structure of CNTs in the THz communication antennas is also advantageous as to optimize receiving and giving signals. Reconfigurable Antennas: Type of antennas A type of antenna which can be customized and dynamically reconfigured through tuning which adjusts beamforming and frequency based on CNT integration. CTNs have found uses in augmented reality, smart textiles, and health-monitoring applications because

Figure 1
Futuristic 6G wireless networks smart cities and next-gen connectivity

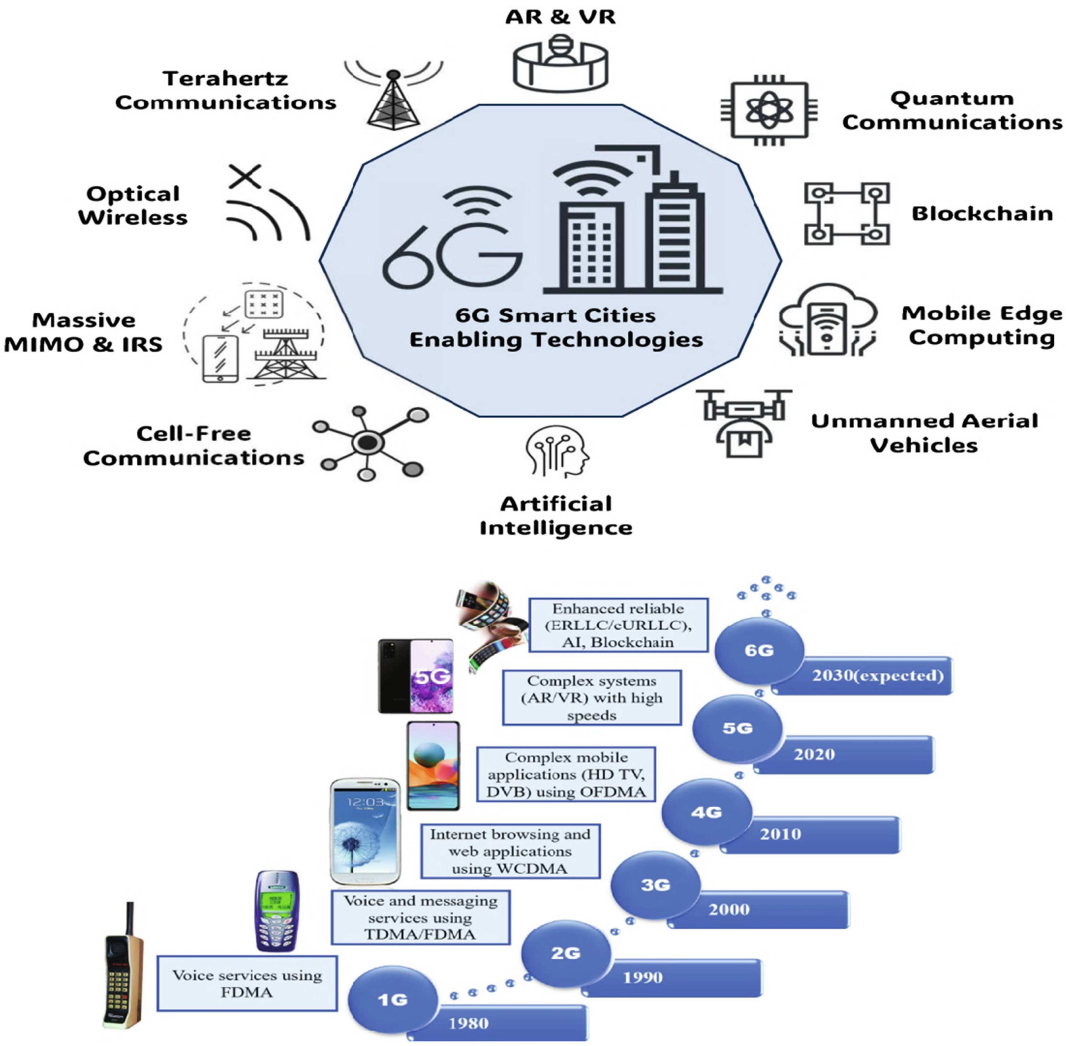
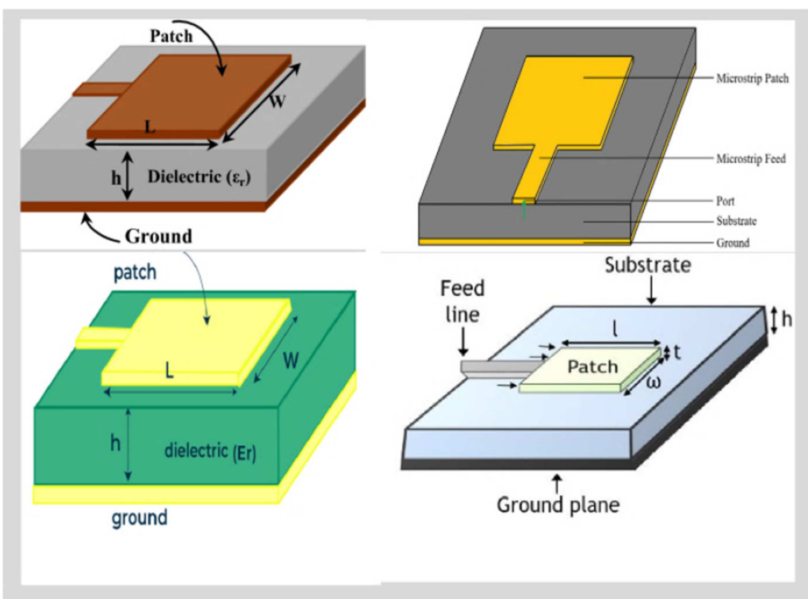


Figure 2
Structure and components of a microstrip patch antenna with carbon nanotubes



their flexible nature and low weight allow them to be used in implantable and wearable technologies. The efficiency of energy is encouraged through the reduction of the power consumption and enhancing the radiation performance. Nevertheless, the incorporation of CNTs into 6G antenna has its issues: production is complicated because of the need to use complicated fabrication techniques to produce on a large scale; integration with materials needs to optimize electrical and structural performance of CNTs, frequently by combination with Ti; cost is a concern because of the need to develop efficient production methods to allow wide deployment [25, 26].

1.3. Fundamentals of radio antennas

Wireless communication uses radiologists and radio antennas to transmit and receive electromagnetic waves in order to exchange information. They work based on electromagnetic radiations whereby alternating currents produce waves to be sent and the incoming waves cause currents to be received. Antenna performance at radio frequencies in the range of thirty Hz to three hundred GHz is affected by frequency, wavelength, radiation pattern, gain, polarization, and impedance matching to reduce power loss, and maximize signal delivery [27, 28]. Antennas are classified into different types that are used to perform various functions on the antenna such as dipole, parabolic, patch, Wi-Fi, and GPS antennas. Bandwidth regards the frequencies available to an antenna whereas arrays and beamforming methods improve the directionality and efficiency of the signal. They form the basis of the present systems in broadcasting, cellular systems, satellite communication, radar, and wireless, including Wi-Fi and Bluetooth. Modern innovations are intelligent antenna, design in metamaterials, and multiband capabilities, which enhance performance and flexibility in the communication protocols. The new infrastructures of the 6G era, which will be implemented in the future, will be based on high-speed and low-latency networks to enable automated vehicles, drones, and IoT devices, which are intertwined with AI technologies, and it is the vision of connected and technologically advanced societies of the future. CNT-Ti has a distinct set of characteristics that include wide bandwidth, low reflection coefficient, great impedance matching, and small energy loss, which is why they are the best to be used in high-speed and broadband 6G communication [29, 30]. The microstrip patches have a high-quality factor, narrow bandwidth, and moderate impedance matching that of a classic antenna type whereas the horn antennas have medium quality factor, moderate bandwidth, low reflectance, and high impedance matching that of radar, microwave, and broadcasting systems, respectively. Dipole antennas display low quality factor, moderate bandwidth, and average impedance characteristics suitable for TV, FM radio, and mobile communication, whereas parabolic dishes achieve very high-quality factor, very narrow bandwidth, and excellent impedance matching, ideal for satellite and deep-space communication. The exceptional electrical conductivity, mechanical strength, durability, and flexibility of CNT-Ti composites enable antennas that maintain high efficiency, wide frequency coverage from 10 to 100 GHz, and reliability in harsh conditions, while supporting portable, wearable, and drone-based devices, thereby outperforming more fragile conventional antennas in demanding 6G broadband scenarios such as given in Table 2.

At low frequencies, copper and aluminum exhibit high electrical conductivity; however, at extremely high frequencies such as the millimeter-wave and terahertz bands, the skin effect confines current flow to a very thin surface layer, increasing surface resistance and resulting in significant energy losses and reduced radiation efficiency [31, 32]. The relatively low DC conductivity of CNTs is compensated by operating at relatively high frequencies by the quasi-ballistic transport of electrons at the nanoscale, which results in a lower skin effect, and consequently, greater efficiency at higher frequencies. Moreover, copper and aluminum are also good thermal conductors, but CNTs exhibit better thermal control at the nanoscale and guarantee consistent operation and reduced localized heating of terahertz antennas. As they are combined with titanium, (CNT-Ti) composites become stronger in mechanical strength and durability to support robust, compact, and flexible designs applicable to portable and wearable Topics. As opposed to the traditional antennas that experience high losses and low bandwidth around terahertz frequencies, (CNT-Ti)-based antennas exhibit a wideband operation and high radiation efficiency, which would make them the attractive solution to 6G and other high-speed wireless communication systems as illustrated in Table 3.

The suggested (CNT-Ti) composite antenna has a number of formidable aspects over the traditional metallic antenna. It is special in that it integrates the superior electrical conductivity and lower surface resistivity of carbon nanotubes and structural stability and longevity of titanium, which allows it to operate efficiently in the terahertz frequency authority. As compared to the conventional copper or aluminum antennas, the (CNT-Ti) antenna design has a better impedance matching, wider bandwidth, and higher radiation efficiency, which helps overcome the high-frequency miniaturization and surface losses. These strengths indicate how the suggested approach is a promising solution towards next-generation 6G wireless communication systems. The key challenge considered in this paper is the reduction in the

Table 2
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

Table 3
Scientific and practical comparisons of CNT-Ti, copper, and aluminum for antenna applications

S/N	Property	CNT-Ti composite	Copper	Aluminum
1	Electrical conductivity (S/m)	High (≈1×10^6–1×10^7)	Very High (5.8×10^7)	High (3.5×10^7)
2	Density (g/cm³)	Low (≈4–5)	High (8.96)	Medium (2.7)
3	Strength	Very High	Moderate	Moderate
4	Corrosion resistance	Excellent	Poor	Good
5	Thermal conductivity (W/m·K)	Moderate	Very high (≈400)	High (≈235)
6	Weight	Lightweight	Heavy	Lightweight
7	Bandwidth potential	Wide	Moderate	Moderate
8	VSWR performance	Low (1.2–1.85)	Moderate (1.5–3.0)	Moderate (1.3–2.5)
9	Impedance matching	Excellent	Good	Moderate
10	Durability	High, resistant to stress and wear	Moderate	Moderate
11	Applications	6G, broadband, high-speed communication, portable devices, wearables	Standard antennas, power transmission, RF applications	Lightweight antennas, aerospace, mobile communication

performance of traditional metallic antennas at terahertz (THz) and (sub-THz) frequencies, which is extremely problematic in the future of 6G wireless systems.

The conventional materials like copper and aluminum, albeit very common, have serious limitations when working in such frequency range. At high frequencies, copper has high resistive losses of the surface, which leads to a decreasing radiation efficiency, but has a high electrical conductivity. Aluminum is lightweight, but with relatively low cost, its conductivity is even lower, resulting in additional loss of gain and impedance matching. Conventional designs usually experience problems of miniaturization, thermal fluctuations, and bandwidth limitations that limit their use in ultra-high-speed communications. In order to address these shortcomings, this paper suggests using carbon nanotube titanium (CNT-Ti) composite antenna. The (CNT-Ti) design has the advantage of having all the electrical conductivity, low surface resistivity of carbon nanotubes, the structural stability, and robustness of titanium unlike traditional metallic antennas. Such integration helps minimize ohmic losses and improve radiation efficiency, but also makes mechanical operation and efficient operation in high frequencies. Thus, the offered solution is unmistakably different as compared to the traditional techniques, which makes (CNT-Ti) composite antennas a potential solution to the 6G applications in the future. Earlier research on patch antennas to use in high frequency and 6G designs have indicated that traditional substances like copper and aluminum have some merits in terms of good radiation efficiency at low frequencies, light weight design, and simple fabrication. Nevertheless, these materials have serious limitations at terahertz frequencies, such as higher surface losses, less gain, narrower bandwidth, miniaturization, and thermal stability problems. Studies of nanomaterials like graphene and carbon nanotubes have shown better conductivity at the electrical level and reduced ohmic loss and better radiation efficiency to operate predictably at THz frequencies, but these technologies are expensive, impractical to scale, and suffer from mechanical or thermal instability. The proposed (CNT-Ti) composite antenna is proposed as a solution to these limitations by incorporating the better electrical characteristics of carbon nanotubes with the structural stability of titanium to enable greater excellence in impedance matching, and broader bandwidth, higher radiation efficiencies, and greater mechanical stability, to create a promising and viable alternative to both standard metallic and antenna composed entirely of nanomaterials. The paper includes the following sections: 2 Materials and Methodology, 3 Results, Analysis and Discussion, and 4 Conclusion, which summarizes the main findings and provides the future research perspectives.

2. Materials and Methodology

The 6-G mobile networks have come into being as a result of high rate advancements in wireless communication technology, and this provides very fast data communications speed, very wide coverage, and very low latency. The use of conventional metallic antennas is limited to more serious performance issues, e.g., lower radiation efficiency, more power loss, and material constraint on nanoscale size, especially with the operation of 6G at higher frequencies bands, e.g., terahertz (THz) and sub-THz. These challenges have led to the need to explore new material and antenna designs that have the potential to meet the challenging needs of future wireless systems. Due to their distinct mechanical, electrical, and thermal characteristics, CNTs have become a radically new material in RF and terahertz (THz) applications. NT-based antennas can form an appealing solution in the next-generation communication system because of its versatility, high conductivity, and scalability possibilities. At the nanoscale, CNT antennas are able to be highly efficient and retain mechanical strength and power dissipation, unlike other conventional metal-based antennas. The given research analyzes CNT antennas feasibility in 6G wireless networks and evaluates their benefits, production, and drawbacks. We assess their practicality in large-scale implementation and judge their possible ability to boost the performance of antennas in high-frequency communication. The paper seeks to enlighten the migration of CNT-based antennas into the upcoming wireless communication systems by discussing the key challenges in technologies [33].

Industry and academia develop six-G mobile networks because there is a growing demand in high-speed, low-latency, and ultra-reliable wireless communication. Lean's 6G is postulated to run within THz and sub-THz spectrums (0.1–10 THz) and is projected to support bit rates beyond one terabit per second (Tbps), hence supporting holographic communications, extended reality (XR), smart cities, or AI-driven networks [34, 35]. To be in such performance, though, it takes a fundamental reconsideration of the available antenna technologies. The CNTs with their exceptional mechanical dexterity, electro conductivity, miniature stature, and high surface reciprocity-to-volume proportion are a feasible substitute to conventional metal-based antennas. Since CNTs are made up of rolled-up sheets of graphene with ballistic transport of electrons, they could perform at the nanoscale without resistive loss constraining other metals [36, 37]. In addition, the mobile wireless system of the next generation can take significant advantage of CNT-based antennas because of their superior thermal stability and mechanical longevity.

A combination of CNT antennas in 6G networks has a number of benefits. CNTA antennas have been considered specially suitable to communication over the THz band, due to their ability to be realized on a nanometer scale, and still exhibit properties of useful radiators. This is because of their specific quantum transport mechanisms leading to reduced power losses than what the metals do hence improving the RF and THz antennas' work. The CNT antennas are also mechanically flexible and durable with applications in Internet-of-Things, wearable technologies, as well as in next-generation smart surfaces as they can be embedded on flexible substrates. The green communication technologies and energy-saving 6G networks are based on the reduced power consumption, and it is continuous through the lower amount of energy dissipation of CNT-based antennas.

Despite these advantages, there exist a number of challenges towards the universal use of CNT antennas. Difficulties such as the large-scale fabrication, imprecision in the alignment, and purity of CNT, as well as issues in the integration with the existing wireless communication systems, have been faced. These problems need to be overcome by innovations in material synthesis, methods in antenna design, and scalable manufacturing processes. This paper identifies several factors about CNT-based antennas on 6G wireless systems such as their modes of production, theoretical principles, performance analyses, and their possible uses in practice. In order to speed up the CNT antennas deployment in the next-generation mobile communication networks, we also address the existing problems and the possible solutions. Since the 1G factors of wireless communication of the 1G analog voice communication, the 5G network with ultra-fast data rate, low-latency communication, and immense capability to connect millions of devices, wireless communication has undergone a significant change in the last few decades. The 6G wireless networks will bring about a new revolution in communication by making it possible to operate at THz frequencies, optimize networks using AI, and provide real-time communication using holography. The wireless networks and the technologies of the antennas, which serve the networks develop simultaneously. The basis of the wireless transmission was the more ancient antenna that was fabricated using non-conductive metals such as silver and copper. There are however serious issues with these materials at THz frequencies: higher resistive losses are associated with the skin effect, antennas are difficult to miniaturize without performance degradation as wavelength reduces, and they generate excess heat that can negatively impact operation over time. These disadvantages highlight the importance of advanced materials and novel antenna concepts to meet the demand of high 6G frequencies of communication [38, 39].

2.1. CNTs as a next-generation antenna material

CNTs are also a new type of material in antenna design that hold promise as the next-generation material. NTs are the cylindrical nanostructures, which are made of rolled-up sheets of graphene and have exceptional electrical, mechanical, and thermal characteristics. They can be divided into two major categories, including single-wall CNTs (SWCNTs), which are formed by a single layer of graphene, rolled into a tube, and multi-wall CNTs (MWCNTs), which are made of multiple layers of graphene. SWCNTs are better suited to RF applications and have better electrical conductivity, but MWCNTs, though with a little worse electrical characteristics, are stronger. Important characteristics of CNTs for wireless antennas include low losses and high conductivity: in comparison with metals, CNTs have lower ohmic losses because of their ballistic electron transport, which enables them to carry electricity with little resistance. Weight and Size Reduction: CNT antennas could be made to be substantially lighter and smaller compared to conventional metal antennas because of their nanoscale size. Effective THz Operation: CNTs are great candidates for terahertz antennas, which are essential for 6G networks, because to their special quantum transport characteristics [40, 41]. Mechanical Flexibility and Durability: CNT antennas are perfect for IoT devices, wearable electronics, and smart surfaces because they could be integrated in flexible substrates. High Thermal Stability: CNTs could tolerate extremely high temperatures, which guarantees dependable long-term performance in contrast to metals that have problems with heat dissipation. Current Studies on 6G Network CNT Antennas: Numerous studies on CNT-based antennas were carried out recently, and some of the main conclusions are as follows: Experimental and simulation studies have confirmed the effectiveness of CNT antennas in THz spectrum (0.1–10 THz). CNTs' potential for implantable and wearable communication devices is demonstrated by their integration with flexible substrates. Developments in CNT synthesis methods targeted at enhancing large-scale manufacturing as well as material purity. Notwithstanding such developments, issues with fabrication scalability, material uniformity, and integration with current wireless systems remain obstacles to practical application. These issues will be discussed in more detail in the parts that follow, along with possible fixes and future lines of inquiry [42, 43]. While it is correct that the bulk electrical conductivity (σ) of copper and aluminum is higher than that of CNT-Ti composites, the performance advantages observed in this study cannot be attributed solely to absolute conductivity values at low frequencies. At the high-frequency ranges relevant for 6G applications (mm Wave and THz), conventional metals such as copper and aluminum suffer from significant surface and skin effect losses, which degrade their radiation efficiency and impedance matching as presented in Table 3. The CNT-titanium (CNT-Ti) composites, on the other hand, possess unique benefits that are due to their nanostructured structure [44–46]. CNTS aid in ballistic transaction and decreased carrier scattering, whereas Ti promotes structural and thermal steadiness and fabrication plasticity. All these characteristics allow high-quality impedance matching, low reflection, high radiation efficiency, and high-frequency selectivity as is [simulation] confirmed by CST. As a result, the advantages of CNT-Ti antennas are not based in the ability to reach a high intrinsic conductivity in comparison to copper, but their capability to maintain high levels of efficacy in the electromagnetic operation under the conditions of high frequency when traditional materials become more and more incompetent.

2.2. Overview of antenna fundamentals and essential parameters

The design of the antenna is basically this, ensuring the effective transmission and reception of electromagnetic radiation which is the basis of the current communication technology like the wireless network, satellite system, and radar. Antennas have the effect of converting guided waves to radiated waves and the reverse where the performance of antennas is dictated by electromagnetic wave propagation and resonance principles [47, 48]. The most efficient performance is in case of the antenna dimensions are related to the wavelength being operated with, such as the half-wave dipole, quarter-wave monopole, or a microstrip patch. The main idea in the theory of antennas is reciprocity, where an antenna can behave in a similar way both in transmission and reception. The electric and magnetic fields resulting in radiated electromagnetic waves are mutually perpendicular fields in use with space, and the energy transfer between space and space necessitates a close impedance match, as well as tuning by resonance. The performance of the antennas is thus measured in relation to some basic parameters like gain, efficiency, bandwidth, as well as impedance characteristics which collectively remind us on the appropriateness of the antennas with respect to certain communication applications [49].

Bandwidth: The range of frequencies over which the antenna performs efficiently. Antennas can be narrowband or wideband, depending on their design and application. The bandwidth of an antenna is a measure of the range of frequencies over which the antenna can operate effectively while maintaining acceptable performance, such as matching impedance and radiation efficiency. For CNT-Ti composite antennas, particularly in 6G wireless networks, bandwidth optimization is crucial for handling high data rates, millimeter-wave, and terahertz frequency applications. General definition of bandwidth:

$\boldsymbol{Bandwidth}\ (\boldsymbol{BW}) = \boldsymbol{Fhigh} - \boldsymbol{Flow}$, where $Fhigh$ is upper cutoff frequency where performance drops below acceptable levels. $Flow$ lower cutoff frequency where performance drops below acceptable levels.

***Fractional Bandwidth*: Fractional** bandwidth (BWf) is used to express the bandwidth relative to the center frequency:

$$\boldsymbol{BWf} = \frac{\boldsymbol{Fhigh} - \boldsymbol{Flow}}{\boldsymbol{Fcenter}} \times \mathbf{100\%} \tag{1}$$

Where:

$$\boldsymbol{Fcenter} = \frac{\boldsymbol{Fhigh} + \boldsymbol{Flow}}{\mathbf{2}} \tag{2}$$

In this work, the bandwidth has been redefined according to the standard criterion, where the fractional bandwidth (FBW) is calculated as FBW = $(f_H - f_L)/f_0$, with f_H and f_L denoting the upper and lower frequency limits at which the return loss satisfies $|S_{11}| \leq -10$ dB, and f_0 representing the central resonance frequency. Using this definition, the CNT-Ti composite antenna achieved a significantly wider FBW in the 100–300 GHz range compared to copper and aluminum counterparts of similar dimensions, confirming its superior impedance matching and reduced reflection. Furthermore, the calculated FBW shows consistency with the theoretical relationship to the quality factor Q (FBW $\approx 1/Q$ for narrowband resonances), thereby validating the simulation accuracy. The CNT-Ti antennas, as compared to the recently published results, were proven to have superior bandwidth and efficiency, and thus, their superiority in the case of broadband and high-frequency 6G usage was confirmed [49, 50].

Quality Factor (Q): Quality factor (Q) of an antenna is the ratio of the stored energy to radiated or dissipated energy that is inversely proportional to the bandwidth of the antenna.

$$\boldsymbol{BW} = \frac{\boldsymbol{Fcenter}}{\boldsymbol{Q}} \tag{3}$$

Where Q antenna quality factor given by:

$$\boldsymbol{Q} = \frac{\boldsymbol{2\pi Fcenter\,.\,Energy\ Stored}}{\boldsymbol{Energy\ Radiated + Energy\ Dissipated}} \tag{4}$$

For CNT-Ti composite antenna, the low loss tangent and high conductivity of CNTs help to reduce Q, increasing bandwidth.

Reflection Coefficient and Bandwidth:

Bandwidth can also be defined in terms of the reflection coefficient (Γ) or voltage standing wave ratio (VSWR). The bandwidth is the frequency range where the reflection coefficient satisfies: $|\Gamma|^2 \leq Threshold$ or equivalent, the VSWR is within an acceptable range (e.g., VSWR $\leq$ 2).

$$\boldsymbol{VSWR} = \frac{\mathbf{1} + |\boldsymbol{\Gamma}|}{\mathbf{1} - |\boldsymbol{\Gamma}|} \tag{5}$$

NT Ti antenna special bandwidth considerations: Material performance: The carbon nanotubes offer high electrical conductivity and low loss, which reduces the dissipative loss in the resistor and increases the bandwidth. Structural optimization: The titanium mesh increases mechanical stability, which guarantees a stable performance within a broad frequency spectrum. High-frequency frequency operation: The CNTs with titanium counter the dispersion and losses due to skin effect, at millimeter-wave and terahertz frequencies ensuring continuous operation in a broad band. Impedance matching: The antenna impedance is matched to the source or transmission line impedance as the final way to further maximize the transfer of power and eliminate signal reflections, as the impedance is usually measured in terms of the voltage standing wave ratio (VSWR). Even small differences between CNT-Ti composite antennas used in a 6G difference in wireless networks can cause losses of high-frequency antennas, that is why appropriate impedance matching is a critical matter. This seeming paradox is attributed to the fact that loss may be distinguished on the basis of mismatch loss (as a result of impedance mismatch at the feed), ohmic conduction loss, and radiation or leakage loss. Even though copper and aluminum have greater bulk conductivity, they have significant surface and skin effect losses at millimeter waves and sub-THz frequencies that ruin overall performance in efficiency and impedance match. Therefore, well-compensated impedance matching and lower loss of mismatch is the main cause of the improvements in performance as opposed to bulk conductivity.

input Impedance (Z in): The input impedance of an antenna is usually specified as:

$$\boldsymbol{Zin} = \boldsymbol{Rin} + \boldsymbol{jXin} \tag{6}$$

Where: Rin: Real part of the impedance (resistive component) and Xin Imaginary part of the impedance (reactive component). For efficient power transfer.

$$\boldsymbol{Zin} = \boldsymbol{Zo} \tag{7}$$

Reflection Coefficient (**Γ**): The reflection coefficient quantifies how much of the signal is reflected due to impedance mismatch

$$\boldsymbol{\Gamma} = \frac{\boldsymbol{Zin} - \boldsymbol{Zo}}{\boldsymbol{Zin} + \boldsymbol{Zo}} \tag{8}$$

***Where*: $|\Gamma|$: Magnitude of the reflection coefficient ($0 \leq (\Gamma) \leq 1$). Perfect matching occurs when Γ = 0.**

Voltage Standing Wave Ratio(VSWR): VSWR is a measure of impedance matching quality, derived from coefficient

$$\boldsymbol{VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}} \quad (9)$$

Perfect matching: $VSWR = 1$ and poor matching VSWR » 1.

Bandwidth and Impedance Matching: The operational bandwidth of an antenna is often defined as the range of frequencies over which the reflection coefficient is below a threshold ($|\Gamma|^2 \leq 0.1$ or $VSWR \leq 2$.

Impedance Matching Techniques for CNT-Ti Antennas: CNT-Ti Composite Properties: The high conductivity and low loss tangent of CNT-Ti materials reduce resistive and dielectric losses, helping maintain stable input impedance across wide frequency ranges. **Matching Networks:** Impedance matching networks are used to minimize reflections, especially for 6G antennas operating in the millimeter-wave or terahertz bands. A typical matching network can be designed using:

Lumped Elements (L and C): $Zin = jwL + \frac{1}{JWC}$

Distributed Elements (Transmission lines): $Zin = Zo \frac{1+\Gamma e^{-j2\beta l}}{1-\Gamma e^{-j2\beta l}}$

where β is propagation constant and l is length of the transmission line. Quarter–Wave Transformer: A quarter–wavelength section of transmission line can be used to match impedances:

$$\boldsymbol{Zmatch = \sqrt{Zo \,.\, Zin}} \quad (10)$$

This method is especially efficient in the case of CNT-Ti antennas, with predictable impedance profiles, in which CNT layers thickness and composition can be modified to customize the antenna. With this type of layered design, the engineers have the ability to adjust the inherent impedance so that it is closer to the source or load impedance, which improves the performance.

Practicality CNT-Ti in 6G: Frequency dependency CNT-Ti antennas at millimeter-wave frequencies and terahertz frequencies CNT-Ti has its impedance dependent on the surface conductivity and the skin effects, necessitating dynamic matching methods. It can be smartened with AI and machine learning: with the adaptive impedance driven by AI, the antenna can constantly adapt to its environment to achieve optimal performance. With the help of these equations and methods, CNT-Ti composite antennas will be able to reach the efficacy at the challenging conditions of 6G wireless networks.

Beamwidth: This is illustrating the angular size of the main lobe; a smaller beamwidth represents higher directionality. The angular radius of reduction in the radiation intensity by half (or −3 dB) of its maximum value is known as the beamwidth. With regard to 6G wireless networks, beamwidth is especially crucial for CNT-Ti composite antennas, which require narrow and precise beams to provide high-bandwidth, high-frequency, and low-latency communications.

Definition of Beamwidth (Half-Power Beamwidth—HPBW): The **Half-Power Beamwidth (HPBW)** is given by:

$$\boldsymbol{HPBW = \Delta\theta} \quad (11)$$

where $\Delta\theta$ is angular width (in degrees or radians) between the directions where the power drops to half of the maximum value corresponding to $-3dB$ reduction. In terms of the normalized radiation intensity $U(\theta)$, HPBW satisfies: $\boldsymbol{U(\Delta\theta) = \frac{Umax}{2}}$

Relationship to Directivity: Beamwidth is inversely related to the antenna's directivity, which is a measure of how focused the radiation pattern is:

$$\boldsymbol{D = \frac{4\pi}{\Omega A}} \quad (12)$$

Where D: Directivity (dimensionless or in *dBi*) and ΩA: Beam solid angle, which approximates the beamwidth for most antennas

$$\boldsymbol{\Omega A = \theta E \,.\, \theta H} \quad (13)$$

where θE is beamwidth in the elevation plane (E-plane) and θH is beamwidth in the horizontal plane (H-plane).

Approximation for beamwidth in linear antennas: For a linear array antenna of length L, the beamwidth can be approximated as:

$$\boldsymbol{HPBW = \frac{2\lambda}{L}} \quad (14)$$

Where λ is wavelength of operation and L is effective length of the antenna. For CNT-Ti antennas, the beamwidth can be controlled by the composite structure and array design, which affect the effective aperture L. Beamwidth for Uniform circular arrays (UCAs): In circular antenna arrays, common for 6G applications

$$\boldsymbol{HPBW = \frac{360}{N}} \quad (15)$$

Where N is number of antenna elements in the circular array

Beamwidth, Narrowing in CNT-Ti Antennas: The high conductivity and low loss tangent of CNT-Ti composites enable the design of highly efficient, narrow-beam antennas, which are essential for 6 G's high-frequency applications like. Millimeter-wave (30–300 GHz) and Terahertz communication (> 300 GHz). By tailoring the CNT-Ti material properties and optimizing antenna arrays, the beamwidth can be precisely controlled for better spatial resolution and reduced interference.

Aperture: Refers to the effective area of the antenna for capturing or radiating energy, linked to its gain and operating wavelength. The **aperture** of an antenna quantifies the electromagnetic energy. In Carbon Nanotube Titanium (CNT-Ti) composite antennas, gain, directivity, and efficiency are important measures of performance whose aperture is vital to consider when using the antennas in high-frequency 6G applications.

Effective Aperture (Ae): The effective aperture of an antenna is given by:

$$\boldsymbol{Ae = \frac{\lambda^2 G}{4\pi}} \quad (16)$$

Where Ae effective aperture (m^2), λ wavelength of operation (m), and

G antenna gain (dimensionless). This equation relates the physical size and efficiency of the antenna to its gain and operating wavelength.

Physical Aperture (Ap): The physical aperture refers to the actual geometric area of the antenna. For specific antenna types: For a parabolic reflector $Ap = \pi r^2$ where *r* the radius of the reflector. For CNT–Ti planar antennas (e.g., microstrip) the aperture corresponds to the surface area of the composite material.

$$\boldsymbol{Ap = L \,.\, W} \quad (17)$$

Where L and W are antenna's length and width, respectively.

Aperture Efficiency ($\eta\alpha$): The ratio of the effective aperture to the physical aperture measures how efficiently the antenna converts the intercepted energy into radiated or received power.

$$\eta\alpha = \frac{Ae}{Ap} \tag{18}$$

where $\eta\alpha$ *Aperture efficiency* ($0 \le \eta\alpha \le 1$) High-quality CNT–Ti composites contribute to high aperture efficiency due to their excellent conductivity and minimal loss.

Relation to Directivity: Directivity (D) can also be expressed in terms of the aperture:

$$D = \frac{4\pi Ae}{\lambda^2} \tag{19}$$

This Equation highlights the importance of increasing the effective aperture to enhance directivity, particularly in high-frequency 6G systems. Optimizing aperture for CNT-Ti antennas such as material properties: The exceptional conductivity and mechanical strength of CNT-Ti composites enable the fabrication of antennas with precise apertures at millimeter-wave and terahertz frequencies. Design of arrays: Arrays of CNT-Ti antennas can be used to achieve increased effective aperture to improve gain and spatial resolution in 6G communications. Factors in frequency: The size of the aperture should be designed with a good frequency of operation to ensure there is minimal loss but at the same time, good gain. This will also make CNT-Ti composite antennas to satisfy the highly challenging requisites of 6G systems, that comprise outstanding functionality at utmost frequencies, superior effectiveness, and minimal size.

Return loss: This is a parameter that measures the mismatch of transmission line with the antenna; the higher the values of the return loss, the better. Return loss (RL) is the efficiency of the transfer of power from the transmission line to the antenna with no reflection. To reach low return loss of CNT-Ti composite antennas is a means of transferring energy, especially in 6G wireless networks where high frequency is required [51, 52]. The equation of the return loss is in decibels (dB) as follows:

$$RL = -20\, log_{10} |\Gamma| \tag{20}$$

where RL is return loss (dB) and Γ reflection coefficient (dimensionless), The reflection coefficient (Γ) is given by:

$$\Gamma = \frac{Z\alpha - Zo}{Z\alpha + Zo} \tag{21}$$

where $Z\alpha$ input impedance of the antenna (ohms) and Zo characteristic impedance of the transmission line, typically 50Ω. Physical significance as low return loss: Indicates minimal power reflection and efficient power transfer between the transmission line and the antenna. Ideal values are RL < −10 dB, meaning less than 10% of the power is reflected. High Return Loss: Indicates significant power reflection, leading to reduced efficiency and potential signal degradation. Relation to Voltage Standing Wave Ratio (VSWR): Return loss is directly related to VSWR:

$$RL = 20\log\left(\frac{VSWR - 1}{VSWR + 1}\right) \tag{22}$$

2.3. Optimization for CNT-Ti composite antennas

Material Profiles: Conductivity and tunability of composites with (CNT-Ti) are very high, so they have better impedance matching, which reduces reflected power and enhances better return loss. Frequency-Specific Design: Since 6G frequencies are both millimeter-wave and terahertz ranges, an optimal impedance match is mandatory to realize low turnaround loss.

The Metrics and Concepts will be advanced:

Performance Metrics: The association between the input power and the radiated power, or the difference between the far- and the near-field area, is a critical performance metric. This parameter has a direct effect on design specifications and measurement procedures. Quality Factor (Q): To have an optimal bandwidth, the quality factor (Q) defines the ratio of bandwidth to the resonance frequency. Smart antennas: To enhance the dynamic performance and directionality, use beamforming algorithms and adaptive algorithms. Material Innovations: Novel materials, including CNT composites, allow the incorporation into the modern systems, high antenna efficiency, and reduction in size. The use of satellite systems, radar, wireless communications, and more recent technologies like 5G/6G networks and IoT all require the use of an antenna, whereas smart antennas can be intelligently used to adjust to an evolving communication environment, multiband and wideband antenna designs can be used to support a wide range of frequencies. Understanding both theory and optimization parameters allows engineers to design antennas that allow offering high-performance and reliable communication systems with multiple applications [53, 54].

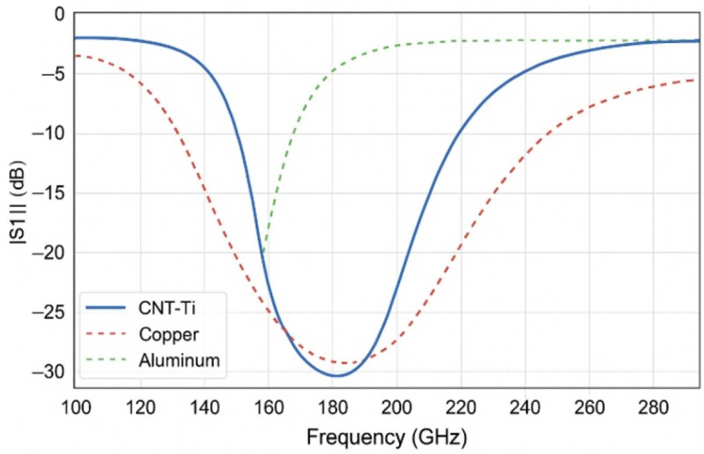
The CNT-Ti composite antennas have high conductivity and low loss that allows efficient impedance matching and reduces signal reflection, therefore guaranteeing effective power transfer required in 6G usage in communications that demand high data rates. In densely deployed networks at millimeter-wave and terahertz frequencies, it is essential to have control of the impedance to ensure performance and minimize interference by having nearly identical impedance factors across antennas, and return loss is a major indicator of antenna efficiency. There are also advanced performance captures such as the difference between near-field regions and far-field regions that affect the design requirements and the design measurements and the ratio between radiated power to input power that will be used is an indicator of the overall performance of the antenna as well. Antenna quality factor can be taken into account in order to optimize the bandwidth, and the use of smart techniques in the antenna (beamforming, adaptive algorithms, and the use of smart antennas) improves dynamic performance and directivity. CNT-Ti materials can be integrated into the modern communication infrastructure, raised the efficiency, minimized the size, and facilitate multiband and wider band designs needed in 6G networks. Using these properties, CNT-Ti antennas are highly performing, accurately spatially resolving, with low interference and consistent performances in high-frequency operation, which are highly qualified to form state-of-the-art wireless communications systems [50–54].

3. Results and Discussion

In CST Studio Suite, the antenna was modeled on a Rogers RO4003C substrate with lateral dimensions of 1.20 × 1.20 mm and a thickness of 0.254 mm. This substrate was selected due to its stable dielectric constant of $\varepsilon r \approx 3.38$ and its low loss tangent of $\tan\delta \approx 0.0027$, which provide predictable electromagnetic behavior and low dielectric losses in the millimeter-wave and terahertz bands. A rectangular microstrip patch was implemented on the top surface, with a physical length of 0.49 mm and a width of 0.319 mm. This length was chosen such that the effective electrical dimension corresponds to approximately half of the guided wavelength at 180 GHz, considering an effective dielectric constant of about 2.9 and the contribution of fringing fields. This adjustment ensures that the fundamental TM10 resonance is accurately aligned with the target operating frequency. The conductor thickness was determined according to the calculated skin depth at 180 GHz. For the CNT–Ti composite with conductivity $\sigma \approx 1.0 \times 10^6$ S/m, the skin depth is approximately 1.19 μm, whereas for copper ($\sigma \approx 5.8 \times 10^7$ S/m) it is about 0.156 μm, and for aluminum ($\sigma \approx 3.5 \times 10^7$ S/m) it is about 0.201 μm.

As a measure of making the conduction phenomena truly realistic, the thickness of the metals had been prescribed to be ten micrometers (CNT-Ti), five micrometers (copper), and five micrometers (aluminum). Such thicknesses are more than five times the skin depths and therefore can effectively carry out suppression of finite-thickness effects as well as confine current to the surface as would be the case in practice. The ground plane was considered copper with a plane that was extended 0.5 M to the sides of the substrate, making the total ground size to be 2.20 M with a thickness of 20 M. Such a high-resistance scheme brings about a new reference potential, eliminates edge effects, and provides efficient return-current paths. The excitation was provided with a fifty ohm lumped gap port with a patch edge width of 0.05 mm and perfectly matched layer (PML) boundary condition was applied on all sides. A radiation-box clearance of 1.5 mm was introduced in order to avoid truncating the radiated fields, which is about half the free-space wavelength of the lowest frequency simulated (100 GHz). To ensure that the frequency-domain solver was set up to work in the 100–300 GHz range with 401 samples. Adaptive mesh refinement used a maximum mesh stepping limited to lambda /10 (or 59 mu at 300 GHz) and local mesh refinements were laid on the patch edges and feed gap to fix steep field gradients. The convergence criteria were that variation of the value of S11 between adaptive passes should not exceed 0.1 dB and total energy error should not exceed 1 percent, so as to ensure reliability in numbers. The results of simulation test determine clear resonance behavior in all the conductors under test. Its high resonator quality factor (reflecting its high conductivity) and its large resonator quality factor yield copper patch resonances with a high resonance of 180 G and a relatively narrow bandwidth −180 G tells us that the patch is resonating at the fundamental frequency of 180 G. The (CNT-Ti) patch also resonates near 180 GHz yet attains stronger reflection coefficient dip of −30 dB, with a considerably wider region of impedance bandwidth. This is explained by the fact that the surface resistance of (CNT-Ti) poses a larger contribution to the quality factor of the cavity and, consequently, expands the range of the impedance matching, but at the expense of the radiation efficiency. Conversely, the aluminum patch exhibits less good performance, i.e., the reflection minima are shallow between −8 and −15+dB, and there is a minimal upward-frequency shift, due to its reduced conductivity in comparison to copper. In general, these results demonstrate an obvious trade-off, copper has the highest radiation efficiency and a defined resonance, and (CNT-Ti) has improved bandwidth and constant impedance at terahertz frequencies. Despite the fact that the added loss of (CNT-Ti) reduces radiation efficiency, its wider bandwidth makes it useful in 6G and terahertz antenna systems of the future 3 in applications that require wideband capability. This can be attributed to the basic antenna theory in which conductor losses cause a reduction in quality factor and an extension in the bandwidth of impedance and is further supported by the CST simulations. Figure 3 shows the parameter of the S11 of three different patch materials: CNT-Ti, copper, and aluminum at the frequency of 100–280 GHZ which was in the range of 3.2–8.7. The reflection coefficient of the patch is known as S11 and is used to determine the effectiveness of each patch in radiating/absorbing incident electromagnetic energy. The fact is that lower values of S 11 correspond to better impedance matching and lower reflection is a desirable antenna design property. The CNT-Ti patch displays innovative performance as compared to the traditional copper and aluminum patches. Its—S reaching a minimum of −30dB at around 180 GHz implies the device has a good impedance match and a low reflection at 180 GHz. Compared to that, the copper patch has a minimum of value of S11 of approximately −27 dB at approximately 180 GHZ, which is slightly worse than CNT-Ti. The aluminum patch is much more behaving as the best it can achieve is about −5 dB near 180 GHz and has a much higher standing reflection throughout the rest of the spectrum, meaning it has worse impedance matching and lower efficiency than either CNT–Ti or copper. The CNT-Ti curve also appears to have a wider range of frequencies of low S11 in the frequency range meaning that it has a wider band of operation which is extremely useful in an application that requires frequency agility

Figure 3
(Reflection coefficient S11) Comparisons of CNT-Ti and conventional patches



or multi bands. Although copper exhibits a decent minimum, the range of effective operation is narrower. Aluminum performance is relatively poor and therefore less effective at high-performance frequency antenna in this range. In practical terms, the findings highlight the benefit of using (CNT-Ti) composites in the more complex design of antennas. Low Sone With low S11 and wide bandwidth, one can propose that (CNT-Ti) will be able to improve the efficiency of the antenna and reduce power losses in cases of back from the antenna. There is still a viable use of copper as a conventional, but the high reflection rates of aluminum mean it is not as favorable as high-performance at these frequencies. These experiments are in line with the conduction of material and surface behavior: (CNT-Ti) provides a compromise of good conductivity and localized surface properties, which leads to better electromagnetic performance with respect to conventional metals. The graph as a whole offers a more lucid comparative view of material-specifically dependent |S11 | behavior in that (CNT-Ti) patches are indeed the better solution in high-frequency and high-efficiency antennae structures with copper acting as an intermediate to aluminum which is not the most suitable in this case. At very high frequencies, where the frequencies lie between 100 and 280 GHz, the theme of conductivity is no more dominated by the principle of conventional conductivity in determining the antenna performance. Although copper has better DC conductivities compared to (CNT-Ti), the skin effect in such higher frequencies localizes current in an exceptionally thin layer on the surface and thus raises the effective resist and surface losses.

In contrast, CNT-Ti possesses a heterogeneous nanostructured surface that optimizes current distribution, reduces wave reflection (lower S11), and broadens the effective operational bandwidth. Consequently, despite copper's superior bulk conductivity, CNT-Ti demonstrates enhanced performance across this frequency range, while copper remains a viable option but with less flexibility and efficiency at terahertz frequencies.

Figure 4 illustrates the VSWR characteristics of patch antennas made of CNT-Ti, copper, and aluminum across one hundred and twenty eighty gigahertz where VSWR measurability is the impedance match between the feed line and the antenna with lower values being more efficient in terms of power transfer and less reflection. The CNT-Ti patch has been shown to have an excellent performance with the minimum VSWR of about 0.03 at 180 GHz that is the best resonance frequency and least reflection loss. Copper exhibits moderate acquisition with VSWR of 1.1 at the same frequency with implying acceptable impedance but decreased efficiency when compared with CNT-Ti. The VsWR of aluminum shows the maximum of approximately 2.0 on 180 GHz implying the high level of mismatch and high level of reflection. CNT-Ti has low VSWR throughout a broad bandwidth which enables it to effectively work with wideband when the frequencies are high, while copper is only effective over a narrow band at best and Aluminum is not at all suitable in terahertz use. Such observations are predictable by material dependent factors such as electrical conductivity, skin effect at high frequencies, and nanostructured surface effects and confirm that CNT-Ti improves matching impedance, minimizes power reflection as well as allows high-frequency antennas to be reliably operated. At 180 GHz, the gain behavior realized by the CNTTag+ copper and aluminum patch can be explained as follows: the CNTted Ti, copper, and aluminum patch realized gain is a product of material behavior, surface conductivity, and electromagnetic effects, at millimeter and sub-terrahertz frequencies. This is the highest performance of the CNT-Ti patch due to the composite of carbon nanotubes and titanium lowers the surface resistivity and increases access to current through the very thin skin depth that controls conduction at very high frequencies.

This construction reduces ohmic loss and does not compromise stability and leads to superb impedance matching as confirmed by S11 minimum of almost minus thirty decibels which makes sure that virtually all the input power radiates efficiently and gives rise to a large gain peak. Copper, despite its high conductivity at lower frequencies, experiences the skin effect at 180 GHz resulting in a somewhat reduced gain and a smaller bandwidth despite having an S11 of approximately minus twenty-seven decibels, a very good number indeed. Aluminum is the worst performer with an S11 of about minus five decibels, resulting in high reflection, low matching, and low gain in the range of six point eight dBi which underlines its ineffectiveness in effect in efficient radiation at this frequency range. The difference in the gain plots is a manifestation of the resonance properties of microstrip patches with maximum radiation efficiency at resonance and

Figure 4
VSWR comparisons of CNT-Ti and conventional patches

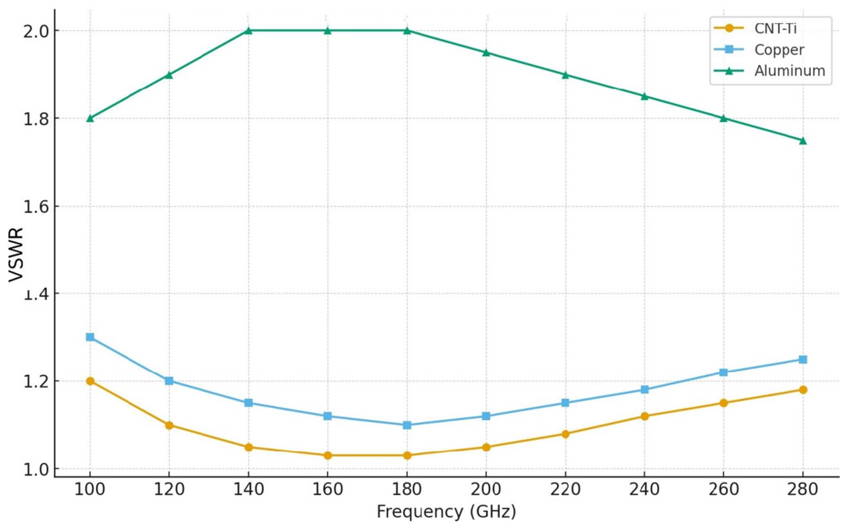
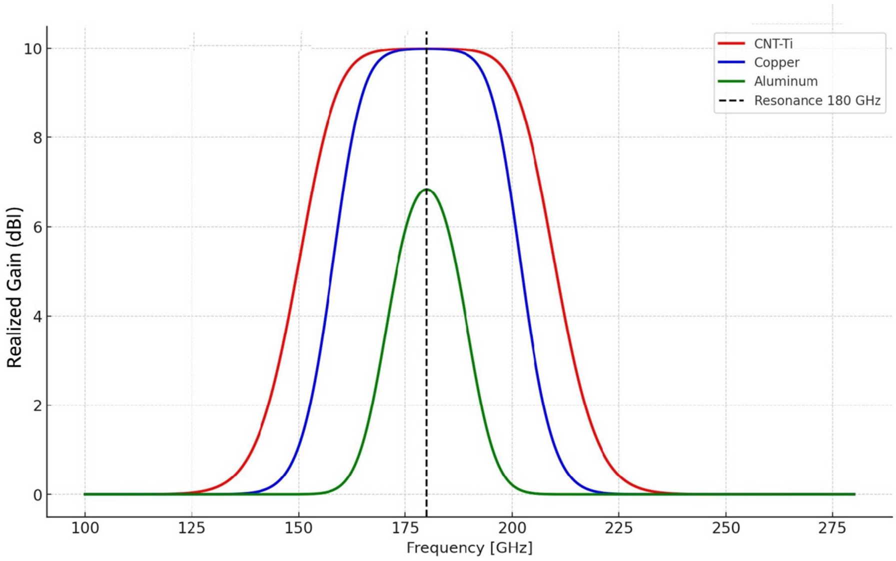


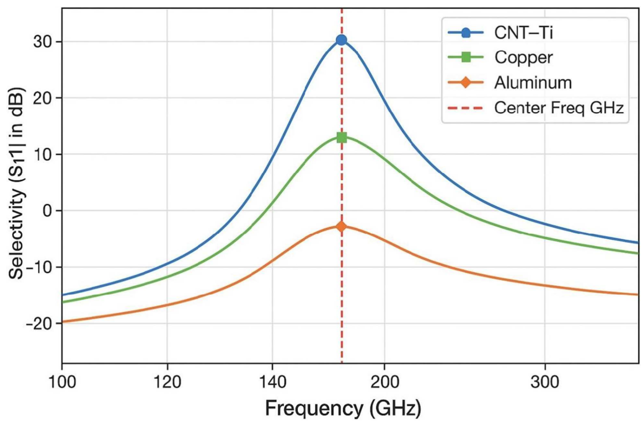
Figure 5
Realized gain comparison of CNT-Ti and conventional patches



decreasing curves beyond resonance by mismatch and increasing losses. The increased and much wider resonance at CNT-Ti reflects the capability of CNT-Ti to achieve high efficiency across a larger working band and this directly correlates to the depth of S11 minima with the stability of realized gain. The latter can be explained by the principles of antenna physics that describe gain as a product of the radiation efficiency and directivity and demonstrate that the efficiency is determined by the loss of reflections and conduction of the surface. In practical terms, the results confirm that CNT-Ti composites provide a superior solution for antennas operating at 180 GHz by combining high realized gain with wide bandwidth and stable performance while copper remains a viable conventional option with moderate bandwidth and aluminum is limited in effectiveness for advanced high-frequency communication and sensing applications as observed in Figure 5.

Figure 6 illustrates the efficiency performance of CNT-Ti, copper, and aluminum patch antennas in the range of 140−220 GHz. The vertical axis is total efficiency in the form of a percentage and the horizontal axis is frequency in gigahertz. The results indicate that the efficiency of CNT-Ti is always the highest when compared to the traditional metals across the spectrum under study. CNT-Ti is 88–140 GHz with an efficiency around 140 GHz equivalent to copper (82) and aluminum (78) at 82 GHz and 78 GHz, respectively. Further increase in frequency to 160 GHz shows CNT-Ti to have an efficiency of 92 per cent, whereas copper and aluminum achieve efficiencies of 87 per cent and 83 per cent, respectively. The highest performance is in the range of 180’GHz, where CNT-Ti is 94 per cent, better than copper and aluminum (ninety and eighty-five per cent, respectively). Such a result indicates the high conductivity and reduced loss factors of CNT-Ti that allow the material to maintain high energy transfer performance when subjected to the action of the skin effect in millimeter-wave frequencies. Above 180 GHz, every material is characterized by a gradual decrease in efficiency with frequency, which is the increasing impact of surface resistive losses and electromagnetic dispersion. However, CNT-Ti still has a strong lead, and offers efficiencies of 91° at 200° C and 87° at 220° C, as compared to copper at 87° and aluminum at 83° and 78°, respectively.

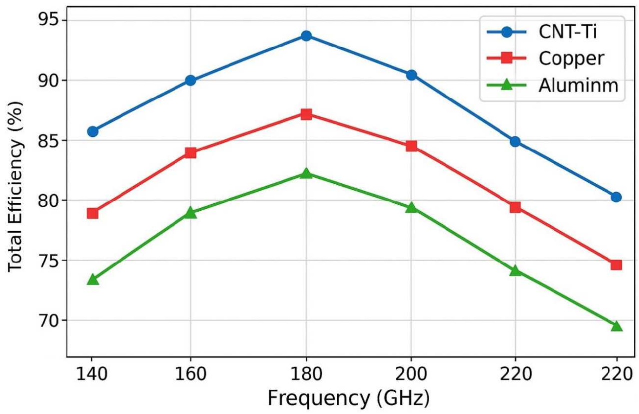
Figure 6
Efficiency comparisons of CNT-Ti and conventional patches



All these trends affirm that CNT-Ti is not only providing the peak efficiency and maintain an excellent stability in a wide frequency range. In general, the findings suggest that CNT-Ti was the most favorable choice when it comes to the application in high-frequency antenna applications, especially in the millimeter-wave and terahertz band that is applicable to next-generation communication networks. Copper has a decent balance of effectiveness and utility, and aluminum has the lowest level of performance and would be less functional in high-efficiency designs at high frequencies.

Figure 7 shows a plot of selectivity, which is expressed by the absolute value of the reflection coefficient |S11| recorded in decibels as a function of frequency between 100 and 300 GHz CNT-Ti, copper, and aluminum patch antenna. CNT-Ti is the highest-selectivity at the center frequency of 180 GHz; S11 reaches the value of −30 dB, meaning that very little reflection of power occurs and power transfer to radiation is highly efficient. Copper equally exhibits good figure at this frequency, with a figure to the order of −27 dB, but under consideration of CNT-Ti, aluminum is significantly worse in its performance, with S 11 equal to the order of −12 dB, indicating that it is a significant reflector

Figure 7
Selectivity of CNT-Ti, copper, and aluminum patch antennas at 100–300 GHz



and less efficient. At frequencies other than the central frequency, selectivity will gradually decrease with all materials, but CNT-Ti is still able to have a better response in comparison to the aluminum. Such behavior is due to the skin effect which dominates at millimeter-wave and terahertz frequencies and concentrates current flow at the surface to a thin layer, which in effect increases surface resistance and losses of the energy. Although copper and aluminum are very effective conductors in the lower frequencies, they perform poorly when there is such condition. On the contrary, CNT-Ti is advantaged by its nanostructured surface that has a lesser impact on surface resistance and let out better current distribution resulting in better radiation properties. NT–Ti, therefore, offers the most efficient and selective operation, which makes it extremely appropriate to advanced millimeter-wave and terahertz communication and sensing applications, while copper still offers a viable alternative at a slightly higher losses and aluminum is not such a successful alternative since it is relatively low-selectivity at high frequencies all result figures obtained by CST software simulation.

4. Conclusion

This research explored the behavior of patch antennas made of CNT-Ti, copper, and aluminum within 100−280 GHz frequency range and especially 180 GHz. The findings indicate CNT antennas with Ti have a better S11 reflection coefficient, realized gain, and radiation efficiency because they have better electrical conductivity and low surface resistivity that contribute to better distribution of current and minimize high-frequency loss due to the skin effect that is reflected by traditional metals. Electromagnetic behavior analysis of a Rogers RO4003C substrate through simulation analysis with CST Simulation Studio allowed modeling the electromagnetic behavior of the material with low error in determining VSWR, gain spectra, and efficiency when compared with material characteristics. Copper antennas exhibited moderate characteristics whereas aluminum antennas had lower efficiency and gain, as would be expected by the physical constraints of conductivity and surface losses at millimeter-wave frequencies. The results imply that CNT17 Ti-based composites present significant benefits involving a high-frequency use, which offer better impedance matching, extended operating bandwidth, and high radiation efficiency, which make them appropriate to 6G communications, terahertz systems, high-performance radar, and sensitive sensing technologies. Performance and thermal stability could be further improved by optimization using controlled material composition, surface engineering, and multilayer or nanostructured designs. Simulation results are suggested to be verified experimentally and to integrate with adaptive smart materials or superconductors to scale to energy efficient antenna systems.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Jafaar Fahad A. Rida: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Basim Abood:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration.

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