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Review

Nanoscale antenna systems: Transforming wireless communications and biomedical applications

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Abstract: This article provides an overview of nanoscale antenna systems in wireless communications and emerging biomedical applications. The research examines the importance of nanoscale antennas and the significance of nanotechnology in antenna layout. It delves into numerous layout concerns along with challenges of miniaturization, frequency selection and trade-offs between size, bandwidth, performance and radiation properties. The paper also explores the role of nanomaterials in antenna packages, specializing in their properties and overall performance-improving properties. It explores synthetic methods and techniques for incorporating nanomaterials into antenna designs, opening the way for new designs and improved performance. In the field of wireless communication, the article includes miniaturized antennas for wearable devices, Internet of Things (IoT) applications, millimeter wave, terahertz communication systems and it also explores antenna designs for compact wireless devices with constrained form factors overcoming challenges due to size limitations. In the biomedical field, antennas integrated into implantable medical devices and biosensing platforms are explored. The article examines the use and fabrication of biocompatible materials for biomedical antennas by considering their applicability in biomedical environments. Performance analysis and characterization techniques for nanoscale antennas are presented, including calibration methods, radiation sample analysis, gain, efficiency, impedance matching and analysis of performance parameters in various typical application scenarios. It helps to optimize antenna configuration for various cases. The article concludes with a discussion of key findings and contributions to the study. It highlights future directions and potential developments in nanoscale antenna systems, including power efficiency and energy collection, reliability and robustness in active areas and integration with wireless communication systems and networking. Finally, this article presents treasured insights into the design, fabric packages and research of nanoscale antenna systems. It gives a roadmap for future studies and improvement, focusing on the transformative capability of nanoscale antennas in Wi-Fi communications and biomedical applications.

Keywords: Nanoscale; biomedical; antenna; communication; healthcare; wearable; drug delivery

1. Introduction

Nanoscale antennas have received extensive interest in recent years because of their importance in rising applications, requiring increased overall performance for compact Wi-Fi communications and biomedical gadgets [1]. The ability to run in restricted shape factors and harsh environments inclusive of technological advances needed for smaller antenna structures. This has caused the demand for nanoscale antennas, which offer specific advantages and possibilities to triumph over the restrictions of traditional antenna systems [2]. Nanomaterials are regularly mixed with nanofabrication strategies, taking into account unique control of antenna form, electromagnetic properties [3], and performances. Utilizing nanotechnical principles, these antennas open new possibilities for superior Wi-Fi convertion, biomedical sensing and different rising fields (see Figure 1). The importance of nanotechnology in antenna design can't be overstated.

Nanoscale antennas take benefit of the particular properties exhibited by nanomaterials, inclusive of carbon nanotubes, graphene, nanowires and nanoparticles [4]. These nanomaterials have unique electrical, thermal and optical properties which can substantially influence overall antenna performance. For example, carbon nanotubes and graphene provide top notch electric conductivity and mechanical stability, making them appropriate for high-frequency and bendy antenna designs. Nanowires and nanoparticles offer opportunities to the electrical properties of antennas, which includes improving their air efficiency or tuning their resonant frequencies [5]. The use of nanomaterials in antenna designs enables miniaturization and complements overall performance. Traditional antenna systems face challenges whilst trying to achieve miniaturization without sacrificing performance and bandwidth [6]. Nanoscale antennas overcome limitations by using nanomaterials, making the antenna smaller while retaining their desired electromagnetic properties.

Nanoantennas, diverse in shape from rods to spheres, offer a spectrum of advantages. Rod-shaped antennas excel in enhancing polarization effects, crucial for selective light manipulation. Triangular antennas exhibit efficient resonance, enhancing light-matter interactions. Alternatively, bow-tie nanoantennas maximize field enhancement in their gap region, essential for enhancing Raman spectroscopy signals. These varied shapes allow tailoring of optical properties, enabling applications ranging from enhanced sensing to advanced imaging in nanotechnology.

The ability to shrink antennas to nanoscale opens up new possibilities for the Internet of Things (IoT) driving devices, that is, if they are wearable, it opens new avenues for simple devices such as electronic sensors and biomedical implants [7]. Furthermore, nanotechnology allows precise control of the antenna properties and functions. Nanofabrication techniques enable precise fabrication of antennas, and optimize their resonant frequency, radiation pattern and impedance matching level. This level of application can improve performance in complex environments, to match antenna-specific application requirements.

In conclusion, nanoscale antenna systems have emerged as an important area of research and development in wireless communications and biomedical applications. The benefits of nanotechnology in antenna design cannot be underestimated, as miniaturization, increased efficiency and tailored power generators are new nanotechnology to be integrated into antenna designs to address the unique advantages of nanoscale antennas in compact wireless devices [8], wearable electronics, IoT applications and advances in bio-medical sensors. These advances will open the door for researchers and engineers to unlock new opportunities and meet the challenges of the ever-evolving needs of emerging applications.

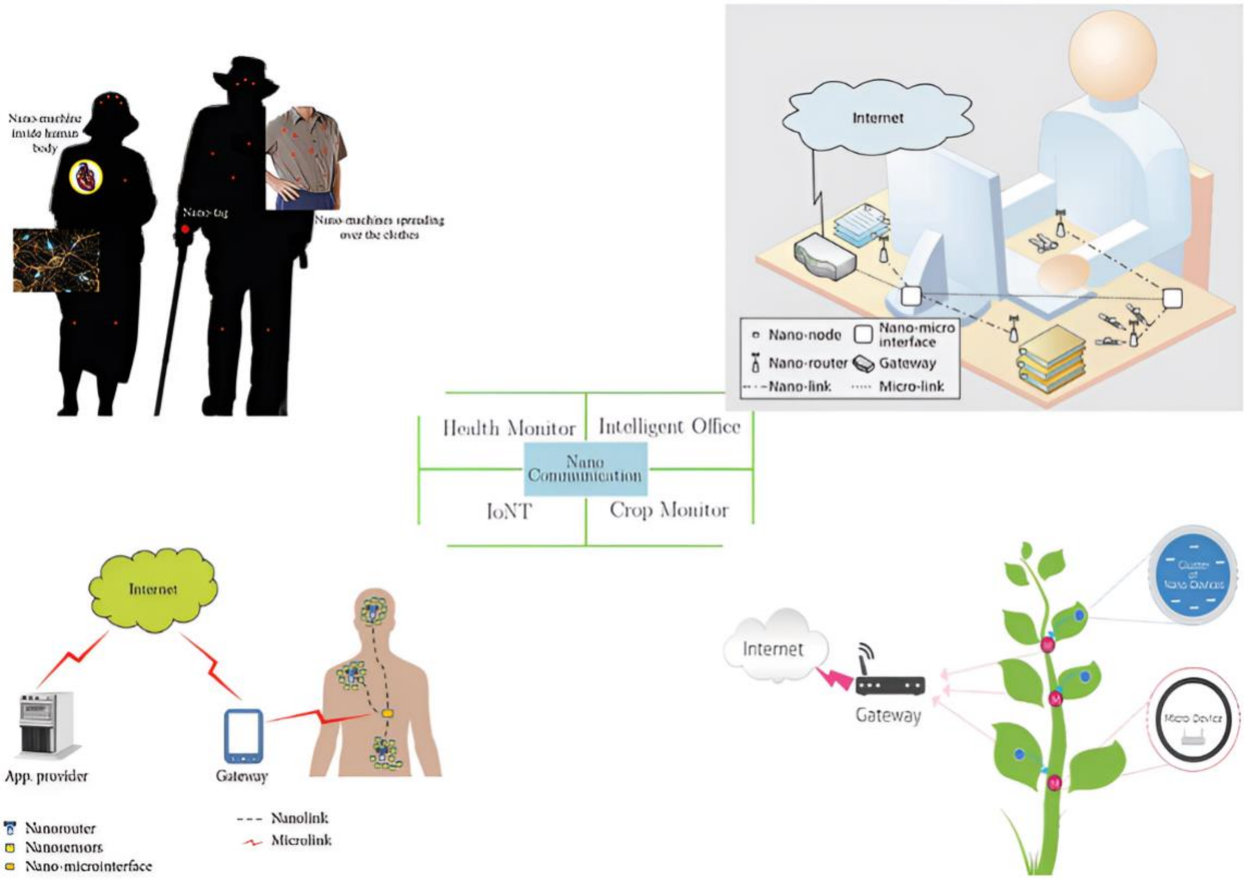

Figure 1. Visualized nano applications in various concepts [9].

2. Nanoscale antenna design principles

The design of nanoscale antennas requires careful attention toward quite a few aspects to attain the most efficient overall performance at small sizes. These issues are critical to cope with the challenges related to nanoscale antenna layout. One vital component is miniaturization challenges, where bandwidth and radiation efficiency can be reduced with decreasing antenna length [10]. To conquer this, other strategies, together with metamaterials and engineered structures used in monitoring or provide high-quality design. Moreover, the frequency choice and tuning technique performs a vital function in acquiring the desired resonant frequency for a nanoscale antenna. It includes tunable functions that permit dynamic frequency adjustments, enabling frequency agility and reconfigurability. Finally, there are trade-offs in length, bandwidth, performance and radiation traits in nanoscale antenna layout. This confined physical dimensions of nanoscale antennas which tend to reduce bandwidth in comparison to coarse-scale antennas. In order to acquire improved overall performance and desired radiation, reaching outstanding stability with bandwidth requirements is key for a device [11]. Advanced methodologies and optimization techniques are employed to enhance efficiency, manipulate radiation characteristics and meet the specific requirements of emerging applications. By considering these design aspects, researchers can develop various shapes (see Figure 2) of nanoscale antennas that meet the demands of compact wireless devices for biomedical applications.

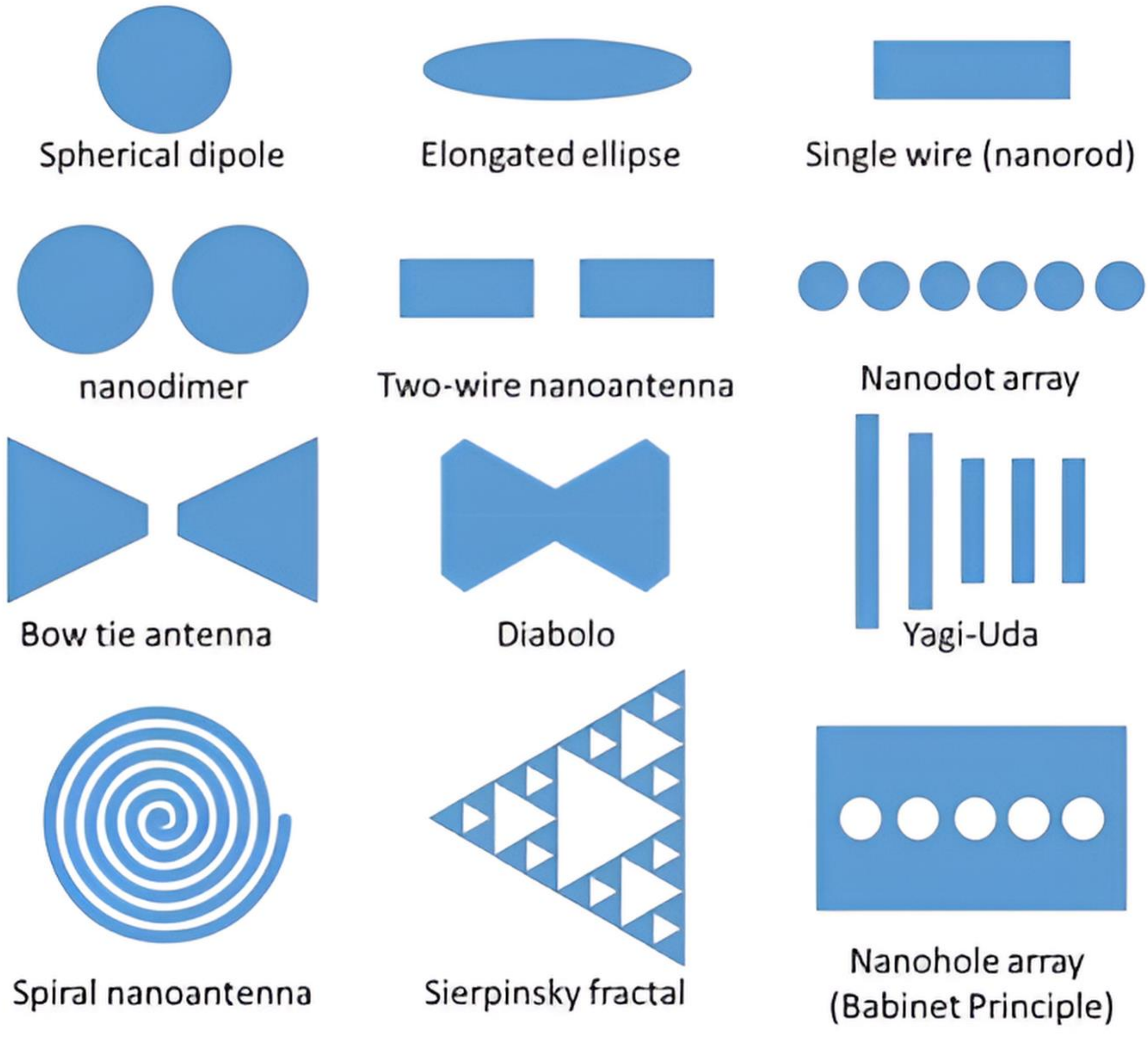

Figure 2. Nanoantenna shapes [10].

2.1. Miniaturization challenges and techniques in antenna design

Miniaturization of antennas poses significant challenges in achieving efficient radiation and reception capabilities while reducing the physical size of the antenna. As antennas are scaled down to the nanoscale, the achievable bandwidth and radiation efficiency tend to decrease due to the limitations imposed by miniaturization [12]. Traditional antenna designs may not be suitable for nanoscale applications, requiring innovative approaches to overcome these challenges. The connection between the differential refractive index of nanoscale antennas and the excellent performance of micro-antennas lies in their shared principle of manipulating light at subwavelength scales. Nanoscale antennas, due to their small size, exhibit high sensitivity to changes in the refractive index of the surrounding medium. This property enables them to detect minute variations in the environment. When integrated into micro-antennas, these nanoscale components contribute to enhanced signal reception, radiation efficiency and beam directionality. By harnessing the unique properties of nanoscale antennas, micro-antennas can achieve superior performance characteristics, making them invaluable in applications such as communication, sensing and imaging.

One of the primary challenges in miniaturization is maintaining electrical performance at reduced nano-dimensions. The antenna's physical length influences its resonant frequency, radiation sample and impedance matching factors. However, as the scale decreases, it becomes harder to hold the preferred electric traits, leading to reduced performance [13]. To overcome these challenges, numerous techniques were developed in nanoscale antenna layout. Metamaterials, engineered structures and superior fabrication procedures permit the introduction of unconventional antenna designs. Primarily metamaterial-based nanoscale antennas make use of synthetic substances with their properties not located in natural substances [14]. These metamaterials can show off bad refractive indices, enabling more advantageous performance in miniaturized antennas. By carefully engineering the structure and composition of these materials at the nanoscale stage, it becomes possible to control and manipulate electromagnetic waves, allowing high overall performance for miniaturized antennas [15]. Furthermore, the use of tunable substances is another technique to deal with miniaturization in demanding situations. Tunable materials exhibit properties that may be modified with the aid of outside stimuli, together with electrical or magnetic fields, temperature or pressure elements. Incorporating these materials into nanoscale antennas permits for dynamic control of the antenna's resonant frequency [16]. This allows frequency tuning, reconfigurability and flexibility to distinctive wireless conversation standards. Additionally, superior layout optimization techniques play a critical function in miniaturized antenna layout. Finite element method (FEM), genetic algorithm (GA) and different numerical optimization algorithms are employed to attain the desired overall electrical performance within constrained bodily dimensions [17]. These strategies enable the tuning of antenna parameters, together with their length, shape and the intrinsic cloth properties, to optimize performance metrics together with their radiation efficiency, their bandwidth and their impedance matching factors.

Another issue of miniaturization-demanding situations is the effect of losses and efficiency. When the antenna size decreases, the quantity availability for radiation decreases as well. This can cause decreased radiation efficiency and expanded losses [18]. Designers deal with those challenges by using incorporating matching networks, minimizing material losses and optimizing radiation factors to enhance its efficiency

2.2. Frequency selection and tuning methods for nanoscale antennas

Frequency choice and tuning are important issues inside the design of nanoscale antennas to reap the best overall performance for unique programs. Resonant frequency of an antenna is, broadly speaking, decided via its physical dimensions. However, miniaturization challenges in nanoscale antennas can make it hard to reap the favored resonant frequency [19]. Therefore, frequency selection and tuning strategies are used to adjust the antenna's resonant frequency to suit the desired operating frequency. One usual method for frequency tuning in nanoscale antennas is the incorporation of tunable substances. These materials exhibit properties that may be changed by means of external factors along with electric or magnetic fields, temperature and stress. By integrating the movable components into the antenna machine, the resonant frequency can be dynamically adjusted, allowing frequency agility and reconfigurability. This gives the power to conform to unique operating frequencies and conversation standards [20]. Another method to frequency tuning is using reconfigurable systems. These systems can alternate their bodily structure or their geometry to change the resonant frequency of the antenna gadget. Resonant frequency of the antenna may be changed via adding a cell or adjustable components, including microelectromechanical structures (MEMS) or liquid steel. This permits for actual-time frequency tuning and adaptableness to converting environmental conditions or communication requirements [21]. In some cases, frequency selection and tuning may be achieved by using outside circuitry. This entails incorporating digital additives, consisting of varactors or tunable filters, inside the antenna gadget. These additives can actively adjust the resonance frequency of an antenna through controlling the electrical properties of the circuit. This technique offers unique frequency tuning skills and allows for fine-grained control over the antenna's working frequency.

2.3. Trade-offs between size, bandwidth, efficiency and radiation properties

In nanoscale antenna design, trade-offs exist between various parameters such as size, bandwidth, efficiency and radiation properties. These trade-offs arise due to the inherent limitations of miniaturization and the constraints imposed by the operating frequency and application requirements. Size is a crucial trade-off in nanoscale antennas. When the antenna's size decreases, its achievable bandwidth typically decreases as well. As the physical dimensions of an antenna determine its resonant frequency, and reducing its size limits the frequency range in which the antenna can operate effectively, designers must carefully balance the desired size reduction with the bandwidth required for a particular application.

Efficiency is another important trade-off in nanoscale antenna design. Miniaturized antennas often experience higher losses due to reduced volume available for radiation. These losses can lead to lower radiation efficiency and decreased overall performance. Design techniques, such as incorporating matching networks, optimizing radiation elements and minimizing material losses, are employed to enhance their efficiency [22]. However, achieving high efficiency in miniaturized antennas can be challenging and may require additional design considerations and trade-offs.

Radiation properties, including radiation pattern and polarization, also need to be considered in nanoscale antenna design. The compact size of nanoscale antennas can limit their ability to produce desired radiation patterns or polarization states. Trade-offs may arise between achieving specific radiation characteristics and miniaturization. Advanced design methodologies, such as metasurfaces or engineered structures, can be employed to manipulate their radiation properties and achieve the desired radiation pattern or polarization state while considering the constraints of miniaturization [23].

Balancing these trade-offs is crucial to achieving the desired performance in nanoscale antennas. Designers must carefully consider the specific application requirements and prioritize the parameters that are most critical for the given application. By understanding and optimizing these trade-offs, researchers and engineers can develop nanoscale antennas that meet the performance goals and constraints of emerging wireless and biomedical applications.

2.4. Nanoscale antennas are different from conventional antennas

Nanoscale antennas stand as a paradigm shift from conventional antennas, driven by the unique electromagnetic properties that emerge at the nanometer scale. While traditional antennas operate in the macroscopic realm, responding to electromagnetic waves based on their size relative to the wavelength, nanoscale antennas operate on an entirely different scale. The key differentiator lies in their size [24]. Nanoscale antennas are intricately crafted structures, often comparable in size to the wavelengths they interact with. This size reduction begets novel effects, most notably Plasmon resonance. This phenomenon arises due to the confinement of free electrons' oscillations, leading to exceptional properties field enhancement and localization. Unlike conventional antennas, nanoscale counterparts can manipulate and amplify electromagnetic fields with unprecedented precision, enabling an array of applications. Quantum effects also come into play at the nanoscale, altering the electromagnetic interactions profoundly. As dimensions approach atomic scales, phenomena such as quantum tunneling and discrete energy levels influence the antenna’s behavior, altering radiation patterns and polarization responses. Such effects are nonexistent in conventional antennas. Moreover, the ability to engineer nanoscale antennas with tailored shapes and materials allows precise tuning of their resonant frequencies, opening avenues for multispectral applications and overcoming limitations of conventional designs.

In applications, the differences between nanoscale and conventional antennas become evident. Nanoscale antennas find applications in areas like nanoscale imaging, sensing, spectroscopy and communication [25]. Their ability to confine and manipulate light on subwavelength scales grants them unparalleled resolution and sensitivity. Conventional antennas, due to their larger sizes, cannot achieve the same level of precision or performance in these domains. In essence, nanoscale antennas represent a disruptive leap in electromagnetic manipulation. Their unique properties transcend the limitations of conventional antennas, enabling innovations across fields, from electronics and information technology to medicine and environmental monitoring. As researchers delve deeper, unlocking the full potential of these miniature marvels, their differences from conventional antennas become increasingly profound.

3. Nanomaterials for nanoscale antennas

Nanoscale antennas require specialized substances that show off specific properties on the nanoscale level to gain efficient electromagnetic wave manipulation. Nanomaterials play a crucial component in enabling the functionality and performance of these antenna structures. These features offer improved electrical, mechanical and optical properties, making them suitable for a variety of antennas to make use of [26]. Nanomaterials, along with carbon nanotubes (CNTs), have acquired an awful lot of interest within the development of nanoscale antennas. CNTs have incredible mechanical properties, high electrical conductivity and precise electric properties, making them ideal for antenna design. CNT-based antennas offer terrific radiation characteristics and can be incorporated into numerous devices, such as bendable and wearable electronics [27].

Graphene, a two-dimensional nanomaterial, has also emerged as a promising candidate for antenna programs. It has famously high electrical conductivity, terrific mechanical power and broadband electromagnetic absorption properties. Its precise shape allows for easy integration into nanoscale antennas, offering exquisite radiation performance and huge bandwidth talents [28].

Nanowires have won prominence as building blocks for nanoscale antennas because of their unique electric and optical properties. These extremely thin wires may be tailor-made to unique dimensions and showcase awesome field confinement and radiation properties [29]. Nanowire-based antennas provide tunable resonance frequencies, high radiation efficiency and compatibility with various substrates.

Nanoparticles, together with gold and silver nanoparticles, are utilized in nanoscale antenna design to influence its radiation properties. These metal nanoparticles show off robust plasmonic resonances which could improve the antenna's radiation traits. By strategically placing nanoparticles in the antenna shape, the close-to-field distribution may be manipulated, essential to improving radiation performance [30]. Other nanomaterials collectively with nanocomposites, nanocrystals and quantum dots also are being investigated for their capability in nanoscale antennas. These substances offer great electric, optical and magnetic capabilities that may be used to improve the antenna performance [31]. Nanocomposite involve the polyester-styrene polymer which is embody with permittivity nanoceramics powers for easy fabrication of low-price antenna (see Figure 3).

Finally, nanomaterials provide a platform for designing and fabricating high-performance nanoscale antennas. Their unique properties permit efficient electromagnetic wave manipulation, improved radiation traits and huge bandwidth abilities. As studies in nanotechnology progress, the development of novel nanomaterials and their integration into antenna designs will further enhance the field of nanoscale antenna technology (see Figure 3).

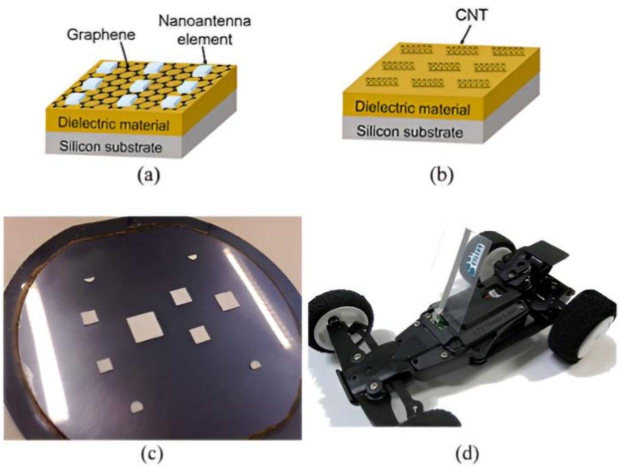

Figure 3. (a) Biosensor for detection of bacteria [32], (b) CNT-based antenna, (c) antenna elements with nanocomposite [33] and (d) printed nanowire antenna [34].

3.1. Overview of nanomaterials suitable for antenna applications

In the sector of nanotechnology, new possibilities were opened for the layout and designing of nanoscale antennas with the use of distinctive nanomaterials. These nanomaterials offer precise properties which could improve the performance and efficiency of antennas for a diverse range of applications. Here we offer a description of some typically used nanomaterials in antenna systems.

Carbon nanotubes (CNTs) are one of the most studied sort of nanomaterials utilized in antennas [35]. These cylindrical systems showcase exquisite mechanical properties and electric conductivity, making them appropriate for antenna elements and interconnections. CNT-based antennas have proven promising results in radiation performance and improved frequency strength operation.

Graphene, in which carbon atoms are organized in a two-layer lattice, is a promising new nanomaterial for antennas. Graphene shows high electric conductivity, flexibility and broadband electromagnetic absorption properties. Its unique properties high-performance and wideband operation [36].

Nanowires, with their nanoscale dimensions, provide great opportunities for antenna miniaturization. These extremely-thin wires, often fabricated from materials like silver, gold or semiconductor substances, can be engineered to gain preferred electrical and optical properties. Nanowire-based antennas provide flexibility in design, permitting radiation and integration with other devices or systems [37].

Nanoparticles that are mainly metallic, such as gold and silver, have attracted attention due to their plasmonic properties. These nanoparticles showcase strongly localized floor plasmon resonances, permitting improved light-matter interactions [38]. When integrated into antenna structures, nanoparticles can change the near-subject distribution, leading to improved radiation properties, sensitivity and expanded tunability. Besides these carbon-based nanomaterials and nanoparticles, different substances inclusive of nanocomposites, nanocrystals and quantum dots are being investigated for antenna packages. Nanocomposites, which consist of a matrix fabric embedded with nanoparticles or nanofillers, provide advanced mechanical strength and greater electromagnetic properties.

Nanocrystals, such as semiconductor nanocrystals or quantum dots, show off specific optical properties that can be used inside the fabrication of antennas for wavelength selectivity or optical functionality [39]. It needs to be noted that the selection of nanomaterials for antenna programs depends on the particular needs of antenna design, along with operating frequency, length constraints, radiation efficiency, environmental elements and integration of multiple nanomaterials in hybrid structures [40,41]. In conclusion, nanomaterials play an important role in improving antenna technology by offering unique properties and performance (see Table 1).

Table 1. Literature of antenna type and problems solved.

Serial Number	Type antenna	Problem solved	Ref.
1	Spherical dielectric	The suggestion of a novel approach to controlling their chiral dipolar emissions	[42]
2	Spiral	New design of spinal nanoantenna for solar energy harvesting with wavelength range from 400 to 1600 nm	[42]
3	Plasmonic nanoantenna	With designed nanoantennas can achieve Nano laser regime	[43]
4	Isolated dielectric	Tailor the scattering characteristics of nanoantennas	[44]
5	Dipole	Modeling optical of smart multi-beam cross dipole nanoantenna made by graphene with wavelength 1550 m	[45]
6	Two wire	Optimization methods that can be adapted easily for many other nanoantenna applications, facilitating the development of improved nanostructure	[46]
7	Nanorod	Model of broadside nanoantenna made of single silver nanorods with comprehensive experiments	[47]
8	Yagi–Uda	The design of the antenna is achieved with only one reflector and one direction, it is ultra-compact, cost-effective and simple in structure	[48]
9	Metal dieletric	Design of a compact hybrid metal-dielectric nanoantenna system that is based on the Yagi-Uda design	[49]
10	Yagi-Uda	Modification of conventional anti-reflection coating for improved performance of solar cells	[50]
11	Dielectric nano dimer	Comprehensive analysis of the Fairfield scattering of dielectric nano dimer antennas excited precisely by Gaussian beam	[51]
12	Nanodot array	A simple and very cost-effective design is suggested here for a plasmonic nanoantenna array used in the fabrication of metal-enhanced fluorescence	[52]
13	Plasmonic Sierpiński fractal	Design method based on an electron beam lithography with a focused helium ion beam	[53]
14	Nanolithographic Yagi-Uda	Direct electrical measurement of the nanoantenna array response	[54]
15	Yagi-Uda	The nanoantenna was designed to work and respond to a wavelength of 1550 m	[55]
16	Yagi-Uda	Optimization of the radiation and absorption characteristics of a modified Yagi-Uda nanoantenna array	[56]
17	Nanohole array	Using Au nanohole arrays as deposition masks to fabricate arrays of multi-layered composite nanoantennas	[57]
18	Yagi-Uda, Bowtie	Design combination of Yagi-Uda and Bowtie nanoantenna, experiment for wavelength 785 nm and 1500 nm	[58]
19	Diabolo	Design of a gold diabolo antenna system that shows a higher magnetic field enhancement with geometric changes compared to that of an electric field set-up	[59]
20	Yagi-Uda	Analysis of shape using particle swarm optimization algorithm to a achieve higher directivity at a wavelength of 500 nm	[60]

3.2. Properties and characteristics of nanomaterials relevant to antenna performance enhancement

Nanomaterials show off unique properties and traits that lead them to be noticeably suitable for reinforcing antenna overall performance. These properties arise from their nanoscale dimensions, surface properties and quantum effects. Here we discuss some key properties of nanomaterials appropriate for advanced antenna performance [61]. First, nanomaterials offer a higher floor-to-volume ratio, improving the interaction with electromagnetic waves.

This stronger interplay facilitates advanced radiation efficiency, increased sensitivity and higher sign reception. The big floor location of the nanomaterials allows a energy switch among the antenna and the encircling medium. Secondly, nanomaterials generally tend to have exceptional electrical properties. Materials together with carbon nanotubes, graphene and steel nanoparticles show off high conductivity, which reduces antenna structure and improves signal transmissions.

This conductivity additionally enables higher impedance matching, mainly due to stronger antenna performance and reduced mirrored image losses [62]. In addition, nanomaterials can showcase precise optical properties, together with plasmonic resonance and tunable optical response. Metallic nanoparticles and structures with plasmonic properties can modulate and control electromagnetic fields at the nanoscale. These optical traits permit for the design of antennas with stepped forward radiation patterns, beam steering competencies and enhanced interactions.

Another important belongings is mechanical flexibility. Nanomaterials like carbon nanotubes and graphene provide top notch mechanical energy and versatility, enabling the fabrication of flexible and conformal antennas. This flexibility allows for antenna integration on curved surfaces or bendy substrates, expanding the possibilities for antenna deployment in various applications [63].

Additionally, nanomaterials can show quantum outcomes, together with quantum confinement or quantum dots' length-based optical properties. These quantum consequences enable the design of antennas with precise frequency selectivity, enabling multi-band or broadband operation. The particular quantum properties of nanomaterials provide new possibilities to tailor antenna properties to unique software needs. Finally, the properties of nanomaterials, along with their excessive high surface-to-quantity ratio, electric conductivity, optical properties, mechanical flexibility and quantum results, offer possibilities for antenna performance to improve. By leveraging these properties, nanomaterials enable advanced radiation performance, enhanced sign reception, flexibility in layout and tailor-made frequency responses. These improvements make contributions to the improvement of nanoscale antenna systems for emerging Wi-Fi and biomedical applications.

3.3. Fabrication methods and integration techniques for incorporating nanomaterials into antenna systems

The successful incorporation of nanomaterials into antenna structures requires unique fabrication strategies and integration strategies to ensure the greatest overall performance and capability [64]. Here we discuss some common techniques for fabricating nanomaterial-based antennas and methods for their simple integration in antenna systems. The most extensively used synthetic technique is the deposition method, which entails the managed deposition of nanomaterials onto substrates or templates. Techniques inclusive of chemical deposition (CVD), bodily deposition (PVD) and atomic layered deposition (ALD) allow the precise deposition of controllable solid nanomaterials with high uniformity [65]. These deposition strategies are suitable for generating thin films, nanowires or nanoparticle arrays as antenna factors.

Another approach is the self-meeting technique, where nanomaterials are guided to spontaneously set up themselves into desired patterns or systems. Self-assembly techniques leverage the inherent properties of nanomaterials, inclusive of their surface chemistry or intermolecular forces, to acquire controlled meeting [66]. This technique affords flexibility, bearing in mind the fabrication of big antennas or complex 3-dimensional systems. Lithographic strategies including electron beam lithography (EBL) or photolithography are often used to appropriately outline nanomaterials [67]. These strategies can fabricate nanoscale functions and structures, ensuring precise alignment and manipulation of antenna dimensions. Lithography strategies are specifically suitable for fabricating completely nanowire-based or graphene-based antennas.

To ensure the seamless integration of nanomaterials into antenna structures, various strategies are used. One commonplace method is the transfer procedure, wherein nanomaterials are transferred from growth substrates to goal antenna substrates. This switch method ensures the preservation of nanomaterial properties and the proper alignment of antenna factors [68]. Additionally, nanomaterials may be incorporated into antenna systems through direct boom or synthesis on the antenna substrate, allowing better cloth-substrate compatibility. In [69], the antenna was designed and fabricated, the layout use polyethylene terephthalate and silver nanoparticles radiators for the helical monopole antenna which make it changed into compacted antenna

Finally, the fabrication techniques and integration strategies for incorporating nanomaterials into antenna structures are essential for accomplishing high-performance nanoscale antennas (see Figure 4). Deposition techniques, self-meeting techniques, lithography strategies and transfer techniques allow the perfect fabrication of nanomaterial-based antenna elements. Seamless integration is ensured through transfer procedures, direct growth or synthesis techniques. By making use of these fabrication and integration tactics, researchers and engineers can harness the specific properties of nanomaterials to increase antenna designs for emerging wireless and biomedical real-world applications.

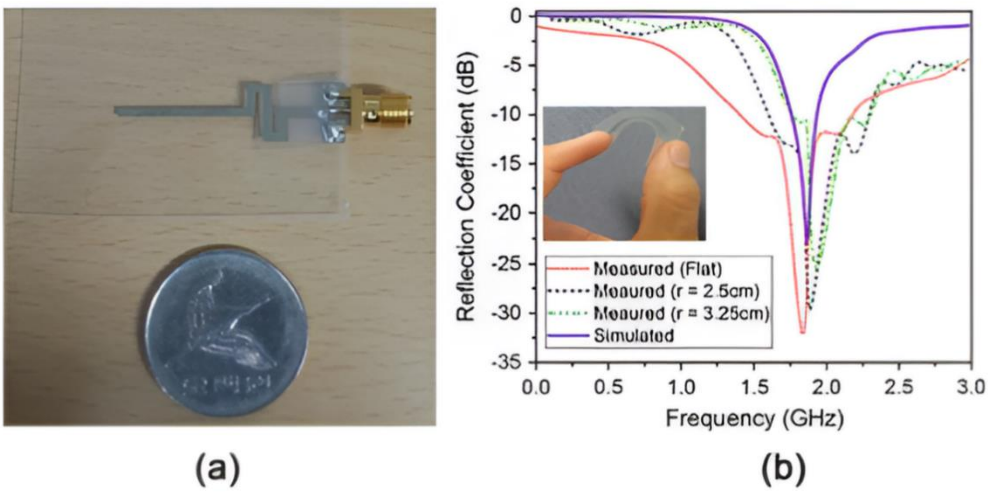

Figure 4. (a) Fabricated antenna with polyethylene terephthalate and (b) result measured in various bending conditions with simulation coefficient [69].

4. Nanoscale antennas for wireless communication applications

Nanoscale antennas have emerged as promising solutions for wireless communication systems, enabling compact and efficient antenna design. These antennas operate at the nanoscale level, and offer many advantages such as miniaturization, improved performance and compatibility with emerging wireless technologies. Thus, nanoscale antennas are designed to operate in different frequency bands such as microwave, millimeter wave [70] and the terahertz range. This antenna exhibits unique electromagnetic properties, delivering increased radiation efficiency, improved directness and reduced signal loss.

Their small size and high efficiency make nanoscale antennas ideally suited for operating devices less complex than smartphones, tablets and wearables in a limited space: (IoT enabled), 5G and beyond. The proliferation of wearable devices and the rapid improvement of the Internet of Things (IoT) have created a desire for smaller antennas that can perform in unlimited geographical locations. This antenna allows wireless communication with small gadgets that are portable, and commonly battery operated [71,72].

Miniaturized antennas for wearables and IoT applications face unique challenges due to their reduced size. These antennas must exhibit efficient radiation, wide bandwidth and good impedance matching despite their limited physical dimensions. Achieving these requirements often involves innovative design techniques and the utilization of nanoscale and metamaterial-based structures.

Nanoscale antennas, such as patch antennas, microstrip antennas and monopoles, are commonly employed in wearable devices and IoT applications [73]. These antennas can be printed on flexible substrates, integrated into clothing or accessories, or even embedded within the devices themselves. By utilizing nanoscale antenna designs, manufacturers can meet the stringent size and performance requirements of wearable devices while maintaining reliable wireless connectivity.

Furthermore, metamaterial-based antennas offer additional benefits for miniaturization. Metamaterials possess unique electromagnetic properties that enable the creation of compact and efficient antenna structures [74]. These materials can exhibit negative refractive indices, which allow for the manipulation of electromagnetic waves and the design of unconventional antenna geometries. By incorporating metamaterials into miniaturized antennas, designers can achieve enhanced performance, increased bandwidth and improved radiation properties.

Miniaturized antennas play a crucial role in enabling seamless wireless communication in wearable devices and IoT applications [75]. Their compact size, efficient operation and compatibility with nanoscale and metamaterial structures make them essential components in the advancement of connected technologies. As wearables and IoT continue to evolve, the development of miniaturized antennas will remain a focal point for researchers and engineers, driving innovation in wireless communication and enabling new applications and functionalities. The technology that involves physical medical components such as wearable device and IoT enable the tracking of health updates from the patient and will help monitor chronic disease (Figure 5) [76].

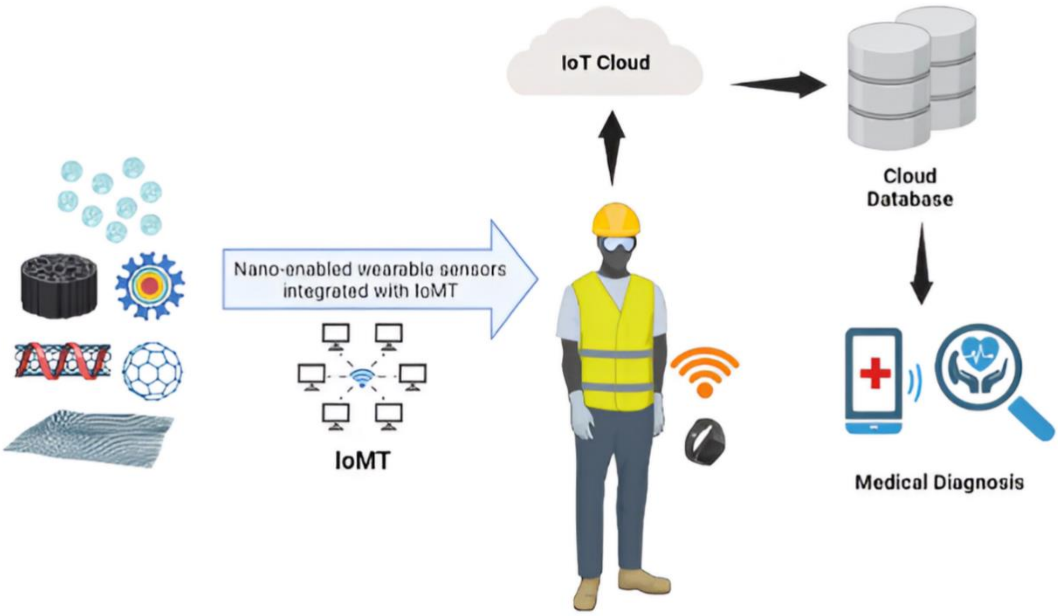

Figure 5. IoT nano wearable sensor for health care monitoring [76].

4.1. Antennas for millimeter-wave and terahertz communication systems

Millimeter-wave in addition to terahertz communication structures have attracted enormous interest because of their ability for high capability and huge bandwidth availability. Antennas designed for these frequency stages play an important role in permittingDID U PAY

Wi-Fi verbal exchange at these higher frequencies [77,78]. Millimeter-wave antennas operate within the frequency range from 30 to 300 GHz, and terahertz antennas as much as 300 GHz [79]. These frequencies provide benefits such as wide bandwidth and high statistics rate, suitable for programs that include 5G communications, wireless backhaul and future Wi-Fi standards. Designing antennas for millimeter-wave and terahertz frequencies poses specific challenges due to their short wavelengths and elevated sensitivity to fabrication imperfections. Achieving efficient radiation, true impedance matching and extensive bandwidth calls for cautious design and the usage of superior technologies [79].

Various antenna designs were proposed for millimeter-wave and terahertz communication structures, along with microstrip antennas, slot antennas, horn antennas and waveguide antennas [80]. These systems are designed to perform optimally on this high-frequency range, considering the specific properties of electromagnetic waves in these frequencies. In addition to this, technology along with beamforming and phased array structures are typically used to improve the performance of millimeter-wave and terahertz antennas. These strategies permit beam steerage, spatial multiplexing and increased coverage variety, addressing the demanding situations of route loss and constrained range related to higher-frequency communications. As millimeter-wave and terahertz communication systems increase, the development of small antennas will become paramount. These antennas play a key role in ensuring reliable and high-speed wireless communications and pave the way for new applications and innovations in areas such as wireless networks, IoT, imaging and sensing.

4.2. Antenna designs for compact wireless devices with constrained form factors

Compact Wi-Fi devices, along with smartphones, drugs and wearable gadgets, often have stringent shape necessities that pose demanding situations for antenna design [81]. These devices call for miniaturized antennas that could operate effectively inside restricted bodily areas whilst maintaining reliable wireless connectivity.

Designing antennas for compact Wi-Fi devices calls for careful consideration of length, efficiency and radiation properties. Various antenna designs have evolved to satisfy those necessities, which include planar inverted F antennas (PIFAs), meandered antennas, chip antennas and folded dipole antennas. These designs are characterized with the aid of their compact size and potential to match the restrained form elements of transportable gadgets. Moreover, superior techniques inclusive of antenna integration, multiband and wideband designs and compact antenna arrays are hired to similarly optimize the overall performance of antennas in compact gadgets. These techniques ensure efficient radiation, large bandwidth and reliable wireless communication at the same time as meeting the size obstacles imposed by way of the device's form component. In addition to design concerns, fabric choice and fabrication techniques play critical roles in developing antennas for compact wireless devices. Utilizing materials with high permittivity or permeability, in addition to advanced production techniques like microelectromechanical systems (MEMS) and additive manufacturing, enables the introduction of miniaturized antennas with advanced performance.

Efficient and compact antenna designs for wireless devices with constrained form factors are essential for seamless wireless connectivity and optimal performance. As portable devices continue to evolve and become more integrated into our daily lives, the development of antennas that meet the requirements of size, efficiency and reliability remains a critical area of research and innovation.

The integration of nanoscale antennas into wearable devices has revolutionized both wireless communications and biomedical applications. Recent review shows that these miniature antennas, operating at the nanoscale, have brought unprecedented advancements to the functionality and utility of wearables in healthcare. In the realm of wireless communications, nanoscale antennas enable wearables to establish seamless connectivity with other devices and networks. Due to their compact size and efficient radiation properties, these antennas overcome the limitations of space constraints in wearables while ensuring reliable data transmission. This paves the way for real-time health monitoring, data synchronization and remote diagnostics, enhancing the overall effectiveness of wearable devices in healthcare settings [82].

Moreover, the impact of nanoscale antennas extends significantly to the biomedical domain. Their ability to operate in confined spaces and interact with biological materials has led to innovative solutions for diagnostic and therapeutic purposes. Nanoscale antennas integrated into wearables can facilitate non-invasive monitoring of vital signs, such as heart rate, temperature and glucose levels. They also enable the collection of high-resolution data that can be analyzed for disease detection and management. Furthermore, these antennas enable the concept of "smart" wearables that interact with the human body at a cellular level. They can facilitate targeted drug delivery, monitor biomarkers and aid in the development of personalized medicine approaches. This integration of nanoscale antennas not only enhances the diagnostic accuracy and treatment efficacy of wearables but also opens doors to novel applications in areas such as tissue engineering and regenerative medicine [83].

In essence, the incorporation of nanoscale antennas for wireless communications in wearable devices has had a transformative impact on their biomedical applications. The convergence of wireless connectivity, nanotechnology and healthcare has ushered in an era of wearable devices that not only enhance communication but also contribute significantly to the advancement of medical science and patient care.

5. Nanoscale antennas for biomedical applications

Nanoscale antennas have emerged as promising technologies for biomedical applications, offering unique capabilities for wireless communication, sensing and imaging in biological systems [84]. Nanoscale antenna incorporation into biomedical devices opens new avenues for diagnosis, treatment and physiological monitoring. One of the major areas where nanoscale antennas are finding significant utility is in implantable medical devices. These gadgets, which include pacemakers, neurostimulators and drug delivery devices, require reliable wireless communications for records transmission, energy switch and remote control [85]. Nanoscale antennas, because of their small size and high performance, can be without problems connected wirelessly, decreasing the want for cumbersome outside additives. Another essential application of nanoscale antennas in biomedicine is biosensing systems. These systems use the unique properties of nanoscale antennas to discover and display biomarkers, pathogens and different biological dealers [86]. By integrating nanoscale antennas into biosensors, it's more feasible to wirelessly transmit real-time information from sensing factors into external devices for evaluation and diagnosis. Thus, it turns out that fast, non-invasive monitoring of plenty of fitness statistics and enhancing patient care and diseases, is controlled. Nanoscale antennas also play a significant role in biomedical imaging techniques by incorporating nanoscale antennas into imaging probes or contrast agents [87], making it possible to enhance imaging resolution, sensitivity and specificity. These antennas can have interaction with electromagnetic waves to supply superb photos, allowing higher visualization of organic systems, mobile methods and molecular interactions by means of programs in areas including cancer imaging, drug delivery research and cellular biology research (Figure 6) [88]. Furthermore, nanoscale antennas provide the gain of being highly compatible with nanomaterials and nanofabrication strategies. This results in the improvement of multifunctional nanoscale antenna systems that may be integrated with one-of-a-kind nanomaterials, including nanoparticles or nanowires, to enhance overall performance.

In the end, nanoscale antennas maintain extremely good capacity in biomedical applications (see Figure 7). Their small length, performance and compatibility with nanomaterials lead them to be perfectly suited for Wi-Fi communication, sensing and imaging in biomedical gadgets and platforms. Continued research and improvement in this subject, which has revolutionary ability, is anticipated to result in more development and applications of nanoscale antennas in biomedicine.

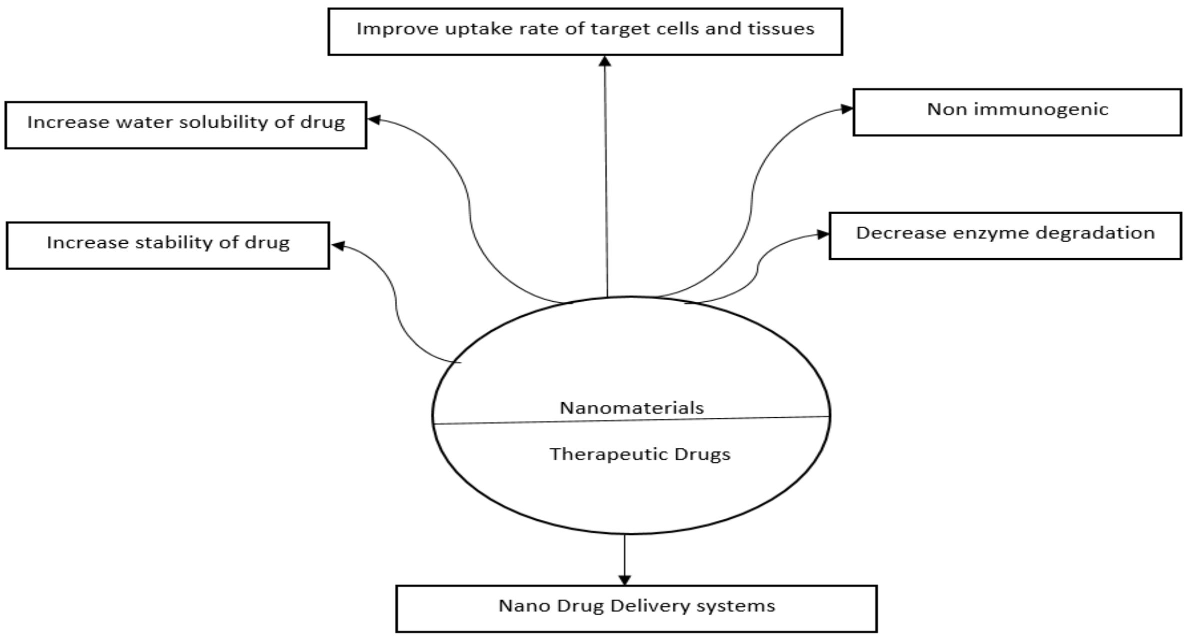

Figure 6. Characteristics of nanomaterials required for application of nano drug delivery system.

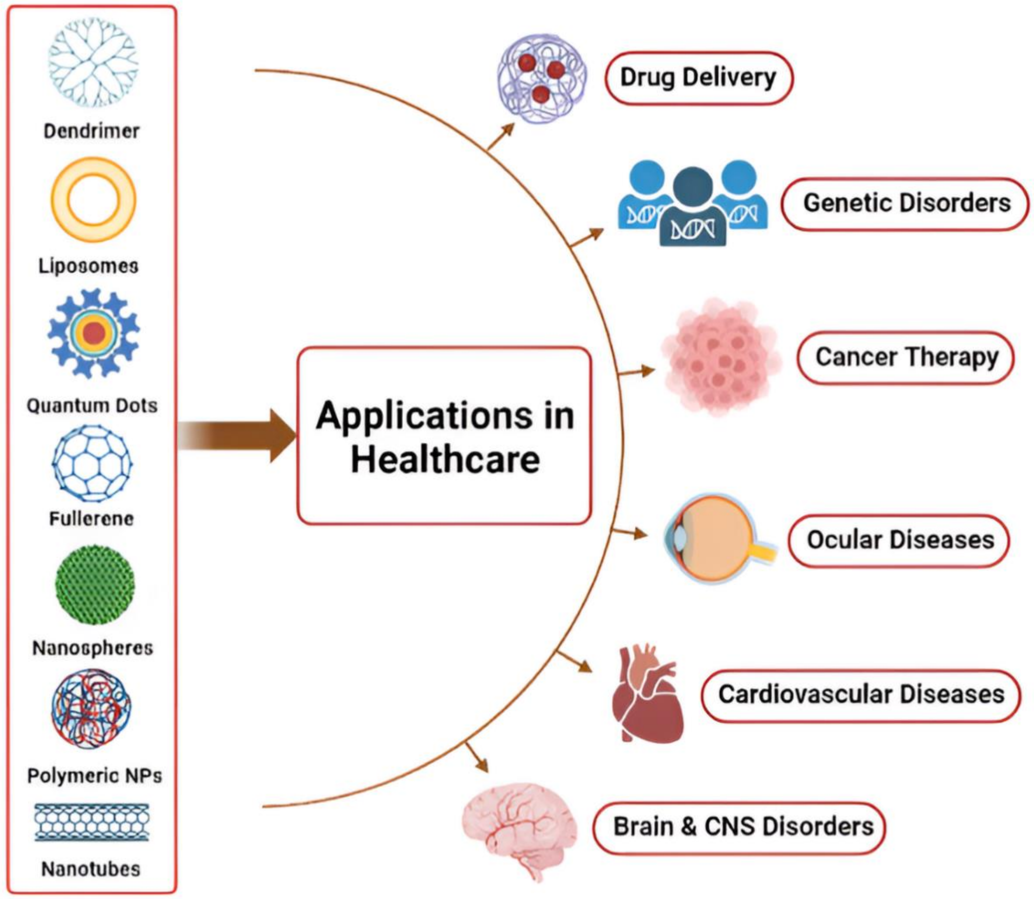

Figure 7. Graphic representation of many Nano systems for biomedical [88].

5.1. Integration of antennas into implantable medical devices and bio-sensing platforms

The integration of antennas into implantable clinical devices and bio-sensing systems is a vital element of making use of nanoscale antennas in biomedical programs. Implantable clinical gadgets, such as pacemakers, neural stimulators and drug delivery systems [89], require miniaturized antennas to enable Wi-Fi communication with external gadgets. These antennas must be carefully designed and integrated into the device structure to ensure efficient wireless data transmission and power transfer.

For bio-sensing platforms, antennas play a crucial role in wirelessly transmitting the data collected by the sensing elements to external devices for analysis and diagnostics [90]. The integration of nanoscale antennas into these platforms allows for real-time monitoring of various health parameters without the need for wired connections, providing convenience and minimizing patient discomfort.

The integration process involves careful consideration of factors such as antenna size, compatibility with the surrounding biological environment and power efficiency. Advanced fabrication techniques, including microelectromechanical systems (MEMS) and additive manufacturing, are employed to ensure precise integration of antennas into the desired locations of the biomedical devices or sensing platforms. In [91], an implantable biomedical fluid whose size is in the millimeter range was developed (Figure 8a) with tiny bio-bot skeletal muscle cells (Figure 8b) done by [92]. The magnetic helical can be observed in a single cell of human embryonic kidney genes (Figure 8c) by [93]. This shows the level of research done with implanted medical devices.

Therefore, by successfully integrating antennas into implantable medical devices and bio-sensing platforms, it is possible to harness the capabilities of nanoscale antennas for wireless communication, remote monitoring and real-time data transmission. This integration enables improved patient care, enhanced diagnostics and the development of advanced biomedical technologies.

Implantable and biocompatible nanoscale antennas are garnering attention for their potential in biomedical applications. The suitability of these antennas for implantation depends on factors like their size, material composition and potential interactions with biological tissues. Biocompatibility ensures minimal immune response and long-term integration within the body [90]. When selecting nanoscale antennas for biomedical use, factors like frequency range, size and sensitivity are crucial. Compatibility with imaging techniques and the ability to target specific tissues influence antenna choice. However, challenges such as heating effects and potential interference with biological processes must be addressed to avoid adverse effects. Implantable antennas can introduce complications like tissue damage, heating or interference with medical devices. Balancing these risks with potential benefits is vital. Enhancing efficiency involves optimizing antenna design for maximum power transmission and reception, minimizing energy loss and addressing heat dissipation issues. Advanced materials, innovative designs and careful tuning can improve antenna performance. In conclusion, the quest for implantable and biocompatible nanoscale antennas holds promise in revolutionizing biomedical applications [91]. Selecting suitable antennas, mitigating risks and improving efficiency will drive progress in this transformative field.

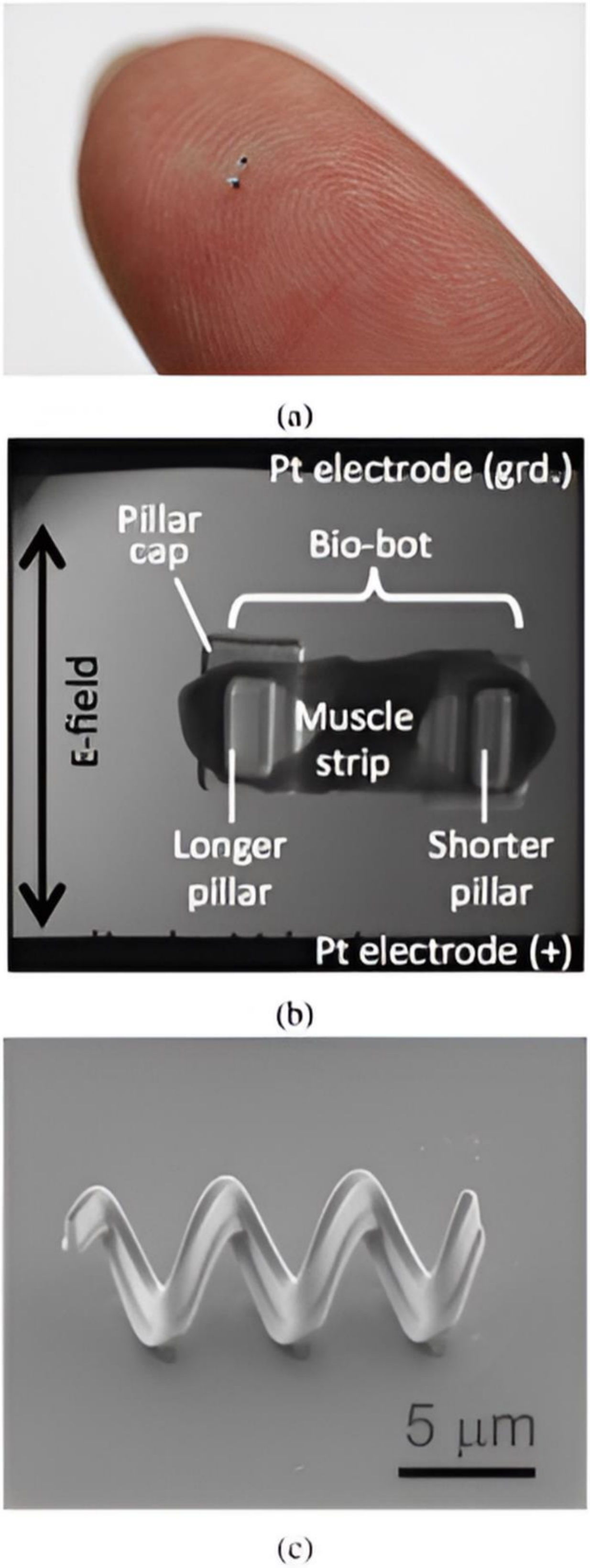

Figure 8. Picture of an implantable medical device in the human body: (a) nano scallop that swims in biofluid, (b) bio bot powered by skeletal muscle cell and (c) artificial bacteria flagella [93].

5.2. Biocompatible materials and fabrication techniques for biomedical antennas

When designing antennas for medical applications, it is important to consider biologically compatible materials and appropriate manufacturing processes. The materials and construction techniques used, play an important role in ensuring that antennas are compatible with the natural environment, as well as functional and durable. Biocompatibility is important to preventing adverse reactions or neural reactions when antennas are in contact with the human body. Materials that include scientific polymers, ceramics and biocompatible metals inclusive of gold or titanium are typically used for biomedical antennas. These substances have shown true biocompatibility, low toxicity and high stability in the body. Methods for biomedical antennas have to account for the precise needs of the utility and the preferred antenna configuration. Various techniques such as microfabrication, thin film deposition and 3D printing are used to fabricate antennas with precise sizes and configurations suitable for biomedical applications [94]. These techniques allow the fabrication of smaller antennas that can be used in smaller devices to be integrated into physiological sensing platforms.

Another important consideration is the antenna performance in biomedical environments. The presence of body tissues, fluids and wireless implants can significantly impact the performance of antennas. The propagation characteristics of electromagnetic waves can be affected by the complex dielectric properties of tissues, leading to signal attenuation, reflection or distortion. Antenna design must take into account these factors to optimize antenna performance in biomedical environments. Advanced simulation and modeling techniques, such as finite element analysis (FEA) and electromagnetic field simulation, are used to predict and analyze the antenna performance in specific biomedical environments [95]. These tools help in understanding the electromagnetic interactions between the antenna and the surrounding tissues or implants, allowing for the optimization of antenna design parameters.

There are more cases of nanoscale assisted therapy that have shown promise, like hyperthermia treatment, where targeted tissues are heated to destroy cancer cells. By integrating these antennas into wearable devices, controlled heating of specific regions within the body becomes feasible [96]. The antennas can absorb electromagnetic energy and convert it into localized heat, effectively damaging cancer cells while sparing healthy tissue. Such a non-invasive approach holds potential for enhancing the effectiveness of cancer treatments and minimizing side effects.

Nanoscale antennas embedded in wearable devices can play a crucial role in neuromodulation therapies for pain management. These antennas can interact with neurostimulation systems, delivering electromagnetic signals to targeted neural pathways. By fine-tuning the frequencies and intensities of these signals, wearable devices can help alleviate chronic pain conditions such as neuropathy or migraines. This novel approach offers patients a more tailored and adjustable solution, minimizing the need for invasive procedures [97]. Reference [98] elucidated the role of nanotechnology in controlling superior peroxidase-like activity and catalysis across a broad range of pH values and temperatures, comparable to that of natural enzymes.

Finally, the selection of biocompatible materials and appropriate fabrication techniques are critical for the successful development of biomedical antennas. These antennas must be able to function effectively within the biological environment, while also meeting the requirements of wireless communication, sensing or imaging. By using biocompatible materials and employing suitable fabrication methods, antennas can be designed to ensure compatibility, performance and long-term functionality in biomedical applications.

6. Measurement techniques for nanoscale antennas

Accurate measurement techniques are crucial for evaluating the performance of nanoscale antennas. Due to their small size and intricate structures, specialized measurement methods are required to capture their radiation properties and electrical characteristics. Common measurement techniques include near-field scanning, remote sensing and vector network analyzers (VNAs). Near-field scanning techniques, such as near-field scanning optical microscopy (NSOM) or near-field scanning microwave microscopy (NSMM), characterize the electrical distribution and near-field radiation patterns of nanoscale antennas enabling them to be optimized. These techniques provide valuable insights into the antenna's behavior at proximity, allowing for detailed analysis and optimization [99]. Far-field measurements are employed to determine the antenna's radiation pattern, gain and directivity. These measurements involve placing the antenna in the far-field region of an antenna measurement system and analyzing the radiated electromagnetic waves. Far-field measurement setups, such as anechoic chambers or compact antenna test ranges, are commonly used for accurate characterization.

Vector network analyzers (VNAs) are instrumental in evaluating the impedance matching and overall electrical performance of nanoscale antennas. VNAs allow for precise measurement of S-parameters, reflection coefficients and transmission coefficients, providing insights into the antenna's efficiency, bandwidth and impedance-matching capabilities [100].

6.1. Characterization of radiation patterns, gain, efficiency and impedance matching

Characterizing the radiation patterns, gain, efficiency and impedance matching of nanoscale antennas is crucial to understanding their performance. Radiation patterns determine the directionality and spatial distribution of the radiated electromagnetic waves. Techniques such as pattern measurements using scanning systems or holographic methods are employed to visualize and analyze the radiation patterns of nanoscale antennas [101]. Gain is a measure of the antenna's power radiated in a particular direction compared to a reference antenna. It quantifies the antenna's ability to concentrate radiation in a specific direction. Gain measurement techniques, such as the standard gain method or the three-antenna method, are utilized to determine the gain of nanoscale antennas.

Efficiency measures the effectiveness of converting electrical power into radiated electromagnetic waves. It is determined by evaluating the power radiated by the antenna compared to the power supplied to it. Efficiency characterization involves careful power measurements and considerations of losses in the antenna system [102].

Impedance matching is essential to optimize the transfer of power between the antenna and the transmission line or device. Characterization of impedance matching involves measuring the reflection coefficient, input impedance and return loss of the antenna. Techniques like network analysis or Smith chart measurements are used to evaluate the impedance-matching capabilities of nanoscale antennas.

6.2. Evaluation of performance parameters in different application scenarios

The evaluation of performance parameters for nanoscale antennas in various application scenarios is vital to assess their suitability and effectiveness. Different application scenarios may have specific requirements and constraints, such as frequency bands, communication distances or environmental conditions.

Performance evaluation involves analyzing parameters like gain, efficiency, bandwidth, directivity and radiation pattern stability in different scenarios. For wireless communication applications, the evaluation may focus on factors like signal strength, signal-to-noise ratio or data transmission rates [103].

In biomedical applications, performance evaluation may involve assessing the antenna's compatibility with biological tissues, sensitivity to interference or the ability to penetrate body tissues for wireless implant communication or bio-sensing.

By evaluating performance parameters in different application scenarios, researchers and engineers can optimize the design and operation of nanoscale antennas to meet specific requirements and achieve desired performance levels.

7. Case studies and applications

The successful implementation of nanoscale antenna systems in emerging wireless and biomedical applications has led to groundbreaking advancements and transformative solutions. Several examples demonstrate the efficacy and impact of these systems in addressing key challenges and pushing the boundaries of technology [104]. For wireless communications, nanoscale antenna systems have made it possible to design compact and efficient devices. For example, in emerging wearable technologies, smartwatches and fitness trackers have been equipped with nanoscale antennas to provide seamless wireless connectivity while maintaining a small form factor. These antennas ensure portable connectivity reliability and efficient data transfer, enhance the user experience and enable the Internet of Things (IoT) ecosystem [105].

In the biomedical realm, nanoscale antenna systems have revolutionized healthcare applications. One notable example is the inclusion of nanoscale antennas in implantable medical devices. These antennas facilitate wireless communication between the device and external systems, enabling real-time monitoring, control and data transmission. This breakthrough technology has paved the way for advancements in remote patient monitoring, enabling healthcare providers to closely monitor patients' vital signs and adjust treatments accordingly [106].

Furthermore, nanoscale antenna systems have found applications in biosensing platforms. By utilizing the unique properties of nanomaterials, such as their high sensitivity and selectivity, these antennas enable precise detection and analysis of biological signals. They have been used in biosensing devices for applications such as biomarker detection, enzyme reaction monitoring and DNA sequence analysis. These developments could have a profound impact on diagnosis, drug development, and personalized medicine.

These case studies exemplify the successful implementations of nanoscale antenna systems in emerging wireless and biomedical applications. The integration of these antennas has revolutionized wireless communication, improved healthcare monitoring and enhanced biosensing capabilities. As research and development in this field continue, we can expect further advancements, driving innovation and transforming various industries.

7.1. Real-world use cases highlighting the advantages and challenges of nanoscale antennas

Real-world use cases have provided valuable insights into the benefits and challenges related to nanoscale antennas. The fundamental advantage is their compact length, which lets them be integrated into smaller gadgets without compromising performance. For instance, in wearables, nanoscale antennas have been effectively utilized in smartwatches, fitness trackers, and various portable devices, enabling seamless communication while also maintaining a sleek and functional design for efficient performance. [107]. Another advantage lies in the enhanced performance of nanoscale antennas. By leveraging the unique properties of nanomaterials, such as their high conductivity and tunability, these antennas exhibit improved efficiency, broader bandwidth and higher gain compared to conventional antennas. This translates to better signal quality, increased data transfer rates and extended communication range, which are crucial in various applications ranging from wireless communication networks to biomedical sensing systems [108].

However, nanoscale antennas also pose certain challenges. One significant challenge is related to fabrication and integration. Fabricating nanoscale antennas requires sophisticated techniques, such as electron beam lithography or chemical doping, which can be time-consuming and expensive, in addition to careful design considerations to ensure optimal performance and compatibility with other materials to integrate nanoscale antennas into practical devices [109].

Moreover, nanoscale antennas can be susceptible to environmental factors and interference. For instance, in wireless communication systems, signal degradation and interference from surrounding objects or materials can impact the performance of nanoscale antennas. Therefore, careful consideration of the operating environment and effective shielding techniques are essential to mitigate these challenges.

Real-world use cases have demonstrated the advantages of nanoscale antennas in terms of size, performance, and integration. However, addressing the fabrication complexities and environmental challenges remains crucial for the widespread adoption of these antennas in various applications [110]. Continued research and development efforts are essential to further optimize nanoscale antenna designs, improve their reliability and explore innovative solutions to overcome existing challenges.

8. Conclusion and outlook

In conclusion, this comprehensive review paper has highlighted key findings and made significant contributions to the field of nanoscale antenna systems in emerging applications within wireless communication and biomedical domains. Through our exploration, we have uncovered important insights and paved the way for future advancements in this exciting field.

Key findings:

- Nanoscale antennas play a crucial role in enabling wireless communication and biomedical applications, offering unique advantages such as miniaturization and enhanced performance.

- Nanomaterials, including carbon nanotubes, graphene, nanowires and nanoparticles, exhibit properties that can improve antenna performance, opening up new possibilities for design and fabrication.
- Design considerations for nanoscale antennas include addressing miniaturization challenges, selecting appropriate frequencies and managing trade-offs between size, bandwidth, efficiency and radiation properties.
- Integration of antennas into wearable devices, Internet of Things (IoT) applications and biomedical platforms presents novel opportunities for wireless communication and healthcare technologies.
- Characterization techniques allow for the evaluation of nanoscale antenna performance, including radiation patterns, gain, efficiency and impedance matching, providing valuable insights for optimization and design improvement.

Future directions and potential advancements:

- Further research and development are needed to explore advanced nanomaterials, fabrication techniques and design methodologies to enhance the performance and capabilities of nanoscale antenna systems.
- Power efficiency and energy harvesting techniques should be investigated to enable sustainable and autonomous operation of nanoscale antenna systems.
- Ensuring the reliability and robustness of nanoscale antennas in dynamic environments is crucial for their successful deployment in real-world applications.
- Integration of nanoscale antennas with advanced wireless communication protocols and networks, such as 5G and beyond, will enable seamless connectivity and enhanced performance.
- Exploring the potential of nanoscale antennas in emerging fields, such as the Internet of Medical Things (IoMT) and smart healthcare systems, holds promise for revolutionizing healthcare delivery and monitoring.

Finally, this assessment paper gives key findings and insights related to the layout, substances, applications and overall performance of nanoscale antenna systems. It identifies future directions and possible improvements, and highlights the need to proceed to conduct research and development to unlock the potential of nanoscale antennas in wireless communications and biomedical fields. With continued development, nanoscale antenna systems are poised to define the future of wireless technology and biomedical applications, driving innovation and improving lives.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest

Author Contributions:

Akinola did the survey and write up while Reddy did the editing and correction.

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