Review

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Material advancement in technological development for the 5G wireless communications

Abstract: The rapidly increasing number of mobile devices, voluminous data, and higher data rate is pushing the development of the fifth-generation (5G) wireless communications. The 5G networks are broadly characterized by three unique features: ubiquitous connectivity, extremely low latency, and very high-speed data transfer via adoption of new technology to equip future millimeter band wireless communication systems at nanoscale and massive multi-input multi-output (MIMO) with extreme base station and device densities, as well as unprecedented numbers of nanoantennas. In this article, these new technologies of 5G are presented so as to figure out the advanced requirements proposed for the nanomaterials applied to antennas in particular. Because of massive MIMO and ultra-densification technology, conventional antennas are unable to serve the new frequency for smaller sizes, and the nanoantennas are used in 5G. The nanomaterials for nanoantennas applied in wideband millimeter waves are introduced. Four types of nanomaterials including graphene, carbon nanotubes, metallic nanomaterials, and metamaterials are illustrated with a focus on their morphology and electromagnetic properties. The challenges for the commercialization of 5G and nanomaterials are also discussed. An atomistic modeling approach is proposed for the development of novel nanomaterials applied in 5G and beyond.

Keywords: 5G wireless communications, nanoantennas, nanomaterials, electromagnetic properties

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1 Introduction

The scientific and technological development of wireless communications benefits to the community and people in their daily life [1–3]. Progress and demand in society, in turn, propel the innovation and development of wireless communications systems. In the next decade, a mobile traffic may increase thousands of times, and billions of connections for communicating devices are expected compared to what we are experiencing today [3,4]. Moreover, the rapid development of essential services including electronic banking, electronic education, electronic health, and electronic commerce causes a large growth in data volume and requires low latency and high reliability to support applications [2,5,6]. On-demand information and entertainment using reality and virtual reality are progressively delivered and spread via wireless communication systems [7,8]. A wide range of data rates has to be supported up to multiple gigabits per second, and tens of megabits per second need to be guaranteed with high availability and reliability [7,9,10]. The 5G wireless communications based on the fourth-generation (4G) can be developed to meet the required performance need.

The 5G wireless communications are a converged system with multiple radio access technology integrated [11–13]. Figure 1 shows a summary of the novel technology applied in 5G. Compared with existing 4G, 5G supports high frequencies and spectrums. The 5G wireless can work on millimeter waves of 30–100 GHz [14]. The 5G wireless communications can offer tremendous data capabilities, unrestricted call volumes, and infinite data broadcast [5,15]. There is a significant improvement in terms of signaling, management, and accounting procedures in the 5G communications, thereby they can accommodate needs from diverse applications outside the traditional mobile broadband category [16]. Technologies such as MIMO can significantly improve the air interface spectrum efficiency. The application of MIMO can enhance connectivity and promote speed in data access. The increase in the computing power in 5G ensures a low latency of about 1 ms [14]. The devices can enjoy virtually
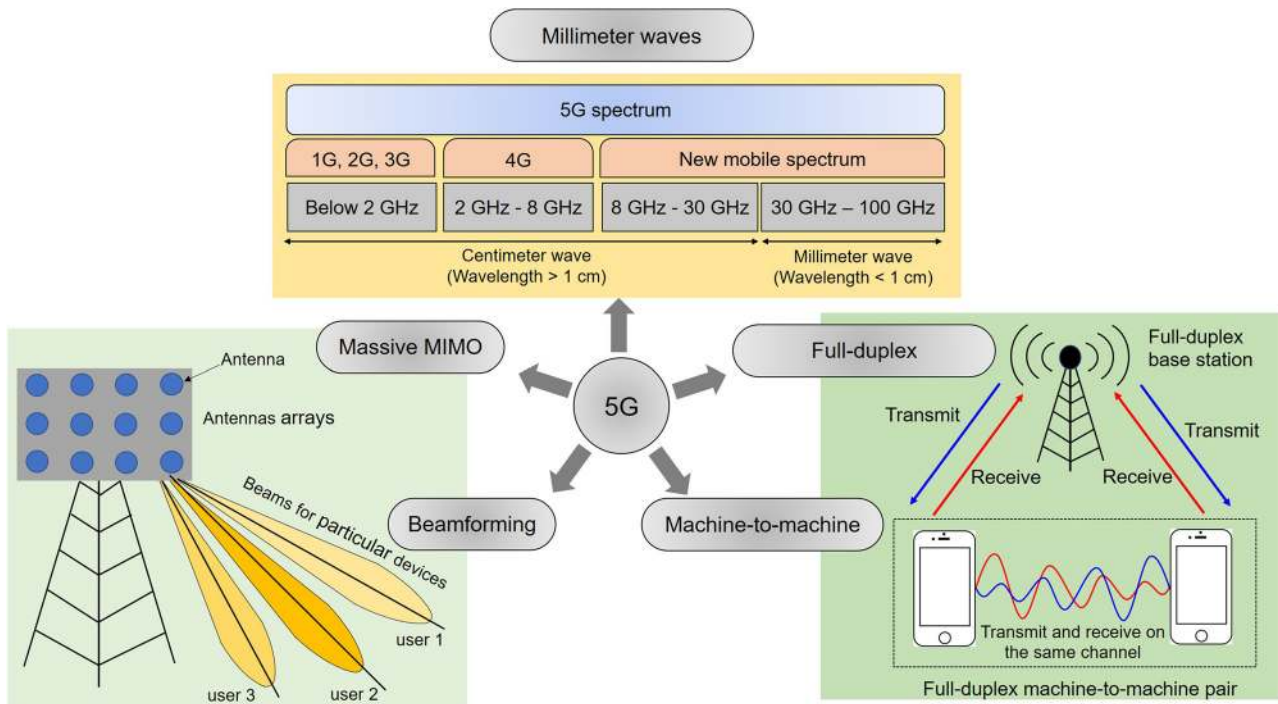
Figure 1: Advanced technologies including millimeter waves, massive MIMO, beamforming, full-duplex, and machine-to-machine applied in 5G wireless communications making it smarter, faster, and more efficient.

instantaneous speed on connecting to the network. The reduced latency, high data speed, ultra-reliability, and massive connectivity of the 5G wireless communications can drastically change our lives and enable a new generation of applications, services, and business opportunities [9]. For example, low latency communications open up a new world for remote medical care, procedures, and treatment. Other advanced technologies include beamforming which focuses on a wireless signal in a specific direction rather than broadcasting to a wide area, full-duplex that is able to transmit and receive data at the same time, and machine-to-machine that enables the handling of billions of nodes [17].

When the operating frequency of systems increases to millimeter waves, the miniaturization degree of components continuously grows with multiple antennas included. Nanotechnology, which provides a set of tools to create nanoscale components, has been widely used in the 5G wireless communications [18–20]. The physical size of antennas is similar to that for 4G, whereas the individual element size is smaller allowing more elements due to the application of MIMO technology. Integrating several of these nanocomponents into a single microsize device can enable the development of more advanced nanodevices with unique properties and further allow these devices to achieve complex tasks in a distributed manner [11]. As the device is reduced to the

nanoscale, the size effect is obvious, causing a significant increase in heat consumption, and a dramatic degradation in stability and reliability [21]. The small size of nanomaterials also confines the charge excitations and movements within the nanomaterials, discretizing continuous electronic structures and gradually changing optical spectra abrupt [22]. Nanomaterials can interact with the electric field, the magnetic field, or both the fields, and the performance of wave absorption is significantly enhanced in nanomaterials [23]. Nanomaterials can be utilized for microwave absorption and to drive the interaction between light and matter at the gigahertz region of the electromagnetic spectrum [22]. The electromagnetic response of nanomaterials is determined by the permittivity and permeability, correlated with the energy storage and dissipation. Specifically, the real portion of permittivity and permeability mainly determines the amount of loss of reflection at the air–nanomaterial interface. The microwave energy reflected by the interface between air and nanomaterials accounts for a little proportion of the total energy, and the most proportion of microwave energy is reflected by the substrate [24]. The most important properties of microwave absorbing are the imaginary portion of permittivity and permeability for nanomaterials. The interaction between the nanomaterial and the

electromagnetic wave unavoidably causes the loss of microwave radiation including the dielectric loss and the magnetic loss. The dielectric loss and the magnetic loss are quantified by the imaginary portion of permittivity and permeability, respectively. The dielectric and magnetic losses are associated with the loss of electric and magnetic field energy that are dissipated as heat, and they can be used to evaluate the attenuation of electromagnetic waves [25]. The maximum dielectric loss is associated with the dielectric resonance of nanomaterials, and the maximum magnetic loss is associated with the magnetic resonance of the nanomaterial. Traditional materials such as metal and semiconductors are no longer appropriate. The development of advanced nanomaterials for high-frequency operation and miniaturized ultra-high-speed electronic devices is critical. Establishing the relationship between the nanostructure and the properties of nanomaterials is necessary for designing and synthesizing nanomaterials with promising performance.

Both experimental and modeling approaches have been employed to figure out the relationship between the structure and the properties of materials at nanoscale. Specifically, a modeling scheme using molecular dynamics (MD) simulations that can depict atomistic interactions inside the material system provides a powerful approach for evaluating atomistic movements based on material science and inherent behaviors of actual materials [26–29]. MD simulations can serve as an effective computational experiment for characterizing material responses, predicting properties, and verifying theoretical hypotheses [30–32]. MD simulations have been successfully applied in building bottom-up models starting from the chemical structure of basic constituents and in predicting the behavior of constitutive molecules out of the current capability of experiments [33–37]. Compared with experimental approaches, MD simulations provide a theoretical foundation for developing materials that have unique properties due to their nanoscale dimensions and for assembling smaller components into complex nanodevices with improved and sometimes novel properties and characteristics.

This article reviews the advanced technologies, especially nanotechnology applied in the 5G wireless communications, as well as the recent progress in nanomaterials and their behavior. Advanced technologies applied in 5G such as millimeter waves and massive MIMO are represented, and the corresponding demands for nanomaterials applied in nanoantennas that are critical for receiving and transmitting radio waves have been discussed. Four promising nanomaterials, namely, graphene, carbon nanotubes (CNTs), metallic nanomaterials, and metamaterials for nanoantennas are discussed with emphasis on the relationship between the structures and their excellent performances. Finally, the current challenges and limitations for the commercialization of the 5G wireless communications are addressed. The potential of MD simulations that are important for the future development of nanomaterials is also discussed. The review of nanotechnology and nanomaterials applied in 5G devices provides a solid knowledge base for accelerating the development of 5G technology.

2 Key technologies for the 5G wireless communications

2.1 Millimeter waves

One fundamental technique of the 5G wireless communications is the use of spectrum at frequencies above 8 GHz. Previously cellular networks, including 1G, are operated at a frequency of 850 and 1,900 MHz [38]. 2G and 3G networks are then operated at additional frequency bands and spectrum around 2,100 MHz, and 4G technology is operated at additional frequency bands and spectrum around 600 MHz, 700 MHz, 1.7 GHz, 2.1 GHz, 2.3 GHz, and 2.5 GHz [39,40]. Currently, the range of frequencies extending from several hundred MHz to a few GHz is nearly fully occupied [4]. More frequencies are needed to allow increased capacity for mobile networks [41,42]. The only way forward is to make use of high frequency. The high radio frequency known as millimeter waves has been adopted in 5G allowing for a massive increase in transmission speeds [43,44].

Millimeter waves are mainly suitable for short-range transmission compared with traditional bandwidths. The greater the attenuation that describes the amplitude of a signal decays over distance is, the shorter the waves travel [45]. Furthermore, millimeter wave signals exhibit reduced diffraction and a more specular propagation than their microwave counterparts, and hence, they are much more susceptible to blockages [4]. Millimeter waves are more easily obstructed by the walls of buildings, trees, and other foliage, and even inclement weather. The signal of mobile terminals in the 5G wireless communications is easily interfered with by surrounding metal devices [44]. Macro base stations spaced many miles apart are sufficient for signal transmission in the 4G wireless communications;

however, in the 5G wireless communications, the range of base station towers is far lower, and the size of the base station can be reduced in the 5G wireless communications. Considering the short travel distance for 5G, macro base stations still connect in the frequency range of less than 6 GHz, and numerous miniature base stations composed of nanodevices that operate at millimeter wave frequencies are distributed and connected [46]. The 5G wireless communications no longer depend on the construction of large-scale base stations as 3G and 4G did, but instead use many miniature base stations to complement traditional cellular towers. Such highly densified miniature base stations provide an efficient solution to the short transition of millimeter waves.

2.2 Massive MIMO antennas

Massive MIMO systems where macro base stations are equipped with antenna arrays can accurately concentrate transmitted energy to mobile devices [43]. A massive MIMO system comprises an array of hundreds of antennas simultaneously serving multiple user terminals [47,48]. Each single-antenna user in a massive MIMO system can scale down its transmit power proportional to the number of antennas at the macro base stations to achieve the same performance as a corresponding single-input single-output system [49]. Massive MIMO has allowed multiple orders of magnitude in the improvement of energy efficiency, data speed, and capacity [50] as well as enhanced link reliability and coverage [7]. For example, numerical averaging over random terminal locations has shown that approximately 95% of terminals can receive a throughput of 21.2 Mb/s per terminal, whereas the array antennas offer a downlink throughput of about 20 Mb/s for 1,000 terminals [47].

Compared to a single antenna transmitting and receiving the signal in all directions for 4G, the massive MIMO in the 5G network enables the energy radiation in the intended directions through beamforming and beamsteering, which can reduce intercell interference [51]. A directional beam can reduce power consumption as all radio frequency signals are targeted toward a receiving unit instead of being scattered in all directions [52]. The directional beam is obtained using an array of antennas allowing the beam to be guided through a combination of constructive and destructive interference and to focus the signal on a specific device [46]. As there

are arrays of multiple antennas embedded in multiple dispersed base stations, a larger number of individual antennas are required for the 5G network [53]. Moreover, the performance of massive MIMO systems is generally less sensitive to the propagation environment than in point-to-point MIMO [49]. Beamforming can help massive MIMO arrays to make more efficient use of the spectrum around them with reduced latency.

These two critical evolutionary technologies for the 5G wireless communications, namely, the adoption of millimeter waves and massive MIMO antenna arrays for beamsteering unavoidably engender substantial challenges for antenna systems [54]. Conventional antennas in portable devices, such as those found in 4G terminals, are not suitable for millimeter waves. Antennas for the 5G wireless communications are easily affected by surrounding components such as batteries and shielding cases when they are integrated into a real terminal such as a mobile phone [55]. The size of antennas used for 5G is down to micrometers and even nanometers at frequencies from low band to high band, and thus, very large numbers of antennas can conceivably fit into portable devices [56]. The antennas cannot be fabricated simply by reducing the size of classical metallic antennas down to nanometers [57], because the low mobility of electrons in nanoscale metallic structures and the high resonant frequencies of small-size antennas result in a large channel attenuation and difficulty in implementing transceivers at such a high frequency [57,58]. The use of traditional metallic materials for nanoantennas to implement wireless communications has become impossible. Identifying the best materials for nanoantennas to be applied in 5G is a challenge. For instance, the efficiency and the bandwidth of an individual nanoantenna are a function of its dielectric constant, and so nanoantenna materials for the 5G network require a lower dielectric constant [59,60]. Since each nanoantenna element acts as both a transmitter and a receiver, it is critical to isolate the elements from each other so as to prevent the leaking of transmitted signal from one element into the receiving portion of an adjacent element. Nanoantenna materials with the correct properties are ideal for reducing this crosstalk and also for eliminating reflections from other parts of the device that can interfere with the desired signal.

Figure 2 shows the nanoantennas modulus for millimeter wave spectrum bands at 5G user terminals where the antenna elements are placed on the dielectric substrate. The substrate materials for the antenna modules are critical for flexibility and antenna performance as well as cost-effectiveness. These materials are featured by scalable permittivity and low loss tangent
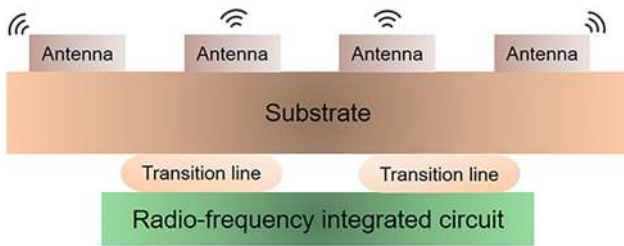
Figure 2: Schematic diagram of integrating 5G antennas for millimeter wave spectrum bands. The antenna arrays are placed on the substrate, and the radio frequency-integrated circuit is located on the opposite side of the substrate.

values at high radio frequencies. As the antenna is integrated with various components, it needs to attain minimum warpage avoiding the damage of surface-mount components. Specifically, warpage can be quantitatively characterized using parameters such as Young's modulus [61]. Thermal stability and rigidity are also important design considerations [62]. The excessive heat created by a circuit is typically harnessed using external heat sinks. In cases where the antenna modules for millimeter waves are extremely small in dimension, the antenna material is exposed to high heat temperatures and can result in unexpected mechanical deformation. Such thermal expansions of the antenna material can lead to damages and cracks in the solder balls between the antenna pads and the integrated circuit. Antenna materials with a coefficient of thermal expansion values closer to that of the integrated circuit decrease the probability of such incidents [63].

3 Nanomaterials of nanoantennas in 5G

The 5G wireless communications require antennas with a greater capacity, wider wireless spectrum utilization, high gain, and steer ability due to the cramped spectrum utilization in the previous generation. Conventional antennas are unable to serve the new high frequency due to limitations in fabrication and installation mainly in smaller sizes. Metallic nanoparticles are frequently used to conduct inks used for antennas [64]. These particles, due to their high surface area, can interact with atmospheric water or oxygen, causing the antenna to oxidize and degrade more rapidly than bulk metals [65,66]. The use of carbon-related nanomaterials such as graphene and CNTs has promising antennas with smaller

sizes and thinner dimensions, capable of emitting high frequencies [67–70] because the available bandwidth is inversely proportional to the antenna size. Nanoantennas almost two orders of magnitude below the dimensions of current on-chip antennas are appropriate for 5G.

3.1 Graphene-based nanoantennas

Graphene has a single layer of carbon atoms packed into a hexagonal structure. It exhibits many astonishing properties, including mobility of charge carrier of $2,00,000 \, cm^2 \, V^{-1} \, s^{-1}$ at room temperature, Young's modulus of $1.5 \, TPa$, the fracture strength of $125 \, GPa$, and thermal conductivity of $5,000 \, W \, m^{-1} \, K^{-1}$, rendering it the stiffest of materials and the highest of mobility [71–74]. Graphene also has a high conductivity of up to 4.9×10^8 S/m and sheet resistance of less than $30 \, \Omega/m$ with 90% optical transparency [65]. Graphene has become an attractive material for the manufacturing of ultra-high-speed electronics due to its excellent switching characteristics and tunable properties. For example, conductivity is one of the most important properties of graphene-based antennas, which can be controlled via an applied bias voltage and doping methods [71,75]. Since a graphene layer is one atom thick, it allows for unprecedented electrostatic confinement and is extremely flexible. Graphene monolayers have been shown to support ultra-confined surface plasmon polariton (SPP) waves even at terahertz frequencies, with moderate loss and strong field localization and confinement [76–78]. Specifically, SPP waves are electromagnetic waves guided along by a metal–dielectric interface and generated by means of high-frequency radiation [79,80]. The properties of plasmonic propagation can be tuned dynamically, enabling frequency reconfiguration [75,81]. Moreover, the graphene atomic monolayer can support very high electron concentrations due to its large tunability in terms of chemical potential [76,82]. On the basis of these properties, graphene is a potential material for use in electronics for antennas.

The use of graphene material promises antennas with smaller sizes and thinner dimensions, which are capable of emitting high frequencies [83,84]. The basic configuration of graphene-based nanoantenna is shown in Figure 3(a). The nanoantenna is composed of a graphene layer (the active element), along with a metallic flat surface (the ground layer), and a dielectric material layer in between the former two layers [85–87].
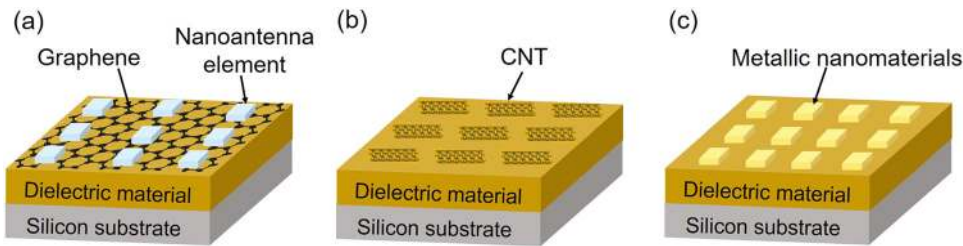
Figure 3: Schematic diagram of (a) graphene-based nanoantennas, (b) CNT-based nanoantennas, and (c) metallic nanomaterial-based nanoantennas.

Graphene-based nanoantennas utilize smaller chip area than other conventional metallic counterparts. By adjusting the dimensions of a graphene nanoantenna, the radiation frequency can be tuned to a wide spectral range [85,88]. Graphene-based nanoantennas are hundreds of times smaller in size than conventional microstrip antennas, with higher bandwidth and gain than metallic nanoantennas [89]. The dimension of graphene-based nanoantennas is almost two orders of magnitude smaller than that of metallic on-chip antennas, and hence, they can provide intercore communications in the terahertz band [90]. These inherent features of graphene can offer both size compatibility with increasingly shrunken processor cores and adequate bandwidth for massively parallel processing. Graphene-based nanoantennas have shown excellent behavior in terms of the propagation of SPP waves in the terahertz frequencies [57,91,92]. SPP in graphene is confined much more strongly than it is in conventional noble metals and is electrically and chemically tunable through electrical gating and doping. A speed of up to terabits per second can be achieved by using graphene-based nanoantennas.

3.2 CNT-based nanoantennas

CNTs, which are one-dimensional materials, have also been applied as nanoantenna materials because of their unusual electronic and electromagnetic properties including aligned axial transition dipoles, large absorption cross-sections, and high quantum efficiencies [93–96]. CNTs have an extremely high conductivity approaching the quantum limit, minimizing resistive losses in the antenna [97–100]. Due to the nearly defect-free structure of CNTs, CNT-based nanoantennas can suffer much less from power loss due to the surface and edge roughness compared with metal-based nanoantennas [97,101,102].

A basic configuration of an antenna array made up of CNT-based nanoantennas is shown in Figure 3(b). The electron movement in CNTs is caused by ballistic transport through the nanotubes [103–105]. CNTs can represent different electrical properties that exist in two forms: metallic and semiconducting [104,106]. Armchair CNTs are metallic without energy band gap [107,108]. Semiconducting CNTs are varied with energy band gaps of up to around 1.5 eV based on their chirality and diameter, corresponding to infrared radiation [103,106]. For example, if the width of the infrared emission and absorption spectra in nanotubes is in the order of 0.15 eV, it is expected that approximately 10 different frequency channels can be created [97]. Moreover, the emitted light is polarized, and optical absorption is also polarization dependent (polarization along the nanotube axis is strongly favored). This enables one to double the number of available communication channels by using parallel and perpendicular nanotubes. Recent advances in nanotube fabrication have enabled the commercial fabrication of arrays of CNTs with good control over density, diameter, and length of the CNTs.

CNT-based nanoantennas are capable to efficiently mold the energy flow with respect to its intensity and direction through proper control of the length of CNTs and material properties via an appropriate choice for the material in the gap [109–111]. For example, metal and their compounds can be applied in the gap. It is found that such nanoantennas can interrelate free space radiation with intense near-fields in the feed point [109]. As the energy flow at any given distance from a point dipole is proportional to the radiated energy [112], a field enhancement indicates an improvement in the energy flow efficiency. The CNT-based nanoantennas with a metallic sphere in the gap can represent an efficient far-to-near field converter, supporting a considerable field improvement in the antenna feed [113]. The skin effect in CNTs can be ignored when the operating frequency reaches terahertz [114] because the

electrons in CNTs conduct through the π-bond of carbon atoms, which also occurs in thin graphite sheets [115,116]. CNT-based nanoantennas have a low power dissipation, leading to high antenna efficiency with respect to a metal wire of the same size [117,118]. When a CNT-based nanoantenna carries several microamperes of current under an applied voltage of a few volts, it emits the maximum of a few microwatts of power to its surrounding environment [114]. As the required communication range increases, it is possible to amplify the transmission power using numbers of nanotubes in parallel. CNTs have an extremely large impedance of about 10 kΩ/μm compared to the normal feeding line (approximate 50 Ω/μm), resulting in the problem of impedance mismatch when building an antenna [100,119,120]. CNT bundles can be applied to solve this problem [115,121].

Graphene-based and CNT-based nanoantennas can bear high heat because of their high thermal conductivity. Specifically, the thermal conductivity of CNTs can be more than 2,000 W/(m K) [122] and that of graphene can be about 5,000 W/(m K) [123]. Such a high thermal conductivity enables the nanoantennas to dissipate heat by the antenna surface. Moreover, both the CNTs and graphene have a large surface area because of specific structures. Such a large surface area can cause an increment in heat loss. Both the high thermal conductivity and the larger surface area contribute to the CNTs and graphene bearing the high temperature. When the temperature is too high, CNTs and graphene start to oxidize. The graphene oxides can still be used for nanoantennas due to their good microwave absorption [124]. However, CNTs can be oxidized at the temperature of about 700 K [113], significantly affecting the electromagnetic properties. The efficiency of heat dissipation for nanoantennas should be improved to prevent the CNT-based nanoantennas from the damage of high temperature. One of the methods is to replace the CNTs by the CNT-based materials. CNTs are incorporated with ceramics. For example, the conductivity and the imaginary parts of permittivity value for SiO_2 matrix reinforced by 10 vol% CNT are almost stable from 400 to 800 K [125]. Another method is to deposit nanoparticles such as CdS on the surface of CNTs. For example, when 12 vol% CdS nanoparticles are loaded on CNTs, the elevated temperatures have less effect on the permittivity value [126]. The third method is to design nanoantennas with reasonable structures, optimizing the topologies of the nanoantennas array. For example, the nanoantennas can be arranged in different arrays such as linear irregular array, spiral array, thinned array, and circular ring array to improve the efficiency of heat dissipation [127]. The nanoantennas can have a split-ring structure, enabling an increment in the amount of space available between nanoantennas elements. A large free space in nanoantennas array contributes to heat dissipation. The fourth method is the addition of metal plates that function as heat dissipation fins that can be arranged between and around the antenna elements. These metal plates are electromagnetically transparent to specific radio wave frequencies. As a result, the addition of heat dissipation fins increases the efficiency of heat dissipation without disrupting the radio waves of the nanoantennas.

3.3 Metallic nanomaterial-based nanoantennas

Although the traditional metal waveguide has low loss and little signal interference, its structure is difficult to miniaturize and integrate [128–131]. Metallic nanomaterials show promising characteristics and thus can be used for nanoantennas in the 5G network [132–135]. For example, the nanostructures of metallic nanoparticles support surface plasmon resonances (SPRs), which are charge density oscillations that generate highly localized electromagnetic fields at the interface between a metal and a dielectric [136–139]. The electromagnetic waves can be localized on the surface of the nanoparticle, adopting the terminology of localized SPRs [140–142]. Localized SPRs associated with collective oscillations of free electrons can generate large field confinement in an extremely small volume [143,144]. A key property of metallic nanoparticles is the frequency of localized surface plasmons, which depends on the size, shape, and composition of the nanoparticles as well as the sensitivity to the dielectric environment [145–147]. The basic configuration of an antenna array composed of metallic nanomaterial-based nanoantenna is shown in Figure 3(c). Metallic nanomaterial-based nanoantennas have many intriguing properties such as directivity gain, polarization control, intensity enhancements, decay rate enhancement, and spectral shaping [143,145,148,149]. They are formed by pairs of metal nanostructures [150–152]. The resonance wavelength and the intensity of the localized fields in nanoantennas are strongly dependent on the structural geometry and the refractive index of the surrounding medium [145,153].

3.4 Metamaterial-based nanoantennas

Metamaterials have also been used as materials to increase the performance of nanoantennas because of their unique electromagnetic properties. Metamaterials are artificial structures materials made from assemblies of multiple elements from composite materials such as metals and plastics and engineered to provide electromagnetic properties not readily available in nature [154]. For example, the metamaterials can have negative permittivity and negative permeability at the same frequency. The electromagnetic wave can be refracted in the opposite direction with the wave propagation in metamaterials [155]. The metamaterials can be classified into different types including the electric negative metamaterials, magnetic negative metamaterials, and double-negative metamaterials based on their permittivity and permeability created by various structures [156]. Figure 4 shows the structure of metamaterials with different electromagnetic properties for a antenna array. For instance, the electric negative metamaterials can use the metallic thin wires to obtain the negative permittivity values. The parallel metal wires display high pass behavior for an incoming plane wave and their electric field is parallel to the wires. The magnetic negative metamaterials with a negative permeability value can have a structure of split ring resonator, which is composed of two concentric metallic rings and separated by a gap. The double-negative metamaterials have a negative refractive index, and their structures are a combination of the thin wire-based structures with split ring resonator-based structures. The tunability of electromagnetic characteristics of metamaterials is achieved by altering the shape, size, and arrangement direction of individual metamaterial resonators or by manipulating the near-field interactions between them [157].

The use of metamaterials in antenna design not only dramatically reduces the size of the antenna and achieve the miniaturization of antenna size but can also improve nanoantennas performance such as enhancing bandwidth, increasing gain, and generating multiband frequencies of antennas operation [156]. The metamaterial-based nanoantennas can overcome the restrictive efficiency and bandwidth limitation for nanoantennas. Moreover, as the metamaterials with novel electromagnetic properties that cannot be obtained in natural materials, the metamaterial-based nanoantennas can make the radiation properties of nanoantennas more controllable and promising [158]. Depending on the design purpose of the nanoantennas, the metamaterials can be used as different functions of the nanoantennas. For example, metamaterials can be arranged to surround the nanoantennas elements of an antenna array, improving the antenna gain [159]. Metamaterials can also be used as a superstrate placed above the radiation surface, increasing the obtained bandwidth of the nanoantennas [160].

3.5 Comparison of nanomaterials

As the total consecutive available bandwidth for millimeter waves is not enough to support the terabit-persecond data rate, terahertz band communications are envisioned as a key wireless technology to satisfy the future demands within 5G and beyond [161]. Graphene, CNTs, metallic nanomaterials, and metamaterials can be used for millimeter wave and even terahertz band frequency. The electromagnetic properties, namely, permittivity and permeability of graphene, CNTs, metallic nanomaterials, and metamaterials, are tunable and
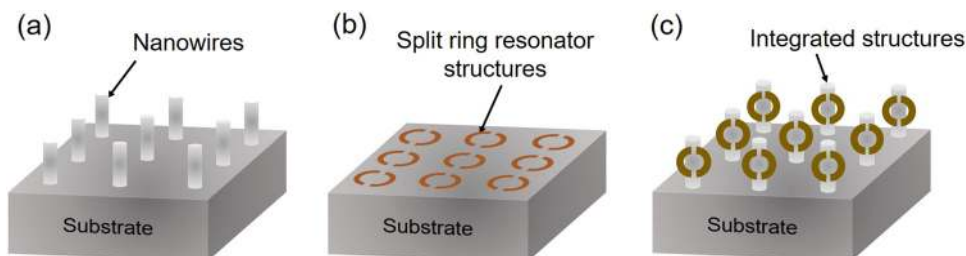

Figure 4: The antenna array made up of metamaterials with different structures and different electromagnetic properties. (a) The nanowires of metamaterials have a negative permittivity value and a positive permeability value. (b) The metamaterials have a structure of split ring resonator composed of two concentric metallic rings and separated by a gap. They have a positive permittivity value and a negative permeability value. (c) The nanoantennas element has an integrated structure of the nanowire and the split ring resonator. The metamaterials have a negative permittivity value and a negative permeability value.

highly dependent on their structures. The electric, mechanical, and thermal properties of graphene, CNTs, and copper commonly used as metallic nanoantennas have been summarized in Table 1. It is clear that the graphene exhibits superior performance, including the highest electrical conductivity, electron mobility, thermal conductivity, and mechanical properties. The properties of nanoantennas include radiation efficiency indicating the efficiency of antennas in performing the conversion from electric signals to electromagnetic waves, radiation directivity indicating the concentration of radiation in the direction of maximum radiation, and radiation pattern representing the antenna radiation as a function of direction. By comparison, it is found that (1) as the conductivity of graphene can be tuned via chemical potential by means of chemical doping and electrostatic bias voltage, the radiation properties of graphene-based nanoantennas can be tuned via chemical potential. Compared to graphene, CNT-based nanoantennas have less tunability with more plasmonic loss due to the curvature effect [166]. However, the radiation properties of metallic nanoantennas cannot be easily tuned and SPP waves on such nanoantennas exhibit large Ohmic losses. (2) The graphene-based nanoantennas have high radiation efficiency than CNT-based and copper-based nanoantennas. Moreover, the radiation efficiency of a single CNT as nanoantennas is lower than that of copper-based nanoantennas. The low radiation efficiency of copper-based nanoantennas is correlated with the low conductivity of copper [161], and the low radiation efficiency of single CNT as nanoantennas is due to the large reactance resulting from classical and quantum effects of nanometer radius [167]. (3) The graphene-based nanoantennas have higher directivity than CNT-based nanoantennas, and directivity of CNT dipole antenna is higher than copper nanoantennas at the low Terahertz band frequency range. (4) The gain of nanoantennas patterned on graphene can be enabled or disabled by tuning the gate voltage, and the pattern of nanoantennas arrays can be changed only by the gate voltage variation [71]. This is different from other types of nanoantennas arrays, where the radiation pattern is modified by switches or phase shifters. The graphene-based nanoantennas have better radiation properties such as high radiation efficiency and directivity compared with CNTs and metallic-based nanoantennas, showing great potential in the 5G wireless communications.

4 Key challenges of wireless communications

4.1 Commercialization

Although 5G is available in some countries, its widespread adoption is limited [168–170]. There are more than a dozen different technologies under development as part of 5G, including massive MIMO, beamsteering, and millimeter waves [171,172]. Although some technologies such as MIMO are quite mature, others such as millimeter waves are still arguably in their infancy. This problem is compounded given that not every operator can deploy all the available technologies. For example, one operator prefers to deploy millimeter wave small cells, aiming for dense, ubiquitous coverage. Meanwhile, another operator finds that millimeter wave technology is not mature enough instead of focusing on MIMO and beamsteering technologies. In this simple example, it can be seen that investment can be split across different technologies. When this is extrapolated across more than a dozen technologies used in 5G, it is obvious how investment can be diluted, and the focus could be distracted.

Another problem that prevents the global adoption of 5G is the cost of the technologies adopted. As millimeter wave signals cannot travel as far as the lower-frequency wave in 4G, 5G requires more base stations to be manufactured and installed [173].

Table 1: The electrical, thermal, and mechanical properties of graphene, CNTs, and copper (the metal that most commonly used in antenna)

	Electrical conductivity (S/m)	Electron mobility (cm^2 V^{-1} s^{-1}) at room temperature	Current density (A cm^{-1})	Thermal conductivity (W m^{-1} K^{-1})	Young's modulus (GPa)
Graphene	108 [162]	2 × 105 [163]	109 [162]	5,000 [122]	1,500 [164]
CNT	106–107 [162]	8 × 104 [163]	109 [162]	3,000 [123]	270–950 [164]
Copper	5.96 × 107 [162]	32 [163]	106 [162]	400 [162]	130 [165]

Moreover, the radio frequency front-end module, i.e., the basic electronic part that receives and transmits radio signals between two devices, needs to be able to handle millimeter waves [174,175]. New functions are required for the components included in radio frequency modules such as filter and power amplifier, further increasing the cost. The high-frequency range of 5G requires more power to achieve the bandwidth and huge mobility of the data required. 5G promises enormous data rates among the user, device, and base station towers. However, many places in the world lack the infrastructure to keep such high-speed networks up and running. Building intermediate networks to provide that link is crucial.

There are several methods proposed to avoid the diluteness of investment and to reduce the high cost in nanomaterials. One method to lower the manufacturing cost is to integrate circuits for reducing the number of network elements. For example, the integration of the nanoantennas and the feed network can reduce the complexity of the antenna array and the feed network, decreasing the size of the antenna array [176]. The nanoantennas can be integrated with radio frequency devices such as filter and power amplifier in the same structure to reduce the number of devices and save the cost [177]. If the silicon substrate of nanoantennas and radio frequency devices can be built on the same flexible plastic substrate, attachment costs are removed without the diluteness of investment on the nanoantennas and the radio frequency front end. Another method to reduce the cost of the 5G wireless communications is to reduce the investment of nanomaterials applied in the 5G wireless communications. For example, the artificially structured electromagnetic materials with the properties that cannot be obtained in natural materials can be developed by modeling approaches such as the MD simulations. Moreover, as the size and the shape of nanomaterials can directly alter their electromagnetic properties, the approach of MD simulations can directly predict the properties of nanomaterials, and the predicted results are reliable because of the comparable and even the same size applied in simulation and experimental tests. Optimizing properties of nanomaterials by modeling approaches can significantly reduce the investment in the nanomaterials. The technology of AI and machine learning can also be applied to predict and optimize the performance of nanomaterials and nanodevices. For example, the vertical and horizontal beamforming from massive MIMO nanoantennas can be optimized by AI and machine learning to enhance radio capacity and coverage without additional infrastructure investment.

4.2 Nanomaterials

Three basic characteristics of the 5G wireless communications, namely, high data rate, low transmission latency, and massive connectivity, address the most urgent wireless communication issues in terms of present demand and suggest the innovations that will take place in the next generation of wireless communications [178–181]. Terahertz waves will be adopted in the next generation, indicating that the existing materials for nanoantennas cannot meet the higher requirement for nanomaterials [182]. Integrating existing nanomaterials will be an effective method for novel material design in the next generation of wireless communications [183,184]. Due to the limitation of the size to a few nanometers, it is difficult, costly, and time consuming to directly make use of experimental approaches for the material design and elements integrated into nanodevices. From these aspects, MD simulations can be adopted to design nanodevices with anticipated properties [185–188]. The nanomaterials with the electromagnetic properties unable to be obtained in natural materials can be synthesized, and their properties can be optimized with the help of MD simulations. For example, CNTs that have outstanding electric properties, high thermal conductivities, and low density can integrate with magnetic metallic nanoparticles such as to enhance the magnetic interaction between the nanomaterials and the electromagnetic waves [189,190]. The details of synthesis and optimization for novel nanomaterials by integrating CNTs and nanomaterials are shown in Figure 5. As the size and the shape of nanomaterials affect their electromagnetic properties, the permittivity and permeability of CNTs and nanoparticles with different shapes are first predicted by the MD simulations. The relationship between the nanostructure and the properties of individual elements can be figured out. Following, CNTs integrate with metallic nanoparticles with different structures; and the corresponding properties are predicted. The interfacial properties between the individual elements can be investigated at nanoscale with effective methods proposed for improvement of properties. Finally, the novel nanomaterial with optimized properties is obtained by structural reconfiguration. The properties of integrated nanomaterials can meet the future requirement of nanoantennas for 5G and future 6G wireless communications.

Furthermore, it is important to control the energy consumption of nanomaterials in nanoantennas. This is because the heat caused by the electromagnetic loss of nanoantennas can result in an environment with an
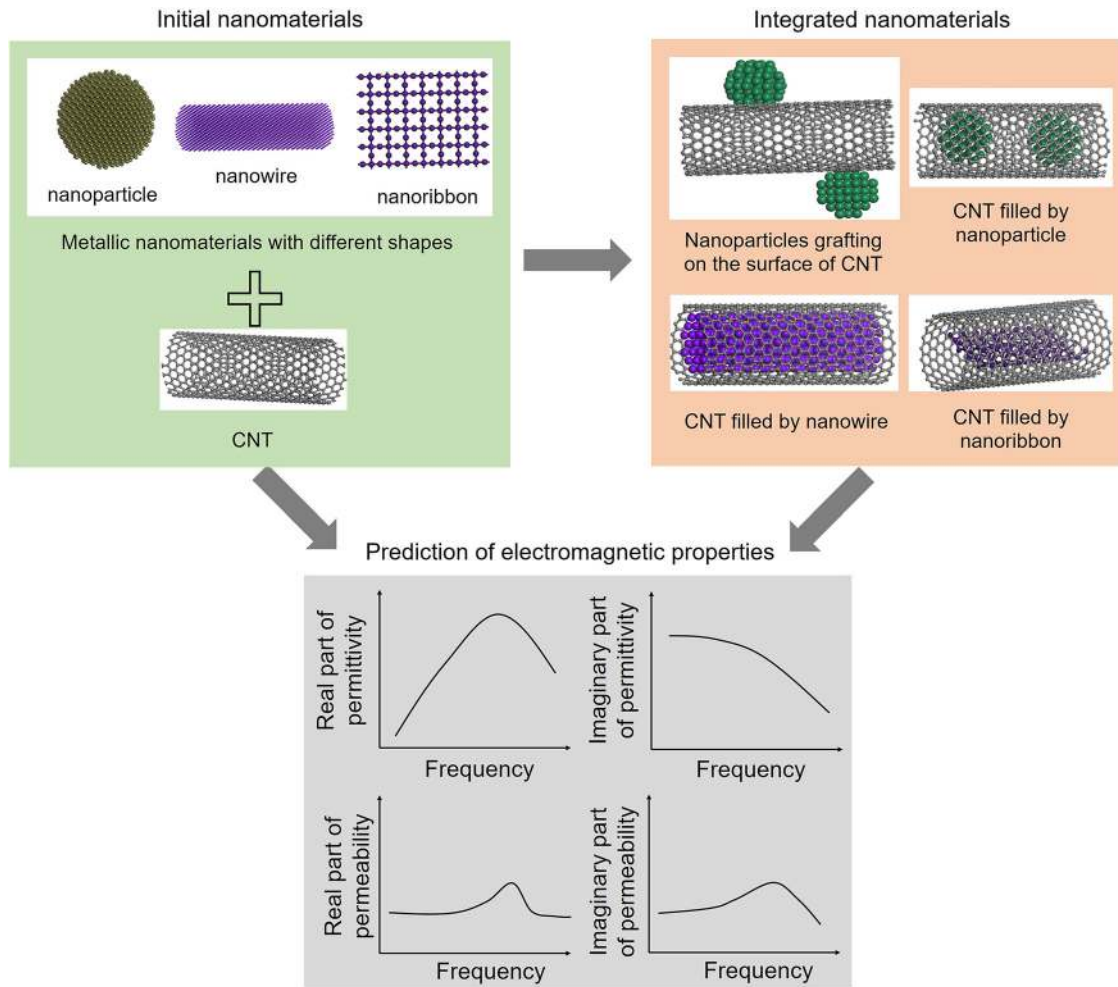
Figure 5: The role of MD simulations in systemization and optimization of nanomaterials. The relationship between the nanostructure and the properties of nanomaterials for nanoantennas can be figured out by MD simulations. The properties of integrated nanomaterials are optimized to meet the requirement of nanoantennas.

elevated temperature degrading the performance of nanoantennas. For example, the imaginary part of permittivity that determines the dielectric loss part of the electromagnetic loss is not constant and highly dependent on the temperature; the imaginary part of permittivity increases with an increase in the temperature, resulting in an increase in the dielectric loss. The high-temperature absorption nanocomposites can be used in nanoantennas to reduce energy consumption. For example, CNTs and graphene can be incorporated with ceramics such as SiC and SiO_2 because of their high strength, less oxidation, high thermal stability, and thermal conductivities at higher temperatures. The metallic and ceramic nanoparticles can be deposited on the surface of CNTs and graphene.

5 Conclusions

5G applications and technologies transform mobile broadband to enhanced mobile broadband for a ubiquitous ultra-fast experience, enable massive machine-type communications, and empower network applications that require ultra-high reliability and ultra-low latency. 5G is still in its infancy due to the limitations of its technologies and the cost of its materials. The commercialization of 5G around the world will take time, as we must wait for the cost of the nanotechnology and nanomaterials to be reduced. In this study, a review is presented on the development of technologies and nanomaterials of nanoantennas and the conclusions are summarized as follows:

(1) The adoption of advanced technologies such as millimeter waves, massive MIMO, and miniature base stations in the 5G wireless communications promotes the application of nanotechnology in 5G.

(2) The antennas, which are the essential network element in 5G, must support the adaptation to the 5G-oriented network transition, the flexible coordination with other equipment, and intelligent network applications. The size of the antennas in 5G is reduced to nanoscale because the available bandwidth is inversely proportional to the antenna size.

(3) Nanomaterials such as graphene, CNTs, metallic nanomaterials, and metamaterials are potential materials for 5G nanoantennas due to their unique electromagnetic properties and outstanding thermal conductivity and strength.

The pursuit of faster date speed and lower latency with the increment in connection density promotes the innovations of next-generation wireless communications where the terahertz waves will be adopted. A higher requirement in the properties of nanoantennas is put forward. It is promising and economical to design nanomaterials with anticipated properties by integrating nanomaterials using the approach of MD simulations.

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