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Applications of Nanomaterials in 5G Wireless Communications: A Comprehensive Review

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Rapid increase in mobile devices, huge data volumes, and fast data transfer laid emphasis on extending wireless communication from first generation 1G to fifth generation 5G in a span of four decades between 1980–2020. 5G network offers huge connectivity with high data speed and minimal latency. This network is specified by three characteristics such as MIMO (Massive Multi-Input Multi-Output), adoption of latest technology, and high base station. This paper made an attempt to review the applications of some nanomaterials like graphene, carbon nanotubes, metamaterials, and MXenes in designing nanoantennas of wide bandwidth that suit 5G networks.

Швидке зростання мобільних пристроїв, величезні обсяги даних і швидка передача даних зробили акцент на розширенні бездротового зв'язку від першого покоління 1G до п'ятого покоління 5G впродовж чотирьох десятиліть між 1980 і 2020 роками. Мережа 5G пропонує величезний обсяг зв'язку з високою швидкістю передачі даних і мінімальною затримкою. Ця мережа характеризується трьома характеристиками, такими як MIMO (масивний багатовхідний багатовихідний зв'язок), впровадження новітніх технологій і висока базова станція. У цій статті зроблено спробу розглянути застосування деяких наноматеріялів, таких як графен, вуглецеві нанотрубки, метаматеріяли та максени, у розробці наноантен із широкою пропускною здатністю, що підходять для мереж 5G.

Key words: 5G, graphene, carbon nanomaterial, metamaterial, MXene.

Ключові слова: 5G, графен, вуглецевий наноматеріял, метаматеріял, максен.

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1. INTRODUCTION

Wireless communication has become part of our daily life. Day-to-day human life was completely dependent on scientific and technological advancements of wireless communication [1]. As per the literature, mobile traffic was estimated to increase drastically in coming years with billions of devices for communication [2]. In addition to this, huge growth in important services like education, banking, e-commerce and health lead to transfer of huge data [3]. Hence, there is a strong need for high reliability and low latency supporting these sectors [4, 5]. Information through wireless networks was distributed based on reality and virtual reality. This needs large bandwidth with applications that support data rate up to number of gigabits per second [6]. In this context, the journey of mobile communication from 1G to 5G is of significance [7].

The journey of mobile communication has been witnessing various significant advancements in terms of connecting, communicating and accessing information. From the advent of normal mobile phones with limited features to smart phones with high data speed, the journey of mobile networks started with first generation (1G) in 1980s and reached fifth generation (5G) as on today.

First Generation (1G): Advent of Mobile Communication. Even though the foundation for 1G mobile network was laid in 1940s, it is considered that real development of the mobile networks was started in 1980s. These networks used analogue technology and were designed primarily for voice calls. 1G network had several limitations like limited capacity and poor call quality, lack of security, *etc*.

Second Generation (2G): Advent of Digital Communication. During 1990s, 2G mobile networks emerged by overcoming the limitations of 1G networks and adopting digital transmission methods to improve the mobile communication. Adoption of digital signals in 2G networks enhanced the efficiency by allowing more users reducing size and cost of mobile phones.

Third Generation (3G): Mobile Internet. 3G networks were introduced in new millennium leading the era of mobile internet with high data

Network evolution [7].

speed. The data rate increased from 40 kbps to 40 Mbps between 2G to 3G transformations. This one led to web browsing, sending emails and access to multimedia on mobile phones. This one was major change that led to various applications making mobile devices as one of the powerful tools for information and entertainment. 3G mobile networks could offer video calling but with poor quality.

Fourth Generation (4G): The Rise of Mobile Broadband. 4G networks emerged by 2010 with significant increase in data speed, decreased latency, high quality real time video, online gaming, *etc*. 4G networks also could ignite production of IoT devices and their applications. More bandwidth and low latency created new opportunities for smart homes and other IoT innovations.

Fifth Generation (5G): More Than Just Faster Internet. 5G was designed to enhance the data transfer speed reduce latency and improve reliability as compared to earlier generations. This network can support larger number of devices as compared to previous generations. They can be used in applications related to healthcare, manufacturing, transportation, and entertainment. 5G can be applied in Edge Computing and Artificial Intelligence. 5G is continuously growing as MSP (Mobile Service Providers) throughout the globe with different applications in 2020s.

Based on the performance, required 5G wireless communications are being designed. Technologies like multiple radio access are combined to convergent 5G wireless communications systems [8]. Figure 1 shows some of the advanced technologies like millimetre waves, massive MIMO, beam forming, full-duplex and machine-to-machine used in 5G.

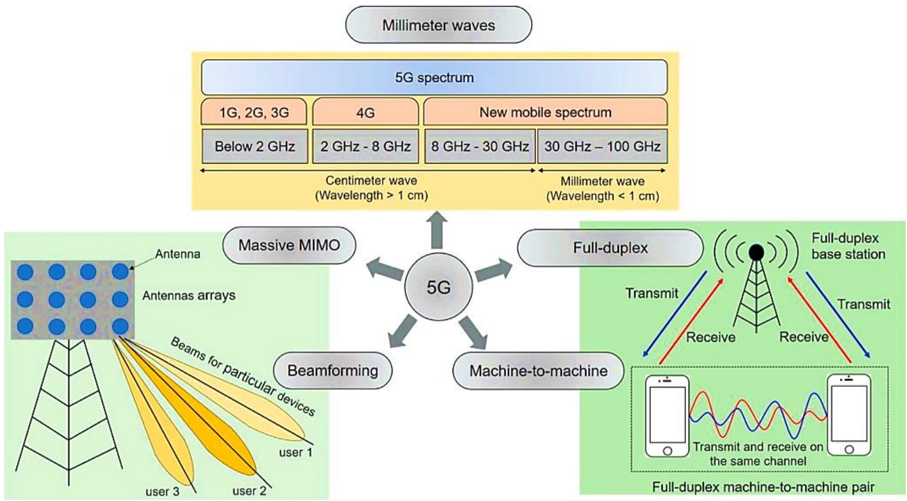

Fig. 1. 5G wireless communication network with advanced technologies [12].

When compared to 4G, 5G can operate with higher frequencies between 30 GHz and 100 GHz [9]. It can handle large data and unrestricted call volumes [10, 11]. Processes like accounting, administration and signalling in 5G networks are significantly improved. This can overcome the drawbacks in various applications utilizing regular broadband category mobiles. MIMO technology can be preferred to enhance efficiency of air interface spectrum, which can improve connectivity and allow fast data access. In addition, by increasing the computing power in 5G, low latency of about 1 ms can be obtained [7].

Usage of 5G network enables us to enhance the speed of the devices connected to that network. Millions of nodes are being managed with duplex transmission that send and receive data simultaneously. Since the operating frequency of 5G communication lies in millimetre wave range, the size of the components can be reduced making this network more efficient. Usage of number of antennas along with MIMO technique reduces the size of components paving a path for more elements being integrated into a single device. This enabled in developing innovatory nanodevices that can take up complex tasks in parallel.

Nanotechnology can produce these components easily and with cost effectiveness. Nanomaterials due to their small size increases consumption of heat decreasing the stability. However, nanomaterials support light–matter interaction in GHz range improving wave absorption. Their electromagnetic properties are determined by their permittivity and permeability. Reflection loss at air–nanomaterial interface is mainly dependent on permittivity and permeability. Maximum microwave energy is reflected by the substrate while a small amount of energy is reflected at air–nanomaterial interface. Absorption of microwave radiation depends on the imaginary components of permittivity and permeability. Similarly, dielectric loss and magnetic loss that arise due to interaction of electromagnetic waves with nanomaterials can be estimated with the help of these parameters. Dielectric and magnetic resonance of nanomaterials depend on maximum dielectric and magnetic losses. It is a known fact that traditional materials such as metals and semi-conductors do not suit for high frequency devices, it is eminent that nanomaterials with suitable properties are to be investigated [12].

Keeping this in mind, an attempt was made to review the recent advances in nanomaterials used in 5G networks. Since 5G networks mainly use nanoantennas to receive and transmit radio waves (millimetre waves), nanomaterials like graphene, carbon nanotube (CNT), nanowire, and metamaterial that support 5G networks are being reviewed.

2. TECHNOLOGY BEHIND 5G MOBILE COMMUNICATIONS

5G mobile communication is empowered by various technologies that include wide bandwidth technology, mm-wave technology, massive MIMO, dynamic spectrum sharing and many others. However, taking the usage of materials into consideration, we confine our review to millimetre waves and massive MIMO technologies.

2.1. Millimetre Waves

5G wireless communication mainly operates at frequencies over 8 GHz. Since the frequencies between hundreds of MHz to few GHz are almost occupied [13, 14], more frequencies are required to improve the capacity of mobile networks. This can be achieved by adopting millimetre waves [15]. As compared to other microwaves, millimetre waves exhibit low diffraction and more specular transmission. This limits their propagation at obstructions like trees, buildings including bad weather. This drawback can be overcome by using multiple base stations designed with nanodevices that operate at millimetre wave frequencies [16]. Similar to 3G and 4G big base stations are no required in case of 5G. Instead, multiple small base stations replace conventional cellular towers.

2.2. Antennas Used in MIMO

MIMO (Multiple-Input Multiple-Output) is a radio-antenna technology used as a prime component in 5G Networks. It utilizes number of antennas at the transmitter as well as receiver improving the capacity and quality of the radio link. It is capable of transmitting and receiving multiple data signals in parallel over the same radio channel. This technology has low latency and consumes less power as each terminal with multiple antennas can send data much faster than SISO (Single-Input Single-Output) systems. In addition, the antennas may be grouped to reduce the space [4]. MIMO technology enables advanced beam forming techniques to improve data rate and reduce interference resulting to low latency [17, 18].

Designing of huge MIMO antennas and development of millimetre waves for 5G led to significant changes in antenna systems. Regular antennas used in 4G are not suitable for millimetre waves. In case of a mobile phone, 5G antennas get impacted by surrounding components [19]. Here, fabrication of nanosize antennas is not possible and also it is difficult to use regular metallic materials for nanoantennas that suit wireless communications. Hence, suitable materials for nanoantenna applications in 5G are difficult. Since the bandwidth and efficiency of a nanoantenna depend on dielectric constant, materials with low dielectric constant should be selected for nanoantennas in a 5G network. As every element in a nanoantenna act as transmitter and receiver, each element needs to be separately spaced to avoid crosstalk because

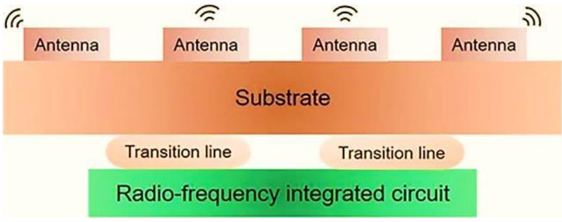

Fig. 2. Integrated 5G antenna structure for millimetre waves [12].

of signal interference into neighbouring elements. This is achieved in 5G terminals by mounting the elements of antenna on a dielectric substrate. Figure 2 shows an integrated structure of 5G antennas for millimetre waves.

Substrate materials are to be selected based on permittivity, loss tangent, cost, and antenna performance. The warpage of the antenna must be minimal after integration of various components. Due to extremely small dimensions, antenna materials can undergo mechanical deformation when exposed to high temperatures. This can be reduced by using antenna materials with thermal expansion coefficient comparable to that of integrated circuits.

3. NANOMATERIALS IN 5G NETWORKS

Nanoantennas play significant role in 5G networks. These antennas were being developed by using various types of nanomaterials. In this context, graphene-based materials for designing nanoantennas are of prime importance. Graphene exhibits high conductivity and tolerance to oxidation as compared to other metals, which is assigned to its high surface area. Graphene antennas produce higher gains than conventional antennas. They are capable of picking up radio signals from long distances with better coverage, low energy consumption and enhanced performance in remote areas [20, 21]. Another antenna with cost effective graphene-based conductive ink that can be printed with any shape or size was reported. These antennas are suitable for small applications in consumer electronics. Graphene and CNTs can produce antennas with smaller size. Since bandwidth and antenna size are inversely proportional to each other [22], smaller-size devices produce higher frequencies. Nanoantennas, which are very smaller than the present antennas, suit 5G networks.

3.1. Graphene-Based Nanoantennas

The conductivity of graphene may be tailored through doping. This property might be crucial in designing a graphene-based antenna. It is reported that graphene layers of one atom thickness exhibit excellent electrostatic confinement with high flexibility. Graphene monolayers support ultraconfined surface plasmon polariton (SPP) waves with moderate loss even at terahertz frequencies, SPP waves are high frequency electromagnetic waves specifically steered along by a metal-dielectric contact. Frequency can be altered by tuning plasmonic propagation characteristics dynamically [23].

Monolayers of graphene atoms can be chemically tuned to high degree supporting very high electron concentration. These properties signify graphene material to be suitable for antennas. Figures 3, 4, 5 display a basic nanoantenna made of graphene (*a*), CNT (*b*), and with nanomaterial (*c*). As shown in these figures, it consists of a layer of dielectric material sandwiched between two components a graphene layer (active component) and metallic flat surface (ground component). By varying the size of graphene antenna, various frequency ranges can be obtained. Graphene-based antennas are much smaller than microstrip antennas having high bandwidths in terahertz region [24].

3.2. CNT-Based Nanoantennas

CNTs exhibit nearly defect free structure, surface and edge roughness, which lead to low power loss in CNT-based nanoantennas as compared to their metal-based counterparts [25]. Figure 4 shows the structure of CNT-based nanoantenna array, in which electrons transport through nanotubes by ballistic transport.

CNTs exhibit different electrical properties based on their diameter and asymmetry. In this context, it is to be noted that metallic armchair CNTs has zero band gap while semi-conductor CNTs possess 1.5 eV energy gap that correspond to infrared radiation. It is observed that nearly ten frequencies can be produced in a nanotube, if the emission and absorption spectra in infrared region are nearly 0.15 eV. In addition, optical absorption is polarization dependent and the light emitted was polarized. Polarization takes place along the axis of the nanotube. The number of channels can be enhanced through usage of parallel and perpendicular nanotubes. CNT arrays, which have control on length, diameter, and density, are being produced in recent times. Selection of appropriate material for the gap and having a grip over the length of CNT will be helpful in designing CNT-based nanoantennas that can control the intensity and direction of energy flow [26].

Nanoantennas with gap filled with metals or metallic compounds are capable of generating open space radiation by interacting with strong near fields. If the gap is filled with a metallic sphere, these antennas can convert far to near fields. CNT antennas are more efficient as compared to metal wire antennas due to low power dissipation. Maximum

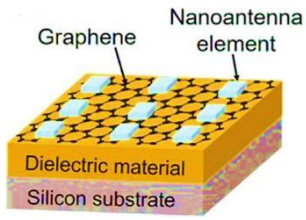

Fig. 3. Graphene-based nanoantenna [12].

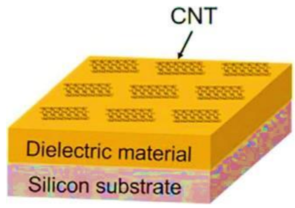

Fig. 4. CNT-based nanoantenna [12].

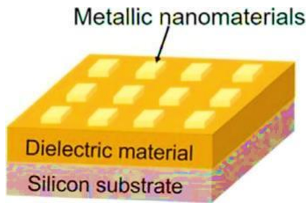

Fig. 5. Nanomaterial-based nanoantenna [12].

power can be delivered by CNT antenna on application of few volts. By using parallel nanotubes, transmission power can be boosted in large communications. Impedance mismatch in CNT antennas can be minimised by using CNT bundles. Both graphene and CNT have excellent thermal conductivity, and hence, nanoantennas can withstand heat up to 5,000 W/(m·K), while antennas with CNT can up to 2,000 W/(m·K). Large surface area of graphene and CNT results in increased heat loss. Oxidization of CNTs at about 700 K can influence the electromagnetic characteristics. Hence, graphene oxide can be used for designing nanoantennas with good microwave absorption.

In order to design nanoantennas, which can withstand excess heat, CNTs can be replaced with CNT-based materials. Ceramics are mixed with CNTs. If we consider a ceramic SiO_2 strengthened with ten volume percent of CNTs, its conductivity and imaginary value of permittivity between 400 K and 800 K are nearly steady. Similarly, twelve percent volume of nanoparticles of ceramic CdS deposited on the surface of CNT will have less impact on permittivity with increased temperatures. Usage of spiral, thinner, circular, and irregular arrays will increase the impact of heat dissipation. Positioning of metal plates around and in between the elements of antenna improves heat dissipation without any interference with the radio waves.

3.3. Metallic-Nanomaterial-Based Nanoantennas

Generally, metal waveguides are used in communication networks whose loss is low and minimum signal interference. As the size of these waveguides cannot be integrated and minimised, metallic nanomaterials are of good choice for nanoantennas in 5G network [26]. It is reported that surface plasmon resonances (SPRs) produce highly localised electromagnetic fields at the metal–dielectric interface, which can be taken up with nanostructures of metallic nanoparticles [27]. Localised SPR refers to electromagnetic waves contained on the surface of a nanoparticle and the SPRs help in confining large field to very small volume. The frequency of SPRs depends on size, shape, and composition of the nanoparticles as well as their sensitivity to the dielectric environment. Basic structure of a nanoantenna array with metallic nanomaterials is shown in Fig. 5.

A metallic-nanomaterial-based antenna is characterized by intensity, spectral shaping, control on polarization, directivity gain, *etc*. They are generally made of a pair of two metal nanostructures [28]. Structure and refractive index of the surrounding medium impacts resonance wavelength and localised field strength in nanoantennas significantly.

3.4. Metamaterial-Based Nanoantennas

Metamaterials exhibit negative values of permittivity and permeability [29]. Antennas designed with metamaterials exhibit increased gain and directivity. Usage of metamaterial in nanoantennas reduces its size and enhances performance. Metamaterials can be used for applications with limited space and requirement of high performance. Figure 6 depicts antennas made of metamaterials with different structures.

Metamaterial nanowires exhibit negative permittivity and positive permeability values. At the same time, metamaterials with split ring resonator structure consists of two concentric metallic rings with gap in between. They exhibit positive permittivity and negative permeability values. Metamaterial-based nanoantennas enhance the performance, bandwidth, gain and can operate at multiple frequencies. These antennas improve radiation properties as compared to natural materials. Elements of nanoantenna surrounded by metamaterials will increase antenna gain. Bandwidth of nanoantennas can be enhanced by

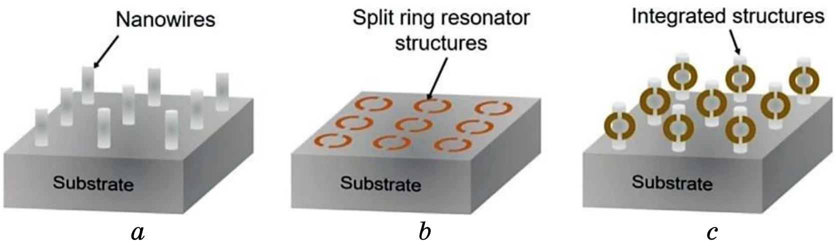

Fig. 6. (*a*) Antenna with metamaterial nanowires; (*b*) antenna with metamaterials of split ring resonator structure; (*c*) nanoantenna with integrated structure of the nanowire and split ring resonator [12].

using metamaterials as superstrate at the top of radiating surface [30].

A metamaterial antenna based on split ring resonator, which can operate at 5G band, was presented. The size of this antenna is very compact ($0.5\lambda_0 \times 0.39\lambda_0$) having −10 dB wide bandwidth of 4.36 GHz. This configuration could achieve a gain of 3.69 dB and directivity of 5.7 dB. This technique could reconfigure the antenna and could control the frequency shift through change in the slot position [31].

From the above three sections, we have seen that graphene, CNT, metallic nanomaterials and metamaterials are being used for designing nanoantennas in 5G network. In future, 5G networks with terahertz band will play a significant role [30]. For millimetre waves and frequencies in terahertz range, materials whose electromagnetic properties depend on structure, *i.e.*, graphene, CNTs, metallic nanomaterials, and metamaterials, can be used. Based on electrical, mechanical, and thermal properties, graphene, CNT and copper are frequently used in metallic nanoantennas. It is reported that the performance of graphene is better than other materials. The electrical conductivity, current density and thermal conductivity are highest for graphene followed by CNT followed by copper at room temperature. Graphene-based nanoantennas have great radiation efficiency than the other two materials. In addition, a single CNT has lower radiation efficiency than copper-based nanoantennas. This is due to low conductivity of copper in case of copper-based antennas and high reactance in case of single CNT nanoantennas [32].

3.5. MXene-Based Nanoantennas

MXenes pronounced as 'maxeens' are 2*D* nanomaterials discovered in 2011. They are 2*D* materials belonging to class of ceramics. MXenes are derived from MAX crystal. Their structure combines titanium-nitride and titanium-carbide molecular sheets exhibiting high conductivity and inherent volumetric capacitance. Applications of MXenes include sensing, energy storage, medicine, *etc*. and in electronic devices. They can be easily structured by ordering millions of carbon, transition metals and nitrogen with emphasis on stable arrangement. These ceramics produce 3*D* materials, when substituted with Ti_3AlC_2 powder in hydrofluoric acid through selective removal of aluminium. 2*D*-Ti_3C_2 nanosheets (MXene) can be derived through exfoliation. MXene is similar to graphene with different properties. MXene was first demonstrated in 2011 by transforming the three-dimensional materials Ti_3AlC_2 representing MAX phase into a 2*D* material [33]. Recent developments in microwave devices utilize lightweight carbon-based composites instead of metals. These materials are used for permanent coating on microwave structures. In this context, MXene-based dipole antenna and microwave transmission line with different thicknesses of MXene was reported with one-step spray coating technique [34].

Similarly, Xene RFID tags were also implemented for wireless applications. Further, $Ti_3C_2T_x$ MXene was used to fabricate an optical modulator using an inkjet-printed microring resonator [35]. Patch antennas with MXene films of varying thickness for 5G applications demonstrated up to 99% efficiency as compared to copper structure [36]. For the first time, microwave resonators and antennas were developed by using MXene membranes [37]. They fabricated a microstrip antenna and resonator for sub-6 GHz 5G applications using a Ti_3C_2-MXene membrane (Fig. 7). They designed a resonator with MXene that revealed 1.5 GHz, 2.5 GHz and 3.5 GHz frequencies suitable for 5G communications, which are comparable to regularly used metals. This membrane was used as microstrip antenna with 1.841 GHz frequency and amplitude of 38.895 dB, respectively. This MXene antenna was capable for wireless transmission in 5G networks, whose thickness and weight reduced by nearly 40% and 70% as compared to similar struc-

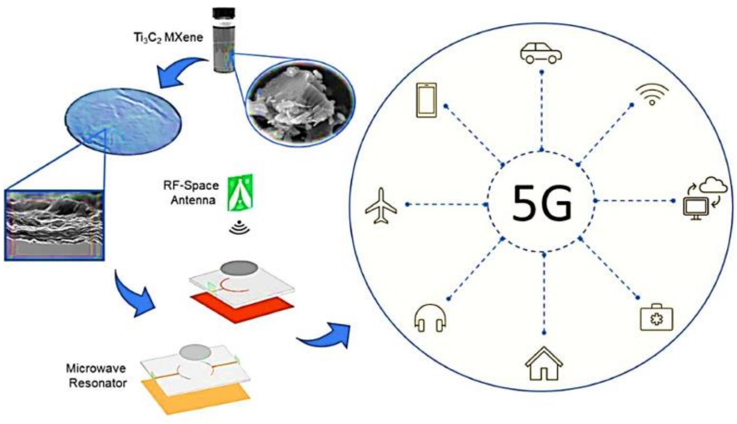

Fig. 7. Applications of MXene resonator and antenna in 5G networks [37].

tures based on copper. In addition, it was observed that operation frequency of resonator could be changed through varying the size of MXene circular membrane leading to frequency tuneable structures for 5G applications.

4. Future of Nanomaterials in 5G Networks

Even though nanomaterials are being part of designing nanoantennas in 5G networks adoption of terahertz waves clearly indicate the gap between existing current materials and increased demand for nanomaterials. Hence, the unique material designs are essential for next generation wireless communication. These designs should be capable of integrating the existing nanoparticles. As it is expensive and time consuming to go for new material design and nanoscale elements, MD (molecular dynamics) simulations may be preferred to create nanodevices with required properties. Using this simulation technique, electromagnetic properties can be tailored in a nanomaterial, which is not possible with natural material. For example, magnetic metallic nanoparticles integrated with CNTs improve magnetic interaction between the nanomaterials and electromagnetic waves. Figure 8 demonstrates a novel material with combination of nanomaterials and CNTs in different forms whose permittivity and permeability are predicted by using MD simulations. CNTs are integrated with metallic nanoparticles of

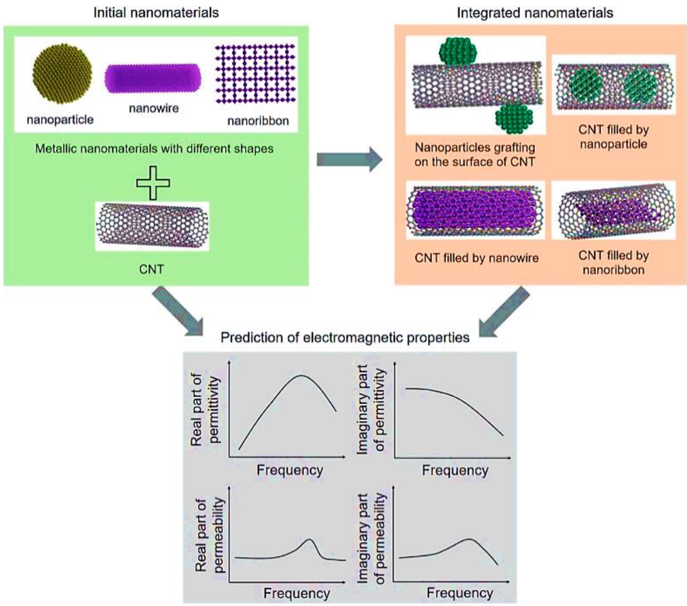

Fig. 8. Designing of nanoantennas through MD simulations [12].

different shapes and the output characteristics are predicted. Efforts to improve the quality of material were explored at nanoscale.

MD simulations are used to determine the relation between structure and properties of nanomaterials. The characteristics of nanomaterials can be computed through MD simulations to meet the requirements of nanoantennas. Structural reconfiguration is taken up in final stages to design a nanomaterial with suitable properties. The properties of integrated nanomaterials can satisfy the requirements of nanoantennas used for 5G and upcoming 6G wireless networks. Materials' combination may decrease surrounding heat and improve antennas efficiency, reduce energy consumption, energy absorption and save environment.

5. CONCLUSIONS

5G-communication-network technology is likely to revolutionize the whole communication setup in the near future and can heavily impact sustainability. It is capable of allowing mass communication, high bandwidth, low latency and high reliability. High cost of 5G components limits its usage extensively. Development of low cost nanomaterials may enhance the usage of 5G technology. In brief, we tried to review the importance of nanomaterials in nanoantennas used for 5G network. Graphene, CNTs, metallic nanomaterials, and metamaterials, which are used in 5G nanoantennas, are reviewed. It is observed that development of nanomaterials that suit generation of terahertz waves through 5G network with less latency and high data rate is eminent. In addition, it is reported that nanomaterials with required properties are to be developed and combined using MD simulations, which is one of the cost effective methods. 5G network is right now available in a few countries only. Only technologies like mm waves, MIMO, and beam steering are being used in 5G. Except MIMO, other technologies are in developing stage. Depending on the choice of the operator, particular technology is being used. 5G is also capable of playing a significant role in upcoming smart cities with intelligent data transportation, contributing to environmental protection. This network can improve remote health care through advanced IoT devices. 5G can thus play a key role in creating a sustainable future. The consumer attitude towards 5G is important because the acceptance and commitment of users is essential for the successful spread of the technology and the exploitation of the opportunities it offers. The study sheds light on consumers' acceptance of technology and their attitude, which will be a decisive factor in the extent, to which 5G technology can contribute to the achievement of sustainability goals [38–43].

In summary, a novel approach to fabricate nanoantennas with nanomaterials that support 5G communication networks was increasing rapidly. In due course of time, it is evident that the existing components made with metals will be replaced with carbon-based materials. Already, research in the direction of using graphene, CNTs, metallic nanomaterials, metamaterials for developing nanoantennas in 5G networks were in progress. However, development of MXene-based nanoantennas is not so extensive, which need to be more focussed. In view of various advantages exhibited by MXenes as compared to other carbon-based materials, emphasis needs to be laid in this direction. As mentioned in the above section, microwave resonators and antennas with Ti_3C_2 circular MXene membrane were designed. Implementation of lightweight MXene membranes in microwave resonators and antennas was very feasible. This can satisfy the requirements of 5G networks. As the computed and measured results confirm the efficiency of MXene membranes in microwave structures, future investigations may completely replace copper in microstrip antennas. This might lead to development of potential MXene-based microwave devices with various frequency bands and applications suitable for 5G networks.

REFERENCES

1. Qian Clara Li, Huaning Niu, Apostolos Tolis Papathanassiou, and Geng Wu, *IEEE Vehicular Technol. Magazine.*, **9**: 71 (2014); doi:10.1109/MVT.2013.2295070
2. Jeffrey G. Andrews, Stefano Buzzi, Wan Choi, Stephen V. Hanly, Angel Lozano, and Anthony C. K. Soong, *IEEE Journal on Selected Areas in Communications,* **32**, Iss. 6: 1065 (2014); https://doi.org/10.1109/JSAC.2014.2328098
3. Eiman Al Nuaimi, Hind Al Neyadi, Nader Mohamed, and Jameela Al-Jaroodi, *Journal of Internet Services and Applications,* **6**: Article No. 25 (2015); https://doi.org/10.1186/s13174-015-0041-5
4. Afif Osseiran, Federico Boccardi, Volker Braun, Katsutoshi Kusume, Patrick Marsch, Michal Maternia, Olav Queseth, Malte Schellmann, Hans Schotten, Hidekazu Taoka, Hugo Tullberg, Mikko A. Uusitalo, Bogdan Timus, and Mikael Fallgren, *IEEE Communications Magazine*, **52**, No. 5: 26 (2014); https://doi.org/10.1109/MCOM.2014.6815890
5. Baris Atakan, Sebastia Galmés, and Ozgur B. Akan, *IEEE Transactions on Nanobioscience*, **11**, No 2: 149 (2012); doi:10.1109/TNB.2011.2181862
6. Nisha Panwar, Shantanu Sharma, and Awadhesh Kumar Singh, *Phys. Commun.*, **18**: 64 (2016); https://doi.org/10.48550/arXiv.1511.01643
7. Kevin Moore, *A Timeline from 1G to 5G: The Evolution of Mobile Communicatio* (2023); https://www.mpirical.com/blog/the-evolution-of-mobile-communication
8. Ao Zhou, Oral Büyüköztürk, and Denvid Lau, *Cement and Concrete Composites*, **80**: 287 (2017); https://doi.org/10.1016/j.cemconcomp.2017.03.019
9. Federico Boccardi, Robert W. Heath, Angel Lozano, Thomas L. Marzetta, and Petar Popovski, *IEEE Communications Magazine*, **52**, Iss. 2: 74 (2014); doi:10.1109/MCOM.2014.6736746
10. Ganesh R. Patil and Prashant S.Wankhade, *Int. J. Comput. Sci. Mobile Comput.*,

3, Iss. 10: 203 (2014);
https://ijcsmc.com/docs/papers/October2014/V3I10201441.pdf
11. M. Kanerva, M. Lassila, R. Gustafsson, G. O'Shea, L. Aarikka-Stenroos, and J. Hemila, *Exel Composites*, **1**: 1 (2018); https://static1.squarespace.com/static/5a8aabc751a5840b490cefc3/t/5f7aae0124f75f5a9dc76fb0/1601875457903/Exel_whitepaper_2018_1.pdf
12. Shelesh krishna saraswat, *Materials Today: Proceedings* (2023); https://doi.org/10.1016/j.matpr.2023.04.435
13. Federico Boccardi, Robert W. Heath, Angel Lozano, Thomas L. Marzetta, and Petar Popovski, *IEEE Communications Magazine*, **52**, Iss. 2: 74 (2014); doi:10.1109/MCOM.2014.6736746
14. Guangyi Liu and Dajie Jiang, *Chin. J. Eng.*, **2016**: Article ID 5974586, (2016); http://dx.doi.org/10.1155/2016/5974586
15. Gokul P Nair, *International Journal of Computer Science and Mobile Computing (IJCSMC)*, **2**, No. 4: 124 (2013); https://ijcsmc.com/docs/papers/ICMIC13/ICMIC13S14.pdf
16. M. T. Sebastian, R. Ubic, and H. Jantunen, *Int. Mater. Rev.*, **60**: Iss. 7: 92 (2015); https://doi.org/10.1179/1743280415Y.0000000007
17. Ahmed Farahat Mohamed and Amin Babiker A/Nabi Mustafa, *International Journal of Scientific Research (IJSR)*, **5**: Iss. 2: 1044 (2016); https://www.ijsr.net/archive/v5i2/NOV152542.pdf
18. Michael Green and Xiaobo Chen, *J. Materiomics*, **5**, Iss. 4: 503 (2019); https://doi.org/10.1016/j.jmat.2019.07.003
19. Anjan Kumar, Sangeeta Singh, Dilip Kumar Sharma, Mohammed Al-Bahrani, Mohammed Ridha H. Alhakeem, Amit Sharma, and T. Ch. Anil Kumar, *RSC Adv.*, **13**, Iss. 2: 1402 (2023); https://doi.org/10.1039/D2RA07349H
20. Ehab Ali, Mahamod Ismail, Rosdiadee Nordin, and Nor Fadzilah Abdulah, *Front. Inform. Tech. EL.*, **18**, Iss. 6: 753 (2017); http://doi.org.10.1631/FITEE.1601817
21. Tianmin Ren and R. J. La, *IEEE T Wirel. Commun.*, **5**, Iss. 10: 2814 (2006); doi:10.1109/TWC.2006.04580
22. Kamran Behdinan, Rasool Moradi-Dastjerdi, Babak Safaei, Zhaoye Qin, Fulei Chu, and David Hui, *Nanotechnol. Rev.*, **9**: 41 (2020); doi:10.1515/ntrev-2020-0004
23. Marc Esquius-Morote, Juan Sebastian Gómez-Díaz, and Julien Perruisseau-Carrier, *IEEE T Terahertz Sci. Technol.*, **4**, Iss. 1: 116 (2014); doi:10.1109/TTHZ.2013.2294538
24. M. Tamagnone, J. S. Gómez-Díaz, J. R. Mosig, and C. J. Perruisseau, *J. Appl. Phys.*, **112**, Iss. 11: 114915 (2012); doi:10.1063/1.4768840
25. S. A. Maksimenko, G. Y. Slepyan, A. M. Nemilentsau, and M. V. Shuba, *Phys. E*, **40**, Iss. 7: 2360 (2008); https://doi.org/10.1016/j.physe.2007.09.196
26. Xiaotian Lin, Qiang Han, and Jianzhang Huang, *Nanotechnol. Rev.*, **8**, Iss. 1: 79 (2019); doi:10.1515/ntrev-2019-0007
27. Pierre Franck, Christophe Brun, Yap Chin Chong, Dunlin Tan, Edwin Teo Hang Tong, Stéphane Bila, Dominique Baillargeat, and Beng Kang Tay, *IEEE 13th Electronics Packaging Technology Conference (07–09 December, 2011)* (Singapore: IEEE: 2011), p. 167; doi:10.1109/EPTC.2011.6184408
28. Ivan S. Maksymov, *Rev. Phys.*, **1**: 36 (2016); https://doi.org/10.1016/j.revip.2016.03.002

29. V. Giannini, G. Vecchi, and J. G. Rivas, *Phys. Rev. Lett.*, **105**: 266801 (2010); doi:10.1103/PhysRevLett.105.266801
30. Huali Hao, David Hui, and Denvid Lau, *Nanotechnol. Rev.*, **9**, Iss. 1: 683 (2020); https://doi.org/10.1515/ntrev-2020-0054
31. D. Guha, M. Biswas, and Y. M. M. Antar, *IEEE Antennas and Wireless Propagation Letters*, **4**: 455 (2005); doi:10.1109/LAWP.2005.860211
32. Mondher Labidi and Fethi Choubani, *19th IEEE Mediterranean Microwave Symposium (MMS)*, **04**, Iss. 01 (2019); doi:10.1109/MMS48040.2019.9157282
33. Anjan Kumar, Sangeeta Singh, Mustafa K. A. Mohammed, and Dilip Kumar Sharma, *Int. J. Mod. Phys. B*, **37**, No. 07: 2350067 (2022); doi:10.1142/S0217979223500674
34. Michael Naguib, Murat Kurtoglu, Volker Presser, Jun Lu, Junjie Niu, Min Heon, Lars Hultman, Yury Gogotsi, and Michel W.Barsoum, *Advanced Materials*, **23**, Iss. 37: 4248 (2011); doi:10.1002/adma.201102306
35. Asia Sarycheva, Alessia Polemi, Yuqiao Liu, Kapil Dandekar, Babak Anasori, and Yury Gogotsi, *Sci. Adv.*, **4**, No. 9: eaau0920 (1) (2018); http://doi.org.10.1126/sciadv.aau0920
36. Meikang Han, Yuqiao Liu, Roman Rakhmanov, Christopher Israel, Md Abu Saleh Tajin, Gary Friedman, Vladimir Volman, Ahmad Hoorfar, Kapil R. Dandekar, and Yury Gogotsi, *Adv. Mater.*, **33**, Iss. 1: 2003225 (2020): doi:10.1002/adma.202003225
37. Kasra KhorsandKazemi, Ehsan Hosseini, Shujun Hu, Rakesh Narang, Shibo Li, Mohammad Arjmand, and Mohammad H. Zarifi, *Applied. Mat. Today*, **26**: 101294 (2022); https://doi.org/10.1016/j.apmt.2021.101294
38. Boglárka Eisinger Balassa, Nikolett Gyurián Nagy, and Norbert Gyurián, *Journal of Cleaner Production*, **467**: 142964 (2024); https://doi.org/10.1016/j.jclepro.2024.142964
39. Yuhan Yao, Xuefeng Xia, Zhao Cheng, Kangkang Wei, Xiantao Jiang, Jianji Dong, and Han Zhang, *IEEE J. Sel. Top. Quantum Electron.*, **26**, Iss. 5: 1 (2020); doi:10.1109/JSTQE.2020.2982985
40. Ian F. Akyildiz, Shuai Nie, Shih-Chun Lin, and Manoj Chandrasekara, *Comput. Netw.*, **106**: 17 (2016); doi:10.1016/j.comnet.2016.06.010
41. Huali Hao, David Hui, and Denvid Lau, *Nanotechnol. Rev.*, **9**, Iss. 1: 683 (2020); https://doi.org/10.1515/ntrev-2020-0054
42. Anjan Kumar, Sangeeta Singh, and Mustafa K. A. Mohammed, *Int. J. Energy Res.*, **46**, Iss. 21: 20180 (2022); doi:10.1002/er.8305
43. Anjan Kumar, Sangeeta Singh, and Mohammed Al-Bahrani, *Surf. Interfaces*, **34**: 102341 (2022); doi:0.1016/j.surfin.2022.102341