ROLE OF NANOMATERIALS OF NANOANTENNAS IN 5G WIRELESS COMMUNICATION AND KEY CHALLENGES

TAMALAM MANOGNA

Department of ECE (Microwave & Radar)
Assistant Professor, SRK Institute of Technology
Enikepadu, Vijayawada, Krishna Dt. A.P

Abstract

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. 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. 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 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.

Keywords: Antennas, Bandwidth, Communication, Graphene, Magnitude, Nano-Materials, Size, Speed

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 mod- ulus 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.

Graphene also has a high conductivity of up to 4.9×10^8S/m and sheet resistance of less than 30 Ω/m with 90% optical transparency. 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. 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. Specifically, SPP waves are electromagnetic waves guided along by a metal–dielectric interface and generated by means of high-frequency radiation. The properties of plasmonic propagation can be tuned dynamically, enabling frequency reconfiguration. Moreover, the graphene atomic monolayer can support very high electron concentrations due to its large tunability in terms of chemical potential. 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. 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.

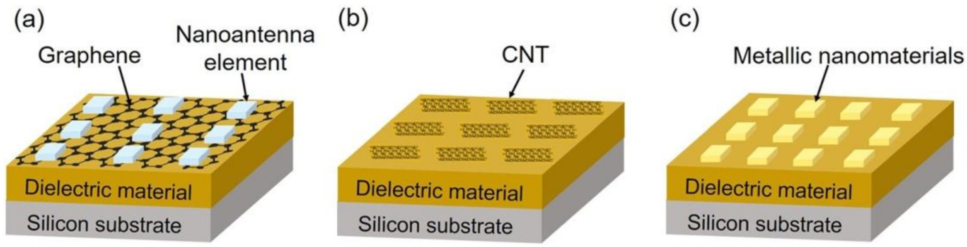

Figure 1: Schematic diagram of (a) graphene-based nanoantennas, (b) CNT-based nanoantennas, and (c) metallic nanomaterial-based nanoantennas.

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. Graphene-based nanoantennas are hundreds of times smaller in size than conventional micro-strip antennas, with higher bandwidth and gain than metallic nanoantennas. 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. These inherent features of graphene can offer both size compatibility with increasingly shrunken processor cores and adequate bandwidth for massively parallel processing. Graphene-based nano-antennas have shown excellent behavior in terms of the propagation of SPP waves in the terahertz frequencies. 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.

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 effciencies. CNTs have an extremely high conductivity approaching the quantum limit, minimizing resistive losses in the antenna. 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. The electron movement in CNTs is caused by ballistic transport through the nanotubes. CNTs can represent different electrical properties that exist in two forms: metallic and semiconducting. Armchair CNTs are metallic without energy band gap. 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. 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. 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.

The CNT-based nanoantennas with a metallic sphere in the gap can represent an efficient far-to-near field converter, supporting a con- siderable field improvement in the antenna feed. The skin effect in CNTs can be ignored when the operating frequency reaches terahertz because the electrons in CNTs conduct through the π-bond of carbon atoms, which also occurs in thin graphite sheets. CNT-based nanoantennas have a low power dissipation, leading to high antenna efficiency with respect to a metal wire of the same size. 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.

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. CNT bundles can be applied to solve this problem.

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) and that of graphene can be about 5,000 W/(m K). 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.

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. 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. 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. 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.

Metallic nanomaterial-based nanoantennas

Although the traditional metal waveguide has low loss and little signal interference, its structure is difficult to miniaturize and integrate. Metallic nanomaterials show promising characteristics and thus can be used for nanoantennas in the 5G network. 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. The electromagnetic waves can be localized on the surface of the nanoparticle, adopting the terminology of localized SPRs. Localized SPRs associated with collective oscillations of free electrons can generate large field confinement in an extremely small volume. 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. Metallic nanomaterial-based nanoantennas have many intriguing properties such as directivity gain, polarization control, intensity enhancements, decay rate enhancement, and spectral shaping. They are formed by pairs of metal nanostructures. 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.

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 electro-magnetic properties not readily available in nature. 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.

The metamaterials can be classified into different types including the electric negative metamaterials, magnetic negative metamaterials, and double-negative metamaterials based on their permit- tivity and permeability created by various structures. 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 electro- magnetic 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.

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 band-width, increasing gain, and generating multiband frequencies of antennas operation. The metama- terial-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. 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. Metamaterials can also be used as a superstrate placed above the radiation surface, increasing the obtained bandwidth of the nanoantennas.

Key challenges of wireless communications

Commercialization

Although 5G is available in some countries, its wide-spread adoption is limited. There are more than a dozen different technologies under development as part of 5G, including massive MIMO, beamsteering, and millimeter waves. 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.

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

Electrical conductivity V^{-1} s^{-1}) (S/m)	Electron mobility (cm^2 at room temperature	Current density cm^{-1})	Thermal (Aconductivity (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. 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. 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. 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.

Conclusion

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 coordi- nation with other equipment, and intelligent network applications. The size of the antennas in 5G is reduced to nanoscale because the available band-width 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.

References

[1] Ali E, Ismail M, Nordin R, Abdulah NF. Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research. Front Inform Tech EL. 2017;18:753–72.

[2] Boccardi F, Heath RW, Lozano A, Marzetta TL, Popovski P. Five disruptive technology directions for 5G. IEEE Commun Mag. 2014;52:74–80.

[3] Cabellos A, Laser I, Alarcón E, Hsu A, Palacios T. Use of THz photoconductive sources to characterize tunable graphene RF plasmonic antennas. IEEE Trans Nanotechnol. 2018;14:390–6.

[4] Chen X, Meng F, Zhou Z, Tian X, Shan L, Zhu S, et al. One- step synthesis of graphene/polyaniline hybrids by *in situ* intercalation polymerization and their electromagnetic properties. Nanoscale. 2014;6:8140–8.

[5] Fagbohun OO. Comparative studies on 3G, 4G and 5G wireless technology. IOSR-JECE. 2014;9:88–94.

[6] Hsu Y-W, Huang T-C, Lin H-S, Lin Y-C. Dual-polarized quasi Yagi–Uda antennas with endfire radiation for millimeter- wave MIMO terminals. IEEE T Antenn Propag.

2017;65:6282–9.

[7] Jang J, Chung M, Hwang SC, Lim Y-G, Yoon H-J, Oh TK, et al. Smart small cell with hybrid beamforming for 5G: theoretical feasibility and prototype results. IEEE Wirel Commun. 2016;23:124–31.

[8] Jorswieck EA, Badia L, Fahldieck T, Karipidis E, Luo J. Spectrum sharing improves the network efficiency for cellular operators. IEEE Commun Mag. 2014;52:128–36.

[9] Laser I, Kremers C, Cabellos-Aparicio A, Jornet JM, Alarcón E, Chigrin DN. Graphene-based nano-patch antenna for ter- ahertz radiation. Photon Nanostruct. 2012;10:353–8.

[10] Lin W, Ziolkowski RW, Baum TC. 28 GHz compact omnidir- ectional circularly polarized antenna for device-to-device communications in the future 5G systems. IEEE T Antenn Propag. 2017;65:6904–14.

[11] Liu DQ, Zhang M, Luo HJ, Wen HL, Wang J. Dual-band platform-free PIFA for 5G MIMO application of mobile devices. IEEE T Antenn Propag. 2018;66:6328—33.

[12] Mueller CH, Miranda FA, Dayton JA. Tunable dielectric materials and devices for broadband wireless communica- tions. Cleveland, USA: NASA Glenn Research Center; 1998.

[13] Nair GP. Nanocore – a review on 5G mobile communications. Trivandrum, India: International Journal of Computer Science and Mobile Computing; 2013. p. 124–33.

[14] Naqvi AH, Lim S. Review of recent phased arrays for millimeter- wave wireless communication. Sensors. 2018;18:3194.

[15] Rappaport TS, Shu S, Mayzus R, Hang Z, Azar Y, Wang K, et al. Millimeter wave mobile communications for 5G cellular: it will work! IEEE Access. 2013;1:335–49.

[16] Rosker ES, Sandhu R, Hester J, Gorsky MS, Tice J. Printable materials for the realization of high performance RF

[17] Tianmin R, La RJ. Downlink beamforming algorithms with inter-cell interference in cellular networks. IEEE T Wirel Commun. 2006;5:2814–23.

[18] Zhang S, Chen X, Syrytsin I, Pedersen GF. A planar switchable 3D-coverage phased array antenna and its user eff ects for 28-GHz mobile terminal applications. IEEE T Antenn Propag. 2017;65:6413–21.