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Electromagnetic Nanocommunication Networks: Principles, Applications, and Challenges

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ABSTRACT Nanoscale devices, also called nanomachines, form communication networks and cooperate with each other so that they can be used to perform complicated tasks. Such networks of nanodevices, named nanonetworks, envisioned to serve the functionality and performance of today's Internet. This paper presents a comparative review of the state-of-the-art electromagnetic (EM) nanonetworks highlighting their potentials and challenges in a comprehensive manner. We first introduce the promising areas of applications of nanonetworks; therein, we explain how it can be useful in biomedical fields, environmental domains, consumer products, military systems, and on-chip wireless communications. Then, the survey focuses on the basic principles of fundamental physical layer issues enabling nanonetworks; the discussion includes frequency bands, modulation and demodulation, and EM properties of nanoparticles. Subsequently, the study provides an overview of transmission characteristics including channels, channel coding, and energy constraint nature of nanonetworks. Furthermore, we provide an in-depth discussion on nanoantenna highlighting its variants and their characteristics; give an overview of network layer issues; and discuss the security issues in EM nanonetworks. The study argues that despite the significant recent development of EM communication as one of the most desired modes of nano communications, the limited capabilities of nanomachines introduce a new set of challenges and unique requirements and pose unseen characteristics that need to be deliberately addressed. On that, the review finally provides a critical discussion on the applicability of EM mode for nano communication networks highlighting the future challenges with a set of perspectives of possible solutions.

INDEX TERMS Molecular communications, electromagnetic communications, nanonetworks, terahertz (THz), nanoantenna, applications of EM nanocommunication, challenges of EM nanocommunication.

I. INTRODUCTION

Nano- to micro-meter sized devices, customarily known as nanomachines, can accomplish simple tasks such as sensing, storing, computing, and actuation [1]. Nanonetwork is referred to as a set of interconnected nanomachines that collaborate and share the same medium for communication [2]. Researchers paid deep attention to nanonetworks due to its promised applications in many fields such as health

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monitoring, environment surveillance, targeted drug delivery, regenerative medicine, military technology, industrial and consumer goods applications, waste/population control, and tracking down the chemical or biological skirmish in nanoscale domain etc [3]–[7]. Four fundamental nanocommunication techniques are being researched: acoustic, mechanical, chemical or molecular, and electromagnetic communication. EM nanocommunication uses electromagnetic waves for information carrier with the framework of wireless communication system. In molecular communication, nanodevices communicate among themselves by

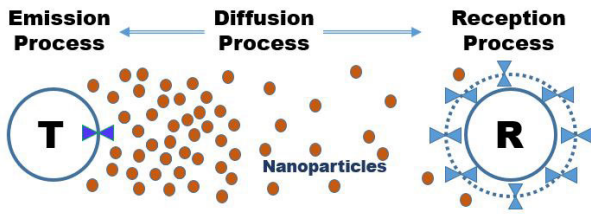


FIGURE 1. A generic end-to-end representation of molecular communication nanonetworks depicting emission, diffusion and reception process of nanoparticles (T: Molecular Transmitter, R: Molecular Receiver).

using molecules (called molecular or chemical signals) as information carrier. All of living beings enjoy naturally developed biophysical transceivers on their particular communication pathways for information exchange and control in and between organs [8]. In acoustic communication, information signal is transmitted by varying acoustic energy e.g., pressure variations. However, in acoustic communication, the integration of the traditional acoustic transducers and radio frequency transceivers is practically impossible in nanoscale devices because of their size and communication principle. Transmission of information data in nanomechanical communication is achieved through direct and physical contact between transmitting and receiving antennas [9]. Therefore, two principal options for communication among nanomachines have been imagined; a) chemical or molecular communication and b) electromagnetic communication [10], [11].

The data encoded molecules carry information from the transmitter nanomachine to receiver nanomachine in molecular communication. Figure 1 shows an end-to-end physical model for molecular nanocommunication network. Based on the types of carrier molecules, molecular communication techniques are categorized as walkaway-based, flow-based or diffusion-based. Energy efficient and bio-compatible devices called bio-nanomachines, as fabricated from biological materials, are able to interact with biological cells and organic molecules [12]. form of molecular communication often referred as neuro-spike communication is also one of the fields of concern in which the neuro-transmitters are used as information carriers, while electro-chemical impulses are used for transmission. It is used for inter-cellular communication and can also be regarded as a hybrid model which involves both the molecular communication of neuro-transmitters and transmission of impulses [13], [14]. On the other hand, inter-organ communication communications is presented in [15] by providing the communication analysis of Boolean logic AND and OR for biochemical pathways.

Electromagnetic nanocommunication follows the conventional modulation and demodulation of electromagnetic signals utilizing elements that are manufactured from unique nanomaterials [7], [10], [16]. It utilizes electromagnetic signals with the structure of wireless nanotechnology. However, due to their size and complexity, it is nearly impossible to circuit a vast number of nodes. In addition, it is hard to

incorporate the conventional EM transceivers into the nanomachines. Nonetheless, the use of carbon nanostructure is a potential method to build up the electronic nanocomponents. Present-day advances in carbon nanostructure and molecular nanoelectronics opened new way to develop nanoelectronic peripherals like nanobatteries [17], nanoscale energy harvesting systems [18], nanomemories [19], and nanoscale logical circuitry and even nanoantennas [20], [21]. The intrinsic behaviour and features of nanomachines defer from conventional devices functioning at macroscale level, and peculiar characteristics at nanoscale level ought to be uncovered [22].

Then the question comes what is the intuitive motivation to realize molecular communication using the EM nanocommunication. The perspective can be explained as follows. Akka *et al.* theoretically examined the propagation of EM waves inside the human body cell such as blood, skin, and fat for single-path and multi-path layers [23]. The frequency range was considered from 0.01 to 1.5 THz frequencies, and the calculation was associated with the path-loss, bit error rate, signal to noise ratio, and channel capacity. The authors observed that blood has higher path-loss than skin and fat, and the path loss is found to be directly proportional to frequency and distance. They numerically showed that, at transmit power 15 to 5 dBm, communication is feasible over the 0.01–1.5 THz band; however, to get a higher communication distance, a new communication model requires to be introduced. Analytical results depict that wireless nanosensor communication through the human body is possible, but thermal noise is too high to transmit the THz waves inside the human body. The propagation of electromagnetic waves in general and THz waves in particular through the human body experiences spreading, absorption, and scattering [24]. Inside the human body, the signals are absorbed by different types of molecules such as water in the blood plasma and hemoglobin in the blood cells. This radiation is unable to break molecules; however, it induces internal vibrations and, thus, eventually leads to produce heat [24]. Neurons in the nervous system can be excited by an electrical signal. It can store, process, and transmit information through chemical and electrical signaling mechanisms [25]. The concept of hybrid nanocommunication introduced in [26] also highlighted the importance of the interplay between the molecular communication, EM approach, and neural communication forms of nanonetworks.

The objective of this paper is to provide a survey of the EM nanonetworks covering a wide range of features and issues, including physical layer characteristics, network architectures, applications, security perspectives, and research directions.

A. EXISTING SURVEYS AND OUR CONTRIBUTIONS

Some of the early survey and perspective works on EM mode of nanocommunications were reported in [6], [7], [10], [11], [22], [27], [28]. Since then the applicability of nanonetworks using EM approach has been studied from different

viewpoints and updated insights and understanding were covered by a number of works [2], [9], [29]–[32]. Recently, a few reasonable discussions and surveys on EM nanonetworks are available in the literature [24], [33]–[37]; however, the spectrum of EM mode of nanocommunication is so enormous that many critical issues and aspects are often missed out. Moreover, this field is constantly being studied and the existing literature is continuously evolving. As such, it is necessary to investigate and present all the recent advancement made in this field collectively in a single platform.

In Table 1, we show a comparative scenario on the scope of our paper with that of the existing surveys to distinguish the contribution of this paper from existing works. We also examine previously undiscussed directions in our manuscript. The main contributions of our work are highlighted below:

- We investigate the recent advances in electromagnetic nanocommunication networks, its communication types, network architecture and features from three perspectives namely, i) applications, ii) principles, and iii) challenges.
- In case of applications, we delve into biomedical applications covering both healthcare systems and diseases and germs propagation control which was missing in previous work. We also present environmental applications, industrial and consumer applications, military applications as well as wireless on-chip applications with recent references.
- We also present in-depth review of basic principles regarding physical layer issues along with transmission characteristics of nano communications and nanoantennas used for EM nanocommunication.
- In addition, we inspect the security of the EM nanonetworks by providing insights about security challenges, attack vectors, and security goals.
- Besides, we provide a set of hints on how to solve the open challenges and issues associated with EM mode of nanonetworks.

B. ORGANIZATION

The rest of this paper is organized as follows. In Section II, we discuss the applications of nanonetworks. Section III present the basics of physical layer issues. In Section IV, we provide the transmission characteristics of nano communications. Whereas Section V presents the discussion on Nanoantennas, Section VI introduces the network layer and security issues. The challenges, open issues, and future directions are discussed in Section VII. The final section concludes this review.

II. APPLICATIONS OF NANONETWORKS

The integration of the nanocomponents (nanoprocessors, nanomemories, nanobatteries, and nanosensors etc.) in a single entity may result in the development of novel nanomachine. More importantly, the way the computer communications enabled revolutionary applications by Internet,

TABLE 1. Comparison of our study with prior works.

Subjects and Issues	Papers
Healthcare Applications	[10], [22], [24], [28]–[30], [32]–[34], [36], [38]–[51]
Industrial Applications	[10], [22], [29], [33], [34], [38]
Environmental and Agricultural Applications	[10], [22], [29], [33], [34], [38], [43], [45], [52]–[56]
Food Science Applications	[33], [45]
Multimedia Applications	[22], [38], [39], [44]
Military Applications	[10], [22], [29], [38], [44]
Supply Chain (RFID) Applications	[57]
Nano-antenna Design	[27], [29], [31], [33], [44], [58]–[69]
Channel Model	[10], [22], [31], [33], [36], [44], [53], [54], [60], [70]–[76]
Channel Coding and Error Correction Coding	[29], [77]–[82]
Energy Model and Harvesting	[22], [29], [33], [43], [44], [47], [48], [60], [72], [73], [79], [81]–[108]
Hardware	[29], [39]
Software	[33], [39], [50], [78], [95], [96]
Topology	[36], [109]
Nanonetwork Architecture	[10], [22], [24], [27]–[31], [33], [33], [34], [36], [38]–[50], [54], [72], [83]–[86], [110]
Routing and MAC Protocol	[10], [22], [27], [28], [30], [31], [33], [37], [42], [44], [48], [50], [56], [63], [72], [73], [76], [78], [83], [88]–[93], [96], [100]–[106], [110]–[127]
Layer-wise Architecture	[31], [33], [44], [50]
Security	[38], [39], [44], [110], [128], [129]
Privacy	[38], [39], [128]
Challenges and issues	[10], [22], [27], [28], [30], [31], [33], [34], [38], [39], [42]–[44], [54], [55], [93], [106], [110], [129]
Solutions to the challenges	[22], [27], [28], [33], [43], [44], [54]
Future Research Directions	[10], [24], [27], [31], [36], [38], [39], [43], [44], [54], [106], [128]–[130]
All of the aforesaid topics and issues	This survey

networking of nanodevices will likewise have the ability to debacle their impediments and extend their conspicuous applications [10], [22], [44], [131], [132]. The resulting nanonetworks have potential to cover bigger sections, to arrive at remarkable areas in a non-obtrusive manner, and to play out extra in-network operation [29], [39]. Here are few examples:

A. BIOMEDICAL APPLICATIONS

Possible applications of nanonetworks in the biomedical area is huge [24], [30], [32], since, nanoscale is the innate space of proteins, molecules, organelles, DNA, and the principal parts of living tissues [133]. Nanonetwork is able to collect vital information of patient and transfer it to computational systems and thus making more precise and skilful mode of health inspection. The deployment of the Internet of NanoThings (IoNT) in health monitoring systems may render precise diagnosis and help in the case of treatment through exact and targeted drug release, as already being used in tumor detection process [33]. Tattoo-like biological

nanosensors [134] can be installed over or even inside the human body as pills or intramuscular injections to observe glucose, sodium, and cholesterol [135], [136], with a view to inspect noxious elements [137], or to pinpoint any particular type of cancer [138]. A remote interface, for example, a cell-phone or healthcare equipment between these nanomachines and micro-devices could be utilized to gather information and to advance it to a medical services provider.

1) HEALTHCARE SYSTEMS

Electromagnetic nanonetworks would significantly enrich future healthcare systems [31], [40], [139] by virtue of its reduced sensitivity to propagation impacts like scattering and its security advantages for human body cells i.e., non-ionization [140]. With the help of nanobiosensors, e-health monitoring system [22], [41], [49], [51], [85], [109] can be developed, so do e-drug delivery systems [10], [46] by using nanorobots. E-living and e-health system can be provided with the connection of nanonetworks to the internet [131]. Through the in-body networks, patients do not need to go to pathologists to receive any lab tests, as the tests will already be done within the body through monitoring the changes in molecular contents or infections, and these readings could be provided to doctors from the patients' mobile devices [141].

2) DISEASES AND GERMS PROPAGATION CONTROL

Nanosensors can be placed in public locations such as hospitals, airports, restaurants etc., where people come in the reach of numerous diseases, either through close contacts or through viral propagation via the air. Nanosensors can be used to collect and thus pass these information to individual user's services [141]. Networked nanosensors in agriculture can help detecting harmful diseases that may infect livestock or crops. Recent examples in Europe of such harmful diseases are the outbreak of E. Coli on vegetables and mad cow disease [141].

B. ENVIRONMENTAL APPLICATIONS

Plants like trees, herbs, or bushes deliver various chemical compounds for attracting the hunters of the bugs that attack them, or to control their sprouting among various ranches among others [142]–[144]. Those chemical compounds can be detected using chemical nanosensors [134] and nanonetworks can be built encompassing the chemical sensor devices for utilization in agriculture [55], [145]. Biodiversity control, crop monitoring [52], bio-degradation assistance, or air pollution control can be mentioned as the other environmental applications [45], [53], [56], [146].

C. INDUSTRIAL AND CONSUMER APPLICATIONS

Nanotechnology got wide range of applications in the development of modern consumer and industrial products such as pliable and stretchable electronic devices [38], [147], consumer products like sunscreens and cosmetics [148], functionalized nano-materials for self-purifying anti-microbial attires [149], radio frequency identification (RFID) [57] etc.

The incorporation of nanodevices with transmitting and receiving abilities in each and every item, from cooking utensils to the components of every device, will permit the coordination of nearly everything in our everyday life [34], [131]. In an interconnected house or office, nanodevices can be incorporated in each and every item to render a ceaseless connection to the Internet [150]. In addition, as nano-phones and nano-cameras are evolved, the Internet of Multi-media Nano-Things [44] is also waiting for becoming practical.

D. MILITARY APPLICATIONS

Nanonetworks can be utilized in cutting edge nuclear, biological, and chemical (NBC) defenses as well as sophisticated damage identification systems for common arrangements, warriors' shield and combatant wagons etc. A nanosensor network is capable of identifying biological weapons and noxious chemicals with much precision as well as rigor, in diverse situations, from the battle-ground (e.g., commissioned from an automated car and intangible by the eyes of human) to airbase terminal or a meeting chamber (e.g., remained in the paint of wall) [29]. By using nanosensors, the existence of a chemical compound can be identified in an amount as small as one molecule and very much quicker than using traditional micro-scale sensors [22].

E. WIRELESS ON-CHIP APPLICATIONS

Planar nano-transceivers can produce ultra-high-speed links in terahertz frequency that is capable of providing effective and scalable methods of inter-core communication in wireless on-chip networks [151]. This novel methodology would meet the prerequisites of the area-limited and communication-intensive on-chip situation because of both its large frequency band and highly small area overhead. It is mentionable that, the utilization of graphene-based terahertz frequency communication [58] will release congenital multi-cast and broadcast communication competencies at the center level.

III. BASICS OF PHYSICAL LAYER ISSUES FOR EM NANONETWORKS

A. FREQUENCY BANDS

Electromagnetic nanocommunication is referred to as the exchange of electromagnetic signals by the nanoscale components [152]. Communication and signal transmission techniques used in nanonetworks appear to be the most challenging tasks because of the limited computation skills of nanomachines. In view of communication, the particular characteristics observed in novel nanomaterials choose particular frequency band for transmission of electromagnetic signals, the transmission delay, or the magnitude of the transmitted power for a given input energy, among others [153]. Electromagnetic nanocommunication is impossible in currently used frequency range (from hundreds of MHz to few GHz). Because, in this range, the size of the antenna will be a few centimeters. However, diminishing the dimension

of the conventional transceivers to a couple of hundred nanometers would prompt large working frequencies i.e., terahertz frequencies (0.1–10.0 THz) [31], [33]. Therefore, terahertz frequency is recommended as the transmission frequency band of nanonetworks.

Development and design of nanoantennas are being researched. Graphene nanoribbons (GNR) and carbon nanotubes (CNT) are nominated for EM nanoantenna [154]. Graphene-based nanoantennas are not only the shrinkage of a traditional antennas, but also there are a few quantum marvels that influence the propagation of electromagnetic signals. The result is that the resonant frequency of these nanostructures are found to be up to two orders of amount lesser than that of their nonocarbon-based fellows. Notwithstanding, to determine the operating frequency for electromagnetic nanonetworks, it is required to portray the radiation properties of graphene. So far, reports have been found in the literature both from the optical [155]–[157] and the radio-frequency [20], [158], [159] viewpoints. The primary distinction between the two alternatives depends upon the explanation of the radiation regarding high frequency resonant signals emitted from nanoantennas, or small energy photons emitted by optical nano-transmitters. Even if the difference in origin, the two methodologies conceive the terahertz band to turn into the operating frequency for future electromagnetic nanoantennas [153]. An architecture of nano-devices including nano-sensors, nano-actuator, nano-memory, nano-antenna, nano-electromagnetic-transceiver, nano-power unit, and nano-processor have been presented in [22]. When all these components are integrated, the machine can recognize, compute, or even carry out actuation. Moreover, it was anticipated that nano-devices would possibly exchange information among themselves in the terahertz frequencies.

Terahertz frequency band, which spans the electromagnetic spectrum from 0.1-10.0 THz [160], remained as the least investigated frequency bands for communication [125]. Terahertz frequency radiation shows some common properties with infrared and microwave radiation because its spectrum lies in between of these two. As in the case of infrared and microwave radiations, terahertz frequency radiation is found to be non-ionizing [140] and also propagates in a line of sight. It penetrates a large variety of non-conducting materials as microwave radiation does. On contrary to X-rays, the insignificant photon energies of terahertz frequency radiation generally do not cause any harm to living tissues and Deoxyribonucleic acid (DNA) [161] and it isn't an ionizing radiation. Non-ionizing terahertz frequency radiation is able to infiltrate through wood, paper, cardboard, masonry, clothe, ceramics, and plastic etc. Unlike microwave radiation, the penetration depth of terahertz frequency radiation is lesser. Terahertz frequency radiation got restricted access through fog and cloud and is unable to go through metal, liquid, or water. Since, it can travel some space through human body cell, it may take up the place of medical X-rays. However, because of its larger wavelength, pictures created utilizing THz frequency signal got poor resolution than X-rays and should be upgraded.

Moreover, the the range of the terahertz frequency signal propagation in air is restricted to a order of few hundreds of centimeters due to the strong absorption characteristics of the earth's atmosphere. The usable frequency band of the THz channel is determined by molecular absorption [162]. Therefore, terahertz frequency radiation appears to be incompatible for long range communications. Notwithstanding, at distances of the order of 10 meters, the frequency band may in any case permit numerous helpful appliances in imaging and development of high frequency wireless network structures, particularly indoor operations [163], [164]. Also, creating and recognizing coherent THz frequency signal experience technical challenges, though cheap business enterprizes currently present in the 0.3-1.0 terahertz range (the smaller part of the range), including resonant-tunneling diodes, gyrotrons, and backward wave oscillators.

B. MODULATION AND DEMODULATION

One of the most key difficulties with nanocommunication is the necessity for an proper modulation and demodulation scheme as well as an earmark channel access technique. Pulse position modulation (PPM) technique incorporating time-hopping (TH) has been introduced as a modulation and multiple access mechanism for multiuser nanocommunications [165]. Energy-efficient PPM modulation technique combined with TH would strengthen nanomachines to exchange information concurrently with improved efficiency. In light of the asynchronous trade of femtosecond-long pulses, a modulation and channel sharing technique is introduced for exchanging binary data signals in an electromagnetic nanonetwork [166]. In [125], a pulse-based MAC protocol for electromagnetic nanonetworks has been presented. The introduced protocol has been designed to cope with the quirks of the THz frequency and is comprised by two fundamental steps; a) the transmission process, and b) the handshaking process. At last, for self-powered nanosensors, the authors in [98] have designed an energy model which efficiently catches the correlation between the energy consumption and the energy harvesting processes. Using various orthogonal time-hopping sequences, a couple of pulse-based modulation techniques are proposed for high-speed communication processes [167]. Notwithstanding, the greater part of these methods proposed for IR-UWB can't adapt to the eccentricities of the terahertz frequency channel and devices' limitations in light of complexity and energy [148]. Time Spread On-Off Keying (TS-OOK) for EM Wireless Nanosensor Networks (WNSNs) has been reported in [162]. The scheme depends on the emission of femto-second-long pulses by adopting an OOK modulation technique. Upon the utilization of proper channel codes, the aggregated network capacity and the single-user capacity are found to excel those of the classical AWGN channel wireless networks.

C. EM PROPERTIES OF NANOPARTICLES

The fabrication of nanostructure devices received too much interest in last couple of years. Optical properties of metallic

nanoparticles are found to be very much appropriate for biomedical applications [168]. For instance, depending upon the size, shape, geometry, and the refractive index (RI) of ambient dielectric, gold nanoparticles have internal electromagnetic characteristics. Precisely speaking, at optical frequencies, the emphatically upgraded Localized Surface Plasmon Resonance (LSPR) of the material allows them to be good light scatterers and absorbers [169]. Additionally, gold nanoparticles (AuNPs) are found to have novel physico-chemical properties, for example, extremely small size, big surface area to mass ratio, and large surface reactivity, existence of surface plasmon resonance (SPR) bands, biocompatibility and effortless surface functionalization [170], and are helpful as differentiation agents in tissue and biological imaging [171]. Regarding absorption and scattering cross-section, the following suppositions should be set up for explaining the electromagnetic properties of the nanoparticle:

- **Size of Particles:** The size of the particles should be smaller than the wavelength in the encompassing environment. For this situation, in the constraint of electrically minute particles, the electromagnetic field is almost unchanged over the volume of the particle, and afterward the resonant characteristics of the configuration can be investigated considering quasi-static approximation.
- **Composition of Particles:** The particles under consideration should be assumed to be homogeneous and isotropic. Moreover, the encompassing material is likewise a non-absorbing, isotropic, and homogeneous environment.

IV. TRANSMISSION CHARACTERISTICS OF NANO COMMUNICATIONS

A. NANONETWORK CHANNELS

An antenna of several tens of nanometers would lean on the utilization of ultra large working frequency, which restricts the spectrum of communication of nanomachines [80]. Nanonetwork channels are formed as the nanodevices are physically separated by up to a few nano- to micro-meter. For nanosensor networks, the fundamental challenges of EM nanocommunications are perceived by information encoding, communication protocols, and terahertz frequency channel model [76]. Extremely large bandwidth and thus very high propagation loss are the main characteristics of terahertz frequency communication [172], [173]. Nanomachines, working in terahertz frequency, practically have so small size that they can be inserted inside human body [174]. However, major drawback of electromagnetic waves in the terahertz frequency is high losses in the tissues and body fluids of microorganisms. During signal propagation in several millimeters, the losses in blood are about 120dB, in skin – about 90dB, and in fat – about 70dB [74]. Therefore, for a distance of a couple of millimeters, the use of repeaters is required for communication among transceiver nanomachines. Regarding the attenuation of electromagnetic signals in human body

cells, the propagation model proposed in [140] characterizes the behavior of THz frequency communication in human skin tissue. Communication spectrum and channel capacity for various transmission parameters were deduced. Utilizing optical parameters of human tissue cells, molecular absorption noise, and path loss have been calculated and checked through broad experimental tests. In addition, SimpleNano, a channel model for WNSNs that is able to transmit in the THz frequency region where a log-distance path loss model along with random attenuation due to the molecular absorption, was estimated in media like the human tissue [175].

A path loss model for wireless nanocommunication in the terahertz frequency is introduced in [54], [70], [172]. The ground of the model is the radiative transfer method in light of the absorption of molecules. The authors figure out the molecular absorption noise, signal path loss, and ultimately, the capacity of the channel of electromagnetic nanonetworks. The findings reveal that, for extremely small propagation distances (of the order of a few hundreds of centimeters), the THz channel nourishes remarkably high bit rates, up to several Tbps, that empowers a drastically unique communication paradigm for nanocommunication networks. In the case of a traveling electromagnetic wave in the THz frequency, the total path-loss A in dB can be found as the summation of the spreading loss in dB, A_{spread} , and the loss in dB due molecular absorption, A_{abs} [172]:

$$A(f, d)[dB] = A_{spread}(f, d)[dB] + A_{abs}(f, d)[dB], \quad (1)$$

where f refers to the wave frequency and d represents the total path length. Since, the wave expands as it disseminates through the channel, the spreading loss elucidates the attenuation, and it is characterized as

$$A_{spread}(f, d)[dB] = 20 \log \left(\frac{4\pi fd}{c} \right), \quad (2)$$

where c refers to the light speed in vacuum. The absorption loss A_{abs} mirrors this decrease in the energy of the wave, and is characterized as:

$$A_{abs}(f, d) = \frac{1}{\tau(f, d)}, \quad (3)$$

where τ represents the transmittance of the medium. This parameter gauges the fraction of incident radiation that can go through the medium and was determined utilizing the Beer-Lambert Law [176]:

$$\tau(f, d) = e^{-k(f)d}, \quad (4)$$

where k represents the coefficient of medium absorption. The last parameter relies upon the configuration of the channel, i.e., the specific composition of molecules encountered through the path, and it is portrayed as:

$$k(f) = \sum_{i,g} k^{i,g}(f), \quad (5)$$

where $k^{i,g}$ refers to the individual coefficient of absorption for the isotopologue i of gas g . As for instance, the air in a room is

mostly consist of nitrogen (78.1%), water vapor (0.1-10.0%), and oxygen (20.9%). In the terahertz frequencies, every gas has diverse resonating isotopologue i.e., molecules that are dissimilar in their isotopic constitution [172]. The ambient noise in the THz frequency medium is principally enriched by the absorption of the molecules [150]. The absorption by molecules existing in the channel not only attenuates the transmitted wave but also offers noise [176]. The same proportion of noise temperature at the receiver is realized by the chunk of molecules found along the path. The noise power spectral density (PSD) is not flat due to the diverse resonant frequencies of every kind of molecules, but has a couple of bumps. Likewise, this sort of noise chiefly appears during the transmission of signals, i.e., there will be mainly background noise if the medium is not being utilized. The parameter that accounts for this event is the emissivity of the medium, ϵ , and it is portrayed as [153]:

$$\epsilon(f, d) = 1 - \tau(f, d), \quad (6)$$

where τ is the transmittivity of the medium. An experimentally validated channel model for molecular communication systems is reported [71]. A communication channel noise model in human body cells at the terahertz frequency is presented in [177]. The findings depict that the channel noise PSD of the order of a few micrometers is at tolerable limits and the amount inclines to decrease with the increase of both frequency and distance. Furthermore, with the result of higher noise in human tissue-channel with higher water concentration, the noise of the channel is additionally dependent upon the constituents of the human body cells. The human body radiation noise is alluded to as the noise caused by the radiation of the human body cells. Accordingly, the noise from human body radiation is portrayed with the help of Planck's function in human body channel [177]

$$B(T_0, f) = \frac{2h\pi(nf)^3}{c^2} \left(e^{\frac{hf}{k_B T_0}} - 1 \right)^{-1}, \quad (7)$$

where k_B and h are the Boltzmann's constant and is Planck's constant, respectively. The human body radiation noise can be estimated to get body radiation noise PSD in W/Hz [178]

$$N_b(f) = B(T_0, f) \frac{c^2}{4\pi(n_0 f_0)^2}. \quad (8)$$

A mechanism by which part of the energy of the signal is transformed into internal kinetic energy of the molecules present in the channel is termed as molecular absorption [176]. The terahertz frequency channel is extremely colored (i.e., highly frequency selective), particularly when the density of molecules is increased or the transmission separation is broadened [162] because molecular absorption loss relies upon the frequency of the signal, the transmission separation, and the density and the specific combination of particles experienced along the medium. EM waves in the THz frequency originate internal vibrations in numerous sorts of molecules that are ordinarily existing in networking situations, for example, water vapor, nitrogen or oxygen, among

others [179]. Therefore, a fraction of the electromagnetic signal energy is first absorbed by the molecules (absorption by the channel) and afterward re-radiated (emission by the channel) [153], [172]. The subsequent noise due to molecular absorption is conglomerated to the transmitted wave and is portrayed as Additive Colored Gaussian Noise (ACGN). It is assumed, for simplicity, that all the absorption energy from the transmitted wave received at the receiver will convert into noise PSD due to molecular absorption at that position. Thus, the noise due to molecular absorption can be displayed as:

$$N_m(r, f) = S_{Tx}(f) \left(\frac{c}{4\pi n f r} \right)^2 \left(1 - e^{-\alpha(f)r} \right), \quad (9)$$

where $S_{Tx}(f)$ is the PSD of the transmitted wave and $4\pi n f r / c^2$ refers to the spreading loss. The total channel noise power spectral density for in-vivo nanonetworks is, therefore, calculated as,

$$N(r, f) = N_b(f) + N_m(r, f). \quad (10)$$

The terahertz frequency channel is extremely non-white. The molecular noise is frequency selective on the grounds that molecular absorption relies upon the configuration of the medium [72]. Therefore, the capacity is achieved by separating the entire bandwidth into several narrow sub-bands and adding the separate capacities [180]. The i -th sub-band is centered encompassing frequency f_i , $i = 1, 2, \dots$ and it got span of Δf . In case, if the width of sub-band is sufficiently narrow, then the channel becomes white and the noise power spectral density can be viewed as sectionally flat. Eventually, the capacity in the unit of bits/s is then obtained as [153]:

$$C(d) = \sum_i \Delta f \log_2 \left[1 + \frac{S(f_i)A^{-1}(f_i, d)}{N(f_i, d)} \right], \quad (11)$$

where d refers to the total path length, S refers to the PSD of the transmitted signal, A represents path-loss of the the channel and N is known as the noise PSD.

B. CHANNEL CODING

The resulting error-prone wireless link is mainly because of the poor capabilities of particular nanodevices and the THz frequency channel characteristics [81]. The loss due to molecular absorption and stringent path loss occur in electromagnetic nanocommunication in terahertz frequencies. Coding play an important role to identify and address transmission errors [79]. An innovative error control technique for EM nanocommunication networks is introduced depending upon the usage of low-weight channel coding [77]. The authors demonstrate that low-weight channel codes might be an option to lessen codeword error rate (CER) without bargaining the attainable data rate or in any event, expanding it, particularly in the case of hard-receiver design. It was also shown that the data rate is found to be maximized for an optimal code weight.

A coding technique with a view to mitigate interference is proposed in [179]. It was analytically demonstrated that

both the multiuser interference and the molecular absorption noise in nanocommunication networks can be alleviated by decreasing the channel code weight, that brings about reduced channel error probability. The minimum energy code for nanonetworks has also been introduced in [181]. The paper concentrates on WNSNs embracing the OOK modulator which emits a signal for 1 and keeps silence for 0 and searches the optimal coding architecture for the minimization of energy of transmission in such networks. However, the information capacity is always insufficient in the existing coding methods and the network resource is not utilized adequately [179], [181]. Moreover, the prerequisite of high data information rate has radically increased in the last three decades [80]. For instance, required wireless information data rates have multiplied at regular intervals and practically moving toward the capacity of wired communication systems [150]. Therefore, it is obligatory to optimize the nanocommunication networks to enhance the capacity of information data of the network. A cross-layer analysis of error-control techniques for nanonetworks in the terahertz frequency is introduced in [81]. The authors developed a mathematical architecture and utilized it to investigate the trade-offs between Packet Error Rate, Bit Error Rate, energy consumption and latency, for five different error-control strategies, in particular, forward error correction (FEC), automatic repeat request (ARQ), two types of error prevention codes (EPC) and a hybrid EPC.

C. ENERGY AND POWER CONSTRAINTS OF NANOMACHINES

A nanomachine consists of an antenna, power supply, CPU module, memory, and it acts like an independent node capable of performing basic undertakings, for example, sensing, storing, computing, and/or actuating at the nanoscale [92]. Inside a WNSN, due to the power and energy limitations of nanosensors, achieving single-hop transmission distances above several meters is implausible [18], [22], [47], [90]. The energy is mainly used to communicate among nanosensor motes [82], [87], [97], [98], [108]. In classical battery-powered devices, the energy decreases until the battery is empty [88]. But self-powered devices have both positive and negative variations [98]. A major challenge of nanosensor device is its energy storage capacity [107]. However, energy harvesting is one of the possible solutions of this specific problem [18], [73], [93]–[96], [103], [182]–[185]. The process is perceived by virtue of a piezoelectric nanogenerator, for which an innovative design of circuitry is originated that is able to reproduce present experimental information data precisely. Energy harvesting processes at the nanoscale proposed in [18], [105], [182], [183] convert a couple of unique types of energy, e.g., acoustic, vibrational, fluidic, or electromagnetic energy into electrical energy. In [141], it was shown that EM nanodevices may use vibrations of nanowires for generating energy. Piezoelectric nanogenerator has experimentally been demonstrated in [184]. It was reported that, if the energy harvesting and the

energy consumption processes can combinedly be designed, the longevity of energy harvesting networks can considerably be increased [186], [187].

It is judicious to think about that the transmitting nanomachine will endeavor to re-transmit if the charge of a nanomachine fully depletes and is not able to reciprocate to a communication request. This would definitely increase the overall network traffic and multi-user interference, and it eventually offer an effect in the energy of the transmitter nanosensors and the adjoining nanomachines [98], [99]. The self-powered nanosensor mote [98] appreciates both the energy harvesting mechanism by virtue of a piezoelectric nanogenerator and the energy utilization method because of electromagnetic communication in the terahertz frequency [89], [153], [162], [172]. The model permits to calculate the probability distribution of the energy of the nanosensors and to examine its variations depending upon several system and network parameters. Conventional energy harvesting mechanisms, for example, solar energy, underwater turbulence or wind power are not applicable in WNSNs [188], [189]. For instance, even though innovative nanoscale components like carbon nanotubes are utilized to upgrade their sensitivities [190], the efficiency of harvesting solar energy by photovoltaic nanocells is extremely low. Furthermore, sunlight is not available in many of the applications of WNSNs. Moreover, due to the technology limitations [22], traditional methods to harvest energy from underwater turbulences or from wind are not suitable in the nanoscale.

D. SENSING AND RECEIVING IN ELECTROMAGNETIC NANONETWORKS

Nanomachines [22] furnished with nanosensors, nanomemory, nanoactuator, nanoantenna, nanoprocessor, nanoelectromagnetic transceiver, and nanopower unit, can trade data through EM nanocommunications. In the communication perspective, the nanomachines will have the ability to achieve more perplexing objectives in a cooperative fashion. For instance, nanosensors are capable of transmitting the recognized data in a multi-hop manner to a sink or to a commanding center. For nano-EM networks, the exploitation of modulation and channel sharing scheme relying on the asynchronous trade of femto-second-long pulses, that are emitted using an OOK modulation, was introduced [166]. A receiver design for EM nanonetworks introduced in [191], makes usage of pulse-based modulation. The receiver is intended to be straightforward and strong, and it depends on a Continuous-Time Moving Average (CTMA) signal identification technique. A single low-pass filter is used in this technique to take decision based on the peak power of the received symbol after the CTMA. Subsequently, the maximum has been correlated with a pre-defined threshold to demodulate the symbol.

V. ANTENNA FOR EM NANOCOMMUNICATION

An antenna is an equipment used for transmitting and/or receiving information signals. A nanoantenna refers to an

antenna that is extremely small, few nano- to micro-meter in dimension, and is used to gain the knowledge about what is happening on an atomic scale. Communication choices for nanonetworks are exceptionally restricted because of the size and ability of nanoantenna [61]. The way the nanomachines communicate relies intensely upon the manner in which they are perceived [132]. Communication among nanodevices is a principal challenge, which is dependent upon the evolution of nanoantennas and the kindred EM transceivers. Besides, the particular function, for which the nanonetworks are intended to be set up, restricts the option of the unique variety of communication. In common frequency range (from a few hundred MHz to few GHz), EM nanocommunication is nearly impractical. Because, in this range, the size of the antenna will be a few centimeters. The size of antenna obliges to operate the communication in THz frequencies which in turn introduces numerous problems in electromagnetic nanocommunication like high attenuation [63], [124]. Notwithstanding, nanoantenna, built from graphene, can overcome this limitation. Graphene along with its derivatives [192], like CNTs [158] and GNRs [154], can be utilised to transmit at terahertz frequencies. For the time being, several types of nanoantenna have been introduced. However, two primary options for EM communication in the nanoscale have drawn attention. Firstly, it was practically confirmed to collect and decode an EM signal by virtue of a nanoradio, i.e., an EM resonating CNT which can demodulate an amplitude modulated or frequency modulated (FM) signal [7]. Secondly, graphene-based nanoantennas have been investigated as possible electromagnetic emitters in THz frequency [158]. The resonant frequency of these nanoframes can be up to two significant degrees beneath that of their noncarbon-based partners.

The characteristics of CNTs as antenna materials are of prime attention since CNTs can be developed to a dimension of few centimeters and can be metallic [193]. Notwithstanding, their emission efficiency can likewise be debilitated as a result of this marvel [130]. CNTs and graphene nanoribbons have been introduced in [154] for electromagnetic nanoantenna. Nanoantennas based on nanomaterials, specially graphene-based nanoantennas [58], [194]–[196] and nano-transceivers [197]–[199] are proposed because the characteristics of graphene permit them to transmit in the THz frequency as well as appropriate to be incorporated into nanosensors. CNTs are introduced as the foundation of an electromechanical nanoradio or nanotransceiver [200] that are able to modulate and demodulate an EM signal by virtue of mechanical resonance. EM nanocommunication approaches include communication in the very high frequency band with receivers using mechanically oscillating carbon nanotubes (nanotube radio) and communication in the THz frequency with receivers using graphene-based plasmonic nanoantennas. Nanoscale transmitter circuitry can be designed by using electromechanical vibrations of nanotubes [201].

Modern theoretical and experimental knowledge indicates that a single carbon nanotube antenna can be developed as

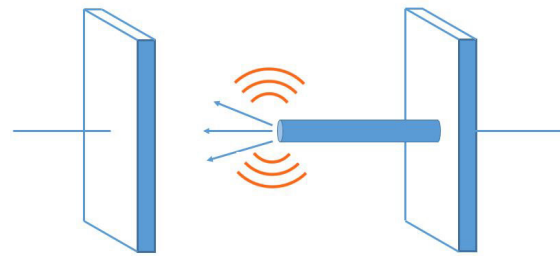


FIGURE 2. A Nanotube radio circuit illustrating receiving of signal by means of electromechanical method where the frequency of the approaching signal resembles the resonance frequency of the nanotube.

the four basic elements of a radio circuitry, i.e., modulator, demodulator, antenna, and tuner, to collect radio broadcasts [200]. The working mechanisms of CNT radio or CNT receiver are very much dissimilar to conventional radios because radio frequency (RF) wave reception, amplification, tuning, and demodulation are electromechanical methods instead of totally electrical. As depicted in Fig. 2, in the event that an approaching radio wave prompts on it, a physical trembles commence on the charged tip of the nanotube. The vibrations tune to the incoming signal as the frequency of the approaching signal resembles the resonance frequency of the nanotube. Thus, the nanotube is able to receive the approaching signal by means of electromechanical method. The basic transmitting characteristics of CNT-based dipole antennas have been examined in [193]. The authors conclude that CNT-based antennas show plasmon resonances exceeding an adequate frequency, have high input impedances (which is most likely useful for incorporating to nano-electronic circuitry), and show extremely low efficiencies. A graphene-based nanoantenna is designed, investigated, and presented in [58], that utilizes the characteristics of SPP signals in semi-finite size GNRs. The outcomes reveal that, unlike their metallic duplicates, graphene-based plasmonic nanoantennas can work at extremely lower frequencies if high mode compression factor of SPP signals is utilized. Figure 3 shows how graphene can be utilized to construct novel plasmonic nanoantennas with graphene layer mounted on top of a metallic flat surface with a dielectric material layer sandwiched in between, which can be used both to support and change its chemical potential by means of material doping.

A nanosensor utilizes the novel characteristics of nanoparticles and nanomaterials to recognize as well as gauge unusual kinds of phenomena in the nanoscale [22]. For instance, nanosensors are capable of identifying chemical amalgamations in amounts as small as one part per billion [202], [203], or the presence of various toxic elements, for example, virus or detrimental bacteria [137], [204]. As depicted in Figure 4, by utilising planar nanoantennas for creating ultra-high speed links, the terahertz frequency can give competent and scalable methods of inter-core wireless on-chip communication network. Figure 5 refers to a graphene-based nano-patch antenna which analyzes the

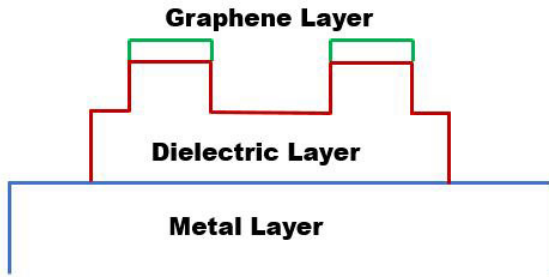


FIGURE 3. A simple schematic diagram of a typical graphene-based plasmonic antenna for terahertz frequency Nano communications with dielectric material layer in between graphene layer and metallic layer.

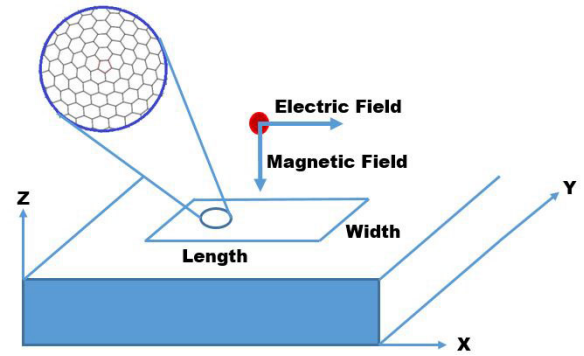


FIGURE 5. A conceptual diagram of a graphene-based nano-patch antenna with specific length and width to determine desired resonance frequency.

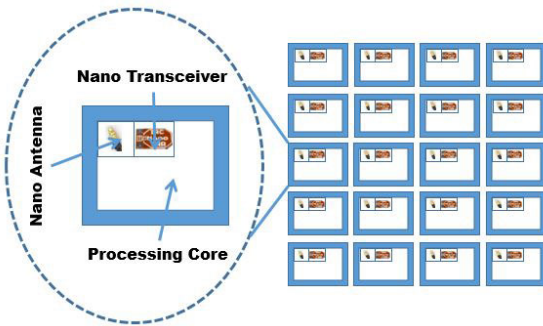


FIGURE 4. Wireless on-chip communication based on nano-antennas and transceiver between the cores of a multiprocessor.

performance in transmission and reception in terahertz frequency. The length and width determine the resonance frequency of a nanoantenna. For different size and the position of the patch regarding the substrate, the impact of a dielectric substrate has likewise been assessed. The authors found that the pattern of radiation of a graphene-based nano-patch antenna is very much similar to that of a metallic counterpart.

Silicon Germanium (SiGe) heterojunction bipolar transistors give numerous performance excellencies e.g., reduced noise, large gain, fair linearity, and satisfactory power handling, reasonable cost, tremendously-integrated, silicon-compatible technology tenet among others [205]. That's why SiGe innovation is generally the best option for some performance-bound high-frequency radio-frequency setups. It likewise gives on-die silicon Complementary Metal-Oxide-Semiconductor (CMOS) staggered metallization with minimal-loss transmission lines, and a set-up of coordinated inactive components, for example, antennas [206], for an actual system-on-a-chip innovation tenet. CMOS-based oscillators are ready to work at a fundamental frequency of 220 GHz [207]. Gallium Nitride (GaN) innovation is typically regarded for high-power applications among others [208]. Photonic devices are being used to originate and identify terahertz frequency radiation [209]–[212].

VI. NETWORK LAYER ISSUES AND SECURITY

A. ROUTING PROTOCOLS

Routing protocol for WNSN [35], [111], [120], [213] is remained in its infancy. Very limited memory storage and computational processing capabilities lead the devices

having limited capability or awareness (e.g., tables of neighboring nodes, topology knowledge) of the communication environment [100], [103], [121], [141]. It is crucial to affirm energy-efficient protocols for communications in WNSNs because of exceptionally energy-constrained nature of nanosensors [101], [112], [114], [117], [119], [127], [181]. Medlej *et al.* presents a fine-grained sleeping mechanism for nodes, whose objective is the reduction of node resource usage and thereby increase the network life [86]. At the nanoscale, the existing communication protocols may not be able to drive the nanosensor nodes to take part in communication among themselves [48], [102]. Therefore, these traditional protocols receive extensive revisions. Based on the mode of communication and propagation media, numerous types of communication protocols have been introduced that include nanomechanical, acoustic, electromagnetic, and molecular communications [37], [83], [90], [105], [106], [113], [115], [116], [118], [123], [150]. A routing framework was introduced regarding the peculiar characteristics of the WNSNs, both in terms of THz frequency nanocommunication and nanoscale energy harvesting [88]. To reduce the complexity of network operation, the WNSN is divided into groups considering a hierarchical cluster-based frameworks. Inside each group, a controller, which is a nanodevice with much increased competencies than a nanosensor, correlates the nanosensors and assembles the information they trade [22]. The performance of the architecture was mathematically assessed regarding capacity, delay, and energy, and was compared with that of the single-hop nanocommunication for a similar WNSN situation. The outcomes exhibit the way the energy consumption per bit and the attainable throughput can jointly be maximized by using the peculiar characteristics of this networking archetype. An NS-3 module, in particular Nano-Sim, design of WNSNs dependent on EM nanocommunications in the THz frequency was presented in [214]. In this primary variant, Nano-Sim gives a straightforward networking design and a protocol scheme for quite an arising innovation. In that very year, they have protracted the apparatus by building an advanced routing protocol and a more efficient MAC protocol concentrating on a WNSN working in a health monitoring scheme [50].

An exterior macroscale health monitoring framework integrating Body Area Nano-NETwork was introduced in [91]. Two diverse energy-harvesting aware protocol heaps utilizing a greedy routing technique and an optimal routing protocol have been framed for managing the nanocommunication of nanosensors wandering consistently in an atmosphere imitating animal veins. An energy-aware MAC protocol has been applied in the two systems to distinguish the accessible nanoscale nodes through a handshake technique. The performance of these two techniques is better in comparison to the straightforward flooding technique. Nonetheless, high data processing capability is required for the optimal technique [104]. To solve the non-white nature of terahertz frequency networking, a channel aware forwarding technique for electromagnetic-based WSN was proposed in [215]. The authors assessed traditional multi-hop forwarding and single end-to-end transmission techniques for electromagnetic-WSNs. To fit the quirk of electromagnetic-WSNs, the channel-aware forwarding technique takes forwarding decision regarding the non-white peculiarities of the terahertz channel. Simulation outcomes reveal that the introduced channel-aware forwarding technique performs better than the conventional forwarding techniques regarding the end-to-end capacity while keeping up practically identical execution for delay. A physical layer-aware medium access control (MAC) protocol for EM nanonetworks in the THz frequency has been introduced in [125] where the transmitter and receiver nanomachines were permitted to simultaneously choose the nanocommunication parameters in an flexible mode. The proposed protocol was found to reduce nanonetwork interference and to increase the likelihood of effectively demodulating the received data. The energy as well as spectrum-aware MAC protocol has been a way with a view to attain incessant WSNs [126]. The target was to accomplish an ample throughput and lifetime optimal access of the channel by simultaneously optimizing energy harvesting and consumption methods in nanonetwork of sensors. In [216], a method was proposed which maximally utilizes the harvested energy for nanosensor nodes in perpetual WSNs communicating in the terahertz frequency. The authors developed an energy design as a Markov selection method taking into account that energy appearances obey a stochastic process. Afsana *et al.*, introduces an upgraded operation technique of nanocommunication over THz frequency for wireless body sensor networks (WBSN) rendering it appropriate for smart e-health appliances [92]. The technique involves a novel energy-efficient forwarding routing for EM nanocommunication in wireless networks comprising hybrid bunches with centralized scheduling; a model intended to know the channel characteristics regarding the collective impact of absorption of the molecules, loss due to spreading, and shadowing; an energy harvesting model and utilization. Deriving outage probability for both single and multilinks, the technique is used to calculate the outage capacity.

B. SECURITY ISSUES

As in any other communication networks, security is one of the major aspect for communications in EM nanonetworks. EM nanonetworks should be secured from both active and passive attacks so that vulnerabilities of the network cannot be exploited by malicious parties or attackers. The main security goals remain confidentiality, integrity and availability (CIA) [217] irrespective of the type of underlying communication systems. In other words, it should be free from eavesdropping, man-in-the-middle attack or impersonation and Denial of Services (DoS). Besides these fundamental goals, the vast application of EM nanonetworks also demands for authorization, authentication, non-repudiation, freshness and forward/backward secrecy depending upon the nature of application. A brief description of these security objectives are defined below:

- Confidentiality: Only desired recipients can read a given message.
- Integrity: Ensure that a malicious party did not modify the message.
- Availability: Ensure services are available whenever desired.
- Authorization: Only authorized members can provide information to the network.
- Authentication: Verify the identity of participating parties in network communication.
- Non-repudiation: Ensure that participating party cannot deny sending of a message.
- Freshness: Ensure data is recent and no adversary can replay old messages.
- Forward secrecy: Ensure a party after leaving the network node is unable to read future messages.
- Backward secrecy: Ensure a party after joining the network node is unable to read any previously transmitted messages.

Approaches for security objectives discussed above are typically achieved by applying classical cryptographic encryption and decryption algorithms and protocols at the application layer in traditional networks. Considering the stringent constraints in EM nanonetworks, the question arises if we can expect to apply cryptographic primitives in nano-communication in a reasonable and efficient manner. Unfortunately, classical cryptographic end-to-end security associations cannot be directly adopted due to both the computational capabilities and data rates of nano devices. Security solutions should be switched to make it well suited for nanonetworks to achieve typical CIA and other security goals. Prioritizing the correct attack models will help significantly when trying to secure nano-communication.

The attackers in EM nanonetworks can be characterized as internal and external attackers based on the level of system access that an attacker has [218]. The internal attackers can have unauthorized access to any credentials required to communicate with other system entities, while external attackers do not have such access. The authors in [218] have

further subdivided the external attackers into local and remote attackers bearing the characteristics of nano-communication systems in mind. The local attackers can control agents that are within or at least in nano-scale vicinity of the vulnerable nano-device to spoof or eavesdrop message. On the other hand, remote attackers are geographically distant and require a substantial effort to first become a local attacker before launching actual attacks. The attackers have also been categorized based on the parameters that govern the environment a nano-scale system which can be controlled such as chemical parameters like pH value and the temperature of the system. These parameters may have a significant impact on the availability of the system and thus facilitate an easy DoS. Based on attacker models, the right set up security mechanisms can be selected or designed.

VII. CHALLENGES AND DIRECTIONS

EM Nanonetworks have many applications. However, since it is in its developing stage, the EM nanocommunications have many challenges [42], [43], [110]. Here we discuss the challenges and open issues that need to be addressed and provides some directions for future research.

A. PHYSICAL LAYER CHALLENGES

- **Frequency Band for EM Nanonetworks:** EM nanocommunication is not feasible using commonly used frequencies i.e., from few hundred MHz to few GHz, because, in this range, the size of the antenna will be in the order of a centimeter. However, reducing the dimension of the conventional antenna to a couple of tens of nano-meters will intrigue to very high working frequency i.e., terahertz frequencies [31], [33]. Therefore, terahertz frequency is recommended as the working frequency of nanonetworks. Since the system bandwidth at THz scale becomes ultra-wide, the fading effect becomes prominent. One way to solve the problem might be converting frequency selective nature of the channels into flat frequency features by dividing into sub-bands and thus mitigating the fading effects substantially.
- **EM Nanocommunication Channels:** Current channel designs for smaller frequencies are not applicable in the terahertz frequencies. Very high molecular absorption loss, reflection loss, thermal noise, and fading severely affect the EM nanocommunication signals [75], [219]–[221]. One path-channel model would give better channel gain and hence longer communication distance compared to multi-path channel models. The adoption of generalized fading channels can also be useful since it captures the channel characteristics more precisely in many situations [222].
- **Modulation and Demodulation:** Modulation technology remains in the focus of research in THz communication technology [223]. New communication techniques such as sub-picosecond or femtosecond long pulses [125], [224], and multi-carrier modulations [224] need to be explored. Very short pulse such

as femtosecond pulses can be used as EM nanocommunication signals.

- **Transceiver Design:** It is required to introduce novel transceiver designs that are capable of operating in terahertz frequencies and, more essentially, capable of using very large available bandwidth [150].
- **Antenna:** Ultra-wide-band and multi-band antennas are required to accredit multi-Gbps and Tbps links in the terahertz frequency [27], [62]. Besides, novel sophisticated antenna arrangements, for example, extremely bigger antenna arrays will be needed to fight against extremely high path loss of the terahertz frequency channel [59], [150]. Graphene-based nanoantenna may appear to be a hope [60]. Noble metals such as gold and silver can be used to fabricate plasmonic nanoantennas. Miniaturized button-like antennas can also be investigated [225].
- **Energy and Power:** Nanodevices' limited energy will constrain data transmission between nodes [84]. The nanoscale devices must be self-powered or should be able to harvest energy [28]. However, due to the technology limitations classical mechanisms to harvest energy are not feasible in the nanoscale. Therefore, new energy harvesting mechanisms are to be developed. Multi-hop communication might be an option to increase coverage range. This will help reducing energy requirements for the communication.
- **Channel Coding:** Information encoding techniques for electromagnetic nanocommunication are needed to be developed that are appropriate for the channel properties [78]. Perhaps, it would be worthy to research on different variants of protograph extrinsic information transfer algorithm for EM nanocommunications to achieve low complexity encoding/decoding. Such approach was previously found effective for wireless body area networks, where low energy and low complexity are highly important [226].

B. NETWORK CHALLENGES

- **Topology:** Nanodevices have relatively low memory storage and poor computational processing capabilities [33] and thus have little topology knowledge of the communication environment. This means that they are unable to look up addresses or perform path calculations [28], [36]. Apart from that, there are concerns how to protect the system of interest from heat dissipation. For example, the nanonetwork operation can cause damage to surrounding tissues in a human body for medical applications. Also, the introduction of various relay nodes there increases network lifetime, but on the other hand it may augment health hazards. Therefore, it is essential to introduce efficient network topology. Linear programming model-based energy-aware network topologies can be adopted [227].
- **Routing:** Since the devices have limited memory, nanosensors might not be able to store protocol code and thus will be incapable of calculating routes to

a destination node [122]. This limitation extends to cooperation between devices [28]. Therefore, innovative MAC and routing protocols are required to utilize the characteristics of the terahertz frequency [22], [172].

C. DIRECTIONS ON SECURITY SOLUTIONS

Security and privacy measures are needed to harbor sensitive information data received by nanosensors [28], [128], [129]. Some directions for securing nano-communications are discussed in [110], [218]. The authors have focused on selected requirements on the cryptographic functionality which include the followings:

- 1) Reliable and resilient way to encompass self-repair and self-securing properties as nanonetworks may be beyond the direct control of humans due to its sheer scale in both size and number of devices.
- 2) Integration of security into the protocol design phase as the introduction of security solution at a later stage can be extremely complex.
- 3) Data centric security with message authentication as basis as the local attackers might have access to the environment of a nano-system.
- 4) Energy-aware and lightweight cryptographic protocols addressing very simple operations that can be executed in nanoprocessors, and finally
- 5) Novel concepts for key management and key storage with dominant role focused towards gateway as the nanodevices will most likely not be able to actively create or exchange keys.

It should be noted that the transfer mechanism process for cryptographic data is upto large extent depends on the type of nano-devices and the communication form that is used. Nano devices which are in the form of miniaturized digital computers can communicate to exchange modulated digital information as explained in previous section. In such case, appropriate lightweight security mechanisms can be used. However, if nano-machines are performing more bio-inspired analogue information processing, we need more lightweight solutions such as the biochemical cryptography proposed in [218].

Since the deployment of traditional cryptographic techniques can be quite challenging in terms of computation and storage, physical layer security also has also been proposed as an appropriate candidate for EM nanonetworks, which exploits the random nature of the physical medium, itself [228]. Physical layer security can be implemented with a low overhead cost which normally includes some feature estimation like received signal strength, carrier frequency offset, channel impulse response, channel frequency response, I/Q imbalance. In [32], physical layer based authentication technique for an in-vivo nanoscale communication system was presented whereby the authors selected distance dependent path loss as the device fingerprint for three nodes system. It was shown that for a given maximum tolerable false alarm rate, the detection rate up to any desired level can be achieved within the feasible region. The authors extended this work

in [229] by studying the authentication for a generic system which comprised of multiple legitimate and malicious nodes operating in the THz band. The authors exploited the high-resolution transmission molecular absorption database for computing the path loss and performed authentication by hypothesis testing. The transmitter identification was also performed via the maximum likelihood and Gaussian mixture model (GMM) expectation maximization algorithm. Similarly, an EM nano random communication system is studied in [230] which ensures secret communication in the terahertz (THz) band. The authors used skewed alpha-stable noise shift keying method in order to transmit random noise signals (RNSs) by taking advantage of the recently developed carbon-nanotube-based random number generator and a graphene-based nanoantenna. The covertness of the RNSs is considered perfect since no method has been able to decode any parameter involved in the communication as of till now. The security is further enhanced by taking real time fluctuating skewness parameter.

D. OTHER OPEN ISSUES

- **Regulation and Standardization:** Regulation and standardization of THz frequency communication is required. It is imperative to design and build up the future nanocommunication standards in terahertz frequency for extremely short-range, for example, separations much lower than hundred centimeter.
- **Toxicity and Biocompatible Nanoantenna:** Antennas are supposed to be biocompatible. Gold is a well-known biocompatible metal and is suitable for biocompatible applications [66]. The numerical calculations and experimental evidence of 3D nanoantennas coated with gold has been presented in [64]. Aksu *et al.* demonstrated high-throughput fabrication of infrared plasmonic gold nanorod antenna arrays [65]. The Internet of NanoThings devices are artificial in nature. Therefore, the deployment of NanoThings may result in unexpected effects on health or pollution. The Internet of Bio-NanoThings is introduced in [43] that may enable applications such as intra-body sensing and actuation networks and environmental control of toxic agents and pollution.

VIII. CONCLUSION

In this paper, we have studied the recent developments in EM nanocommunications. Starting from the surveying of possible applications and state-of-the-art of EM nanonetworks, we have discussed the challenges to face. The discussion on THz frequency communication and routing protocols reveals that THz frequency is the most suitable operating frequency for nanonetworks. The survey finds that adequate study is required for transmission and routing protocols for EM communication using THz frequency. Besides, we found that the most suitable antenna for terahertz communication is graphene-based nanoantenna; and energy harvesting models are also compatible. It can be inferred that nanomaterials

are potential candidates for the development of innovative nanomachines. For example, graphene-based nanoantennas are able to show extraordinary sensing capabilities; graphene-based transistors are smaller and faster as well. To further advance the nanocommunications through EM approach, various challenges need to be solved and our discussion on possible solutions to the open issues might provide some avenues for the future research. We arguably conclude that EM nanocommunications will be an integral part of the next generation software-driven networks. This survey is expected to offer a thorough guidance for the learners and researchers working in the area of EM-based nanocommunications.

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