Nanonetworking in the Terahertz Band and Beyond

From Nano-Bio Interfaces to Quantum Communications

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THE POSSIBILITY TO CONTROL matter at the atomic and molecular scale opens the door to new types of devices that exhibit unprecedented physical properties. For the wireless communications community, the development of miniature transceivers and antennas that operate in traditionally uncharted frequency bands of the electromagnetic spectrum opens the door to transformative applications across scales (from nano to macro), domains (biological and non-biological), and realms (from classical to quantum). In this article, the state of the art in electromagnetic nanoscale communication and networks is presented by following a bottom-up approach.

Digital Object Identifier 10.1109/MNANO.2023.3262105
Date of current version: 00 00 2023

After describing some innovative applications of this technology, the fundamental physical properties and capabilities of nano-transceivers and nano-antennas at optical and terahertz frequencies are reviewed. The main phenomena affecting the propagation of the generated signals are then presented both from the wave and particle perspectives. Starting from the hardware capabilities and the channel peculiarities, tailored communication and networking solutions are discussed, all defining a roadmap to transform fundamental research into socially-meaningful applications.

INTRODUCTION

Nanotechnology provides the engineering community with an advanced set of tools to control matter at the atomic and molecular scale. At this scale, nanomaterials and nanostructures show new properties not observed at the microscopic level. By leveraging such properties, nanodevices with unprecedented applications can be developed. Among others, nanosensors and nanoactuators, which are able to both monitor and control biological processes at the (sub) cellular level, have been experimentally utilized to, for example, analyze circulating biomarkers in body fluids for the diagnosis of deadly diseases, including different types of cancer [1], as well as and to activate or inhibit the response of neurons, in the context of neurodevelopmental and neurodegenerative diseases [2].

Building such nanosensors and nanoactuators today is no longer the main bottleneck, but interfacing with them is. For example, on the one hand, current nano-biosensing systems are generally composed of (i) nanoparticles or nano-patterned micro-surfaces, chemically treated to be sensitive to only some specific biomarker; (ii) an optical excitation system, i.e., a high-power laser that illuminates the nanoparticles; and (iii) an optical measurement system, i.e., a high-resolution spectrum analyzer to measure the reflected signals from the nanoparticles. While nanoparticles are in the submicrometric range, the optical excitation and measurement systems rely on external lab-type measurement equipment (e.g., a microscope or a spectroscopy system). Only recently have portable or wearable devices been considered for the optical excitation of nano-particles [3]. Similarly, on the other hand, current brain-machine interfaces (BMIs) can be categorized either in electrical or optical interfaces. In electrical BMIs, electrodes are utilized to measure and record the voltages associated with the propagation of action potential signals. Nanotechnologies have helped develop non-invasive, flexible, and transparent micro-electrode arrays [4], but these cannot be utilized for stimulation. In optical BMIs, light is utilized to trigger or stop the propagation of action potential signals in genetically modified neurons [5]. While optical BMIs can provide single-neuron resolution, most of the existing solutions generally rely on invasive optical fibers to inject light through the skull. Fundamentally, in all these application examples, *there is a disconnect in the scale between the processes of sensing the information or actuating on the information and the processing and communication of the same.* This is a problem that the nanonetworking community, an interdisciplinary research community with shared expertise ranging from systems biology and nanomaterials to electrical engineering and computer science, has been addressing for more than a decade. In the vision first introduced in [6], the main idea is to integrate the process of information sensing, processing, communication, and, when required, actuation, in the same functional system, namely, a nanomachine. Nanomachines, i.e., embedded nano-systems with a footprint of just a few cubic micrometers, can be embedded inside the human body and are able to communicate among themselves, to propagate events or coordinate a response, and with the macroscale, through a nano-to-micro interface, generally mounted on the body and connected to the Internet. Ideally, this interface is bidirectional and, thus, nanomachines cannot only be remotely monitored but also controlled directly from a healthcare provider's office.

Over the last 15 years, there have been many major accomplishments relating to different approaches to realizing the vision of nanonetworking. For example, many efforts have been focused on first understanding and modeling and then leveraging and exploiting molecular communication techniques found in biological systems [7], [8], [9], [10]. In parallel, the advantageous propagation of acoustic waves in the human body has been the core driver for the development of ultrasonic communication technologies for body-centric communications [11]. In terms of electrical and magnetic fields, low-frequency galvanic electrical currents or magnetically inducted currents have been proposed as a potential interface between nanoscale sensors and actuators and the macroscale [12]. Initially, the use of high-frequency electromagnetic wireless communications, imposed by the use of small antennas that could physically be integrated within a nanomachine, seemed not practical. However, the adoption of innovative nanomaterials and nanostructures opened the door to nanoscale electromagnetic communications in the terahertz band and beyond including the infrared and visible spectra [13], [14], [15]. Today, some of these technologies are at the core of transformative technologies, including quantum interfaces and communications.

In this article, we provide an updated view on the topic of electromagnetic nanonetworks by summarizing the major research accomplishments in the last decade and identifying potential solutions to the remaining bottlenecks and new directions that were not foreseen in the early days of the field. In the "Applications" section, we briefly present some of the key applications of electromagnetic nanonetworks, both in biological and non-biological environments. In the "Transceivers and Antennas for Nano-Communications" section, we focus on hardware and describe the state of the art relating to nano-transceivers and nano-antennas for optical and terahertz communications. In the "Channel Modeling for Nanoscale Electromagnetic Communication" section, we explain and compare the fundamental phenomena affecting the propagation of optical and terahertz signals both in biological and non-biological scenarios in the classical and quantum realms. In the "Communication and Networking Techniques

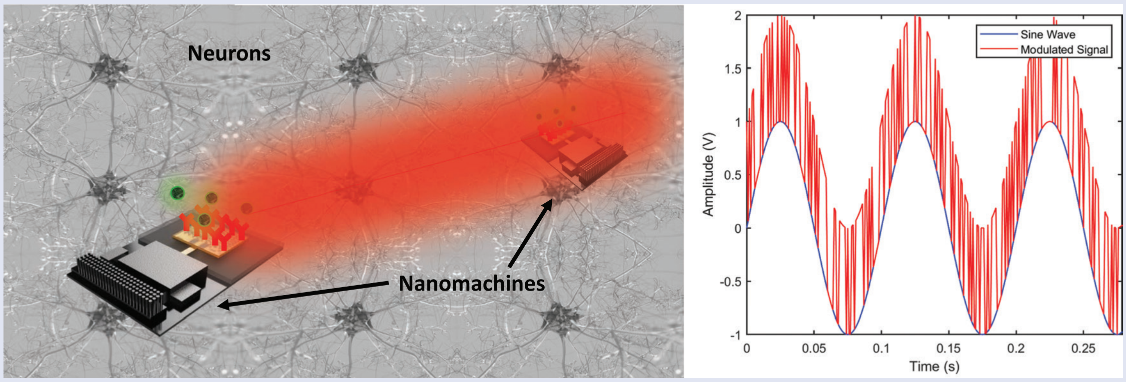

FIGURE 1 A joint nano-communication and bio-actuation system that leverages optical signals to simultaneously stimulate neurons or the neurons' genome and transmit information among nearby nanomachines. The much faster information signal super-imposed on the slowly changing neuron-excitation signal is imperceptible by the neurons.

for Electromagnetic Nanonetworks" section, we discuss the accomplished milestones and identify the critical aspects to be addressed in terms of communications and networking. Finally, we conclude the paper in "Applications" section.

APPLICATIONS

NANO-BIO APPLICATIONS

As per the introduction, many of the applications of electromagnetic nanonetworks are within the biomedical realm. It is relevant to note that, on the one hand, in a traditional wireless communication perspective, there is a clear preference for staying within the lower frequencies of the electromagnetic spectrum (i.e., radiowaves and microwaves), where electromagnetic signals easily propagate and there is minimal interaction between them and the human body [16]. On the other hand, infrared and particularly visible optical frequencies are broadly adopted by the medical community both to monitor (i.e., *see*) and to interact with biological entities [17]. Nanonetworks bring the possibility to interconnect the two ends of the electromagnetic spectrum. For example, as we have recently shown in [18], a bio-functionalized plasmonic nano-antenna can be utilized to both transmit information between nanomachines and simultaneously extract information from its surroundings which is automatically imprinted on top of the transmitted signals, in one shot. The resulting *joint nanoscale communication and bio-sensing system* can help reduce the complexity and size of nanomachines by combining functionalities in a single block (e.g., sensing and communication on a plasmonic antenna). The specific use case of this technology will ultimately depend on the type of sensing being performed and can range from cancer early detection and monitoring based on the detection of cancer biomarkers to the detection of specific viral agents or bacteria before a full-fledged infection is launched.

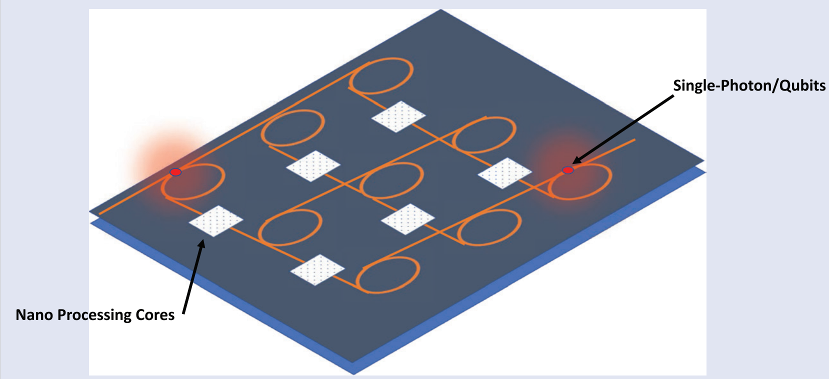

FIGURE 2 A quantum wireless network on chip, where optical or terahertz photons are utilized to carry qubits.

A similar idea could be exploited in the realm of nano-bio-actuation. For example, in optogenetic and optogenomic applications [19], i.e., in systems where light is utilized to control cellular and gene functions, respectively, nanomachines could modulate meaningful information on top of the required cell-programming signaling (see Figure 1). The much different time scale of the optogenetic and optogenomic signaling (in the order of seconds or more) and the communication signaling (potentially as low as femtoseconds) makes the latter imperceptible by the cells and genome. The result is *a joint nanoscale communication and bio-actuation system.* Once again, the specific use case depends on the type of actuation being performed. For example, many neuro-developmental diseases (such as Schizophrenia) or neuro-degenerative diseases (such as Parkinson's or Alzheimer's disease) are the results of a communication problem at the cellular or the genomic levels [20]. Reestablishing those communication processes by external activation could help recover functionalities or enable them in the first place. Other, perhaps more exotic, applications of nanoscale

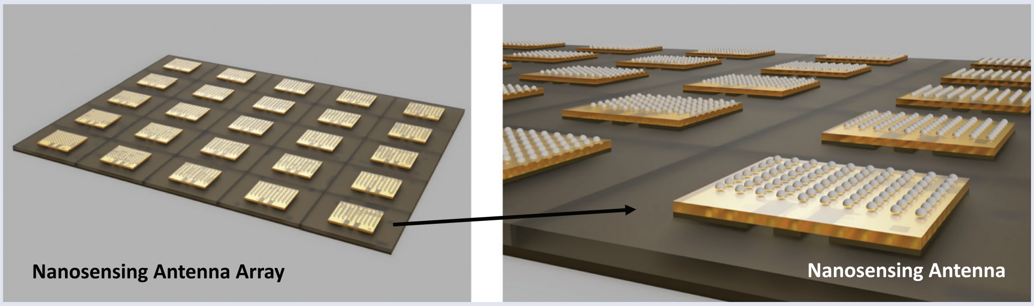

FIGURE 3 An optical nano-antenna array, whose frequency response depends on its sensing status.

communications, sensing, and actuation relate to human brain function augmentation.

NON-BIO APPLICATIONS

At this point, one might think that most of the nanonetworking applications are within the biomedical realm, but there are numerous exciting non-biological applications of electromagnetic nanoscale communication. Still within the realm of sensing, chemical nanosensors can be embedded within smart fabrics and clothing or used to paint the walls to detect the presence of hazardous substances or components in the air we breathe [21]. While some of these applications appear to be very timely after the most recent pandemic, these were already proposed in the very first paper in the field of electromagnetic wireless nanosensor networks [13]. Similarly, bio and non-bio, nanoscale and macroscale networks are expected to be interconnected creating a continuum across scales and bridging the biological, the physical, and the digital world. This ultimate paradigm is what we refer to as the Internet of Nano-Things [22]. Besides sensing, another key set of applications of electromagnetic nanonetworks relates to computing, both in the classical and quantum realms. Indeed, as a way to unleash the true potential of massive multi-core computing architectures, wireless networks on chips enabled by nanonetworks were first proposed in [23]. The fundamental idea is to provide individual cores or a group of cores wired together to a common controller with a wireless communication unit that can be used to exchange information with further computing elements. This is a change in chip interconnect technology with implications across the protocol stack as, for example, multicasting across cores enabling new ways of parallel processing. Now, beyond classical computing architectures, *electromagnetic nanonetworks will also play a role in quantum computing architectures,* for example, as a way to facilitate the transfer of quantum information between quantum computing cores (Figure 2). The controlled propagation scenario and environmental conditions of integrated chips create an excellent medium for the wireless exchange of qubits, whether these are in the form of optical photons or potentially terahertz photons. Note that in this article, we refer to quantum communications in its most strict sense, i.e., as the exchange of qubits, and not as the more popular classical communications secured by an earlier exchange of qubits. Moving to the quantum realm introduces challenges and opportunities for device development, channel modeling, and communication and networking design, as explained in the following sections.

TRANSCEIVERS AND ANTENNAS FOR NANO-COMMUNICATIONS

OPTICAL NANO-COMMUNICATIONS

The largest element in a communication system is usually its antenna. The miniaturization of a metallic antenna to meet the size requirements of a nanomachine imposes the use of very high resonant frequencies. For example, a one-micrometer-long half-wavelength dipole built with a perfect electrical conductor material resonates at approximately 150 THz, which is within the so-called near-infrared spectrum. In addition, as with any resonant dipole, its radiation diagram is almost isotropic. Traditionally, antennas have been mostly utilized in the lower frequency bands, where electromagnetic radiation is intrinsically interpreted as a wave because individual photons have too low energy to be individually detectable. However, there is nothing preventing us from devising antennas for infrared or visible optical frequencies. Of course, building optical nano-antennas was traditionally challenging due to their very small dimensions. For example, the feeding gap of the aforementioned one-micrometer-long dipole antenna needs to be tens of nanometers at most.

Today, thanks to nanotechnologies, we can create such miniature optical antennas that allow us to control light in a similar way we control radiowaves or microwaves [24]. However, their design is not a mere scaling of the dimensions, as there are several unique aspects that need to be taken into account. More specifically, at optical frequencies, metals do not behave as perfect electrical conductors; their conductivity is no longer almost infinite, but finite, and, more important, complex-valued. As a result, surface plasmon polariton (SPP) waves appear within the metal skin depth. This prevents us from adopting many simplifying assumptions commonly used in the design of antennas at lower frequencies. For example, the effective wavelength of an SPP wave is smaller than that of a free-space propagation wave at the same frequency. This leads to smaller antennas, but potentially with lower radiation efficiency. In this direction, we have developed a unified antenna theory for the design of optical nano-antennas in transmission, reception, and reflection [25].

There are several observations to make. First, in the nano-bio community, many times, the terms nano-antenna and nano-participle are utilized interchangeably. However, from the communication point of view, nano-particles are not transmitting or receiving nano-antennas, as they are not converting on-chip electrical currents into wirelessly propagating electromagnetic signals and vice-versa, but their input and output are in the form of electromagnetic radiation. Accordingly, nano-particles and, perhaps more clearly, *nano-patterned micro-surfaces as those utilized in nano-bio sensing can be understood as the nanoscale or microscale counterpart of the very popular intelligent reflecting surfaces (IRS) or reconfigurable intelligent surfaces (RIS), where the sensed information controls the properties of the reflected signals; see Figure 3).*

Besides the optical nano-antenna, an optical nano-transceiver is needed to generate, modulate, amplify and filter the signals that the antenna radiates in transmission and, reciprocally, detect and demodulate the signals that the antenna captures in reception. Today, lasers with micrometric footprint have been experimentally demonstrated, such as microring laser sources fabricated on an III-V semiconductor material platform [26]. Such lasers support different operation modes, including continuous wave and pulsed emission, and different modulations, ranging from amplitude and frequency/wavelength to more intriguing properties, such as orbital angular momentum (OAM).Similarly, nano-photodetectors have been demonstrated, effectively showing that a nanoscale optical link is possible [27]. Moreover, for many applications, arrays are needed to either increase the communication distance, the physical layer data rate, or the aggregated throughput at the link and network layers of nanonetworks, for which nano-laser arrays and nano-antenna arrays have been demonstrated.

Moving forward, there are still several aspects to address. In the context of nano-bio applications, there is a need to ensure the biocompatibility of the materials and structures utilized in the development of optical nano-transceivers and antennas. For example, we have shown before [19] that neuronal cultures can be grown directly on III-V semiconductor substrates, such as those utilized in the development of microring lasers and photodetectors. However, when embedding the nanomachine in a biological environment, there are going to be many aspects to take into account. For example, techniques to prevent the immune system from clotting and effectively isolating the nanomachine are needed. This could be achieved by adopting bio-compatible materials to encase the resulting nanomachine. Similarly, mechanisms are needed to defoul or "clean" the optical communication system from biological entities that can obstruct the nano-antenna. Such mechanisms could rely, for example, on the application of low-frequency electrical currents on the antennas or even wireless defouling techniques, based either on lower-frequency electromagnetic radiation or ultrasounds to remove biological debris [28]. Another critical aspect relates to the lifespan of the nano-devices when in a bio-environment, which is a topic that has been only lightly explored by the research community and becomes more relevant as we get closer to the actual in-vivo testing of communicating nanomachines.

For the non-bio applications, in the context of optical wireless networks on chip [29], one of the key challenges relates to the integration of the optical communication unit within the processing core itself at the fabrication stage. In this direction, the major progress in the field of silicon photonics provides optical nanoscale communications an excellent starting point. Shifting towards the quantum wireless networks on chip, some of the key communication components need to be rethought. Fundamentally, the key idea is that, as of today, in optical wireless quantum systems, a qubit is generally transmitted in the form of a single photon or a small group of photons at most (see the "Communication and Networking Techniques for Electromagnetic Nanonetworks" section). Therefore, the key elements needed include single-photon sources, single-photon quantum modulators, or devices to transfer the qubit information into the photon carrier, as well as optical nano-antennas with maximal efficiency or availability to convert on-chip or guided photons to free-space propagating photons [30]. A reciprocal system for the receiver will be needed, and ultimately, all these components need to be integrated into a single platform.

TERAHERTZ NANO-COMMUNICATIONS

Despite the opportunities that come with the adoption of optical frequencies, there are several advantages of wireless systems in lower spectral bands that motivate the exploration of alternative technologies. For example, as we will discuss in the "Channel Modeling for Nanoscale Electromagnetic Communication" section, the longer wavelengths associated with lower frequencies result in much more advantageous propagation. However, such longer wavelengths lead to larger antennas, if conventional materials are adopted. The question to answer is then *is there is any technology that would support the design of nano-antennas that can simultaneously the physical constraints of nanomachines while operating at lower frequencies than the infrared or visible optical bands?*

The answer is yes: Graphene can be leveraged toward this end. Graphene is a one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice, which had been theoretically investigated since the 19th century but experimentally obtained for the first time only in 2004. Graphene has many extraordinary properties, such as very high room-temperature electron mobility and tunability, but more importantly for the nanonetworking community, graphene supports the propagation of highly-confined SPP waves at frequencies in the terahertz band (100 GHz–10 THz) [31]. Compared to metals, graphene supports SPP waves at lower frequencies (THz vs optical) and with higher confinement factor (the SPP wavelength at THz frequencies might be up to 100 times smaller than the free-space wavelength, as opposed to optical systems where this is usually in the order of 10). With this in mind, the use of graphene to develop plasmonic nano-antennas was first proposed in 2010 in [32]. As an example, a graphene-based nano-patch antenna with a maximum length of one micrometer resonates at approximately 1.5 THz, i.e., a frequency two orders of magnitude lower than its metallic counterpart. To provide another reference, a metallic half-wavelength resonant patch designed to resonate at the same frequency would be approximately 100 μm in length and, thus, would not fit in a nanomachine. This original result is what triggered the broad field of electromagnetic nanonetworks in the terahertz band. Since then, different antenna designs beyond dipoles and patches, including bowtie and spiral antennas. In addition, for applications in which the size requirements can be relaxed, such as in the development of the nano-to-macro interfaces or even for macroscale communications, graphene-based plasmonic nano-antenna arrays with a very large number of elements have been proposed [33]. For example, when utilizing graphene, a 1,024 antenna array is less than 1 mm^2. While this would not fit in a nanomachine, it is extremely exciting for other applications in the micro and the macroscale, including upcoming 6 G networks.

In addition to the antennas, graphene can be leveraged in other building blocks of the communication unit of a nanomachine, including terahertz signal generation and modulation. For example, graphene can be utilized either at the gate or even as the 2D-electron-gas channel of high-electron-mobility transistors, where surface plasma waves can be generated and launched through the Dyakonov-Shur instability [34]. Similarly, graphene can be used to modulate on-chip terahertz SPP waves in amplitude, frequency, and phase. For many of these applications, graphene can be integrated with both traditional metallic, dielectric, and semiconductor materials, but also with other 2D materials, such as hexagonal boron nitride or molybdenum disulfide.

Moving forward, there are several aspects that require further attention. First, in order to increase the radiated power and effectively the communication distance and coverage, plasmonic amplifiers that could be integrated on-chip are needed. Similarly, as the terahertz spectrum becomes more widely used, plasmonic filters will be needed both at the transmitter and the receiver to prevent out-of-band emissions and minimize out-of-band noise and interference, respectively. Other critical components that have barely been studied are data converters, both digital to analog and analog to digital. For some applications, particularly sensing applications, direct analog modulation of the transmitted signals (whether carriers or pulses) seems to be a reasonable way.

Switching gears, there is also the opportunity to explore the potential of the terahertz band for wireless quantum links. In particular, the energy of terahertz photons is lower than that of optical photons, which makes terahertz photons more vulnerable to noise and, thus, might require operation in low-temperature or cryogenic conditions. Nonetheless, *the energy of terahertz photons makes them much closer to microwave-based quantum processing platforms, effectively reducing the conversion losses in existing microwave-to-optical quantum conversion systems.* To enable a terahertz wireless quantum link, single THz photon generators, for example, based on very high-quality resonant cavities, quantum modulators or qubit mixers, and very high-efficiency antennas will be needed.

Similarly to the optical case, large-scale integration and fabrication of terahertz nano-devices and biocompatibility of the same are open research questions that need to be explored. For the time being, there is no terahertz equivalent of the silicon photonics manufacturing techniques. In fact, the integration and fabrication of devices with nanoscale features and 2D materials is an open challenge that spans beyond nanonetworking. Similarly, the impact of nanoscale structures in the body is an active topic [35]. As we discuss in the "Channel Modeling for Nanoscale Electromagnetic Communication" section, beyond the structures themselves, there are implications resulting from intrabody electromagnetic radiation. Addressing all these aspects requires close collaboration across the biological, medical, material and electrical engineering communities.

CHANNEL MODELING FOR NANOSCALE ELECTROMAGNETIC COMMUNICATION

In this section, we first describe and compare the three main phenomena affecting the propagation of optical and terahertz signals in the nanoscale. Then, we describe how these need to be captured in the study of wireless quantum links.

SPREADING LOSSES

As discussed in the "Transceivers and Antennas for Nano-Communications" section, common nano-antenna designs, such as half-wavelength resonant dipoles at optical and terahertz frequencies, radiate quasi-omnidirectionally. Therefore, as the radiated signal propagates away from the transmitting antenna, its power is spread over a surface of increasing radius. Accordingly, the electromagnetic power density decreases quadratically with distance. This phenomenon is independent of the frequency of the signal. However, the very small size of nano-antennas results in very small antenna-effective areas. Simply stated, the amount of power that a receiving nano-antenna can intercept is proportional to its size and its efficiency. Therefore, for common nano-antenna designs, it decreases quadratically with frequency. A way to compensate for these losses is to utilize directional antenna designs, in which radiation is not omnidirectionally emitted but focused in a given direction. The challenge is that those directional antennas are intrinsically large in terms of wavelength, and footprint is what nanomachines are trying to minimize. Alternatively, dielectric lenses, immediately on the antenna, can be utilized to focus the signal and, thus reduce the spreading losses.

Comparison: Contrary to popular belief, spreading losses do not necessarily increase at higher frequencies. In fact, if the antenna footprint is kept constant, increasing the frequency leads to a higher gain. However, this higher gain is only present over a narrower beamdwidth and, thus, beam alignment becomes critical. Alternatively, if antennas are designed to be as small as their wavelength supports, the higher the frequency, the smaller the antenna and thus the higher spreading losses. Ultimately, it depends on the target nanoscale application and whether omnidirectional or directional communication is preferred.

MOLECULAR ABSORPTION LOSSES

As the electromagnetic signal propagates, it might interact with different elements found along the channel. At the most fundamental level, electromagnetic radiation interacts with individual atoms and molecules. Such interactions depend on the atoms' or molecules' structure and the radiation photon energy. As discussed in the "Transceivers and Antennas for Nano-Communications" section, the absorption of optical and terahertz photons by different types of molecules is what enables many of the exciting sensing and actuation applications of nanomachines. However, from a communication perspective, when photons are absorbed, electromagnetic energy is converted into kinetic and/or thermal energy inside the absorber. From the communications perspective, this energy is lost, and this is what molecular absorption losses account for. Different elements absorb with different intensities at different frequencies and, thus, molecular absorption losses drastically depend on the application scenario.

Comparison: Generally, the absorption at terahertz frequencies is much higher than at optical frequencies. In the context of nano-bio applications, both terahertz and optical radiation is absorbed by liquid water and, consequently, many different types of cells. However, as shown in Table 1, the overall absorption coefficient can be several orders of magnitude less at optical frequencies. This is a problem for terahertz communication systems, but that absorption is what opens the door to interactions (sensing, actuation) at the nanoscale. For the non-bio applications, while it is commonly believed that molecular absorption by water vapor molecules is the showstopper for terahertz communications, for the majority of frequencies within the terahertz band, molecular absorption does not become dominant over spreading losses until distances in the order of tens to hundreds of meters, i.e., much more than the expected communication range of nanomachines.

BLOCKAGE AND SCATTERING LOSSES

In addition to their molecular composition, the way in which radiation interacts with the elements found along the channel depends also on their relative size as compared to the wavelength. For example, on the one hand, a reflective or absorbing element that is several wavelengths in size might act as an obstacle and fully block the propagation of the signal. On the other hand, metallic nano-particles that are much smaller than the signal wavelength might only slightly deviate the signal direction of propagation by means of diffused scattering. *Comparison:* In broad terms, the much smaller wavelength of optical signals leads to higher scattering losses and an increased probability of blockage. In the context of nano-bio applications, most types of cells and their components can induce the scattering of optical signals. This is not necessarily always a problem, as, for example, it has been shown before that specific cell shapes can result in focusing, similarly to what a lens would do [38]. The much larger wavelength of terahertz signals results in negligible scattering in most of the scenarios. Only large cells, such as red blood cells or neurons, might result in scattering of terahertz radiation. In non-bio applications, the presence of dust, aerosols, and particles results in very large scattering losses at optical frequencies, and minimally impact terahertz signals.

TABLE 1 Comparison of the absorption coefficient in cm^{-1} between the terahertz band and optical frequencies [36], [37].

	1 THZ	500 THZ
Water	240	0.001
Blood	210	60
Adipose tissue	23	0.005
Skin	18.45	3

THE NANOSCALE QUANTUM ELECTROMAGNETIC CHANNEL

As we discussed in the "Transceivers and Antennas for Nano-Communications" section, in quantum wireless communications, a single photon can represent a qubit, for example, when encoding the information in the photon polarization. With this in mind,

- *There is a need to precisely control the direction in which each photon is emitted or radiated.* Therefore, instead of spreading losses, there is a need to model the probability that a photon reaches its intended receiver.
- *Absorption becomes critical.* If the information-bearing photon is absorbed by any element along the channel, the information is lost. Once again, more than absorption losses, there is a need to model the probability that a photon is absorbed along a channel.
- *Similarly, scattering can drastically impact a quantum wireless link.* Changing the direction of propagation of a photon, even if lightly, might result in such information never being delivered to the intended receiver and, thus, lost. As before, there is a need to move from a wave-centric model of scattering to a particle-based probabilistic model of the same.

While there are some studies for the optical wireless quantum channel, there are no physics-supported studies for terahertz wireless quantum propagation. Interestingly, within the broad nanonetworking community, there is another group that has been studying the encoding of information in particles and developing probabilistic models to describe the propagation of such particles, namely, the molecular communications community. While fundamentally different (photons are massless particles as opposed to molecules), many of the methodological tools and strategies could be leveraged and jointly developed.

COMMUNICATION AND NETWORKING TECHNIQUES FOR ELECTROMAGNETIC NANONETWORKS

In this section, we summarize the state of the art and identify new directions relating to communication algorithms and networking protocols for

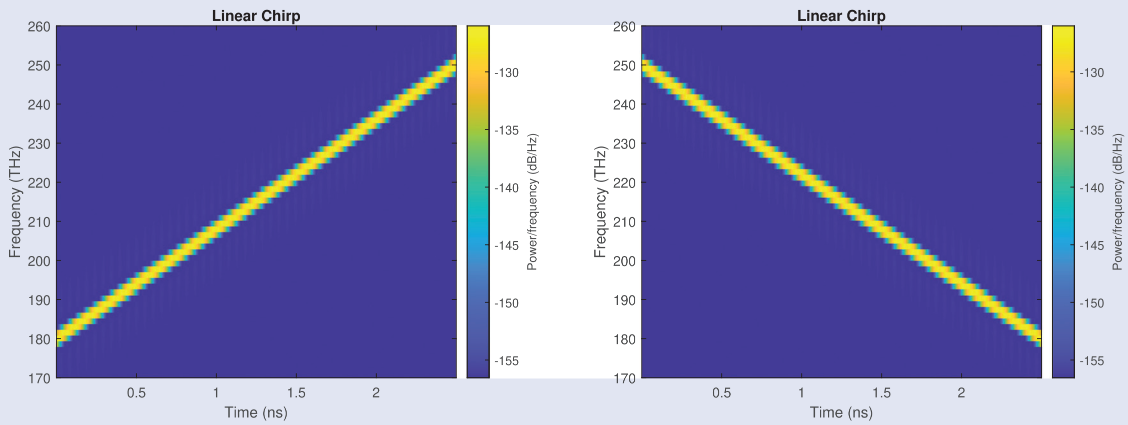

FIGURE 4 Chirp Spread Spectrum communications at optical frequencies, where information is encoded using up-chirps (left) and down-chirps (right).

electromagnetic nanonetworks at optical and terahertz frequencies.

MODULATION AND CODING

Motivated by the capabilities of nanotransceivers and in light of the behavior of the electromagnetic channel at optical and terahertz frequencies, different modulation and coding strategies have been proposed. Originally, the use of very short pulses, just hundreds of femtoseconds long for terahertz-band systems and only a few femtoseconds long for optical systems, was proposed [39]. This type of pulse is commonly found in time-domain spectroscopy sensing systems and they are intrinsically broadband (e.g., the power spectral density of the first-time-derivative of a 100-femtosecond-long Gaussian pulse spans between 0.5 and 3 THz). There have been different ways in which such pulses have been leveraged for communications, starting with low-complexity non-coherent asymmetric on-off keying modulation spread in time (TS-OOK), to pulse-position modulations similar to those found in Ultra-Wide-Band (UWB) technologies.

Another technique that has been proposed for the transfer of information between nanomachines is Chirp Spread Spectrum (CSS) [40]. In the simplest form of CSS, information is transmitted using either an up-chirp (a sinusoidal signal whose frequency continuously increases in time) or a down-chirp (a sinusoidal signal whose frequency continuously decreases in time), shown in Figure 4. In such a scheme, information is encoded in the trend of the changing frequency (increasing or decreasing). Therefore, even in the case of extreme frequency selectivity, the information from a CSS symbol can be recovered as long as the overall increasing or decreasing trend in frequency is detected. Interestingly, CSS is a waveform commonly used in radar applications also at the macroscale, as one can independently control the bandwidth (lowest and highest frequency) and the symbol duration (time to transition between them) and provides multiscale resolution thanks to the different wavelengths at different frequencies.

In addition to the waveform, or how the signal changes in time, there are other parameters that can be modulated and, thus, used to transfer information. For example, the *wavefronts,* or the way in which the field phase distribution changes in space, can also be modulated. Among others, the modulation of OAM (as discussed in the "Transceivers and Antennas for Nano-Communications" section) has increased in popularity in recent years. Specifically, a beam that is said to have OAM manifests a spiral phase in the transverse direction, resulting in a helical wavefront and a phase singularity (a zero-intensity vortex) in the center. Overlapping beams that follow helical modes define an orthogonal basis (see Figure 5). This can be leveraged in different ways; different streams can be sent along different OAM modes, each one with its own amplitude and/or phase modulation, or one stream can be sent by encoding different symbols in different OAM modes. As discussed in the "Transceivers and Antennas for Nano-Communications" section, today, microring lasers able to generate multiple OAM modes have been already demonstrated. Technology allowing, other potential physical layer solutions combining temporal and spatial modulation can become possible, as well as cooperative solutions among nanomachines [41].

When it comes to error control and channel coding, only very few solutions have been proposed to date [42]. For example, in the context of nanosensing networks, low-weight error-preventing codes, which encode the information in codewords that have more logical zeros than ones, were proposed so that less noise and multi-user interference is generated in the network, leading to lower bit error rates. This technique was shown to be more suited to nanonetworks than typical error detection strategies that would require multiple retransmissions to overcome errors (as in nanosensor networks, energy is usually a limiting factor) and than traditional error correcting codes, whose complexity exceeds that computational power of nanomachines. Variations of the low-weight codes have been proposed since then. Beyond these, there are new considerations to take into account when moving to the quantum realm. As we discussed before, quantum wireless communication

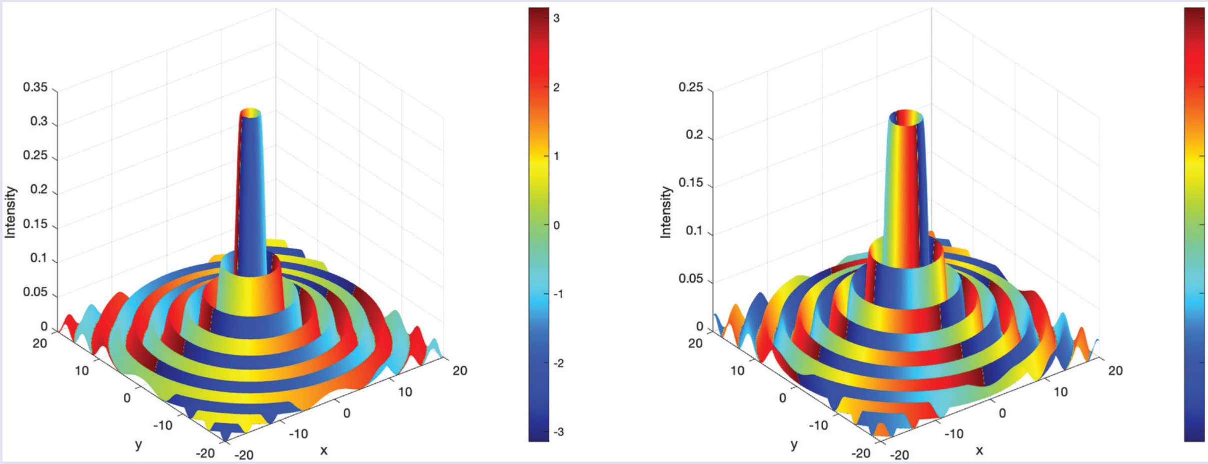

FIGURE 5 Intensity (height) and phase (color) profile of two different orbital angular momentum modes (helical mode 1 on the left and helical mode 2 on the right). The two modes are orthogonal and define an orthogonal basis that can be used for information modulation or multiplexing.

systems commonly encode qubits in photons. There are different ways to do so. In general, any two orthogonal modes of light provide a way of constructing a two-level quantum system that can serve as a qubit. The simplest and perhaps more common is to encode a qubit in the polarization of the photon. Similarly, qubits can be encoded in the OAM mode. Other options would include, for example, encoding the information in the time-arrival of the photon, considering a two-option system. In all these cases, the main challenge posed by the channel and, thus, the main motivation for error control strategies is the fact that the information is carried by a single photon, a photon that can be lost (sent in the wrong direction) or absorbed. Accordingly, increasing the reliability of a quantum wireless system requires increasing redundancy by sending higher numbers of photons with the same information. Mathematically determining the required redundancy based on the probabilistic channel models described in the "Channel Modeling for Nanoscale Electromagnetic Communication" section is an immediate next step.

MEDIUM ACCESS CONTROL, ROUTING, NANO-TO-MACRO INTERFACING AND END-TO-END RELIABILITY

Beyond a single link, there are many aspects that need to be addressed to build actual nanonetworks. Different networking protocols are needed for the different types of applications discussed in the "Applications" section. For example, in nano-bio applications such as cancer early detection and monitoring, ensuring that even if only one nanomachine identifies the target biomarker, its message is delivered, is critical. At the same time, in other applications, many nanosensors might detect the same event, potentially flooding the nanonetwork with redundant messages, and draining all the nanomachines' energy. Overall, information is sparse and bursty and, while throughput is not critical (not many bits are needed to encode the detection of a biomarker), reliability and latency are. In non-bio applications, such as in wireless networks on chip, the fixed topology of the network allows to pre-design and optimize multiple aspects across the protocol stack. In this case, latency and throughput are critical, and reliability is generally assumed given the advantageous channel conditions. With these premises in mind, there have been several medium access control protocols and routing and relaying strategies proposed in the last decade [43].

An aspect that has been much less explored and only recently is starting to be the focus of several research groups is the nano-to-macro interfacing strategy. Such nano-to-macro interfaces or gateways will play a critical role in connecting one or more types of nanonetwork (e.g., electromagnetic and molecular) with macroscale networks. Once again, their design might largely differ between nano-bio and non-bio applications. In nano-bio applications, the nano-to-micro interface is not only a gateway between the nanoscale realm and the existing wireless networks but also between the biological realm (e.g., the human body) and the non-biological realm (e.g., the outside world) [44]. Such a device needs to be mounted on the body, generally in the form of a wearable device (e.g., a smart wristband for nanosensing applications or a head-mounted band for BMIs). In addition, it will need to be able to match the requirements of the two networks, e.g., the rate at which a nanonetwork can ingest control information from the macroscale might be slower than the rate at which this information is received). Above all, the security of such nano-to-macro interface becomes a major concern. From eavesdropping of medical information to jamming of the same or authentication and identity theft can lead to catastrophic medical consequences. This is not the case in non-bio applications.

Significantly less has been done when it comes to quantum wireless nanonetworking. First of all, it is relevant to note that, at the macroscale, there are several theoretical works discussing the quantum internet [45] and some of its key components, including quantum switches, quantum repeaters, and quantum routers. However, the majority of these works utilize black-box models for the actual physics of the transceiver and the physics of the channel, general enough to cover vastly different wired and wireless channels. Across scale but particularly in nanonetworks, where every photon counts, there is a need to rethink many of the underlying assumptions and accordingly define protocols that ensure the end-to-end reliable transport of qubits in realistic conditions. Starting with the link layer, some questions to answer relate to cross-talk and interference between qubits in nearby, overlapping, or crossing quantum wireless links; the design of quantum nano-repeaters; or the dimensioning of the qubit memory or storage in nanorouters. It is relevant to note that these aspects are true also for the macroscale and, in fact, quantum communications are intrinsically nano and, thus, solving these problems in a bottom-up approach can impact multiple fields. Only when we have mechanisms to reliably exchange qubits can we leverage the quantum realm's unique properties, such as entanglement and teleportation, whether these are used to secure traditional networks or enable new communication paradigms.

CONCLUSION

The field of electromagnetic nanonetworks, once considered closer to a science fiction movie than an actual research topic, is becoming a reality. Not only there have been many advancements relating to its enabling device and communication technologies, but innovative applications that can make the most of nanonetworks have been devised, ranging from nano-bio interfaces to quantum wireless networks on chips. None of the aspects discussed in this review article contradict the laws of physics and, thus, it is only a matter of time till their implementation becomes practical, most likely in 7 G systems.

ACKNOWLEDGMENTS

This work was supported by the U.S. National Science Foundation (NSF) under Grants CNS-2011411 and CBET-2039189.

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