applied sciences

Editorial

Advancing Nanoscale Communication: Unveiling the Potential of Terahertz and Molecular Communication

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In recent years, advancements in nanotechnology have opened up new frontiers in communication systems, bringing the dream of seamless communication at the nanoscale level closer to reality. Among the most promising and cutting-edge areas in this field are electromagnetic (EM) nanocommunication in the Terahertz (THz) band (0.1–10 THz) [1] and molecular nanocommunication (MNC) [2]. The individual developments in these two disciplines and their fusion would lead to a revolutionary approach in communication technology, enabling applications in various domains, from healthcare and biomedical [3,4] to the Internet of Nano-Things (IoNT) [5,6] and on-chip communications [7–9]. The following editorial delves into the goals, significance, and key research areas of THz and MNC, showcasing their vast potential and the transformative impact they could have on nanonetworking.

The advantage of using the THz band is that THz waves offer unique characteristics that make them ideal for nanoscale communication. Apart from possessing higher bandwidths and shorter wavelengths, allowing for faster data transfer and more precise localization, they can propagate as surface plasmon polaritons (SPP), a type of surface wave [10]. On the other hand, MNC is inspired by nature, where information is exchanged through chemical signals. By emulating natural processes, researchers are designing molecular communication models, protocols, and algorithms to enable reliable, energy-efficient, and biocompatible communication at the nanoscale [11–13].

Nanocommunication is a challenging field due to the need for nanoscale devices that are energy-efficient and capable of operating in harsh environments. However, there has been significant progress in recent years, primarily due to the discovery of graphene. Graphene has excellent electrical properties, including high electron mobility at room temperature, which enables the propagation of surface plasmon polariton (SPP) waves. SPP waves are global oscillations of electrical charges at the interface of graphene and a dielectric material. This property has motivated researchers to develop graphene-based plasmonic nano-antennas that can radiate at frequencies in the THz band [14]. Similarly, we could develop new nano-components capable of generating, radiating, and detecting THz signals [15]. Regarding MNC, it is crucial to explore methods for constructing biocompatible transmitter and receiver nanomachines. Recent progress in micro/nanomachines (MNMs) research offers promising technologies for implementing MNMs in 6G application scenarios, particularly in the IoBNT [6]. These advanced nano- and communication technologies could connect biological cells inside the human body to the Internet [16]. The authors in [16] comprehensively summarize possible technologies for constructing MNMs applicable to MNC systems, including sensors, transmitters, and receivers.

Subsequently, the development of a comprehensive nanonetworking protocol stack is essential. This stack should encompass physical, link, network, transport, and application layers, tailored to the specific challenges and requirements of THz and MNC. Until now, for the THz nanocommunication, schemes or protocols were only proposed for the network, link, and physical layers [1]. However, networking protocols for higher layers are also required. A major challenge in developing networking protocols is the scale, as some applications require significantly larger numbers of nanonodes compared to traditional

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Citation: Singh, P.; Jung, S.-Y. Advancing Nanoscale Communication: Unveiling the Potential of Terahertz and Molecular Communication. *Appl. Sci.* **2023**, *13*, 10085. https://doi.org/10.3390/app131810085

Received: 1 August 2023
Accepted: 4 August 2023
Published: 7 September 2023

wireless sensor networks. Additionally, nanonodes are more susceptible to failures since they would rely on harvesting energy from environmental sources. Regarding MNC, most of the research has been focused on the physical layer, that is, modeling the channel and developing modulation [17] and coding schemes [2]. However, after establishing the link, other important aspects, such as network architecture and protocols, should be developed.

Integrating nanonetworks with existing networking infrastructures poses significant challenges due to the fundamental differences in their communication methods. While existing networks rely on carrier-based EM communication, nanonetworks utilize energy-constrained pulse-based communication. Bridging the gap between these macro- and nano-worlds requires specialized gateway nodes, but this aspect has not received sufficient attention in the current literature. Addressing the issue of data acquisition from nanonetworks presents two main challenges. Firstly, the disparity between the demands of nanonetworks and the limited bandwidth of the backhaul link connecting them to the macro-world hampers the overall efficiency. To mitigate this problem, a polling mechanism has been proposed as a potential solution [18]. Various hierarchical network architectures have also been suggested to facilitate body-centric communication and sensing-based applications [6,19]. Secondly, the existing research primarily focuses on enabling uplink communication from nanonetworks to the macro-world. However, to fully harness the potential of envisioned applications, downlink communication, particularly for control-related purposes, is essential. It is crucial for future investigations to concentrate on minimizing the latency of such communication.

Nanocommunication security is an important but challenging topic. The security goals of nanocommunication include confidentiality, integrity, and availability [20,21]. Achieving these goals poses several challenges, such as developing methods for establishing shared encryption keys, minimizing the overhead of secure communication protocols, and developing means for detecting and responding to malicious attacks [20]. Some applications of MNC require secure communication, but very few works have considered the problem of security over MNC links [20,22]. More research is needed to address the security challenges of nanocommunication. This research should focus on developing efficient and effective security mechanisms that are tailored to the unique characteristics of nanocommunication systems.

The THz band is currently not regulated, and the responsibility for shaping its future lies with the scientific community. The IEEE P1906.1 standard serves as a conceptual framework for nanoscale communication networks' development [23]. It defines a common data model based on the YANG data modeling language, facilitating configuration, management, and analysis of nanoscale communication systems. The data model includes several core components, including devices, links, communication protocols, and applications. It also includes a number of extensions that allow it to be used for specific applications, such as molecular and quantum communications. Despite its merits, the standard has some shortcomings. Firstly, it lacks a discussion on the characteristics and references powering solutions for potential nanodevices, which is crucial considering the power consumption challenges in nanoscale communication networks. Secondly, it does not provide specific recommended values and ranges for the transmission power and signal-to-noise ratio for reception, making it difficult to design efficient and reliable systems. Thirdly, the standard does not cover techniques for OSI layers 2 and 3, hindering protocol interoperability with existing communication networks like the Internet. To establish effective standardization for THz-based nanocommunication, substantial research efforts are necessary. Addressing the limitations of the IEEE P1906.1 standard and developing new techniques for nanoscale communication are key focus areas. With further research and advancements, nanoscale communication networks have the potential to revolutionize our interactions with the world around us.

Altogether, the field of THz and MNC is still in its early stages, but it has the potential to revolutionize the way we communicate. With continued research, these technologies will become more powerful and efficient, and they will find their way into a wide range of applications.

Conflicts of Interest: The authors declare no conflict of interest.

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