Industrial Perspectives for Molecular Communication in Future Networks

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Abstract. Molecular communication (MC) has offered a method to establish connectivity between micro/nanodevices and construct multiscale heteronetworks within the body. It is beneficial for achieving the ubiquitous connectivity and precise coverage of 6th Generation (6G) networks, while also expanding the service boundaries of traditional communication networks. In this perspective article, we have summarized the existing technological challenges for MC-based heteronetworking in terms of end-to-end trials, which includes MC transmission theories, development of highly integrated microtransceivers, and interoperability between MC systems and conventional cellular systems. Furthermore, some practical and compromised approaches on MC-based heteronetworks have also been given.

Keywords: Molecular communication · Microdevices · Ubiquitous connectivity · Heteronetworks · 6G

1 Introduction

The signal acquisition for neuronal cells, nucleic acid molecule detection, and haptic sensing have been accomplished through the explosive and persistent advancements in brain-computer interfaces (BCIs), biosensors, nanotechnology, bioelectronics [1], etc. It is imagined that massive micro/nanodevices will be implanted in human bodies for comprehensive and accurate data collection including both physiological and psychological information to realize the amazing scenario of human digital twin in 6G or beyond [2]. Accordingly, a novel communication method is desired for information transmission between these miniature devices, as well as data exchange with conventional network devices. However, the conventional electromagnetic communication (EMC) is not suitable for the communication between microdevices because of their limited size for communication system. In addition, it has been criticized for the poor penetration and biocompatibility with electromagnetic wave propagation in human bodies [3].

The information propagation among microorganisms or cells in nature is using molecules or ions as information carriers which are easily obtained or generated in surroundings [4]. It has attracted considerable attentions for the biocompatible communication at microscale. Inspired by nature, molecular communication (MC) has been innovatively proposed by scientists with biomimic methodology [5]. It is a disruptive

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communication paradigm that utilizes biological molecules as information carriers and biological mediums as communication channels. The MC system, similar to a conventional EMC system, consists of a transmitter, channel, and receiver as illustrated in Fig. 1. The information molecules, such as pheromones, hormones, and neurotransmitters, are initially generated and modulated by the transmitter with bit messages based on their chemical or physical properties. Subsequently, these information molecules propagate through liquid and gaseous mediums/channels to reach the receiver while carrying encoded messages. The receiver then decodes and retrieves the information by deciphering the detected information molecules in a specific method. Moreover, the information transmission mechanism is based on molecules or ions diffusion, which exhibits the essential differences comparing with electromagnetic wave propagation. The related transmission schemes like synchronization, modulation and coding, channel modeling, etc. should be distinguished from conventional EMC.

During past decades, lots of studies on directional MC, mobile MC, MC experimental platforms, etc. have been conducted by academic reseachers [6]. Nonetheless, few viewpoints from industry were revealed. In this perspective article, we have envisioned the crucial role of MC in building the multiscale heteronetworks for more precise bioinformation detection and transmission. Meanwhile, several critical and scientific problems for implementing MC-based heteronetworks and future usage scenarios have also been discussed. Finally, some practical suggestions and outlooks on transmission schemes, design principles of microtransceivers and MC gateway, and possible application scenarios for MC have been considered.

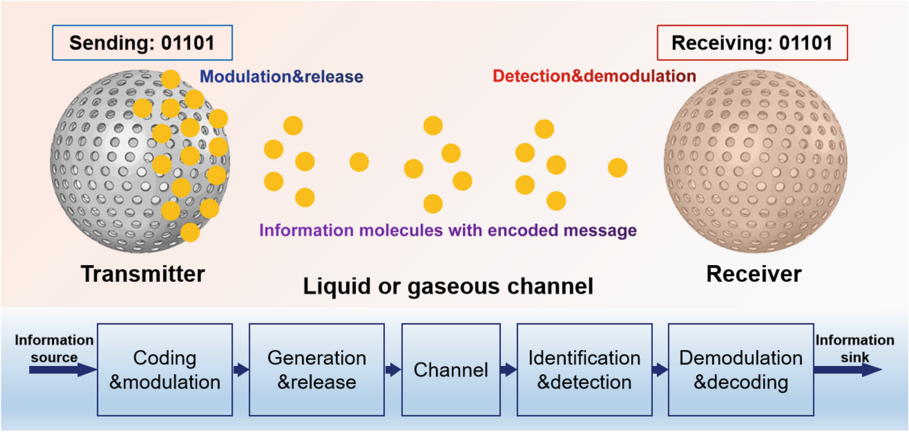

Fig. 1. Schematic demonstration of a typical molecular communication system.

2 Heteronetworking with Diverse Communication Technologies Across Different Scales

The conventional remote medical system consists of various IoT devices with EMC for data transmission [7]. However, these IoT devices are not capable of sensing the molecular biomarkers at very low concentration for human bodies in real time. Therefore, they were failed to meet the requirements of inchoate diagnosis of cancers or epidemic diseases like COVID-19. Micro/nanomachines or devices with micro or nanosize and excellent biocompatibility have obtained much attentions due to their potential applications in drug delivery, tumor cells seperation, and accurate biomolecules detection [8]. Whereas, the lack of an effective communication method hinders these miniature devices from accessing cellular networks for real-time information exchange.

6G is aiming to establish the ubiquitous connectivity and build a digital world. It offers us with an expansive realm to envision the immense potential of future networks incorporating microdevices. The unusual micronetworks in human body with micro/nanodevices, also called the Internet of Bio-Nano Things (IoBNT), will be built [9]. The precise and on-site detection of biomolecular information can be achieved through micro/nanodevices within the human body. Subsequently, the information molecules can be generated and transmitted between each nanonode (micro/nanodevice) based on MC, as illustrated in Fig. 2. In addition, the heteronetworking with cellular networks is of highly significance for further real-time data exchange with conventional network devices outside of bodies. Accordingly, the implementation of a wearable node as a MC gateway is essential to facilitate the information exchange between MC devices and conventional EMC devices. The comprehensive information for human bodies will be conveniently and immediately obtained with massive IoT microdevices deployed in body and real-time data exchange through heteronetworks. Furthermore, the accurate digital twin of human bodies with abundant information can be built, enabling real-time interaction between the physical and digital worlds.

3 Main Challenges for MC-Based Heteronetworking

As aforementioned, there are some essential differences between MC and EMC. The mature EMC system including devices and transmission schemes cannot be directly applied to MC. Generally, the end-to-end validation of MC-based heteronetworking necessitates overcoming three prominent problems or challenges.

Firstly, the Channel Model of MC is Very Complex in Biomedium and Long-Distance MC is Susceptibly Interfered. Molecules or ions diffusion-based MC exhibits the particle property, suggesting the information transmission is easily interfered by obstacles and environmental factors. The directional communication in a long distance should be a bottleneck no matter in micro- or macro-MC scenarios. In addition, the diffusion efficiency of information molecules in biomedium is very slow ~10^{-9} m^2/s [10], which means the propagation time will significantly increase with increasing distance between transceivers. Thus, the channel modeling for MC especially in biomedium of living bodies is crucial. However, few studies were reported. What's more, it is only assuming the transmission between a single transceiver pair. Absolutely, the complexity

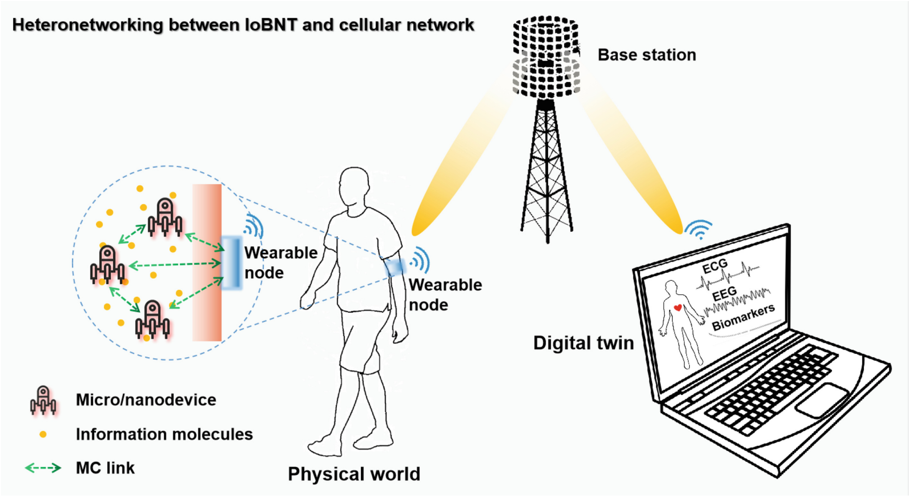

Fig. 2. MC-based heteronetworking between IoBNT and cellular network for precise human digital twin in 6G or beyond.

of the MC system will be greatly improved with the involvement of numerous transceiver pairs, considering synchronization, resource allocation, interference management, etc.

Secondly, There is a Huge Gap Between Requirements and Current Manufacturing Capability of MC Transceivers at Microscale [11]. The experimental validation is the most important part, which relies on the design and synthesis of microtranscievers. As previously reported, lots of experiments with macro MC transcievers have been conducted to demonstrate the feasibility of MC and verify the transmission schemes [12]. Whereas, the trials in macroscenarios can just provide the very limited supportings for MC at microscale because lots of assumptions and mature techniques are not allowed to apply to microdevices. The microfabrication of microtransceivers poses challenging requirements, as they need to integrate diverse functional modules such as signal collection/detection, conversion, processing, control, and output (as illustrated in Fig. 3). To the best of our knowledge, the highly integrated microdevices have not been discovered yet [13]. Furthermore, the data processing module is unlikely to be equiped on microdevice.

Lastly, the Interoperability and Bidirectional Interaction Between the MC System and EMC System for Heteronetworks Remain a Formidable Challenge. The molecular information between microdevices should be converted into physical signals and received by conventional EMC devices, while the electromagnetic signals transmitted from EMC devices should be transformed into molecular signals and received by microdevices. Thus, the heterogeneous gateway or node is necessary to implement the signals or protocols conversion. The MC gateway, unlike its commercial counterpart, is a more intricate device that can be likened to a wireless portable blood glucometer. The biosensing capability of the MC gateway is just the fundamental function, which encompasses molecular information demodulation, protocol conversion, and transmission through 5G or 6G air interface (as demonstrated in Fig. 3) [14]. Conversely, the electromagnetic signal from the cellular network should be initially received by the MC gateway. Subsequently, it will undergo molecular information transformation through bit loading and then be read by microdevices. The portable domestic wireless biosensor should therefore be enhanced and reconstructed as a communication gateway. Furthermore, the accurate, real-time, and remote biomarkers detection can be implemented with commercial biosensors because the enough analytes are present. The demodulation of information carried by a single micro/nanodevice poses a significant challenge for an MC gateway due to the insufficient concentration of information molecules. Although some innovative methods for sensing the analytes with extremely low concentration have been reported [15], the system design especially the gateway will be more complicated.

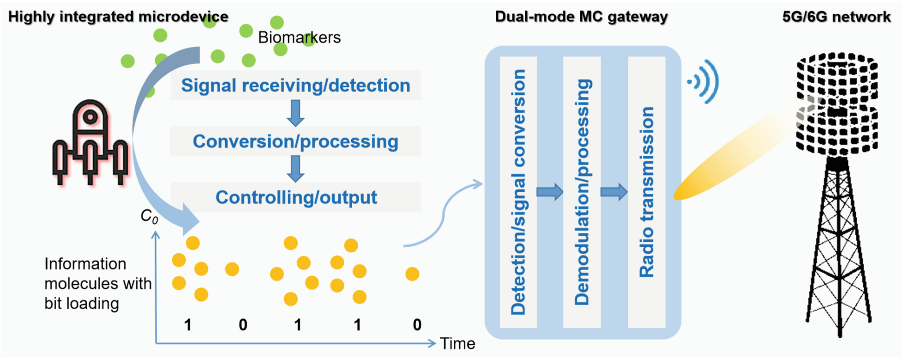

Fig. 3. End-to-end transmission procedures for MC-based heteronetworks. Firstly, micro/nanodevices are employed for the detection of bioinformation/biomarkers (signal receiving/detection), conversion of detected bioinformation into molecular information (conversion/processing), and release information molecules in a specific manner (control/output). Subsequently, the MC gateway receives these information molecules (detection/signal conversion), demodulates the encoded data (demodulation/processing), and transmits the messages to 5G/6G network devices via EMC (radio transmission).

4 Some Practical Suggestions on MC-Based Heteronetworks

From an industrial perspective, it would be highly inspiring to witness the demonstration of comprehensive end-to-end systematic trials. However, few studies were reported because of inadequate interdisciplinary collaborations. The aforementioned technological issues indicate that MC-based networking encompasses a broad range of disciplines, including communication, electronics, nanotechnology, biomedicine, and more. Consequently, it is anticipated that an increasing number of scientists from diverse research backgrounds will actively engage in MC research.

Although it is challenging, some suggestions and feasible strategies have been proposed for the purpose of experimental verification and implementation. **First, the Usage**

Scenarios of MC Should be More Clear and Definite. The diffusion-based information molecules propagation relys on the transmission medium in specific scenario. In addition, the use cases of MC should be thoroughly studied like conventional communication for exhibiting their merits and indispensability. Even more, the specific transmission schemes, devices, and system design may also be tailored to accommodate various MC scenarios.

Second, the Existing Micro/Nanofabrication Technology Cannot Meet the Requirements of MC Transceivers with Conventional System Design. The previous studies on micromachines or biosensors have demonstrated that microdevices possess the capability to selectively convert molecular information into physical signals (e.g., fluorescent signal with specific emission light) through instantaneous chemical reaction or physical interaction [16]. However, the microdevices lack processing capability, making it unlikely for them to comprehend the transmitted signals from other microdevices and subsequently transmit the information with a robust modulation and coding scheme (MCS). Thus, the multi-hop transmission through microdevices is not easily acheived. Currently, it is assumed that only the molecular information detection and signal conversion can be performed by microdevices as biosensors. The MC gateway is capable of capturing the robust signals emitted by swarms of microdevices through regular scanning and detection [17]. The complicated connection procedures like synchronization, random access, etc. should be omitted.

Third, the MC Gateway, Equipped with a Mini-CPU, is capable of Processing Detection Signals from Microdevices and Transmitting Them to the Remote Cellular Network via Electromagnetic Waves. Reversely, the MC gateway can receive messages from remote users through cellular networks and convert them into molecular information. The information molecules in the container of MC gateway can be regularly released by controlling the molecular valve through external physical stimuli. As previously mentioned, microdevices are unable to demodulate the messages carried by information molecules. However, the regular release of molecules from MC gateway has the potential to activate or deactivate functional modules or valves on microdevices, thereby enabling directional motion or drug delivery [18]. Alternatively, the MC gateway may send instructions to microdevices directly by emitting specific photonic signals to initiate the actuation of microdevices [19].

Presently, the communication capability of microdevices is constrained by limitations in microfabrication and transmission mechanisms. They are primarily utilized as microtags in heteronetworks for biomarker detection and signal conversion, rather than functioning as common terminals with comprehensive communication capabilities. On the other hand, molecular communication between visible-sized MC gateways implanted or semi-implanted in human body may be implemented with unparalleled advantages like excellent biocompatibility, electromagnetic interference immune, etc. More details can be further discussed in following studies. In general, deep interdisciplinary collaborations and significant breakthroughs across various fields are still required.

5 Conclusions and Outlooks

In conclusion, micro/nanodevices will play crucial roles in future networks. Molecular communication provides a viable method for message propagation between miniature devices. The innovative concept of the Internet of bionanothings can be implemented within the human body to enable data transmission. In addition, the precise molecular information can be further transmitted to the conventional network devices outside of body for remote interaction with the assistance of MC-based heteronetworking across different scales. This approach allows more wireless microdevices to connect to 5G or 6G networks and provide critical services that are currently unavailable with existing IoT devices. However, several technological challenges need to be overcome, including breakthroughs in MC theories (e.g., channel modeling under specific usage scenario), design and synthesis of highly integrated microtransceivers, and development of dual-mode gateways for heteronetworking.

The experimental validation with interdisciplinary cooperation is significant. It is appreciated that if some practical MC usage scenarios can be confirmed and end-to-end trials can be conducted within the next three or five years. Moreover, the MC-based heteronetworking with conventional cellular networks can be demonstrated.

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Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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