Integration of Molecular Communications into Future Generation Wireless Networks

W. Haselmayr*, A. Springer*, G. Fischer† C. Alexiou‡,
H. Boche¶, P.A. Hoeher‖, F. Dressler**, and R. Schober†
*Johannes Kepler University Linz, Austria, †Friedrich-Alexander-University Erlangen-Nurnberg, Germany
‡University Hospital Erlangen, Germany, ¶Technical University Munich, Germany,
‖Christian-Albrechts-University Kiel, Germany, **Paderborn University, Germany

***Abstract*—In this paper, we discuss the potential of integrating molecular communication (MC) systems into future generations of wireless networks. First, we explain the advantages of MC compared to conventional wireless communication using electromagnetic waves at different scales, namely at micro- and macro-scale. Then, we identify the main challenges when integrating MC into future generation wireless networks. We highlight that two of the greatest challenges are the interface between the chemical and the cyber (Internet) domain, and ensuring communication security. Finally, we present some future applications, such as smart infrastructure and health monitoring, give a timeline for their realization, and point out some areas of research towards the integration of MC into 6G and beyond**

***Index Terms*—Molecular communications, Internet of Bio-Nanothings, 6G, Future generation wireless networks**

I. Introduction

There are various environments, such as inside the human body, where conventional wireless communication using electromagnetic (EM) waves is not feasible or detrimental. In this case, information transmission using chemical signals has been proposed as a promising solution, referred to as molecular communications (MC) [1]. Because of its unique characteristics, the interest in MC has been steadily growing over the past decade and IEEE has even launched initial standardization efforts [2]. In MC, the information is encoded using the concentration, release time, and type of molecules. The propagation from transmitter to receiver can be passive (only diffusion of molecules) or active (diffusion-advection, molecular motors). Moreover, the receivers can also be classified as passive or active, where the former only observe the received molecules and the latter detect the molecules by a chemical reaction. In order to fully exploit the potential of MC systems, their integration with the Internet is crucial.

II. Macro-scale Molecular Communication

In many industrial applications, it is preferable to transmit information wirelessly, instead of using wired solutions. In this case, embedded wireless sensors potentially have to convey information across complex and harsh environments. Unfortunately, in subterranean (e.g., tunnels or mines) and confined industrial environments (e.g., pipe networks including oil, water, and gas pipelines) conventional wireless communication using EM waves may not be feasible, because they suffer from high propagation path loss. For example, in tunnels or underground mines the path loss exponent can be greater than 4 for a wide range of radio frequencies [3]. Moreover, when a tunnel or pipe network cannot act as wave-guide for EM waves the path loss is even greater [4]. In [5], it was shown that radio based sensors are not reliable for some applications in infrastructure monitoring. Although some techniques have been proposed to overcome these problems, MC has been shown to be a promising approach to convey information in such challenging environments [6].

Supported by a €3.26 million grant from the German government, five German universities launched recently the MAMOKO project[1] to investigate the applicability of macro-scale MC for industrial applications. To this end, fluid- and air-based macro-scale MC systems will be designed and practically implemented. Moreover, several practical use cases will be defined where the MC approach is compared with alternative solutions. In another recently launched project[2] (£7 million government investment), four British universities are collaborating to create miniaturized robots that travel along pipe networks to search for damages and carry out repairs. These robots are equipped with sensor, navigation, and communication systems. Although not explicitly mentioned in the project description, using MC for the communication between the robots seems to be a promising approach. Integrating macro-scale communication systems into the next generation wireless networks would support smart infrastructure monitoring. In particular, information could be collaboratively collected by sensors or robots and sent to infrastructure providers. This would enable the providers to monitor critical environments and detect potential damages (e.g., corrosion in pipes) at an very early stage. Moreover, the provider could remotely control the robots to carry out repairs such that complicated and costly roadworks could be avoided. In pipe networks, a regular inspection is essential for their proactive maintenance and rehabilitation. The total value of sewer assets in Europe amounts to €2 trillion.

Since transmission of information using molecules is fundamentally different from using EM-based transmission (e.g., slow transmission rate), the definition of an interface between the chemical and the cyber (Internet) domain is crucial. Moreover, it will be important to ensure secure information transmission to prevent malicious attacks.

[1] Project description: https://www.forschung-it-sicherheit-kommunikationssysteme.de/projekte/mamoko

[2] Project description: https://www.gov.uk/government/news/robots-to-fix-underground-pipes-and-help-cut-roadworks

III. Internet of Bio-NanoThings (Micro-scale Molecular Communication)

The Internet of Things (IoT) refers to the integration of intelligent/smart machines and objects on the Internet. Thus, these smart devices can be accessed and controlled via the Internet. The advances made in the field of nanotechnology, i.e., new materials, such as graphene and metamaterials, enable the development of devices in the nano-meter range, which are referred to as nanothings. The interconnection of nanothings with the Internet is known as Internet of NanoThings (IoNT) and is the basis for various future healthcare and military applications [7]. Nowadays, nanothings are based on synthesized materials (e.g., graphene), use electronic circuits, and EM-based communication. Unfortunately, these characteristics could be harmful for some application environments, such as inside the human body. Thus, recently the concept of Internet of Bio-NanoThings (IoBNT) has been introduced in [8], where nanothings are biological cells that are created using tools from synthetic biology and nanotechnology. Such biological nanothings are referred to as bio-nanothings. Similar to artificial nanothings, bio-nanothings have control (cell nucleus), power (mitochondrion), communication (signal pathways), and sensing/actuation (flagella, pili or cilia) units.[3] For the communication between cells, MC is especially well suited, since the natural exchange of information between cells is already based on this paradigm. MC in cells is based on signal pathways (chains of chemical reactions) that process information that is modulated into chemical characteristics, such as the molecule concentration.

The IoBNT concept enables many future applications. For example, intra-body sensing and actuation, where bio-nanothings that are scattered inside the human body collaboratively collect health-related information. This information is then sent to an external healthcare provider through the Internet. Moreover, it is also possible to receive control signals (e.g., to release drugs) from the healthcare provider. Some applications scenarios for IoBNT, such as cooperative abnormality/cancer detection in blood vessels, using mobile bio-nanothings have been recently studied in [9], [10].

Since the communication in IoBNT is not restricted to the communication between bio-nanothings, an interface between the MC and the cyber (Internet) domain is needed, in order to allow information exchange between the nanonetwork and the Internet. This interface needs to accurately read the molecular information and translate it to EM parameters and vice versa. Developing such interfaces is one of the main challenges for the practical realization of IoBNT. Moreover, the interfaces may be application dependent. Another important issue in IoBNT is the security of information transmission. If this cannot be guaranteed, the opportunities offered by IoBNT can be used maliciously. For example, it can be used to steal personal health information or create new diseases and viruses. To address this issue, methods known from computer networks should be combined with security solutions from nature (e.g., human immune system).

[3]Please refer to [8] for a detailed discussion on bio-nanothings.

IV. Timeline and Research Challenges

The research on micro-scale MC for medical applications (IoBNT), such as intra-body networks, is still in its infancy and faces many challenges. Thus, it may take several decades before such systems can be deployed, i.e., 7G+. On the other hand, macro-scale MC systems (e.g., for smart infrastructure monitoring) are expected to mature much faster and maybe integrated already into the next generation of wireless networks, i.e., 6G.

Despite the great promise that MC holds, there are several research challenges that have to be tackled for its integration into future generation wireless communication systems. These challenges include:

- Development of physical layer techniques for micro- and macro-scale MC
- Development of application-oriented MC testbeds
- Definition of a chemical-cyber interface
- Design of security mechanisms for MC
- Development of sensors and robots with MC capabilities
- Development of bio-nanothings
- Standardization of a layered architecture for MC

At the 6G summit, we plan to highlight the potential of micro-scale and macro-scale MC for integration into future generation wireless communication systems, discuss exciting new applications that will be enabled by MC, explain the related research challenges, and provide first results of several ongoing research projects in this area.

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