Research Challenges on Molecular Communication-Based Internal Interfaces for IoBNT Systems

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Abstract. In this position paper, we describe research challenges on the Internet of Bio-Nano-Things (IoBNT), an emerging paradigm that integrates molecular communication and traditional electromagnetic communication systems into a single communication system. IoBNT systems are expected to bring innovation to conventional healthcare methods. This paper introduces new interfaces, termed internal interfaces to facilitate two-way communication between the edge interfaces and the target molecular communication systems. We assume that the target molecular communication systems are deployed deep inside the body to obtain physiological data, therefore the internal interfaces that make communication between them are essential. This paper describes research challenges associated with internal interfaces.

Keywords: Internet of Bio-Nano-Things · Molecular communication · Medical applications

1 Introduction

The advancement in nanotechnology enables us to fabricate minuscule sensors, with which we can obtain physiological data that are available deep inside in the body, but that is not well-explored due to the limitation of technologies so far. By making full use of the data obtained by bionanosensors for the benefit of human healthcare, future medical systems are envisioned to be integrated into existing computer communication systems.

A new paradigm of the Internet of Bio-Nano-Things (IoBNT) has emerged from the aforementioned background. IoBNT is a novel concept of using bionanosensors to obtain information at the molecular and cellular levels in living organisms, and sharing and controlling it via the Internet [1–3]. If IoBNT is realized, it will be possible to examine and treat patients in remote locations, and expert systems that can diagnose and treat patients without medical experts may be developed to become the medical infrastructure of society.

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The interface bridging between molecular communication (MC) and conventional information and communication technology (ICT) systems is an essential component for realizing IoBNT. It would facilitate an independent development of both MC and ICT systems to realize as a generic interface as possible. Researchers in the field of MC have been focusing on the bio-nanomachine to bio-nanomachine interface (BNI) since its founding in 2005 as a new communication paradigm for nano-scale devices. There are in large two types of interfaces: the one that interconnects MC and ICT systems at the edge of each system, termed as *edge interface*, and the other that relays information from target MC systems working as data sources to the edge interface and vice versa, termed as *internal interface*. For the former, there are a number of research Brain Machine/Computer Interface (BMI/BCI) [11,12], light-based communication interfaces [4,9,13], implantable [5], which operate as converter between the signals in MC system and the ones in ICT system, while the latter are not well explored.

In this paper, we specifically focus on the internal interface and provide a list of research challenges toward the realization of a generic internal interface. We assume that the internal interface is implemented as other MC systems so that we can deploy them in a self-organized manner, and that we can let them operate autonomously within the human body. In such an internal interface, molecular signals are utilized as common languages as in MC systems. However, molecular signals can be too weak to detect, therefore, signal amplification and relaying are necessary.

The rest of this paper describes an architecture of the IoBNT systems in Sect. 2, and research challenges for internal interface for IoBNT in Sect. 3.

2 An Architecture of the Internet of Bio-Nano-Things (IoBNT) Systems

Figure 1 shows an entire architecture of IoBNT systems. The components of IoBNT systems include MC systems, ICT systems, and interface bridging between MC and ICT systems. MC systems work as a data source. The systems, termed as *target MC systems*, are deployed deep inside the human body to collect physiological data, such as the existence and concentration of specific molecules. It may also be possible to encode physical characteristics in the human body, such as heat, pressure, into molecular signals. MC systems consist of bio-nanomachines communicating information through molecular signals. Each of bio-nanomachines is equipped with an interface that allows the communication between other bio-nanomachines, termed as bio-nanomachine to bio-nanomachine interface (BNI).

ICT systems are responsible for sharing data based on the huge infrastructure of the Internet. The physiological data transmitted from MC systems may be analyzed using machine learning and statistical techniques on the cloud within ICT systems so that the data are interpreted and visualized in an accessible

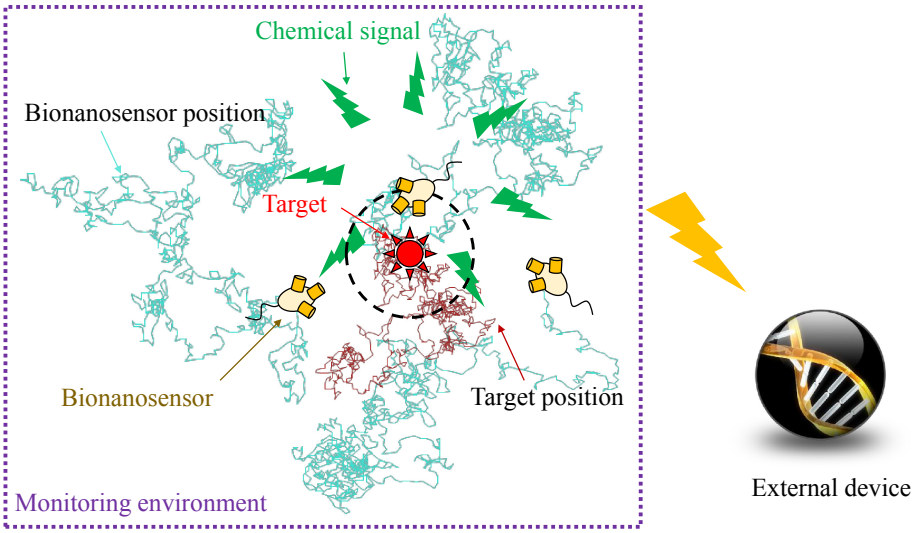

Fig. 1. An architecture of the Internet of Bio-Nano-Things. Adapted from [8].

manner to non-expert users as well as to expert users, such as medical doctors, data scientists.

Figure 2 shows a detailed view of an interface of IoBNT systems. The interface between MC and ICT systems are responsible for converting signals both inside-out and outside-in, which correspond to outmessaging interface (OMI) and inmessaging interface (IMI), respectively [6]. These sub-interfaces, termed as *edge interfaces*, directly communicate with external devices. In this paper, we introduce additional interfaces, termed as *internal interfaces*, that facilitate two-way communication between the edge interfaces and the target MC systems.

3 Research Challenges for Internal Interface for IoBNT Systems

In this paper, we specifically focus on the internal interface between MC and interface MC, and between interface MC and interface MC systems. Molecular signals are utilized as common languages in both directional communication: between other MC systems and interface MC systems, and between external ICT systems and interface MC systems. In both directional communications, molecular signals can be too weak to detect, therefore, (1) signal amplification is inevitable, (2) self-deployment as well as autonomous operation without human intervention is a must, and (3) functionality of relaying information from the target MC and to the external interface is also essential for IoBNT.

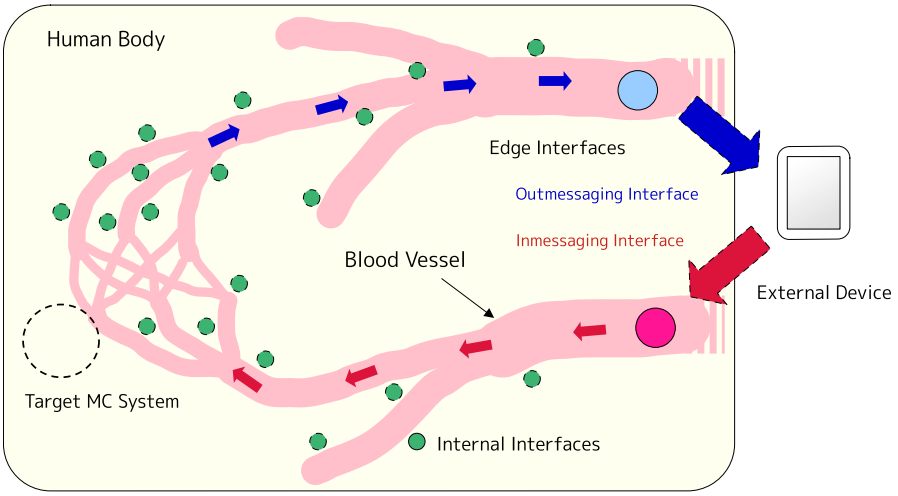

Fig. 2. Interfaces in IoBNT systems.

3.1 Signal Amplification

By utilizing the self-deployment mechanisms discussed in the next subsection, we develop a method for autonomous mobile bionanosensors distributed in space to form self-organized aggregates. By forming macroscopic assemblies of bionanosensors and behaving collectively, we consider implementing functions that are difficult to realize with single bionanosensors. For example, as an interface that interconnects the in vivo and ex vivo environments, a function that converts in vivo molecular signals into electronic signals and a function that amplifies the signal strength will be realized to enable information exchange with existing communication devices. This will enable the interconnection of the bionanosensor network with existing information and communication networks.

Research challenges when designing and developing the signal amplification are what types of signals to use for communication between MC systems. Signals exchanged between MC systems should be determined to neither interfere with nor disturb the operation of other MC systems, especially the target MC system, where molecular signals are exchanged through BNI. On top of that, for the signal amplification, synchronization mechanisms for the aggregated bionanomachines may be also necessary.

3.2 Self-deployment

Forming aggregates is also essential to self-deployment as well as signal amplification. In our work, we proposed a method that mimics the mechanism by which cellular organisms in nature form various spatial structures [7,10]. Many cells in nature use chemotaxis to form various spatial structures. Chemotaxis is the property of a cell to detect the concentration of an attractant and move toward

the direction where the concentration of the attractant is higher. For example, certain bacteria form self-organized spatial patterns by producing and releasing attractants, such as aspartic acid, to form a concentration gradient of attractants in the environment and move in the direction of each other. In addition, when starved, cellular slime molds generate waves of attractants in the environment by releasing attractants themselves or releasing attractants in response to released attractants. Individual cells are known to form aggregates as they move toward the source of the wave.

Research challenges when designing and developing the self-deployment is how to deploy internal interfaces. The internal interfaces may be either statically or dynamically deployed inside the human body. For the former, there is theoretical work to form aggregates and specific patterns in the environments where there is neither flow nor heterogeneity in physical characteristics. It could be much more complicated if we assume the real human body environments, but not yet well explored how to deploy the interfaces statically inside the human body. It may be also possible to dynamically deploy the interfaces by making use of blood vessels as the environment. There are several options not limited to the examples explained so far.

3.3 Signal Relay

We proposed a multi-hop drug transport system [14]. The system consists of two types of bionanosensors: a transmitter that emits a signal molecule containing location information to other bionanosensors when it detects a target to which the drug is to be transported, and a receiver that uses the concentration of the signal molecule emitted by the transmitter as a clue to transport the drug to the target. In this system, we proposed to introduce a repeater that implements an infectious propagation scheme to amplify the signal molecules from the transmitter. In the conventional proposed method, the signal molecules are very weak, so the bionanosensors need to be near each other to propagate the signal molecules, and many bionanosensors need to be deployed. By introducing a repeater that implements the infectious propagation method, we showed that the therapeutic agent can be transported efficiently even with a small number of bionanosensors.

By extending this relaying mechanism among bio-nanomachines, we may be able to develop more reliable and functional relaying mechanisms among MC systems. Research challenges in designing and developing the signal relay are what types of signals to use for communication between MC systems, specifically focusing on how to relay signals. What types of signals are well suited for conveying information among MC systems within the human body. When different types of molecules are well-suited for conveying information, the internal interface may be used for converting signaling molecules into the ones.

4 Conclusion

In this position paper, we described research challenges on the Internet of Bio-Nano-Things (IoBNT) specifically focusing on the intermediate interfaces, termed as internal interfaces. The internal interfaces was introduced for the purpose of facilitating two-way communication between the edge interfaces and the target molecular communication systems. We assumed that the target molecular communication systems were deployed deep inside the body, therefore the internal interfaces that make communication between them are essential. This paper described research challenges associated with the internal interfaces.

References

1. Akyildiz, I.F., Pierobon, M., Balasubramaniam, S., Koucheryavy, Y.: The internet of bio-nano things. IEEE Commun. Mag. **53**, 32–40 (2015)
2. Akyildiz, L.F., et al.: PANACEA: an internet of Bio-NanoThings application for early detection and mitigation of infectious diseases. IEEE Access **8**, 140512–140523 (2020)
3. Balasubramaniam, S., Kangasharju, J.: Realizing the internet of Nano things: challenges, solutions, and applications. Computer **46**(2), 62–68 (2013)
4. Ellis-Davies, G.C.R.: Caged compounds: photorelease technology for control of cellular chemistry and physiology. Nat. Methods **4**(8), 619–628 (2007)
5. Kiourti, A., Psathas, K.A., Nikita, K.S.: Implantable and ingestible medical devices with wireless telemetry functionalities: a review of current status and challenges: implantable/ingestible medical devices. Bioelectromagnetics **35**(1), 1–15 (2014)
6. Nakano, T., Kobayashi, S., Suda, T., Okaie, Y., Hiraoka, Y., Haraguchi, T.: Externally controllable molecular communication. IEEE J. Select. Areas Commun. **32**(12), 2417–2431 (2014)
7. Okaie, Y.: Cluster formation by mobile molecular communication systems. IEEE Trans. Mol., Biol. Multi-scale Commun. **5**(2), 153–157 (2019)
8. Okaie, Y., Nakano, T., Hara, T., Nishio, S.: Target Detection and Tracking by Bionanosensor Networks. SpringerBriefs in Computer Science, Springer, Singapore (2016). https://doi.org/10.1007/978-981-10-2468-9
9. Ozawa, T., Yoshimura, H., Kim, S.B.: Advances in fluorescence and bioluminescence imaging. Anal. Chem. **85**(2), 590–609 (2013)
10. Nakano, T., Okaie, Y., Kinugasa, Y., Koujin, T., Suda, T., Hiraoka, Y., Haraguchi, T.: Roles of remote and contact forces in epithelial cell structure formation. Biophys. J. **118**(6), 1466–1478 (2020)
11. Veletic, M., Balasingham, I.: Synaptic communication engineering for future cognitive brain machine interfaces. Proc. IEEE **107**(7), 1425–1441 (2019)
12. Willett, F.R., Avansino, D.T., Hochberg, L.R., Henderson, J.M., Shenoy, K.V.: High-performance brain-to-text communication via handwriting. Nature **593**(7858), 249–254 (2021)
13. Wu, Y.I., Frey, D., Lungu, O.I., Jaehrig, A., Schlichting, I., Kuhlman, B., Hahn, K.M.: A genetically encoded photoactivatable Rac controls the motility of living cells. Nature **461**(7260), 104–108 (2009)
14. Okaie, Y., Ishiyama, S., Hara,T. : Leader-follower-amplifier based mobile molecular communication systems for cooperative drug delivery. In: 2018 IEEE Global Communications Conference (GLOBECOM), pp. 206–212 (2018)