A Biologically-inspired Intrabody Nanonetwork: Design Considerations

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ABSTRACT

In this position paper, we describe an architecture for intrabody nanonetworks, a new type of body area networks targeted to the molecular environment deep inside the human body. Our approach is to learn from biological systems (e.g., microbial organisms that establish a complex adaptive system in the body) to design an architecture for intrabody nanonetworks. Our initial thoughts on the architectural design as well as testbed are first described. Future challenges are then discussed toward the practical deployment of intrabody nanonetworks.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous; D.3.4 [**Systems and Software**]: Information Networks

General Terms

Design

Keywords

Intrabody nanonetwork, system architecture, bio-inspired approach, microbial ecosystem

1. INTRODUCTION

Body Area Networks (BANs), also known as Body Sensor Networks (BSNs), utilize wireless communication technology to provide future health care applications [1, 2, 3]. A BAN integrates various types of wireless sensors and actuators for continuously monitoring physiological conditions of the human body (e.g., the heartbeat rate, body temperature, body motion, blood glucose level) as well as performing appropriate actions for medical diagnosis and therapy (e.g., administering the correct amount of drug molecules, informing remote doctors for further analysis.)

The area of BANs is expected to advance with nanonetworking technology, which recently introduced the new notion of *intrabody nanonetworks* [4, 5, 6]. It is envisioned in the intrabody nanonetworks that therapeutic nanomachines made in part or whole from biological materials (e.g., functional nanomaterials, artificial cells, genetically engineered cells [7]) are distributed deep inside the human body and that they communicate either molecularly or electromagnetically to perform medical operations with cellular or molecular level precision.

The intrabody nanonetworks of therapeutic nanomachines may be connected to a BAN to expand further the potential of the BAN. When intrabody nanonetworks are integrated, a BAN may be able to use therapeutic nanomachines to manipulate the molecular environment in the human body (Fig. 1). On-body wireless devices (i.e., classical BAN nodes) may act as a base station for nanomachines, where nanomachines are prepared and released into the molecular environment in the body. Nanomachines may have mobility in the body, and they move and collect information about the environment. Nanomachines may also react to or release molecules to modify the environment. Multiple base stations may be placed on/in the body to share information among these devices. Further, these base stations may be connected through a personal device (e.g., a cell phone) to the Internet to interact with remote devices.

One challenge of the intrabody nanonetworks is to design

BODYNETS 2013, September 30-October 02, Boston, United States

DOI 10.4108/icst.bodynets.2013.253511

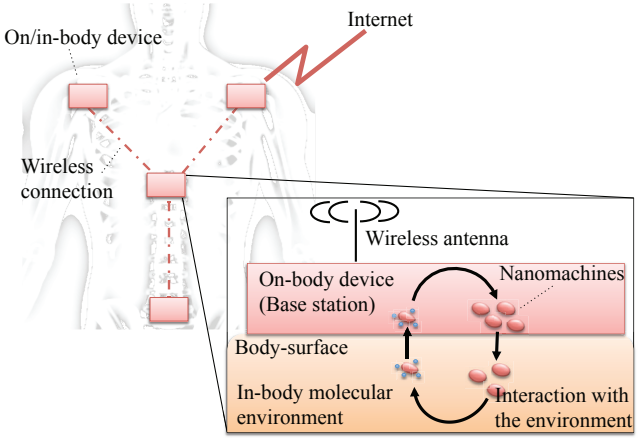

Figure 1: Intrabody nanonetworks

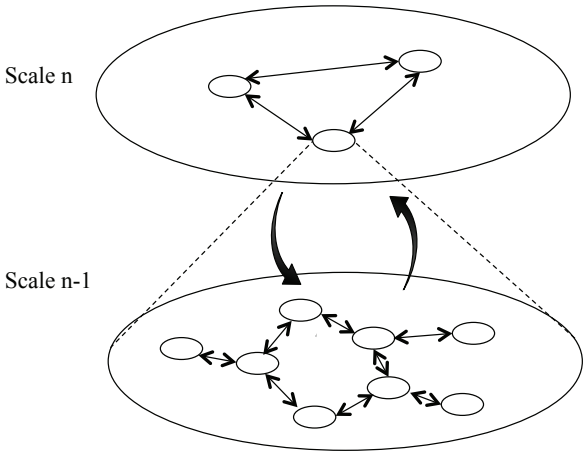

Figure 2: Multiscale modular architecture

a system of nanomachines that robustly functions within the molecular environment deep inside the human body. Nanomachines assumed in intrabody nanonetworks are small-scale devices at the nano (1–100 nm) or micro-scale (0.1–100 μm). These nanomachines are capable of interacting with molecular signals in the environment, however, their range of actions is limited due to their small size. In addition, inherent to the stochastic nature of the environment and nanomachines, single nanomachines are unreliable and fragile. A promising approach to this design challenge may be learned from biological systems, for instance, from microorganisms that establish a complex adaptive system in the human body. Drawing on inspiration from biological systems, we discuss in this paper an architecture for designing robust intrabody nanonetworks that persist in the molecular environment.

In the rest of the paper, we first present our initial thoughts on the architectural design (Section 2) and experimental testbed (Section 3) and then discuss future challenges that need to be addressed to advance the intrabody nanonetwork technology (Section 4).

2. BIO-INSPIRED APPROACH TO ARCHITECTURAL DESIGN

One common practice to system design is to define the architecture of the system. Architecture decomposes a large-scale system into a set of functionally independent smaller units, often refereed to as modules, and specifies the interactions among modules. Architecture thus allows system designers to understand the working principle of the system and accelerates the design and development. In computer networks, for instance, the layered architecture (i.e., the TCP/IP reference architecture) is applied to decompose complex network functionality into a set of manageable modules called the layers [8].

The layered architecture for computer networks may serve as a basis for intrabody nanonetworks design [4, 5, 9]. In addition, architecture of biological systems (e.g., microbial systems) may give us useful design guidelines on how biological materials (i.e., naturally occurring nanomachines) can be integrated to create a sustainable system. Thus, our approach is to examine how biological systems are designed, identify key design principles, and develop an initial architecture for intrabody nanonetworks.

Inspired by the organizing principles of biological systems (e.g., [10, 11, 12, 13, 14, 15]), we propose a multiscale modular architecture for intrabody nanonetworks (Fig. 2). A set of design considerations we propose includes:

- Multiscale nature. Intrabody nanonetworks are likely organized over very different length scales, similar to how biological systems are organized. The length scales include the nano-scale (1–100 nm), micro-scale (0.1–100 μ m), and macro-scale (>0.1 mm), corresponding respectively to the molecule, cell, and tissue/organ levels. A functional module at one scale n is implemented from a set of its components (or underlying modules) that interact at scale $n-1$. Information is transmitted at the same scale as well as across different scales. Similarly, very different time scales are likely involved in the operation and functioning of these modules (e.g., diffusion of molecules occurs in the order of milliseconds, cell motility in seconds, mitosis in 10^3 seconds).

- Emergence. A useful functionality or property may emerge in a module at one scale, resulting from a set of modules that interact locally and massively in parallel at a smaller scale. Known as the collective intelligence in biological systems (e.g., social insects, bacterial communities, neural networks), simple local interactions may induce a useful global functionality or property, such as the adaptability to changing environments.

- Redundant and dynamic modular design. A number of modules may provide the same functionality. Also, a single module may have multiple functionalities, dynamically activate or deactivate a set of selected functionalities, or modify certain functionalities. The redundant and dynamic nature increases the reliability and robustness of the module as in biological systems,

since failures or misbehavior of a small number of modules is compensated by other modules.

- Noise effect. Due to the thermal noise in the molecular environment, functionality of a module becomes stochastic. Stochastic functionality can be overcome by relying on the ensemble of modules. Alternatively, the noise effect may be explored to design a novel functionality. In biological systems, noise often plays an important role in sustaining their life (e.g., introduce genetic diversity in a population of organisms.)

- Interactions and communications. Interactions among a set of modules become the basis to implement a larger-scale functional module. Communication protocols may be defined to specify standardized methods of interactions by which a set of modules performs a function robustly. Communication protocols may be needed for synchronization, media access, localization, routing of information, and in-network processing of information. In biological systems, two types of interactions are often observed: positive and negative feedback to control various functions.

- Evolution. Evolution is a unique feature that biological systems present. A population of biological cells evolve through random changes (i.e., mutation) and selection. Functional modules implemented from biological materials (e.g., biological cells) may thus have the ability to evolve in situ (in the body) to acquire a new functionality.

3. TESTBED

We propose to use an experimental microbial ecosystem [16] as a testbed for research and development of intrabody nanonetworks. Our motivations are threefold:

- First, microbial ecosystems naturally occur in the human body and they provide certain functionality (e.g., the gut flora in the human body is considered another organ). Artificial microbial ecosystems developed using the testbed could be thus naturally integrated into the human body to implement certain functionality for body area nanonetworks (e.g., sensing and collecting of information deep inside the body).

- Second, experimental microbial ecosystems are hierarchically organized, which involve interactions at three different scales: interactions among populations, among individuals, and among molecules. Experimental microbial ecosystems are as such suited for the study of the multi-scale modular architecture shown in Fig. 2.

- Third, experimental microbial ecosystems allow us to understand many other aspects of biological systems through the monitoring and manipulation of the systems. They allow us to (1) reproducibly observe the temporal changes of ecosystems on a laboratory timescale[1], (2) analyze from the population level down to the molecular level at any time point as the experimental microbial ecosystems can be readily cryopreserved, isolated, and sequenced, and (3) manipulate the population of organisms, environmental conditions (e.g., the temperature and chemical composition of the environment), and the intracellular reaction networks by genetic engineering (e.g., by gene deletion, insertion, and replacement.)

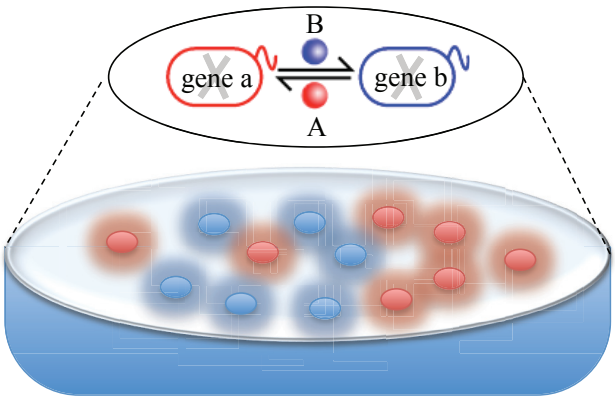

Figure 3: Bacterial ecosystem as a testbed

Fig. 3 shows our testbed designed to investigate key aspects of intrabody nanonetworks such as their multi-scale nature, emergent property, modularity, communication, and evolution. The testbed is based on a previously reported experimental ecosystem, and it is composed of two genetically engineered microbial populations that interact at multi-scales. In one setting, one population lacks a gene necessary for the biosynthesis of a nutrient, which is essential for the population growth, and the other population lacks another gene for the biosynthesis of another nutrient. Neither population alone is able to grow, but the two populations together can continuously grow if the two populations successfully establish mutual relationships by supplying sufficient amounts of essential nutrients required by the other population. The experimental setting can be used to study how initially independent modules (i.e., two different populations of bacteria) may interact, how a larger-scale functionality (e.g., population-level functionality such as the improved survivability) may emerge from locally interacting individuals, and how information is propagated between individuals, between an individual and its population, and between populations during the course of evolution.

4. FUTURE CHALLENGES

The research area of intrabody nanonetworks has just begun. Our future efforts will be made to address the following research questions:

[1]In experimental evolution, for example, genetic changes may occur at random locations and the resultant genome sequences become diverse and stochastic, however, fitness curves (e.g., growth curves) are highly reproducible. It is also possible, from multiple lines of evolution experiments, to statistically determine the location(s) of genetic changes that are likely to occur. It is also possible to identify the dependency of one gene on another in gene expression (i.e., the epistatic relationship) [17]. In this way, reproducibility of particular genetic changes can be determined.

- Bio-inspired approach to architectural design. To what extent is it reasonable? Biological systems are too complex and the current state-of-the-art biology is still far from the complete understanding. How is an emergent behavior possibly designed?
- Implementation and engineering. What materials are available and what techniques are applicable to implement nanomachines and a network of nanomachines?
- Deployment. How are intrabody nanonetworks to be deployed deep inside the human body? How can nanomachines be targeted to specific areas in the body? In deployment, a number of biological barriers need to be overcome, such as immune reactions.
- Sustainability. How long can intrabody nanonetworks in the human body persist? How can we extend their life time? Can we learn from microorganisms that establish mutual relationships with a host organism?
- Controllability. How can intrabody nanonetworks deep inside the human body be controlled externally? Is it feasible to have fully autonomous intrabody nanonetworks that require no external control?
- Energy source. How is the necessary energy for intrabody nanonetworks supplied? What is the possibility of harvesting the energy in any form available in the environment?
- Safety and security. Are intrabody nanonetworks compatible with biologoical systems in the body? Do they interfere with existing components in the body? How are they removed after they are deployed? How are they protected from potential attacks?
- Interfacing with BANs. How can intrabody nanonetworks be connected to implants or wearable devices in current BANs? What forms of communications are available? By integrating intrabody nanonetworks with BANs, what becomes possible?
- Network information theory. What is the capacity of intrabody nanonetworks? How is information best transmitted across different length and time scales (e.g., how is a sensor reading from the nano-scale device transmitted to the micro and macro-scale devices)?

5. CONCLUSION

Intrabody nanonetworks have the potential to manipulate information in the molecular environment deep inside the human body. In this paper, we described an architecture for intrabody nanonetworks with a set of design considerations and an experimental testbed to study key aspects of intrabody nanonetworks. We also discussed future challenges for further design, implementation, and deployment of intrabody nanonetworks.

6. ACKNOWLEDGMENTS

This work was conducted as part of the Humanware Innovation Program of Osaka University, a Leading Graduate School Program supported by Japan Society of the Promotion of Science (JSPS).

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