Molecular Communication

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ABSTRACT

This paper describes research challenges in Molecular Communication, a new and interdisciplinary research area that spans the nanotechnology, biotechnology, and communication technology. Molecular communication allows nanomachines to communicate using molecules as a communication carrier. Key research challenges include controlled propagation of carrier molecules, encoding/ decoding of information onto information molecules, and transmission/reception systems for carrier/information molecules. The authors of this paper are currently investigating the feasibility of molecular communication.

Keywords: nano-scale communication systems, molecular communication, carrier/information molecules, biochemical communication, nanomachine

1 INTRODUCTION

This paper describes research challenges in Molecular Communication, a new and interdisciplinary research area that spans the nanotechnology, biotechnology, and communication technology. Molecular communication allows nanomachines to communicate using nano-scale particles.

Molecular communication is inspired by the observation that in the biological systems, communication is typically done through molecules. For instance, biological systems perform intra-cellular communication through vesicle transport, inter-cellular communication through neuro-transmitters, and inter-organ communication through hormones [1], [2]. Molecular communication is common in biological systems. It has not been, however, generalized to controlled communication between nanomachines. Current nano and bio technology focus on observation and understanding of existing biological systems such as how communication is done within a cell or between cells. Molecular communication would work toward the actual design and control of nano-scale communication systems.

Molecular communication provides a mechanism for nanomachines to communicate over a short distance (tens of micrometers) using molecules as a communication carrier. The class of molecular communication systems considered in this paper consists of sender nanomachines, receiver nanomachines, carrier molecules, information molecules, and the environment that these operate in. Senders and receivers include biologically and artificially created nanomachines that are capable emitting and capturing molecules. Carrier molecules are molecular motors, hormones or neurotransmitters. Information molecules are proteins, ions, or DNAs. The environment is the aqueous solution that is typically found within and between cells.

This paper presents concepts and visions for the molecular communication, designs a few possible molecular communication systems, and discusses key research issues and possible approaches.

2 KEY FEATURES

Key features of molecular communication include use of molecules as a communication carrier and biochemical reactions caused by the information molecules at the receiving side. Unlike existing communication systems that utilize electronic and optical signals as a communication carrier, molecular communication utilizes chemical signals as a communication carrier. In addition, unlike in existing communication where encoded information such as voice, text, and video is interpreted at the receiver, in molecular communication, information molecules cause some reaction at the receiver and recreate a phenomenon and/or chemical status that the sender transmits.

Other features of molecular communication include slow-speed communication, stochastic nature of communication, low energy-consumption communication, and being highly compatible with biological systems. Figure 1 summarizes key features of molecular communication and compares them against to the traditional communication systems.

3 APPLICATIONS

Molecular communication is a completely new paradigm and would potentially enable many new applications in the bionanotechnology. Examples of future applications that molecular communication enables are described below.

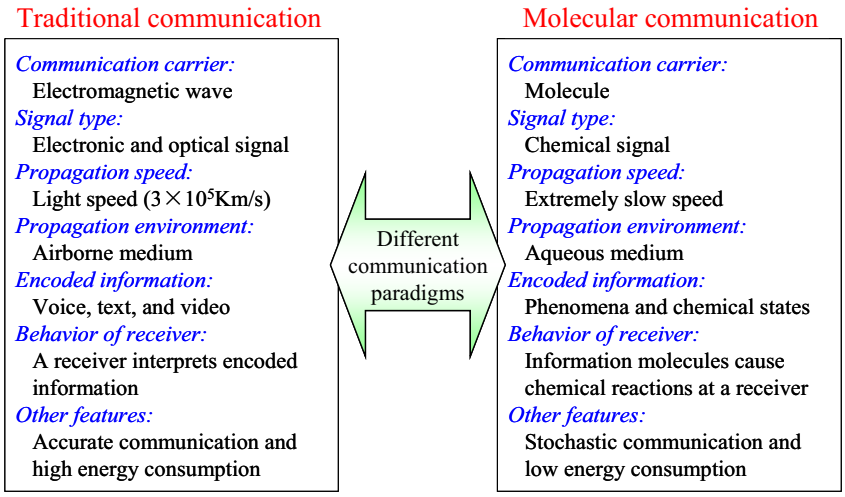


Figure 1: Comparisons of key features.

3.1 Nanomachine Communication

Nanomachines are molecular scale objects that are capable of performing simple tasks such as actuation and sensing. Nanomachines are categorized into two types [3]. One type is artificially created nanomachines which mimic the traditional machines and may be made through using the NEMS technology. The other is nature made nano-machines, often referred to as soft nanomachines, which are found in biological systems (such as molecular motors and receptors). These soft nanomachines only work in the aqueous environment.

Single nanomachines are limited in their sizes and capabilities. Molecular communication, however, provides a viable alternative to using electromagnetic wave for soft nanomachines to communicate and cooperate to perform complex tasks. In addition, controlling behavior of destination nanomachines is possible through biochemical reactions triggered by information molecules.

3.2 Molecular Computing

Molecular devices such as enzyme transistors, biological logic gates and memories have recently been developed in the fields of molecular electronics and molecular computing [4], [5]. Molecular devices are attractive because of their potential capabilities such as super dense packing and their suitability to parallel computations. Molecular communication provides means to interconnect a large number of computational molecular devices and enhances the existing molecular computing architectures.

3.3 Pinpoint Drug/DNA Delivery System

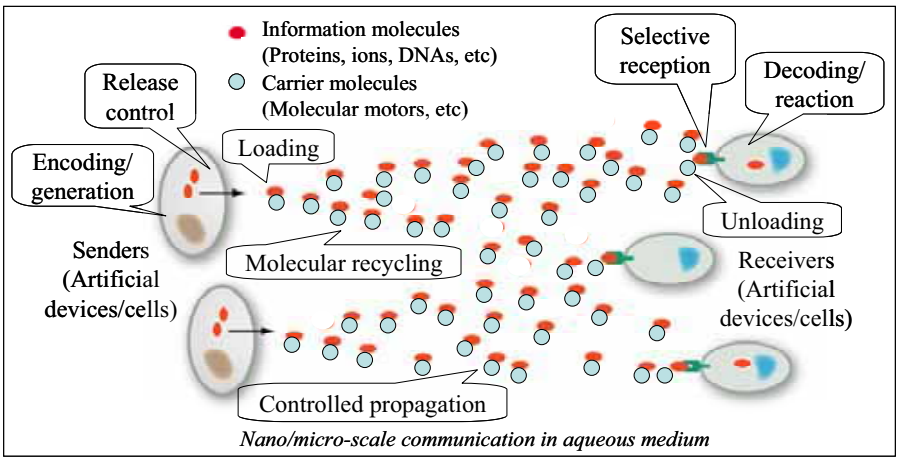
The DDS (Drug/DNA Delivery System) has recently been receiving attention as a new method of medical treatment which alleviates undesired side effects [6]. Molecular communication may provide drug carriers and also mechanisms to deliver drugs in a manner that is friendly to the biological systems. For instance, soft sender nanomachines may be embedded in a human body and emit drug or DNA. Emitted drug or DNA may be attached to hormones and neurotransmitters (acting as carrier molecules) and delivered to the targeted receiver cells through the endocrine/neuroendocrine pathway.

4 EXAMPLE SYSTEMS

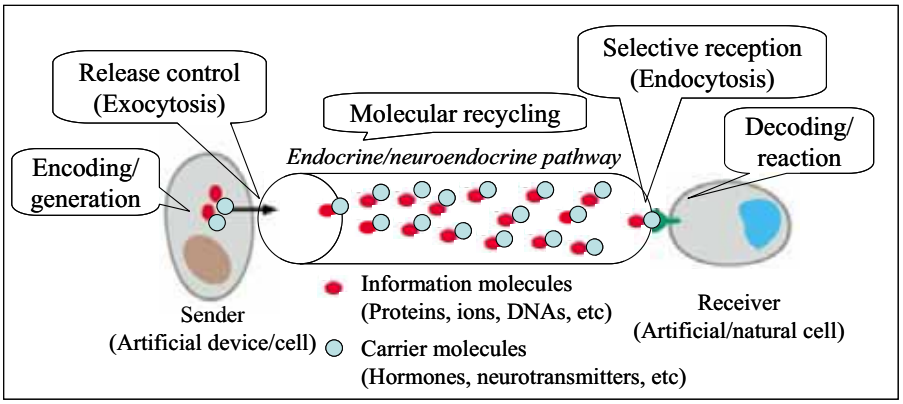
Figure 2 depicts two types of a molecular communication system that we consider in the initial phase of our research.

The first type of a molecular communication system is a closed and autonomous system that operates in an artificially created environment without (or with little) external control (Figure 2 (a)). This type of molecular communication system is applicable to applications such as nanomachine communication and molecular computing described in the previous section. The second type of a molecular communication system is a system which utilizes signal molecules and signal transduction pathways (such as hormones and neurotransmitters) that exist in a biological entity (e.g., a human body) (Figure 2 (b)). This type of molecular communication system is applicable to applications such as pinpoint DDS described in the previous section.

In both types of a molecular communication system, communication process includes; encoding of information onto the information molecules, sending of the carrier/



(a)



(b)

Figure 2: Example molecular communication systems.

information molecules into the environment, propagation of the carrier/information molecules through the environment, receiving of the carrier/information molecules, and decoding of the information represented by the received information molecules into reaction at a receiver. In addition, recycling of carrier/information molecules may be necessary to avoid accumulation at a receiver.

5 RESEACH CHALLENGES

Key research challenges in realizing molecular communication include, among other things, controlled propagation of carrier molecules, encoding/decoding of information onto information molecules, and transmission/ reception systems for carrier/information molecules.

First, in the area of controlled propagation of carrier molecules, major challenges include controlling direction of molecular propagation under the Brownian motion and creation of mathematical and simulation models suitable to describe directed propagation of carrier molecules.

In realizing controlled propagation of carrier molecules, we believe that using linear motor molecules (e.g., kinesins, dyneins, and myosins) and rail molecules (e.g., micro-tubules and actin filaments) to transport information molecules is among the most promising approaches [1], [2], [7]. Motor molecules transport cargos such as vesicles and organelles along the rail molecules within eukaryotic cells in the biological systems. Thus, molecular motors may be able to easily transport information molecules used in molecular communication [8]. In the molecular motor based molecular communication system, technical challenges include loading and unloading of information molecules onto motor molecules, as well as controlling the direction of motor molecules movement when multiple rail molecule paths exist. Note that a scenario where rail molecules move over motor molecules that are planned on a platform is feasible [9], and similar technical issues exist for this scenario.

In creating mathematical and simulation models suitable to describe directed propagation of carrier molecules, both multi-scale aspects (e.g., atom level, molecular level) and dynamic aspects (e.g., movement of carrier molecules and environmental changes) need to be considered, yet, the resulting models should be mathematically and computationally tractable. Existing multi-scale simulators such as OCTA [10] and BioPfuga [11] are limited in their capabilities and may not be suitable for complex simulations that consider multi-scale and dynamic aspects of molecular communication. Thus, we wait for significant research achievement in simulators that can complement the empirical study.

Second, in encoding/decoding of information onto information molecules, technical challenges include creating encoding/decoding algorithms that are robust to environmental noise (e.g., denaturation caused by interaction between information molecules and their environment; changes in temperature and pH in the environment, or interaction with enzyme in the environment). One possible approach is to use 3D structural characteristics of information molecules in encoding such that given information is mapped onto a family of molecules (e.g., protein family that shares similar amino acid sequence). This minimizes the negative impact of changes in molecular structures due to environmental noise. Alternatively, molecular characteristics such as polarity, motion, and magnetization may be used in encoding to minimize the negative impact of the environmental noise. Another possible approach is to use encapsulations. For instance, an inorganic matrix called a layered double hydroxide (LDH) is used to form a stable DNA [12]. The unstable naked DNA strands (either single or double) intercalated into the LDH are sufficient to endure severe physical and biological environments. If we employ this mechanism, a tremendous amount of information may be incorporated into a DNA strand as an information molecule. Alternatively, forms of membrane encapsulations like vesicles may be applicable in order to protect information molecules from the environmental noise.

Finally, in sending and receiving carrier/information molecules, technical challenges include creating senders that generate and release carrier/information molecules in a controllable manner and creating receivers that selectively accept and process carrier/information molecules. One possible approach is to use mutant cells. In the eukaryotic cells, ribosomes synthesize some proteins which are secreted by exocytosis and the cell surface receptors selectively capture the diffused proteins and take them inside the cell by endocytosis [1], [2]. In the process of vesicle transport, export proteins are selected strictly at the endoplasmic reticulum (ER) and recycled between the ER and Golgi apparatus [13]. These mechanisms may be applied to sending and receiving of carrier/information molecules through genetic manipulations. As the first step toward applying such mechanisms in sending and receiving of carrier/information molecules, we believe that empirical study using genetically altered yeasts is among the most fruitful approaches to investigate feasibility. In the successive phases of research, we may artificially create senders and receivers by integrating some controllable components such as artificial cell membrane and receptors [14] in an *in vitro* environment.

6 CONCLUSIONS

This paper presented new concepts and visions of the molecular communication, a new communication paradigm. We are currently investigating the feasibility of molecular communication through empirical study.

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