Molecular Communication for Health Care Applications

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Abstract

Molecular communication is a new communication paradigm and uses molecules as a communication carrier. In molecular communication, information is encoded onto molecules at senders and the molecules propagate to receivers in a controlled manner. The receivers, upon receiving the molecules, decode the encoded information and react biochemically. Molecular communication provides means to deliver information-encoded molecules to receivers and allows biological and artificially-created components to communicate with each other. This paper describes a design of a molecular communication system that may enable future health care applications.

1. Introduction

Molecular communication [1]-[2] is a new communication paradigm using molecules as a communication carrier. Figure 1 depicts an example molecular communication system. In this molecular communication system, senders encode information onto molecules (called information molecules). Information molecules are then loaded onto carrier molecules and directionally propagate to receivers. The information molecules are unloaded from the carrier molecules at the receivers. The receivers, upon receiving the information molecules, decode the information encoded onto the information molecules and react biochemically to the information molecules.

Molecular communication is inspired by the observation that in the biological systems, communication is typically done through molecules [3]-[5]. Using molecules as carrier of information has not yet been, however, explored in the existing research. The current research effort in nanotechnology and biotechnology focuses on observing and understanding biological systems (e.g., observing and understanding how communication is done within a cell or between cells). Molecular communication extends the current effort to include artificially creating communication systems based on communication mechanisms in the biological systems.

Molecular communication is a new communication paradigm, and as such, it requires research into a number of key areas. Key research challenges include 1) design of a sender that generates information molecules, encodes information onto the generated information molecules, and emits the encoded

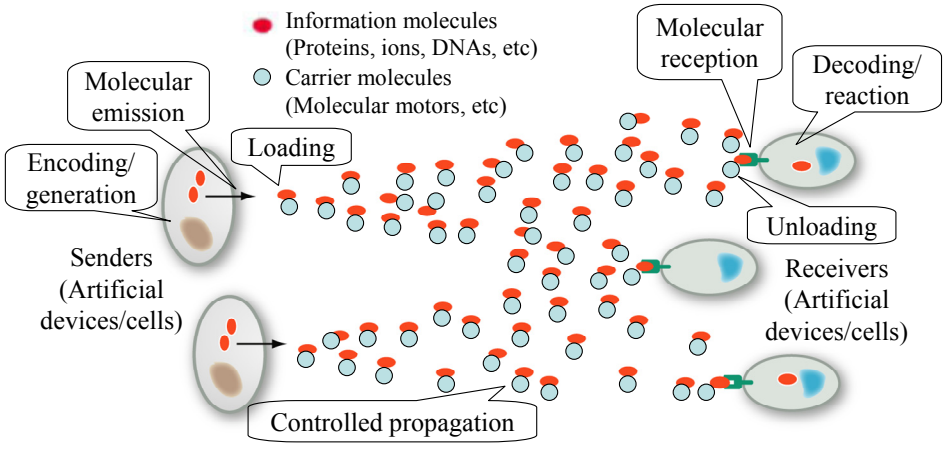

Figure 1. An example molecular communication system.

information molecules, 2) design of a receiver that receives information molecules, decodes the information encoded onto the received information molecules, and biochemically reacts to the received information molecules, 3) design of a molecular propagation system that loads information molecules onto carrier molecules, directionally transports the information molecules from senders to receivers, and unloads the information molecules from the carrier molecules, and 4) design of a molecular communication interface between senders and the propagation environment and also between the propagation environment and receivers to allow for a generic communication such that the molecular propagation system may transport the information molecules independent of their characteristics.

This paper describes detailed designs of system components of molecular communication. In the design of a sender and a receiver, genetically altered mutant eukaryotic cells are used to achieve sending/receiving functionalities. In the design of a molecular propagation system, biomolecular linear motor systems are used to achieve directional transport of information molecules, and DNA hybridization is used to load/unload the information molecules onto/from the carrier molecules [6]. In the design of a molecular communication interface, vesicles that wrap the information molecules are used to allow for a generic communication.

Molecular communication provides means to send, to transport, and to receive molecules and allows biological and artificially-created components such as sensors and reactors to communicate with each other using molecules. Molecular communication, therefore, has potentialities to enable future health care applications such as lab-on-a-chip [7], drug/DNA delivery systems [8], and monitoring of health conditions using implanted biochemical sensors.

The rest of this paper is organized in the following manner. Section 2 presents detailed designs of system components of molecular communication. Section 3 presents the current status of the research and future research plans. Section 4 describes future health care applications that molecular communication may support. Section 5 concludes the paper.

2. Designs of molecular communication system components

This section describes detailed designs of system components in molecular communication, namely, a sender, a receiver, a molecular propagation system, and a molecular communication interface.

2.1. Sender

A sender generates information molecules, encodes information onto the generated information molecules, and emits the encoded information molecules in a controlled manner. In the design, a genetically altered mutant eukaryotic cell is used. In the eukaryotic cells, ribosomes synthesize molecules such as proteins. The synthesized molecules are sorted and transported to cell membrane through endoplasmic reticulum (ER) and Golgi apparatus [9], and the sorted molecules are secreted by exocytosis. If information is encoded on the type of molecules or the concentration of molecules, the genetically altered mutant eukaryotic cell that changes the sorting and secreting molecules in response to the external stimuli such as temperature, light, and molecular injection may act as a sender. The authors of this paper believe that this approach is promising since the eukaryotic cells inherently have essential functionalities for the sender such as molecular generation and emission that may be difficult to create artificially.

2.2. Receiver

A receiver receives information molecules, decodes the information encoded onto the received information molecules, and reacts biochemically to the received information molecules. In the design, a genetically altered mutant cell is used same as the design of the sender. In eukaryotic cells, the cell surface receptors capture molecules. The captured molecules are taken inside the cell by the endocytosis, and biochemical reactions such as gene expression, altered morphology, and cell movement are occurred in response to the type of captured molecules. If decoding of the information encoded onto the information molecules is based on the types of biochemical reactions that occur at a receiver, the genetically altered mutant eukaryotic cell that have chimera receptors [10] that enable to alter the corresponding reactions of the captured molecules may act as a receiver. The authors of this paper believe that this approach is also promising since the eukaryotic cells inherently have essential functionalities for the receiver such as molecular reception and biochemical reactions that may be difficult to create artificially.

2.3. Molecular propagation system [6]

A molecular propagation system transports information molecules directionally from senders to receivers and loads (at senders) and unloads (at

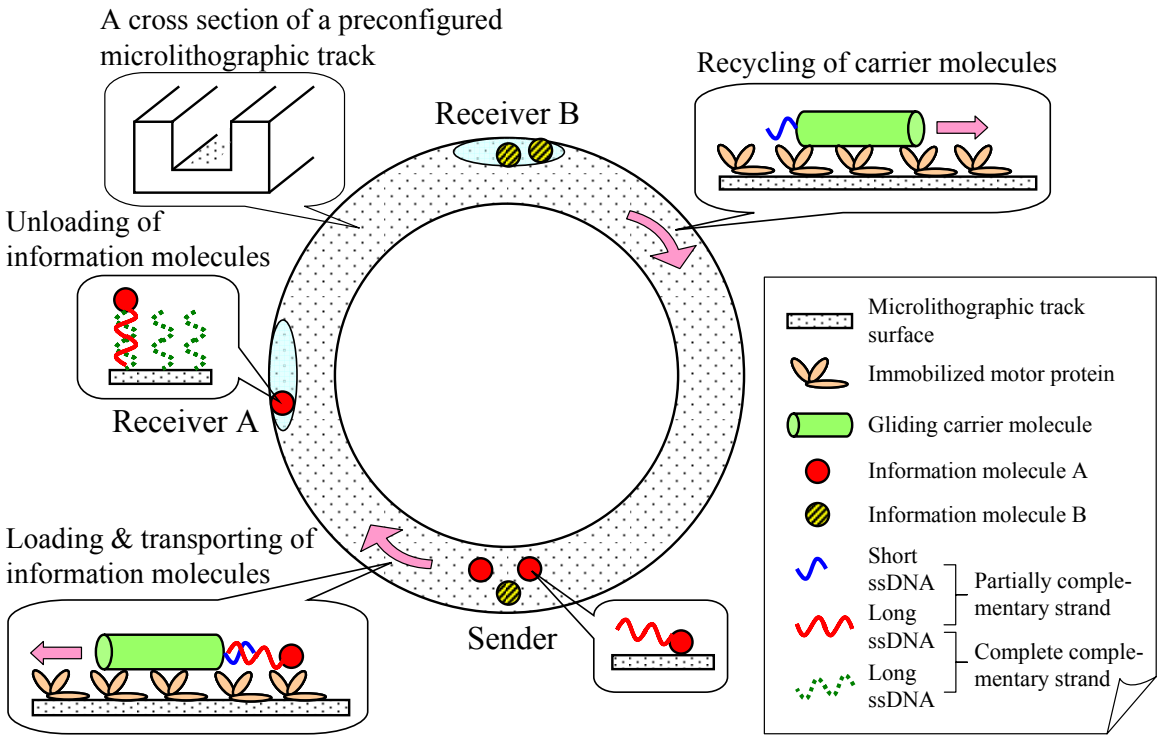

Figure 2. A schematic diagram of a molecular propagation system.

receivers) information molecules onto and from carrier molecules. In the design, biomolecular linear motor systems that protein filaments (carrier molecules) glide over immobilized motor proteins along microlithographic tracks [11] is used to transport information molecules directionally, and DNA hybridization is used to load and unload information molecules onto and from the carrier molecules.

Figure 2 shows a schematic diagram of a molecular propagation system. Short single stranded DNAs (ssDNAs)-linked carrier molecules continuously glide directionally over motor proteins adsorbed to a microlithographic track surface. Information molecules at a sender are coated with long ssDNAs. Parts of the base sequences (i.e., sequences of four bases used in DNA: adenine (A), cytosine (C), guanine (G), and thymine (T)) of the long ssDNA attached to the information molecules are complementary to those of the short ssDNA attached to the carrier molecules. When short-ssDNA-linked carrier molecules pass by a sender, long-ssDNA-coated information molecules are loaded onto the gliding carrier molecules due to DNA hybridization between short ssDNAs attached to the carrier molecules and long ssDNAs coated with the information molecules. The carrier molecule-information molecule conjugates, then, directionally glide towards a receiver over immobilized motor proteins adsorbed to a microlithographic track surface. At a receiver, an array of long ssDNAs is immobilized onto the microlithographic track surface. The base sequences of the long ssDNAs at a receiver are complementary in their entirety to those of the long ssDNAs coated with the information molecules. When the carrier molecule-information molecule conjugate pass by its destination receiver (e.g., receiver A in case of transporting information molecule A), information molecules are unloaded from the gliding carrier molecules because partial DNA hybridization (between short ssDNAs attached to the carrier molecules and long ssDNAs coated with the information molecules) is replaced with complete DNA hybridization (between long ssDNAs immobilized onto the track surface of its destination receiver and long ssDNAs coated with the information molecules). Note that short-ssDNA-linked carrier molecules which unloaded information molecules continue to glide over immobilized motor proteins along the microlithographic track and may load new information molecules at a sender.

These successive loading/transporting/unloading of information molecules and recycling use of carrier molecules can be achieved without requiring external control and electrical/mechanical energy sources.

2.4. Molecular communication interface

A molecular communication interface between senders and the propagation environment and also between the propagation system and receivers allow for a generic architecture such that the molecular propagation system may transport the information molecules independent of their characteristics. In the design, vesicles are used to wrap the information molecules and conceal their characteristics so that the propagation system is designed to transport vesicles independent of the characteristics of information molecules contained in the vesicles. This enables transport of diverse types of information molecules.

Figure 3 shows a molecular communication mechanism using vesicles. A sender infuses information molecules into vesicles on its surface and, then, detaches and emits the vesicles in response to an external stimulus. A molecular propagation system then transports vesicles to a receiver. Upon receiving vesicles, a receiver extracts the information molecules from the vesicles. The vesicles received by a receiver are recycled and sent back to the sender. This molecular communication interface is compatible with the molecular propagation system described in section 2.3 and may use DNAs attached on the vesicle surface to load and unload vesicles at a sender and a receiver [12].

The molecular communication interface using vesicles conceals different biochemical characteristics of diverse types of information molecules from the molecular propagation system. Moreover, the interface protects information molecules from the noise that may exist in the propagation environment (e.g., denaturation caused by interaction between information molecules and their propagation environment; changes in pH, and interaction with other molecules like enzyme in the propagation environment).

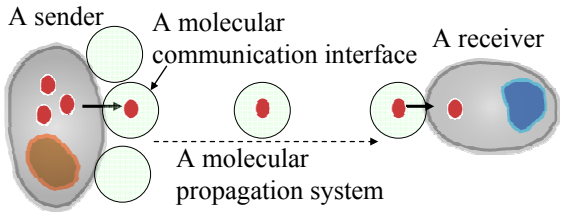

Figure 3. A molecular communication mechanism using vesicles.

3. Current status and future research plans

The authors of this paper are currently conducting biochemical experiments and empirically examining the design of a molecular propagation system described in section 2.3. The experiments use kinesin-driven microtubules (as carrier molecules), microbeads (as information molecules), and oligonucleotides (as short and long ssDNAs). Through the biochemical experiments, the chemical linkage for bonding the oligonucleotides to microtubules was determined. In the next phase of the experiments, the authors plan to examine loading and transporting of oligonucleotides-linked microbeads.

In addition, the authors of this paper are continuously examining the system designs of a sender, a receiver and a molecular communication interface to investigate the feasibility and to narrow down design choices. Especially, they are examining a design of a molecular communication interface that infuses/extracts information molecules into/from vesicles. The authors plan to empirically examine the design of each system component in the next step.

The authors of this paper also investigate an alternative design of a molecular propagation system presented in section 2.3. The molecular propagation system described in section 2.3 needs an artificially preconfigured infrastructure such as motor proteins adsorbed microlithographic tracks. Such infrastructure may not readily available in some molecular propagation environments (e.g., inside a human body). The authors of this paper, thus, are currently designing a diffusion-based molecular propagation system using signal molecules and their transduction pathways that inherently exist in a human body. For example, hormones/neurotransmitters and endocrine/neuroendocrine pathways may be used as carrier molecules and their propagation environments, respectively.

4. Future health care applications

Molecular communication may potentially enable new applications in the health care areas as well as information processing and communication areas. Examples of future health care applications that molecular communication may enable are described below.

4.1. Lab-on-a-chip

Lab-on-a-chip [7] is an emerging technology that integrates the biochemical analysis and synthesis operations such as cell analysis and blood diagnosis on a small chip. In a present lab-on-a-chip technology, microfluidics powered by a syringe is used as a transporting mechanism of molecular samples and reagents. The authors of this paper believe that the molecular propagation system described in section 2.3 may extend and enhance the existing molecular transporting systems by providing new means to deliver the single molecular sample and reagent between operational components such as biochemical sensors and reactors.

4.2. Drug/DNA delivery system

Drug/DNA delivery system has been receiving attention as a new method of medical treatment which alleviates undesired side effects [8]. Molecular communication may provide a mechanism to deliver drugs in a manner that is friendly to the biological systems. For instance, senders may be embedded in a human body and emit drug or DNA. Carrier molecules such as hormones may deliver emitted drugs or DNAs to target receiver cells through the endocrine pathways.

4.3. Monitoring of health conditions

Molecular communication allows biological and artificially-created sensors to communicate with each other using molecules. Biochemical sensors capable of detecting specific types of molecules (e.g., viruses and allergens) may be implanted in a human body. Such sensors may communicate and cooperate to perform complex tasks such as physical health checkups and artificially controlled immunoreactions.

5. Conclusions

This paper describes detailed designs of system components in molecular communication that include a sender, a receiver, a molecular propagation system, and a molecular communication interface. This paper also describes possible applications of molecular communication to future health care.

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