Molecular Communication among Nanomachines Using Vesicles

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ABSTRACT

Molecular communication is a new communication paradigm. It uses molecules as a communication medium and allows nanomachines to communicate over a short distance. This paper describes a design of a molecular communication system using vesicles. In the design, vesicles encapsulate molecules and act as a communication interface between senders and a propagation system and also between the propagation system and receivers. This vesicle-based interface enables use of diverse types of molecules in molecular communication since vesicles encapsulate molecules, and provide uniform interface to the propagation system. The authors of this paper are currently preparing for conducting biochemical experiments to investigate the feasibility of the molecular communication system design using vesicles.

Keywords: molecular communication, nanomachine communication, vesicle, communication interface, information/carrier molecules

1 INTRODUCTION

Molecular communication [1]-[2] is a new communication paradigm. It does not use electromagnetic wave but uses molecules as a communication medium. Communication using molecules is common in biological systems [3]-[4], though it has not been generalized to controllable communication. 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 effort and creates a communication system artificially, based on the communication mechanisms in the biological systems.

In molecular communication, senders encode information onto molecules (called information molecules) and emit the information molecules. Information molecules are then loaded onto carrier molecules that transport information molecules to receivers. The receivers, upon receiving the information molecules, decode the information and react biochemically to the information molecules. Molecular communication provides means for biological and artificially-created nanomachines [5] to communicate over a short distance (e.g., from nano/micro meters to a few meters).

Molecular communication is a new communication paradigm, and as such, it requires research into key system components (i.e., a sender, a receiver, and a propagation system), as well as a communication interface between key system components (i.e., a communication interface between senders and a propagation system and also between the propagation system and receivers).

This paper focuses on a communication interface between key system components and describes a design of a communication interface that uses vesicles. In the design, vesicles encapsulate information molecules emitted from the senders, are transported (with the information molecules inside) to receivers by a propagation system, and secrete the information molecules into the receivers. This vesicle-based communication interface enables use of diverse types of information molecules in molecular communication since vesicles encapsulate information molecules, and provide uniform interface to the propagation system.

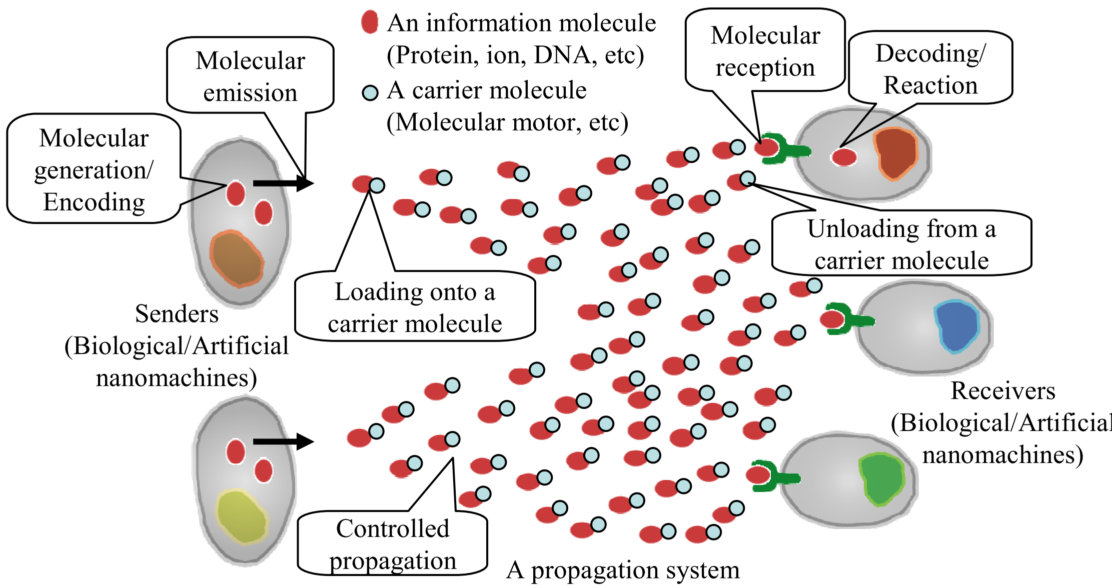
The rest of this paper is organized in the following manner. Section 2 presents an overview of molecular communication system. Section 3 describes a design of a communication interface using vesicles, and discusses key research issues and possible approaches to the design of the interface. Section 4 concludes the paper.

2 AN OVERVIEW OF A MOLECULAR COMMUNICATION SYSTEM

This section presents key system components of molecular communication system and mentions the need for a communication interface.

Figure 1 depicts an example molecular communication system. Key components of a molecular communication system include a sender, a receiver, and a propagation system. A sender generates information molecules, encodes information onto the generated information molecules, and emits the encoded information molecules into an environment. In a propagation system, emitted information molecules are loaded onto carrier molecules that directionally transport the information molecules to an appropriate receiver, and the information molecules are unloaded from the carrier molecules at a receiver. Upon receiving the information molecules, a receiver decodes the information encoded onto the information molecules, and reacts biochemically to the information molecules.

A promising approach to create a sender is to genetically modify eukaryotic cells to perform encoding functionality. This approach is promising because



Short distance (from nano/micro meters to a few meters) communication

Figure 1: An example molecular communication system.

eukaryotic cells inherently generate and emit molecules. In the molecular communication system where information is encoded on the type of molecules (i.e., where different pieces of information is encoded on different types of molecules), the genetically modified eukaryotic cells that control the type of molecules to emit (in response to the external stimuli such as temperature, light, and molecular injection) may act as senders.

Eukaryotic cells inherently receive molecules and react biochemically to the received molecules. In addition, eukaryotic cells may show different reactions to different types of received molecules. These (i.e., being able to receive molecules and reacting differently to different types of incoming molecules) are key functionalities required for a receiver, and the eukaryotic cells, therefore, may act as receivers without requiring any modification.

One approach to create a propagation system is to use biomolecular linear motor systems to achieve directional transport of information molecules, and to use DNA hybridization to load/unload the information molecules onto/from carrier molecules [6]. Figure 2 shows an overview of a propagation system based on this approach. In this approach, an information molecule attached long single stranded DNAs (ssDNAs) is loaded onto a protein filament (carrier molecule) attached short ssDNAs due to partial DNA hybridization at a sender. Note that parts of the base sequences of long ssDNAs attached to the information molecule are complementary to those of short ssDNAs attached to the carrier molecule. The carrier molecule-information molecule conjugate, then, directionally glides towards a receiver over motor proteins adsorbed to a micro lithographic track surface. The base sequences of the long ssDNAs immobilized at a receiver are complementary in entirety to those of the long ssDNAs attached to the information molecule. The information molecule is, upon arriving at a receiver, unloaded from the carrier molecule because partial DNA hybridization is replaced with complete DNA hybridization.

In order for key components of a molecular communication system to function as a system, an additional effort is required to ensure compatibility between the key system components and to integrate them as a generic communication system. For example, in the designs described in this section, a sender and a propagation system are not compatible because long ssDNAs are not attached to information molecules emitted from the sender. The propagation system and a receiver are not compatible because long ssDNAs attached to the information molecules may interfere with biochemical reactions at a receiver. Furthermore, information molecules may be denatured by the noise in the propagation environment. Thus, it is necessary to design a communication interface between senders and a propagation system and also between the propagation system and receivers.

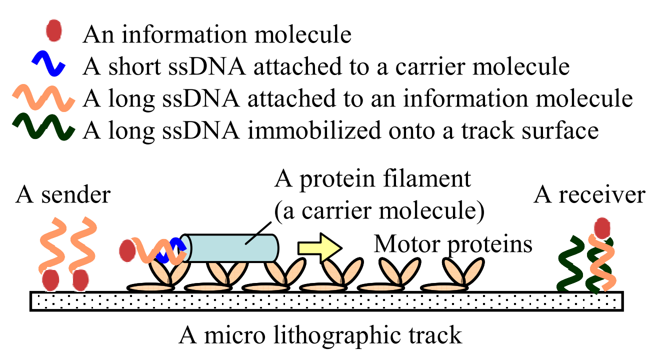


Figure 2: An overview of a propagation system.

3 A COMMUNICATION INTERFACE USING VESICLES

This section describes a design of a communication interface using vesicles, and discusses key research issues in designing the interface.

3.1 Interface Design

In the design of a communication interface, vesicles that encapsulate information molecules are used to achieve compatibility between key system components and protect information molecules from denaturalization in the propagation environment.

Figure 3 shows a molecular communication system using a vesicle-based interface. In this system, long ssDNAs are attached to a vesicle [7] to maintain compatibility with the propagation system described in section 2. At a sender, a vesicle encapsulates information molecules, and is transported (with the information molecules inside) to a receiver by the propagation system. At a receiver, the information molecules are extracted from the vesicle and secreted into the receiver.

With the vesicle-based communication interface in Figure 3, Long ssDNAs are attached to vesicles that encapsulate information molecules, not directly to information molecules. Thus, once information molecules are secreted into a receiver, long ssDNAs will not interfere with the biochemical reactions. With the vesicle-based communication interface in Figure 3, it is also possible to use of diverse types of molecules as information molecules, since vesicles conceal different biochemical characteristics of encapsulated information molecules from the propagation system and provides a uniform interface to the propagation system. In addition, vesicles protect encapsulated information molecules from denaturalization by the noise in the propagation environment.

3.2 Key Research Issues and Possible Approaches to the Design

The vesicle-based communication interface described in section 3.1 increases compatibility among key components in a molecular communication system. Key research issues in designing such a vesicle-based communication interface include how vesicles encapsulate information molecules at a sender, and how the information molecules are extracted from the vesicles at a receiver.

Vesicles may encapsulate information molecules at a sender either through fission [8], reproduction [9], or pore formation [10] of vesicles (See Figure 4). With fission of vesicles (in Figure 4 (a)), A small vesicle is budded from a sender when an external stimulus is applied (e.g., when lysophosphatidylcholine solution is injected near the sender). When this budding occurs, information molecules inside a sender may be incorporated in the small budding vesicle, and long ssDNAs attached to the surface of the sender may also be attached to the surface of the small budding vesicle.

With reproduction of reproduction of vesicles (in Figure 4 (b)), a small vesicle is created inside a sender and extruded from the sender into the environment when an external stimulus is applied (e.g., when micellar solution is injected into the sender). Information molecules inside a sender may be incorporated in the small vesicle, and long ssDNAs inside a sender may be incorporated onto the surface of the small vesicle, during the processes of vesicle reproduction within a sender.

With pore formation of vesicles (in Figure 4 (c)), pores are formed on the surface of a long ssDNAs attached small vesicle prepared near the sender in advance when an external stimulus is applied (e.g., when antimicrobial peptide solution is injected near the small vesicle). Information molecules emitted from the sender may free-diffuse and enter the vesicle.

Information molecules may be extracted from vesicles and secreted into a receiver either through fusion [11] or pore formation of vesicles (See Figure 5). With fusion of vesicles (in Figure 5 (a)), restriction enzymes attached to the terminal end of long ssDNAs attached to a receiver separate a received vesicle from a receiver when complete DNA hybridization occurs between long ssDNAs attached to the received vesicle and long ssDNAs attached to the receiver. The vesicle is then fused with the receiver when

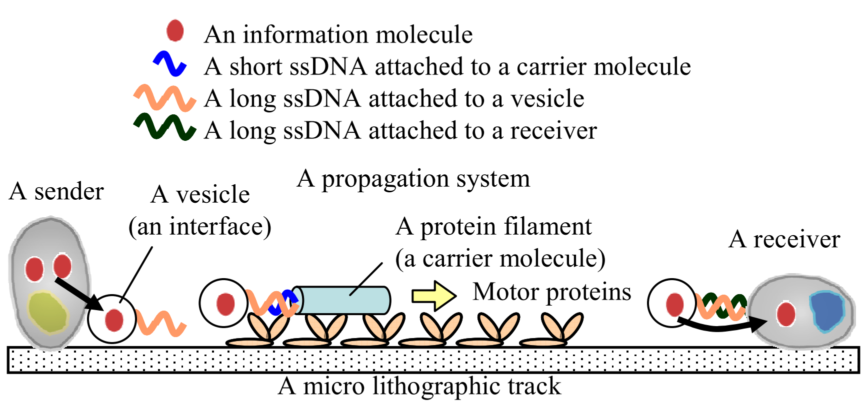


Figure 3: A molecular communication system using a vesicle-based interface.

an external stimulus is applied (e.g., when La^{3+} solution is injected near the receiver). Information molecules may be secreted into the receiver during the processes of vesicle fusion.

With pore formation of vesicles (in Figure 5 (b)), the received vesicle forms pores by antimicrobial peptides attached to the terminal end of long ssDNAs attached to a receiver, and information molecules are extracted from the received vesicle through the pores when complete DNA hybridization occurs between long ssDNAs attached to the received vesicle and long ssDNAs attached to the receiver. The information molecules extracted from the vesicle may be secreted into the receiver by endocytosis.

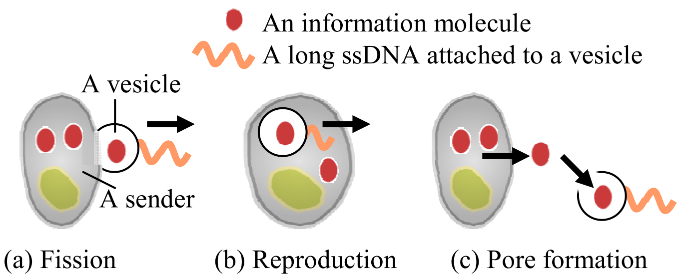


Figure 4: Encapsulating information molecules into a vesicle.

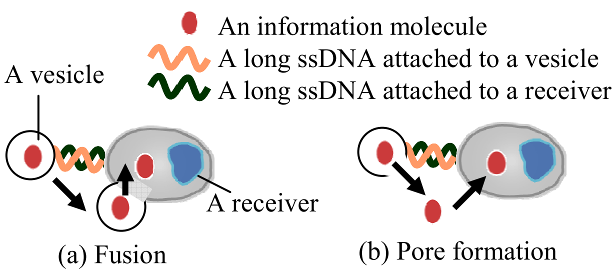


Figure 5: Extracting information molecules from a vesicle and secreting them into a receiver.

4 CONCLUSIONS

This paper describes a vesicle-based interface in a molecular communication system. In the design, vesicles encapsulate information molecules and act as a communication interface ensuring compatibility between senders and a propagation system and also between the propagation system and receivers. This communication interface enables use of diverse types of information molecules in molecular communication since vesicular encapsulation conceals different biochemical characteristics of information molecules from the propagation system and provides uniform interface to the propagation system. In addition, vesicles protect the encapsulated information molecules from denaturalization by the noise in the propagation environment.

The authors of this paper are currently preparing for conducting biochemical experiments to empirically investigate the feasibility of the design of the vesicle-based interface described in this paper.

In addition, vesicular encapsulation may enable encoding of information on the concentration level of information molecules in a vesicle. This is because a vesicle maintains the concentration level of information molecules during the propagation (without leaking the information molecules). This concentration level based encoding may allow a larger amount of information to be encoded than that encodes information on to the type of information molecules. The authors plans to investigate such encoding mechanisms.

REFERENCES

[1] S. Hiyama, et al., "Molecular Communication," NSTI Nanotechnology Conference and Trade Show, vol.3, pp.392-395, May, 2005.
[2] T. Suda, et al., "Exploratory Research in Molecular Communication between Nanomachines," UCI Technical Report, 05-3, Mar. 2005.
[3] B. Alberts, et al., "Essential Cell Biology – An Introduction to the Molecular Biology of the Cell," Garland Publishing, 1998.
[4] H. Lodish, et al., "Molecular Cell Biology (Fourth Edition)," W. H. Freeman and Company, 2000.
[5] G. M. Whitesides, "The Once and Future Nano-machines," Scientific American, Sep. 2001.
[6] S. Hiyama, et al., "A Design of an Autonomous Molecule Loading/Transporting/Unloading System Using DNA Hybridization and Biomolecular Linear Motors," European Nano Systems, pp.75-80, Dec. 2005.
[7] C. Y. Ishii, et al., "Arrays of Mobile Tethered Vesicles on Supported Lipid Bilayers," Journal of the American Chemical Society, vol.125, pp.3696-3697, 2003.
[8] T. Tanaka, et al., "Shape Changes and Vesicle Fission of Giant Unilamellar Vesicles of Lipid-Ordered Phase Membrane Induced by Lysophosphatidylcholine," Langmuir, vol.20, pp.9526-9534, 2004.
[9] K. Takakura, et al., "A Novel System of Self-Reproducing Giant Vesicles," Journal of the American Chemical Society, vol.125, pp.8134-8140, 2003.
[10] Y. Tamba, et al., "Single Giant Unilamellar Vesicle Method Reveals Effect of Antimicrobial Peptide Magainin 2 on Membrane Permeability," Biochemistry, vol.44, pp.15823-15833, 2005.
[11] T. Tanaka, et al., "Membrane Fusion of Giant Unilamellar Vesicles of Neutral Phospholipid Membranes Induced by La^{3+}," Langmuir, vol.20, pp.5160-5164, 2004.