A molecular communication system using a network of cytoskeletal filaments.

Akihiro Enomoto [*], Michael Moore [*], Tadashi Nakano [*], Ryota Egashira [*] ,Tatsuya Suda [*]
Atsushi Kayasuga [**], Hiroaki Kojima [**], Hitoshi Sakakibara [**] and Kazuhiro Oiwa [**].

[*]*Information and Computer Science, University of California, Irvine, CA,USA*
[*]*{enomoto, mikemo, tnakano, egashira, suda}@ics.uci.edu*
[**]*National Institute of Information and Communications Technology (NICT),Kobe, Japan*
[**]*{kayasuga, kojima, sakaki, oiwa}@nict.go.jp*

ABSTRACT

We have proposed Molecular Communication [1][2], a solution for nano-scale communication between nanomachines (e.g., biological molecules, artificial devices). Molecular communication provides a mechanism for one nanomachine to encode or decode information into molecules (information molecules) and to send the information molecules to another nanomachine. Using molecular communication to control communication between nanomachines is inspired by the observation of biological systems which already commonly communicate through molecules. This paper describes the design of a molecular communication system that uses molecular motors and rail molecules (such as microtubules) as a basis for the high-level architecture of molecular communication.

Keywords: Molecular communication, molecular motor, design, information

1 INTRODUCTION

Communication is the process of exchanging information. Information has been encoded on various media (e.g, letter, Moore's signal, telephone, computer internet). After invention of the telegraph, information could be transmitted much faster than any other form of transportation. Nowadays, information has been exchanged in the form of e-mail, internet, cellular phone, etc. Those communication systems have become indispensable for our daily life. However, is there any other form of communication? Looking at our body in nano-scale, there are a huge number of molecules, and biological cells are exchanging their information by using these molecules. Communication exists even in such a nano-scale world. Focusing on nano-scale communication, we have proposed Molecular Communication, a new and interdisciplinary research area that spans over the nanotechnology, biotechnology, and communication technology.

Molecular communication allows nanomachines (e.g., biological molecules, artificial devices) to communicate through the transport of molecules. Nanomachines represent small devices or components that perform computation [3], sensing[4], or actuation. Although there are no manmade nanomachines to perform tasks that impact our daily life, non man-made nanomachines already exist in the form of biological cells and the chemical processes within those cells. For example, molecular motors, such as kinesin, perform mechanical work, serving as an actuator and an active carrier of information [5]. Current biotechnology and nanotechnology have advanced to the point where engineering of nano-scale biological systems is feasible, as demonstrated through modification of DNA to produce new cell functionality. As biology and nanotechnology grow, nanomachines will be created to provide more functionality and to interact with biological systems and other artificial nano-scale applications. To extend nanomachines to perform more complex tasks and increase the impact on technology, nanomachines should cooperate and communicate with each other. Thus, we are developing information and communication technology at the nano-scale and using the available biological molecules.

With current microscopic technology, such as lithography, it is hard to achieve nano-scale level control. On the other hand, molecular communication can be designed to use biological molecules which, in biological systems, have already achieved nano-scale techniques. Because of the size of nanomachines, it is especially difficult to control individual nanomachines. Individual nanomachines can be designed to affect and react to specific molecules, and thus molecular communication is a reasonable approach for communication between nanomachines even in nano-scale (or at least micro-scale.) Also, bottom-up self assembly techniques based on biological systems may help to control and coordinate many nanomachines.

In addition to its scale, since molecular communication is based on biological systems, molecular communication may more easily take on biological features, such as being biocompatible, probabilistic, energy efficient, and parallel. Also, in molecular communication, molecules represent information through chemical structure, sequence information, relative positioning, or concentration (e.g. protein, DNA, calcium propagation). Molecular information thus provides different methods for manipulating and interacting with information since operations performed are also non-binary and information can directly react to other information. Such features provide us different flavor and give us a paradigm shift in communication.

2 MOLECULAR COMMUNICATION IN BIOLOGICAL SYSTEMS

Natural biological systems have already accomplished molecular communication. Biological nanomachines in a biological system continuously exchange information using molecules at the nano or micron scale in a wide variety of mechanisms. Some specific biological mechanisms include intracellular transport and intercellular communication. These mechanisms provide a basis for developing molecular communication. This paper focuses on applying molecular motor transport (an intracellular communication mechanism) to perform molecular communication, and thus the observations are of molecular motors.

A molecular motor is a protein complex that transforms chemical energy (e.g., ATP hydrolysis) into movement at the molecular scale with high efficiency. In intracellular transport, communication within a biological cell is performed using molecules that are carried by molecular motors. Eukaryotic cells use molecular motors (e.g., kinesin and dynein) to transport large molecules (e.g. vesicle, mitochondria, mRNA) that do not diffuse well and and to transport other large cell structures such as organelles and vesicles.

Molecular motors have a unique characteristic of movement along a cytoskeleton in a directed manner. For example, molecular motors bind and transport vesicles of acetylcholine along the axon of a neuron. In contrast to other communication mechanisms, molecular motors move in the direction corresponding to the cytoskeletal track rather than the random Brownian motion of diffusion.

The cytoskeletal track is most often composed of microtubules or actin filaments and is organized by a cell for various functionalities, e.g. cell division. Molecular motors can also control the directionality of transport by occurring in different ratios such as having more active kinesin that results in moving towards the plus end of a microtubule or more active dynein that results in moving towards the minus end of a microtubule.

There also exist a variety of proteins and processes that help construct these networks. γ-tubulin provides a starting point for growing microtubule filaments and MAPs (microtubule accessory proteins) help to stabilize and arrange multiple microtubules to form single cell-scale networks with a variety of functionalities (e.g. transport of molecules between the ER and Golgi, structural support of cells, adjusting of the cell shape in muscles, or dividing or a cell membrane during mitosis.)

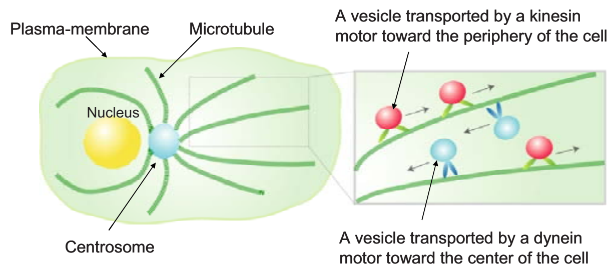

Figure 1. Intracellular communication (vesicles transported by molecular motors)

3 MOLECULAR COMMUNICATION USING MOLECULAR MOTOR

As described in the section 2, molecular communication using molecular motors is observed within a biological cell. To develop an ‘engineered‘ molecule communication system, we need to identify processes and components necessary for molecular communication. In this section, we decompose molecular communication into system components (sender and receiver) and processes (encoding, sending, propagating, receiving and decoding) and propose our design of molecular communication system using molecular motors.

Molecular motors (e.g. kinesin, dynein) transport materials in eukaryotic cells along filaments called rail molecules (e.g. microtubules). To develop a molecular communication system, the system of molecular motors is used for controlled nanomachine communication (Figure 1 right). In this system, rail molecules (microtubules) are deployed between nanomachines, and molecular motors (kinesin) carry vesicles containing information molecules along the rail molecules from sender nanomachines to receiver nanomachines.

3.1. Assumptions about the environment

The environment is assumed to have adequate numbers of molecules available to provide necessary communication components (e.g. rail molecules, molecular motors, information molecules) and be operated under appropriate aqueous condition for those biological proteins. Nanomachines are deployed in some application dependent manner, and the molecular motor communication system is self-organized in an application independent manner. In our design, each nanomachine is assumed to function as both sender and receiver. The molecular communication process is activated in response to an assumed information source that is externally controlled (e.g. a sensor molecule becomes activated cascading into a molecular communication process).

3.2. Components

In our design, the sender nanomachine, receiver nanomachine and rail molecules are considered as system components. The sender and receiver are however unspecified here but must be capable of synthesizing (encoding), sending, receiving and interpreting (decoding) of information molecules (e.g. a sender/receiver may be a biological cell that releases vesicles or a molecule that is released when an input condition occurs). Information molecules must be capable of binding to and releasing from a molecular motor or its cargo which acts as the carrier molecule for transporting the information molecules. The environment contains rail molecules that guide the propagation of molecular motors and provides the necessary molecules (e.g. ATP) necessary to perform transport.

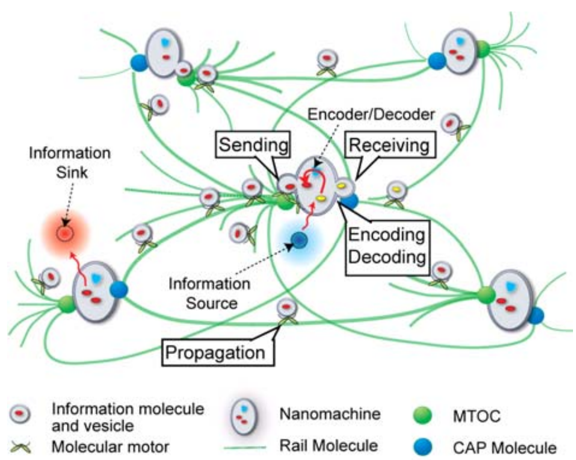

Figure 2. Molecular Communication Using Molecular Motors

3.3. Rail molecule topology

Since molecular motors move along rail molecules, the form of the rail molecule topology determines the direction molecular motors will move among the nanomachines. In biological systems, the microtubule (one type of rail molecule) forms a topology that occurs within the confined volume of a biological cell and often exists in star-like and random mesh forms.

A star-like topology is centered at some location within the cell (e.g. a centrosome). A star topology may provide a mechanism for distributing molecules away from a single point to far away points (e.g. broadcasting molecules from a single source) or to gather molecules to a location within the cell (e.g. gathering molecules for analysis by a nanomachine).

A random mesh topology represents a distribution of microtubules that covers some volume. A mesh may provide a mechanism for evenly distributing molecules through random movement across the topology. Topologies should be adjusted to suit the specific communication needs of an application.

3.4. Communication processes

Conventional communication consists of five communication processes (encoding, sending, propagating, receiving, decoding). Similarly, molecular communication between nanomachines involves the following five processes

Encoding: Sender nanomachines encode information on information molecules (e.g., DNA, proteins, peptides). For example, nanomachines encode information on sequences of peptides and inject the peptides into vesicles. Vesicles can be loaded on molecular motors, and thus a variety of encoded molecules can be sent.

Sending: Sender nanomachines then emit the information molecules encapsulated in a vesicle to molecular motors that move along rail molecules. Information molecules are then attached to and loaded on molecular motors.

Propagation: Propagation is performed through molecular motors that move along rail molecules from sender nanomachines to receiver nanomachines in a directed manner.

Receiving: Receiver nanomachines are assumed to retrieve carrier molecules from molecular motors using protein tags. When molecular motors approach receiver nanomachines, carrier molecules such as vesicles may be fused into receiver nanomachines.

Decoding: In decoding, receiver nanomachines invoke reactions in response to information molecules. For example, peptides (e.g. neurotransmitters) transported through molecular motors in a neuron cause receiver neurons to generate an action potential.

4 CONCLUSION

In this paper, we have described a definition of molecular communication and its characteristics, and have also described initial designs for a molecular communication system that uses molecular motors to perform communication.

We are currently designing various molecular communication mechanisms. Current work on the molecular motor communication system described in this paper focuses on propagation aspects. Propagation by molecular motors is a significant factor when determining which molecular communication system to apply. We are currently investigating through experiments propagation of molecular motors and methods for forming a network of rail molecules in a self-organizing manner.

ACKNOWLEDGEMENT

This research is supported by the NICT (the National Institute of Communication Technology, Japan), by the NSF through grants ANI-0083074, ANI-9903427 and ANI-0508506, by DARPA through grant MDA972-99-1-0007, by AFOSR through grant MURI F49620-00-1-0330, and by grants from the California MICRO and CoRe programs, Hitachi, Hitachi America, Hitachi CRL, Hitachi SDL, DENSO IT Laboratory, DENSO International America LA Laboratories, NTT Docomo and Novell.

REFERENCES

[1] T. Suda, A. Enomoto, R. Egashira, T. Nakano, M. Moore, S. Hiyama, and Y. Moritani, "Exploratory Research on Molecular Based Nano Scale Communication," IEEE INFOCOM 2005, 2005.

[2] T. Nakano, T. Suda, M. Moore, R. Egashira, A. Enomoto, and K. Arima, "Molecular Communication for Nanomachines Using Intercellular Calcium Signaling," IEEE NANO 2005 , 2005.

[3] K. Sakamoto, H. Gouzu, K. Komiya, D. Kiga, S. Yokoyama, T. Yokomori, and M. Hagiya, "Molecular Computation by DNA Hairpin Formation," Science, 288 (2469), pp. 1223-26, 2000.

[4] Gorecki, J. N. Gorecka, K. Yoshikawa, Y. Igarashi, and H. Nagahara, "Sensing the distance to a source of periodic oscillations in a nonlinear chemical medium with the output information coded in frequency of excitation pulses," Phys. Rev. E, 72046201, 2005.

[5] M. Schliwa, and G. Woehlke, "Molecular Motors," Nature, 422, pp. 759, 2003.