Design of a Molecular Communication Framework for Nanomachines

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I. Introduction

Nanomachines are tiny devices constructed out of molecular components, able to perform simple computation, sensing and actuation tasks. Despite their small size, nanomachines have far-reaching applications such as targeted drug delivery within organisms, forced degradation of unwanted materials from food items, bio-detection of items, etc [1].

In our work, we assume that nanomachines will be capable of certain basic functions: communication primitives such as creating and recognizing calcium wave signals, sensing and actuation primitives such as the detection of specific cells and a controlled release of chemicals, movement primitives to follow molecule trails, and computation and memory primitives [1], [2].

Under these assumptions, we propose a middleware framework for nanomachines that allows application developers to design different classes of nanomachines for specific tasks, and provides a rich set of group communication primitives so that the nanomachines can coordinate with each other to accomplish these tasks. We model groups of nanomachines, called quorums, as a first-class entity in our middleware so that quorums can be addressed as a unit and instructed to perform certain tasks without requiring the application developer to take care of error-control and coordination details. Similar to traditional networks, we choose to use a layered approach for the middleware design. A (physical) Hardware Abstraction Layer (HAL) includes communication, sensing/actuation, and movement primitives implemented as biological processes. A (link, network, transport) Middleware Implementation Layer (MIL) uses the HAL primitives to provide implementations for broadcast of messages within quorums, sensing of the environment, reliable communication between nanomachines, routing of information across quorums, etc. Finally, the application layer uses the MIL API to design application-specific nanomachines for handling different problems. Our vision is that application developers should be able to write nanonetworking applications without worrying about the lower-level biological details of communication.

We then begin to design algorithms to implement the middleware methods in the face of noisy biological conditions, under different communication and computation scenarios. We take a first step in this direction by studying calcium signalling for intra-quorum broadcast. We have designed our own simulator for this purpose, and present initial results from our simulations.

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II. Related work

Related work has focused on individual aspects of communication. like an encoding, decoding, and error correction scheme for messages sent through molecular motors [3], mathematical models for communication via molecular motors to illustrate latencies and information rates [4], [5], and analysis of molecular noise and information rate for diffusion based propagation [6]. Our work is complementary. We abstract these different modes of communication into a middleware framework, and build algorithms to implement the middleware group communication methods for coordination among nanomachines. The first piece of work we have done in this regard is to study calcium signalling for intra-quorum broadcast using the model proposed by [7].

The work which comes closest to ours is [8], although it is to be noted that the word *quorum* used in the two papers has different meanings – [8] refers to *quorum sensing* among bacterial cells to infer their concentration, while we use the term *quorum* to refer to a group of nanomachines that behaves in a coordinated manner.

III. Proposed Framework

The *hardware abstraction layer* implements communication, sensing, actuation, and movement primitives. All these primitives have either already been realized in practice or have been proposed in other related research works. Short distance communication can happen by encoding information on waves of calcium ions diffusing across gap junctions at cellular boundaries, or by sending encoded molecular messages enclosed in vesicles traveling along microtubules. Long distance communication is recommended through the diffusion of pheromones [1]. Sensing of chemicals can happen by detecting their concentration in the environment through diffusion, or by having corresponding receptor molecules on the nanomachine surface that trigger desired internal processes [2]. Actuation similarly implies a release of carrier molecules to carry out a required chemical reaction [2]. Finally, the movement of nanomachines has also been realized experimentally through inbuilt motors or propellers.

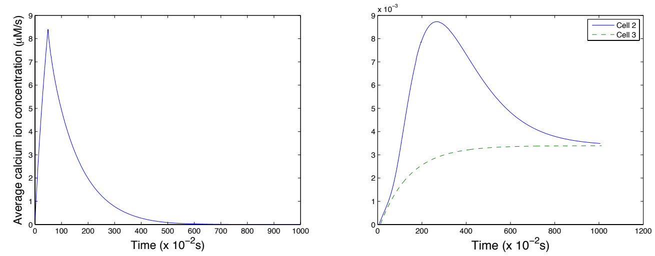
The *middleware implementation layer* of the architecture forms an abstraction of the various nanomachine capabilities and presents them as familiar programming interfaces to the application developer. We observe here that a single nanomachine cannot be overloaded with multiple features, but functionality for sensing, movement, etc must be distributed across different types of nanomachines that can communicate with each other to coordinate their tasks. A single nanomachine will also typically be incapable of producing any effect such as launching a significant amount of antibodies to disinfect a particular body part, and hence multiple nanomachines will have to operate in a coordinated manner. We therefore introduce the concept of *quorums* or groups of nanomachines, where the middleware takes care of intra-quorum communication to ensure smooth coordination among them. These quorums may consist of different types of nanomachines programmed to perform specific actions viz. sensing, actuation and routing. Our inspiration comes from bacterial communication [9]. The MIL API consists of methods callable at the level of a quorum and includes the the *SendMessage* method for sending messages between nanomachines, broadcasting messages to a specific class of nanomachines, routing messages across microtubules, etc; the *SenseEnvironment* method which initiates receptors present on the nanomachine to sense parameters like calcium concentration; and the *ReleasePayload* method which releases chemicals into the environment. Other methods are also provided such as moving a quorum and making links between quorums.

The *application layer* utilizes the middleware programming interface. For example, a targeted drug delivery application can be implemented by a middleware that realizes two types of nanomachines: *sensing nanomachines* that locate the target, and *actuation nanomachines* that carry the actual payload to be dropped off at the infected site. Both types of nanomachines can be clubbed into a quorum that moves as a unit; when sensing nanomachines detect a valid target, they launch a broadcast message within the group addressed to actuation nanomachines to release the drug. This kind of a targeted drug delivery application can be assisted by middleware functionality for intra-quorum coordination, reliable communication and quorum-level routing logic.

IV. Simulation of Intra-Quorum Broadcast

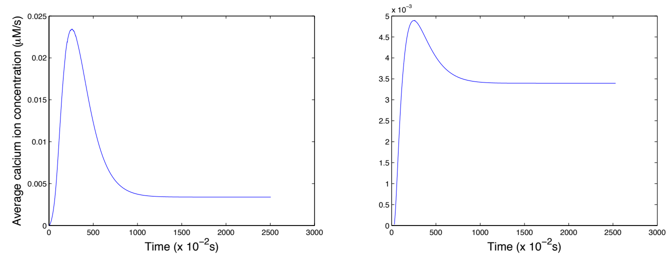
As a first step to implement the middleware methods, we designed a simulator to study algorithms for intra-quorum broadcast. We assume that quorums can either be distributed in the medium or organized into a fixed shape. Through simulations we study the feasibility of intra-quorum broadcast using calcium signaling within a fixed-shape quorum. We implemented our own simulator[1] as existing ones ([5], N3Sim, NanoNS) are based only on propagation via diffusion or molecular motors. For modeling intercellular calcium signaling we have used the Li-Rinzel model along with the Langevin extension given in [7]. Our simulations reveal that since a calcium wave propagates only 2 hops from the source (Fig. 1), we need to introduce signal repeaters in the quorum (Fig. 2). We also showed that a cuboidal structure for quorums is efficient in inferring the direction of the signal originator. This insight can be used to design efficient signal broadcast schemes by intelligently placing repeaters in the quorum.

[1]Code can be found on http://www.cse.iitd.ernet.in/∼cs1080168



(a) Sender (b) Subsequent Cells (2,3 hops)

Fig. 1: Ca^{2+} concentration for cells at different hops



(a) 2 hops from sender (b) 6 hops from sender

Fig. 2: Ca^{2+} concentration with repeaters

V. Future Work

We are currently investigating the design of encoding and MAC schemes for message broadcast within quorums by using calcium signaling. We are also enhancing our simulator for inter-quorum communication through pheromones and microtubule links; this will allow us to study problems regarding latency and reliability of inter-quorum message transfers.

References

[1] I. F. Akyildiz, F. Brunetti, and C. Blazquez, “Nanonetworks: A new communication paradigm,” *Computer Networks (Elsevier) Journal*, June 2008.

[2] T. Suda, M. Moore, T. Nakano, R. Egashira, and A. Enomoto, “Exploratory research on molecular communication between nanomachines,” *In Genetic and Evolutionary Computaion Conference, (GECCO ’05)*, 25-29 June 2005.

[3] F. Walsh, S. Balasubramaniam, D. Botvich, T. Suda, T. Nakano, S. F. Bush, and M. Foghlú, “Hybrid DNA and Enzymatic based Computation for Address Encoding, Link Switching and Error Correction in Molecular Communication,” in *Nano-Net ’08*, Sep. 2008.

[4] M. J. Moore, T. Suda, and K. Oiwa, “Molecular communication: Modeling noise effects on information rate,” *IEEE Trans Nanobioscience*, Jun, 2009.

[5] M. J. Moore, A. Enomoto, K. Oiwa, and T. Suda, “Molecular communication: Uni-cast communication on microtubule topology,” *Proc. of the IEEE International Conference on Systems, Man and Cybernetics*, 2008.

[6] S. Kadloor, R. S. Adve, and A. W. Eckford, “Molecular Communication Using Brownian Motion with Drift,” *ArXiv e-prints*, Jun. 2010.

[7] T. Nakano and J. Shuai, “Repeater design for modeling molecular communication networks,” *IEEE International Workshop on Molecular and Nano-Scale Communications*, 2011.

[8] S. Abadal and I. F. Akyildiz, “Automata modeling of quorum sensing for nanocommunication networks,” *Nano Communication Networks (Elsevier), Volume 2, Issue 1*, March, 2011.

[9] W.-L. Ng and B. L. Bassler, “Bacterial quorum-sensing network architectures.” *Annual Review of Genetics*, vol. 43, no. 1, pp. 197–222, 2009.