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Deterministic capacity of information flow in molecular nanonetworks

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ABSTRACT

Molecular communication enables nanomachines to exchange information with each other by emitting molecules to their surrounding environment. Molecular nanonetworks are envisioned as a number of nanomachines that are deployed in an environment to share specific molecular information such as odor, flavor, or any chemical state. In this paper, using the stochastic model of molecular reactions in biochemical systems, a realistic channel model is first introduced for molecular communication. Then, based on the realistic channel model, we introduce a deterministic capacity expression for point-to-point, broadcast, and multiple-access molecular channels. We also investigate information flow capacity in a molecular nanonetwork for the realization of efficient communication and networking techniques for frontier nanonetwork applications. The results reveal that molecular point-to-point, broadcast, and multiple-access channels are feasible with a satisfactorily high molecular communication rate, which allows molecular information flow in nanonetworks. Furthermore, the derived molecular channel model with input-dependent noise term also reveals that unlike a traditional Gaussian communication channel, achievable capacity is affected by both lower and upper bounds of the channel input in molecular communication channels.

1. Introduction

Nanotechnology envisages the practical realization of very low-end nanomachines that have tiny components to accomplish a simple specific task such as communication, computation, and sensing in a scale ranging from 1 to 100 nanometers. For example, programmable molecular nanomachines that are formed by precisely organized molecule and atom configurations are envisioned to accomplish specific tasks. These machines are also designed with significant abilities to physically configure themselves based on the task requirements or sensing information. They are also considered as part of potential solution approaches for pollution, scarce food resources, and cellular repair [7].

At the same time, existing nanoscale biological entities such as functional living cell components, bacterium, and viruses are also viewed as nanomachines. The realization of such nanomachines has also been worked on by a large set of biochemical methods for many years. For example, biochemists are already tackling the production of functional cell components such as ribosomes that can be used for the synthesis of beneficial proteins. Moreover, bacteria are also genetically programmed to generate principle vital components ranging from human growth hormone to beneficial enzymes for cheese production. Moreover, by mixing viral proteins with a special DNA in a test tube, it might be possible to generate a kind of T_4 phage virus that sticks to a bacterium and injects viral DNA to program the bacterium for the generation of excessive viral DNA and infections [7].

Doubtlessly, a network of communicating nanomachines can also be programmed to share nanoscale information over a nanonetwork so as to fulfill more complex tasks such as collaborative drug delivery, health monitoring, and biological or chemical attack detection [1,10]. In

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nature, biological systems such as immune systems and insect colonies already allow their biological entities to cooperatively share information to achieve specific tasks. For example, in a natural immune system, the white blood cells called B-cells and T-cells communicate with each other via molecular communication to cooperatively sense and eliminate the hazardous pathogens entering the body. The molecular communication among white blood cells enables the biological immune network that is an excellent defense mechanism of organism. As in nature, nanomachines may also be interconnected via molecular communication to form a molecular nanonetwork for a specific task [10].

In the literature, there exist several research efforts toward addressing the unique challenges of molecular communications. In [1], an extensive survey on molecular nanonetworking paradigms is given. In [16], the concept of molecular communication is introduced and the first attempt for the design of a molecular communication system is performed. An autonomous molecular propagation system is proposed in [14] that uses DNA hybridization and biomolecular linear motors to transport information molecules. In [15], a physical channel model for molecular communication is introduced by incorporating three different phases of molecular communication known as molecular emission, diffusion, and reception into a single channel model. In [8], achievable information rate is investigated in the molecular communication channel that is modeled as a timing channel. The time delay experienced in delivery of molecules is considered as a random variable for transferring molecular information. In our previous work [2], we introduced an information theoretical approach for molecular communication, derived a closed-form expression for the capacity of molecular communication channel between two nanomachines and proposed an adaptive error compensation technique for molecular communication. However, none of these works investigates the deterministic capacity of information flow in a nanonetwork and explores the feasibility of networking techniques for the realization of future molecular nanonetworks.

In [3,4], we model point-to-point and multiple-access molecular channels and discuss their achievable molecular communication capacities. The channel models are formed by using the concept of ligand-receptor binding process with deterministic mass-action kinetic mechanisms. However, due to the random nature of the biochemical reactions in molecular communication system, random fluctuations and chemical noise are inevitable for molecular reaction rates [11]. Therefore, it is essential to devise realistic molecular channel models that completely characterize the stochastic nature of physical molecular channels. In this paper, based on stochastic models of molecular reactions, a realistic channel model is first introduced for molecular communication. Then, in order to reveal the unique characteristics of molecular information flow in nanonetworks, we define three different molecular channels as follows:

- *Point-to-point molecular channel* is a molecular communication channel between a Transmitter Nanomachine (TN) and Receiver Nanomachine (RN).

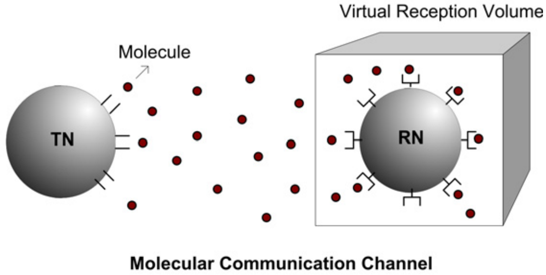

Fig. 1. Molecular communication channel in which TN communicates with RN by emitting molecules. All reactions among the emitted molecules and receptors on RN occur in a virtual reception volume that surrounds the RN.

- *Molecular broadcast channel* is a molecular communication channel in which a single TN simultaneously transmits molecular information to a number of RNs.
- *Molecular multiple-access channel* is a molecular communication channel in which multiple TNs transmit molecular information to a single RN.

For each of these channels, we derive a deterministic capacity expression and investigate the deterministic capacity of molecular information flow for the realization of efficient communication and networking techniques in molecular nanonetworks.

The remainder of this paper is organized as follows. In Section 2, we present a realistic channel model for molecular communication. In Section 3, we first derive deterministic capacity expressions for molecular point-to-point, broadcast, and multiple-access channels. Then, we investigate information flow in a molecular nanonetwork. In Section 4, we give the numerical results on the capacity of the molecular channels and information flow. Finally, we discuss concluding remarks in Section 5.

2. A realistic channel model for molecular communication

In nature, molecular communication among biological entities is based on molecular emission and reception. Molecules are emitted by a biological entity and the emitted molecules freely diffuse in the medium. Then, some of them collide with another entity that has specific receptors for the molecular reception. If the collision point of a molecule overlaps with a receptor site, the collided molecule and receptor react with each other, and a set of such reactions triggers the perception of biologically meaningful information to fire an action potential [6]. Hence, biological entities communicate with each other by emitting and perceiving molecular information. Based on this biological phenomenon, in this paper we devise a realistic channel model for molecular communication as follows.

We assume that a TN and RN are located in an aqueous medium as shown in Fig. 1. The molecules emitted by TN diffuse in the medium and some of them collide and react with the receptors on the surface of RN. Each reaction is an instantaneous event that is triggered with a collision between a molecule and receptor and results