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Forward and Reverse coding for chromosome transfer in bacterial nanonetworks

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ABSTRACT

Bacteria has been proposed in recent years as one approach to achieve molecular communication. Bacterial cells can harbour DNA encoded information and can deliver this information from one nanomachine to another by swimming (motility). One aspect of bacterial communication that could further enhance the performance of information delivery in bacterial nanonetworks is *conjugation*. Conjugation involves forming a physical connection between the bacteria in order to transfer DNA molecules (i.e., plasmids or chromosomes). However, the fragile physical connection between the bacteria is prone to breakage, in particular under mechanical stress. In this paper, a simple *Forward and Reverse* coding process is proposed to enhance the performance of information delivery in bacterial nanonetworks. The coding process involves segmenting messages into blocks and integrating this into the bacterial chromosome. Simulation work have been conducted to validate the efficiency of the coding process, where the results have shown positive performance compared to approaches that do not utilize coding or pure conjugation.

1. Introduction

The field of *molecular communication* aims to enable communication between different nanomachines in a biological environment [1]. This form of nano communication is a new communication paradigm where the communication networks are developed from existing biological systems that are found in nature. In particular, a central objective is the ability to exploit properties of biological systems and their communication capabilities, and reusing these properties for nano communications. Numerous models have been proposed for molecular communication over the years, where examples include molecular diffusion [2], calcium signalling between cells [3], virus nanonetworks [4], as well as the use of bacteria [5–7].

Over the years, bacteria have been utilized extensively for various nanoscale applications. The popular use of bacteria has stemmed from a number of factors. Firstly, the field of synthetic biology has enabled bacteria to be constructed and programmed to target particular characteristics [8]. The use of synthetic biology in bacteria has led to novel applications that include new forms of drug delivery [9], or perform computational capabilities such as logic computation at the nanoscale [10]. Secondly, bacteria have various natural communication mechanisms. These mechanisms range from local communication (e.g. quorum

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sensing), where chemical molecules (e.g. autoinducers) are released and adsorbed by other bacteria, to complex communication processes where *Deoxyribonucleic Acid* (*DNA*) molecules are transferred and exchanged (e.g. conjugation). These various communication capabilities enable the bacteria to survive through harsh environmental conditions (e.g. change in quantity of nutrients availability, temperature) and also enable them to cooperate and support each other as a community. The communication process is also not limited to bacteria of the same species, but can also enable communication between the bacterial cell and different species of bacteria, yeast, plants and even mammalian cells. The last factor is the ability for bacteria to mobilize and move between locations. The motility mechanisms include swimming, gliding, as well as twitching. Therefore, combining these different properties makes bacteria an ideal candidate to support molecular communication.

In this paper, we investigate the use of bacteria as an information carrier for molecular communication. The particular bacteria that we focus as an information carrier is the *Escherichia coli* (*E.coli*). In our application scenario, the bacteria will pick the DNA molecule with the encoded information from a transmitter nanomachine and deliver to a receiver nanomachine. The particular DNA molecule that is used to encode the information is on the bacterial *chromosome*. However, within the environment, the bacteria may transfer their chromosomes (or their parts) to other bacteria, and one technique to perform this transfer is known as *conjugation*. From the performance of the nanonetwork, the conjugation process provides an opportunity for the bacteria to amplify the number of messages, which in turn increases the chance of successful delivery to the destination. However, a key issue with the conjugation process is that only a portion of the DNA may get copied to the receiver bacterium. This in turn will lead to partial messages spreading through the environment and delivered to the destination nanomachine. One reason for the partial message transfer can be due to the sudden breakage in the connections, which may be caused by mechanical stress or certain chemical substances within the environment. In order to counter this issue, this paper proposes the *Forward and Reverse* coding mechanism, which allows partial transfers to occur, where these partial messages will be assembled at the destination nanomachine. We investigate through simulations and found that for particular distances, the coding process helps to increase the probability of successful decoding at the destination nanomachine. This is also the case when the nanonetwork undergoes mechanical stress that may break the connectivity between the bacteria.

The paper is organized as follows: Section 2 presents the current research in bacterial nanonetworks. Section 3 discusses the main properties of the bacteria that we utilize to facilitate multi-hop communication, and this is followed by Section 4 which presents the model for bacterial nanonetworks as well as the *Forward and Reverse* coding process. Section 5 discusses and analyses the results from the simulation work, and finally Section 6 presents the conclusion.

2. Related work

Bacteria have a number of communication processes that enable them to survive as a colony in face of various environmental changes. A number of works have exploited their communication properties to develop molecular communication systems. The simplest form of communication is the *Quorum Sensing*, where the bacteria emits *autoinducers* into the environment, and this is picked up by the local bacteria within the vicinity. The adsorption of the autoinducers will in turn lead to a response, which is production of further autoinducers. Using the density of molecules produced within the local environment can in turn support various functionalities for the bacteria. For example, the bacteria can sense the density of the local population using Quorum Sensing. In [11], the Quorum Sensing process was used to enable synchronization between the nanomachines. The same process was also used for communication between the nanomachines in [12]. The communication process is based on the bacteria that are housed within a nanomachine and produces the autoinducers. The autoinducers will flow out from the nanomachine and diffuse towards the neighbouring nanomachines, which will also trigger local Quorum Sensing in the bacteria housed within the destination nanomachine. However, the diffusion process of the autoinducers can incur large delays. Using the Quorum Sensing for communication, in [13], a number of communication protocols (*Time-Elapsed Communication* (*TEC*), *TEC-SMART*) was proposed to increase the data rate. The main strategy was based on the communication by silence process.

While Quorum Sensing has been proposed for molecular communication, other bacterial communication techniques have also been proposed. In [6], a process of encoding the message and embedding them into a DNA plasmid was proposed for molecular communication. An analysis was conducted in [7] for a single bacterium to deliver encoded DNA plasmid between nanomachines. A multi-hop bacterial nanonetwork was also described in [5], where the bacteria would conjugate with other bacteria within the vicinity leading to a multi-hop situation (this is akin to information dissemination in mobile ad hoc networks). In [14], an experimental validation was conducted on DNA plasmid transfer between bacteria using bacteriophages. The plasmids which were embedded in the bacteriophages would be diffused from the bacteria, and adsorbed by other bacteria that were swimming within the local vicinity.

Although the conjugation process for multi-hop bacterial nanonetworks can be beneficial, the process may result in partial messages delivered to the destination nanomachine. There has not been any proposed solution to counter for partial message delivery, and construction of the messages at the destination. However, the encoding process proposed in this paper can address this issue to increase the probability of successful decoding.

3. Properties of bacteria

In this section, we will list the common bacterial properties that are essential for realizing the bacterial nanonetworks.