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Using bacterial concentration as means of dissipating information through chemotaxis

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ABSTRACT

Utilizing bacteria in communications has emerged as a promising solution to delineating peculiarities at the nanoscale level. Usually, bacteria are used as carriers of molecules, which are exchanged in order to dissipate information. This work proposes a system, whereby bacterial concentration is used to transfer information. Chemotaxis plays a central role in the scheme. The investigation targets the examination and comparison of two different methodologies, where either the server uses chemorepellent or the clients use chemoattractant substances to bring about the chemotaxis effect. Performance of the proposed topologies was investigated through simulation. In the simulated experiments performed, random messages were encoded in the bacterial concentration using a simple on–off keying modulation, which then the receivers decode to recover the initial message. The experiments demonstrate the differences between the two strategies under various topologies, show the superior performance achieved in the case of chemoattractant clients, and highlight the influence of the parameters of distance, number of sensors and number of bacteria per pulse on the received signal amplitude and achievable bit error rate.

1. Introduction

Rapid advances in technology create a demand for ever smaller autonomous devices. Usually, small-scale devices should be able to operate as sensors. In more sophisticated applications, such devices should be able to process and store data in their memory. Finally, these devices should be able to communicate with each other or allow communication between parts of a larger system.

Devices in the scale of a nanometer to several microns are known as nanomachines. Nanomachines will not be able to be highly complex and their individual potential would be limited because of their dimensions. When they are, however, organized within a network, their capabilities, including operational range and sensitivity, will expand [1–4]. When nanomachines communicate with each other, the network formed is known as a nanonetwork.

Nanonetworks are generally split into two categories: (a) biological/molecular nanonetworks and (b) electromagnetically-based networks. In the former, communication is achieved through biological/molecular mechanisms. The use of genetically modified bacteria or other microorganisms is typically proposed. In electromagnetic nanonetworks, nanomachines communicate using electromagnetic radiation emitted by nanoantennas.

Nanonetworks can have a very significant impact in medical sciences [5]. Potential applications include drug delivery and glucose or cholesterol-monitoring systems. Although construction of nanomachines had seemed very difficult until recently, technological advances in areas, such as chemistry and materials science, has boosted their manufacturing tremendously. In that sense, in 2007 the first miniature antenna was built using carbon nanotubes [6]. In 2014, a demonstration of biological communications was performed in a wet lab experiment [7].

In this work, we propose a novel communications paradigm using bacteria or bacteria-like device concentration as the means of dissipating information between a base station and multiple clients. Performance of this process is augmented when utilizing the chemotaxis phenomenon. Chemotaxis is the movement of an organism in response to a chemical stimulus, either toward higher concentration, as is the case in positive chemotaxis,

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or toward the opposite direction in negative chemotaxis [8–13]. Two methodologies are examined: in the case of positive chemotaxis, chemoattractants are released from the Client Sensors (CS), whereas negative chemotaxis is caused by a chemorepellent released from the base station. We modeled both topologies and ran simulations to (a) compare their performance, and (b) investigate the significance of the chemotaxis phenomenon.

2. Related research

Both molecular or biological and electromagnetic nanonetworks are multiple access communication systems, similar to the widely used wireless networks [14]. In electromagnetic nanonetworks, use of extremely small devices capable of communication is proposed. The propagation speed is close to the speed of light, since electromagnetic waves are used to transfer data. Electromagnetic waves, also, operate in the THz band, the bandwidth of which is very broad. However, in such dimensions many peculiarities dominate the communication model, with current protocols failing to provide solutions [15,16,2,17–19].

In molecular nanonetworks, information is encoded in molecules released into the medium and reaching a receiver through diffusion [20–25]. The receiver can detect those molecules with its sensors. Various approaches have also been proposed that use transport channels, which are already present in the human body, such as those in the nervous system [1,5].

In biological nanonetworks, communication is achieved by bacteria "emitting" molecules, which are received by either other bacteria or nanodevices [14,26,27]. Alternatively, information is encoded in plasmids, which are exchanged between bacteria [1,7,24,28–32]. Plasmids are circular DNA molecules allowing bacteria to exchange information horizontally.

A wet lab experiment has been reported in the literature [7], pertaining to a molecular nanonetwork similar to our proposed scheme. In that experiment, plasmids encode data information and are placed in bacteria. These bacteria are released in the medium and travel toward devices that supply them with nutrients. These play the role of relays. Since bacteria are concentrated in a small area, collisions occur often and a plasmid is propagated to the entire population. The receiver is an end-device where the plasmid, hence the data, is retracted from the population. The drawback of this method is that the process of propagating a plasmid to an entire population is relatively slow.

Advantages of biological nanonetworks are biocompatibility and very low energy consumption. However, biological and molecular communication have serious drawbacks that should be considered when designing a network model. Since they depend on diffusion or Brownian motion of the microbes, they are characterized by slow propagation speed of information, a stochastic way of signal propagation and inability to achieve synchronization.

3. Bacterial release network model

A bacterial release network [33] cannot be easily compared to existing communication models, since its properties are fundamentally different. For instance, in diffusion-based models the motion of molecules is generated from random collisions with the particles present in the medium. In the herein proposed model, we suggest the use of bacteria that are motile. Furthermore, bacterial cells can actually choose the direction of movement and follow a path toward the most beneficial area for their survival, a phenomenon called chemotaxis. Positive chemotaxis occurs if cell movement is toward a higher concentration of a chemical substance. Conversely, negative chemotaxis occurs if movement is in the opposite direction. In the case of positive chemotaxis, the chemical stimulus is called chemoattractant, whereas in the case of negative chemotaxis, chemorepellent.

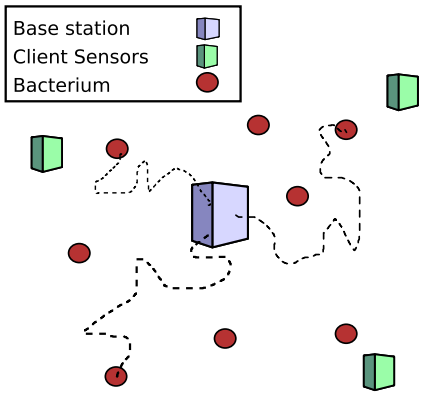

Fig. 1. Released bacteria follow random paths (diffusion).

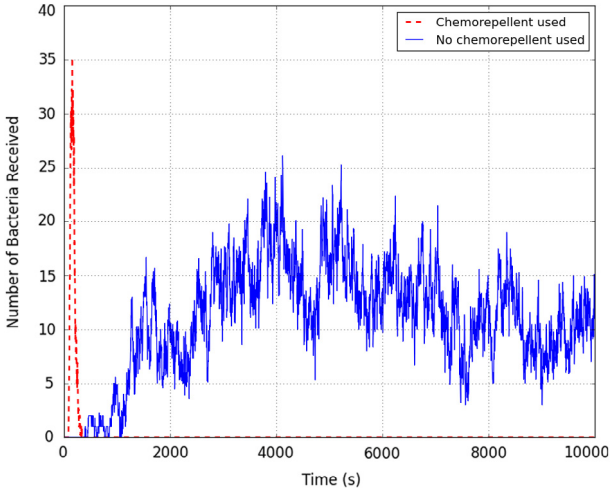

Fig. 2. Signal received at a CS placed at a distance of 2000 μm from the BS, for a chemorepellent topology (red) and a topology which uses simple diffusion only (blue). One pulse of 2000 is released at time 0. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1. Proposed network topology

The proposed communications model consists of two types of nodes; the Base Station (BS) and the CSs. The BS aims at transmitting information to the CSs. The data are encoded using a on–off keying modulation. The BS releases a pulse of bacteria every time it wants to broadcast a logic 1 and does nothing for every logic 0. A CS senses the medium for bacteria and by receiving the pulses is able to reconstruct the initial message.

In [33], it was shown that simple diffusion (Fig. 1) as a strategy for the bacterial movement is very restrictive in the bacterial release network model. Only under chemotaxis is the performance augmented, with a meaningful transfer range and bit error rate being achieved. In order to demonstrate this, in Fig. 2 we compare, via simulation, the signal received for a chemorepellent topology against a topology where only simple diffusion is used. A pulse is released from the BS at time 0. The dashed red line represents the result of the experiment using a chemorepellent, with the blue line reflecting the experiment where no such chemical is present. The benefits of chemotaxis are clearly profound. When a chemorepellent is used, the output signal is linked to a distinct pulse, characterized by a comparatively short delay and high received concentration. The latter is analogous to a higher amplitude of signal reception in a traditional radiation-based link.

By observing the blue line in Fig. 2, one can easily see that in the absence of a chemotaxis agent, there is a greater time