The Impact of Social Behavior on the Attenuation and Delay of Bacterial Nanonetworks

Bige D. Unluturk,* *Student Member, IEEE*, Sasitharan Balasubramaniam, *Senior Member, IEEE*, and Ian F. Akyildiz, *Fellow, IEEE*

***Abstract*— Molecular communication (MC) is a new paradigm for developing communication systems that exchanges information through the transmission and reception of molecules. One proposed model for MC is using bacteria to carry information encoded into DNA plasmids, and this is termed *bacterial nanonetworks*. However, a limiting factor in the models that have been studied so far is the environment considered only in ideal conditions with a single population. This is far from realistic in natural environments, where bacteria coexist in multiple populations of same and different species, resulting in a very complex social community. This complex community has social interactions that include cooperation, cheating, as well as competition. In this paper, the effects of these social interactions on the information delivery in bacterial nanonetworks are studied in terms of delay, attenuation and data rate. The numerical results show that the cooperative behavior of bacteria improves the performance of delay and attenuation leading to a higher data rate, and this performance can be degraded once their behavior switches towards cheating. The competitive social behavior shows that the performance can degrade delay as well as attenuation leading to slower data rates, as the population with the encoded DNA plasmids are prevented from reaching the receiver. The analysis of social interactions between the bacteria will pave the way for efficient design of bacterial nanonetworks enabling applications such as intrabody sensing, drug delivery, and environmental control against pollution and biological hazards.**

***Index Terms*— Bacterial social interactions, channel modeling, chemotaxis, molecular communication.**

I. Introduction

MOLECULAR communication (MC) is an emerging research area envisioned to enable diverse bioengineering applications from precise sensing and diagnosis of diseases in biomedicine, to pollution control and efficient biofuel production [1]. Inspired by the nature's inherent communication mechanisms, various MC models have been proposed in the literature including diffusion-based MC [2], active transport using molecular motors [3], MC over microfluidics [4], [5], calcium signaling within tissues [6], as well as pheromone dispersion [7]. In this study, we concentrate on a specific type of MC where bacteria are utilized as information carriers, which we term as **bacterial nanonetworks** [8]. This is based on a number of bacterial properties that includes the ability to move following a chemical gradient, i.e., bacterial chemotaxis, and ability to hold DNA plasmids that store encoded information as well as mechanisms to transfer them within the population, i.e., conjugation. Chemotaxis and conjugation play crucial roles for the survival of the bacteria. By chemotaxis, bacteria sense the gradient of molecules in the environment and bias its motion towards the attractants and away from the repellents to find more suitable environment for themselves [10]. Besides moving, bacteria also respond and adapt to its environment by exchanging DNA plasmids among them by conjugation such as plasmids containing genes for antibiotic resistance [11].

In bacterial nanonetworks, messenger bacteria pick up information encoded in DNA plasmids from the source using

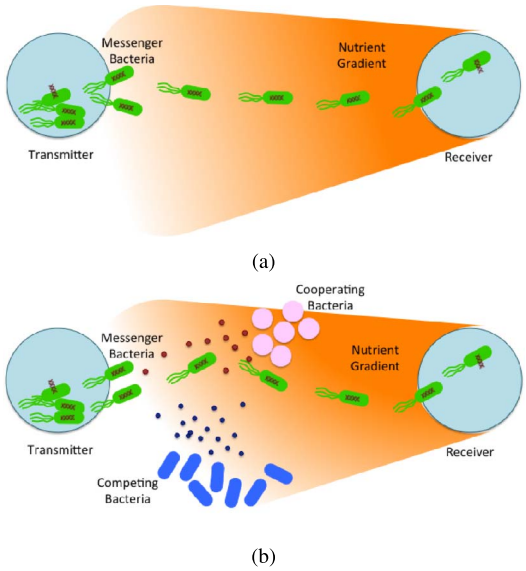

Fig. 1. (a) Bacterial communication in ideal environment. (b) Bacterial communication in realistic environment.

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*B. D. Unluturk is with the Broadband Wireless Networking Laboratory (BWN-Lab), School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: bigedeniz@ece.gatech.edu).

S. Balasubramaniam is with the Department of Computer Science and Engineering, Aalto University, Helsinki, Finland (e-mail: sasi.bala@cs.tut.fi).

I. F. Akyildiz is with the Broadband Wireless Networking Laboratory (BWN-Lab), School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA, and also with the Nano Communication Centre (NC2), Department of Electronics and Communication Engineering, Tampere University of Technology, Tampere, Finland (e-mail: ian@ece.gatech.edu).

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the conjugation process, move actively in the environment following a chemical gradient released from the destination and delivers the information to the destination as illustrated in Fig. 1. Therefore the reliability of this channel depends on the number of bacteria reaching to the receiver. The programmability by genetic engineering and the widespread availability of bacteria who can survive in many diverse and harsh environmental conditions make bacteria a promising information carrier for MC. Furthermore, the possibility of encoding thousands of bits into a single DNA plasmid provides a potential for fast delivery of a huge amount of information between MC nodes and make bacterial nanonetworks stand out among other MC techniques [8].

Researchers have studied bacteria as an information carrier for MC in [7]–[9], [12], [13] which analyze the communication performance of the channel in terms of end-to-end delay, reliability as well as capacity. These studies approach the problem by considering that there is no other bacteria in the environment than the messengers. However, in nature bacteria are always present within microbiomes consisting of several different populations engaging in social behavior with one another [14]. The objective of this study is to investigate the social behavior of bacterial nanonetworks where populations of bacteria interact with each other and the incorporation of it into the design of artificial bacterial nanonetworks.

Bacteria have a highly complex form of community structure that is maintained by different types of social interactions such as competition, cooperation, and cheating leading to formation of biofilms, production of antibiotics, bacteria-host interactions, production of infectious diseases, and developmental processes such as sporulation [14]–[17]. Cooperative behavior manifests in many forms such as hierarchical organization, cooperative sensing, foraging and collective learning. However, during the cooperative process, certain bacteria can switch to selfish behavior in which they do not contribute to the production of public goods but benefit from the ones produced by others. If the ratio of cheaters increases to a critical level, this may even lead to the collapse of the community. On the other hand, competition occurs when bacteria fight for the limited nutrient sources by inhibiting other populations' reach to the resources [18]. In order to evaluate the performance of a bacterial nanonetwork, the social interactions among bacteria and their impact on the information transmission must be investigated. Since all these interactions affect the number of messenger bacteria reaching the receiver, the communication performance of the bacterial nanonetworks will be affected. In our study, we present a realistic environment for MC utilizing bacteria as information carrier where we consider both cooperative and competitive social interactions, and analyze their effects on the communication channel performance, as illustrated in Fig. 1. In particular, we analyze the effects of social interactions between the populations, and how this affects the bacterial propagation, which in turn affects the communication channel.

We can summarize the main contributions of the paper as follows:

- For the first time in literature, we study the bacteria nanonetwork channel on the population level utilizing *Keller-Segel* model and traveling wave solutions to investigate the propagation of bacteria carrying information.
- For the abundant nutrient case where the diffusion of the chemoattractant is strong and the consumption by bacteria is negligible, we identify the chemotactic response to the nutrient gradient and derive closed form solutions for bacterial density at the receiver, as well as the delay and the attenuation of the bacterial channel.
- We investigate the impact of social behavior on the chemotactic response of the bacteria, and analyze the effects of cooperation, competition and cheating on the delay, attenuation and data rate of the channel.

The rest of the paper is organized as follows. In Section II, we present the Keller-Segel model for bacterial propagation and we derive the bacterial density, as well as the delay and attenuation of the bacterial nanonetwork channel. In Section III, the data rate in bacterial nanonetworks is calculated from the bacterial density. Then, in Section IV, we analyze the social behavior of bacteria, where we characterize the effects on their chemotactic response and derive the delay and attenuation when the population faces cooperation or competition. The numerical results are given in Section V and the paper is concluded in Section VI.

II. Traveling Wave Model of Bacterial Chemotaxis

A. General Bacterial Chemotaxis Model

Chemotaxis is the movement of the bacteria in response to chemical changes in the environment to relocate towards favorable environments. This behavior is observed in many bacterial species such as *E. coli*, *Salmonella enterica*, *Pseudomonas aeruginosa* which possess flagella [19]. In this paper, we give a generic propagation model applicable to all motile chemotactic bacteria populations.

Bacterial chemotaxis is studied both at the single-cell level [20] as well as the population level [21] to reveal the causes and mechanisms of the motility process. One approach is using the Keller-Segel model, which presents a system of two coupled differential equations that describes the aggregation of motile bacteria under the influence of diffusing chemoattractants. Besides being the most adopted model for chemotaxis, we chose to use this model due to its intuitive simplicity, analytical tractability and the ability to estimate the behavior of bacterial populations accurately [23].

The general form for the Keller-Segel model is expressed as [24]

$$\frac{\partial n(r,t)}{\partial t} = \nabla(\mu(n,S)\nabla n - n\chi(S)\nabla S) + f(n), \quad \text{(1a)}$$

$$\frac{\partial S(r,t)}{\partial t} = D_S \triangle(S) + g(n,S) - h(n,S), \quad \text{(1b)}$$

where $n(r,t)$ denotes bacterial cell density, $S(r,t)$ denotes chemoattractant concentration, μ is the random motility coefficient of the cells, $\chi(S)$ is the chemotactic sensitivity, D_S is the diffusion coefficient of chemical attractants, $g(n,S)$ is the production rate of chemoattractant, $h(n,S)$ is the degradation rate of the chemoattractant, and $f(n)$ represents the additional

growth term capturing the reproduction of bacteria. Furthermore, t denotes time and r is the distance to the origin where the messenger bacterial population is inoculated initially.

In the literature, each term in (1) takes different forms depending on the properties of the bacterial population and the culture environment. An extensive overview can be found in [21]. The random motility coefficient, i.e., $\mu(n, S)$ in (1) assumed to be a constant μ, accounts for the random, unbiased motion of a bacterial cell [23]. The chemotactic sensitivity, $\chi(S)$, is the response of a bacterium to the chemoattractant gradient which is modeled as $\chi(S) = \chi_0/S$, which accounts for the saturation of the bacterium response when the attractant concentration is high.

The growth term, $f(n)$, represents the increase in the bacterial cell density arising from the replication process. This term may be neglected when the time-scale of the bacteria movement are considered to be faster than the replication process [25] which is the case in our study since we consider that the time frame in which the bacteria will reach the receiver is significantly less than the reproduction time. For time intervals larger than the replication time of the bacteria, a population control mechanism can be used by genetically engineering the bacteria [27] which maintain a stable population without growth by programmed cell death [28]. Therefore, we can assume that the messenger bacteria population under consideration has no growth.

The chemoattractant S defined in the Keller-Segel model in (1), may represent either a nutrient source or a cell-to-cell signaling molecule attracting other bacteria. In this paper, we set the chemoattractant to be a chemical gradient emitted from a nutrient source, e.g., glucose, and the source is colocated with the receiver nanomachine. Furthermore, we consider that the bacteria do not produce any nutrient, i.e., $g(n, S) = 0$, and decay of the nutrient is at a fixed rate, i.e., $h(n, S) = h_0 n + kS$.

The Keller-Segel model in (1) provides a nonlinear set of partial differential equations which is not easy to solve analytically for most cases due to the coupling between the two equations. To decouple the equations, we consider the case where the diffusion of the attractant is strong (D_S large) and its consumption by bacteria is negligible ($h_0 \to 0$). In the next section, we investigate the solutions for (1) in the strong attractant diffusion case.

B. Traveling Wave Solutions for Strong Attractant Diffusion

We consider the asymptotic case for the Keller-Segel model, where the diffusion of the chemoattractant is strong (D_S is large) compared to its consumption, i.e., bacteria do not change the attractant concentration while sensing the attractant gradient [29]. It is considered that the attractant in this case is the nutrient whose concentration is given as $S(r, t)$. Also, we assume that the nutrient source which is colocated with the receiver generates nutrients at a constant rate to establish a steady-state nutrient concentration in the environment. Since the consumption by bacteria does not affect the nutrient concentration profile, we consider that $h_0 = 0$ which makes the diffusion equation for the nutrient density, $S(r, t)$, independent of the bacterial density, $n(r, t)$.

The equations in (1) become

$$\frac{\partial n(r,t)}{\partial t} = \frac{\partial}{\partial r}\left(\mu \frac{\partial n}{\partial r}\right) - \frac{\partial}{\partial r}\left(n\chi(S)\frac{\partial S}{\partial r}\right), \tag{2a}$$

$$\frac{\partial S(r,t)}{\partial t} = \frac{\partial}{\partial r}\left(D_S \frac{\partial S}{\partial r}\right) - kS. \tag{2b}$$

The boundary conditions are defined as

$$\mu \frac{\partial n}{\partial r} - \chi n \frac{\partial S}{\partial r} = 0, \quad (r \to \pm\infty) \tag{3}$$

$$S = 0, \quad (r \to \pm\infty) \tag{4}$$

where the initial conditions are defined as:

$$n(r, 0) = g(r), \quad t = 0. \tag{5}$$

Then, we can easily solve for the concentration of the nutrients $S(r, t)$ considering a continuous release from the receiver considered as a point source colocated with the receiver at r_r establishing a steady-state expressed as

$$S(r, t) = S_0 e^{-\left(\frac{|r-r_r|}{\rho}\right)}, \tag{6}$$

where S_0 is the nutrient release rate from source and $\rho = \sqrt{D_S/k}$ is the exponential mean distance depending on the diffusion coefficient D_S and decay rate k. For distances larger than ρ, the nutrient concentration drops below to $1/e$ of its initial concentration. Since now the nutrient density is known, the response of the bacteria to this density needs to be determined.

To find the bacterial density $n(r, t)$, we define the chemotactic response $\gamma(r)$ as

$$\gamma(r) = \chi(S)\frac{\partial S}{\partial r}, \tag{7}$$

which leads to a constant value for the strong attractant diffusion case due to the cancellation of the r dependent terms in the expression of nutrient density $S(r, t)$ found in (6) and the definition of chemotactic sensitivity, $\chi(S) = \chi_0/S$.

Let's assume that the diffusion of species is weak compared to the chemotaxis so that we can use the method of multiple scales to solve the problem analytically [29]. Considering the constant γ, now we look for a solution to (2) in the traveling wave form expressed as

$$n = \phi(r - \gamma t, t), \tag{8}$$

where $\phi(x, t)$ is the solution for $\gamma \to 0$.

We consider that the bacteria population is inoculated into the environment at a single point which corresponds to an initial bacterial density expressed as $g(r) = N_0\delta(r)$ where N_0 is the total number of bacteria in the inoculated population. Then, the bacterial density $n(r, t)$ is expressed in the traveling wave form as

$$n(r, t) = \frac{N_0}{\sqrt{4\pi\mu_0 t}} exp\left(-\frac{(r - \gamma t)^2}{4\mu_0 t}\right), \tag{9}$$

where $\gamma = \chi_0/\rho$ is the wave speed.

C. Delay and Attenuation

In the bacterial channel, when the transmitter has a message to send, it instantaneously releases messenger bacteria that contains the information encoded into the plasmid, with a cell density N_0 at time $t = 0$. We consider that the transmitter is located at $r = 0$. The release of the bacteria into the channel from the transmitter sets the initial condition of the bacterial cell density for (2).

The propagation of the message is defined as the movement of bacteria released from the transmitter towards the receiver governed by the equations in (2). When a threshold number of bacteria reach the receiver, the message is considered to be delivered. Hence, we are interested in the density of bacteria at the receiver $n(r,t)|_{r=r_r}$, where r_r is the receiver location. Because of the slow nature of diffusion and chemotaxis, not all the bacteria released from the transmitter will reach the receiver. Also, it requires a significant amount of time for a threshold number of bacteria to reach the receiver and successfully deliver the information. Therefore, we are interested in finding the delay and attenuation characteristics of the channel.

The delay of the channel, τ_d, is defined as the time required for the bacteria to reach the receiver, i.e., the time that the traveling wave solution for the bacterial cell density reaches its peak, and can be evaluated as:

$$\tau_d = \{t | \max_t \ n(r_r, t)\}. \tag{10}$$

By using the expression in (9), τ_d is expressed as

$$\tau_d = \frac{r_r}{\gamma}. \tag{11}$$

The attenuation of the channel, Γ, is defined as the ratio of the total number of released cells by the transmitter to the peak bacterial density of the traveling wave at the receiver, which can be represented as

$$\Gamma = \frac{n(r_t, t)|_{t=0}}{n(r_r, t)|_{t=\tau_d}}. \tag{12}$$

By substituting τ_d in (12), the attenuation can be expressed as

$$\Gamma = \sqrt{4\pi \mu_0 (r_r/\gamma)}. \tag{13}$$

III. Data Rate in Bacterial Nanonetworks

In the previous section we derived the bacterial density at the receiver as well as the delay and attenuation in bacterial nanonetworks. Since the information is encoded on the bacterial density, any change in it directly affects the data rate of the network. In this section, we derive the maximum data rate for binary transmission with ON-OFF keying.

We consider that the transmitter releases bacteria with intervals of bit period T_s, where N_0 bacteria are released to transmit bit 1 and no bacterium is released to transmit bit 0. The released bacteria follow the traveling wave model described in Section II-B. To detect the maximum density of the incoming bacterial density wave, the receiver samples the bacterial density at τ_d and decides whether bit 0 or 1 was sent.

T_s corresponds to the separation between two consecutive pulses distinguishable from each other. When T_s increases, the information transmitted in unit time becomes lower. To maximize the data rate, T_s should be minimal. To find the minimum separation T_s, we look for the effects of the previously transmitted pulses on the current pulse. Since the attenuation in the channel significantly increases with time, we assume that only the immediate previous pulse interfere with the current pulse. We choose T_s such that the tail of the bacterial density of the previous pulse, does not exceed 10% of the maximum bacterial density of the current pulse, i.e., $n_p(r_r, \tau_d + T_s) = 0.1 n_c(r_r, \tau_d)$. Therefore the corresponding maximum data rate for this binary transmission can be expressed as

$$R = \frac{1}{T_s}. \tag{14}$$

IV. Social Behavior Analysis for Bacterial Channel

In the nature, bacteria form communities which frequently contain multiple populations [16]. The survival of the bacterial community relies on its complex community structure as well as the coordination between multiple populations. To adapt to the environmental conditions which sometimes become harsh for bacteria to live in such as starvation, extreme temperatures, hazardous chemicals [32], bacterial populations interact through cell-to-cell communication.

There are many types of social interactions that is associated with bacteria such as cooperation, competition and cheating [17]. A good example that exhibits dynamic social interaction between the bacteria happens during fluctuations of nutrient resources. Bacteria may assist and support each other to discover nutrient sources or act selfishly and block other species from reaching the scarce resources. In the following subsections, we investigate how this social behavior affect the performance of the bacterial channel. The two basic social interaction, namely, cooperation and competition, are chosen to be studied in this paper.

A. Impact of Cooperation on Chemotaxis

The cooperative process is achieved when the bacteria cooperate through cell-to-cell signaling. This signaling process is used to attract other bacteria towards them when they are closer to nutrient sources as illustrated in Fig. 1(b) [15]. In the bacterial nanonetwork scenario, we assume to have two populations. The first population is defined to be the messenger population with the encoded DNA plasmids, while the second cooperating population that is closer to nutrient sources will emit chemoattractant molecules to attract the first population.

To incorporate the effects of cooperation into our model, first we define bacterial cell density of the first population as $n_1(r,t)$ and the bacterial cell density of the second population as $n_2(r,t)$. Also, we denote the concentration of the attractant emitted by the second population as $Q(r,t)$. Then, by rewriting the first equation of (1) for the first population we obtain

$$\frac{\partial n_1(r,t)}{\partial t} = \nabla(\mu \nabla n_1 - n_1 \chi_1(S) \nabla S - n_1 \chi_2(Q) \nabla Q), \tag{15}$$

where $\chi(S)$ is the chemotactic sensitivity of the first population to S whereas $\chi_Q(Q)$ is the chemotactic sensitivity of the

first population to Q. The nutrient density S is expressed as in (6).

The bacterial cell density for the second population is written similarly as

$$\frac{\partial n_2(r,t)}{\partial t} = \nabla(\mu \nabla n_2 - n_2 \chi(S) \nabla S). \tag{16}$$

We consider that the second population consists of non-motile bacteria hence its bacterial cell density has established a steady-state profile centered at r_{coop} expressed as

$$Q(r) = Q_0 e^{-\left(\frac{|r-r_{coop}|}{\rho_{coop}}\right)}, \tag{17}$$

where Q_0 is the release rate of the attractant molecule.

Furthermore, we assume that this steady-state profile gives rise to a chemotactic response found as

$$\gamma + \gamma_Q = \chi(S)\frac{\partial S}{\partial r} + \chi_Q(Q)\frac{\partial Q}{\partial r}, \tag{18}$$

which is similar to (7) where γ belongs to the case without any social behavior. Let's define $\gamma_{coop} = \gamma + \gamma_Q$ where $\gamma_Q = \chi_Q/\rho_{coop}$. According to (9), γ represents the speed of the traveling wave. Hence, when cooperation takes place, the speed of the traveling case increases by γ_Q representing the attraction effect of the cooperating population. Moreover, since the wave is arriving to the receiver sooner, it has less time to diffuse which leads to lower attenuation.

Following a similar derivation to (9) in Section II, we obtain the bacterial cell density for the first population as

$$n_1(r,t) = \frac{1}{\sqrt{4\pi\mu_0 t}} exp\left(-\frac{(r-\gamma_{coop}t)^2}{4\mu_0 t}\right), \tag{19}$$

where basically we replaced γ with γ_{coop}. The bacterial density profile with and without cooperation is illustrated in Fig. 2(a) which shows that with cooperation the bacterial density waves move faster.

Then, the delay of the system in the presence of cooperators can be expressed as

$$\tau_d^{coop} = \frac{r_r}{\gamma_{coop}}, \tag{20}$$

whereas the attenuation is expressed as

$$\Gamma^{coop} = \sqrt{4\pi\mu_0(r_r/\gamma_{coop})}. \tag{21}$$

Even though cooperation benefits both populations, eventually there will be individuals in each population who will breakdown the cooperation by pursuing their own interests [35], and these are called "*cheaters*". The cheaters will avoid the cost of producing cooperation molecules while still benefiting from the cooperation. When the ratio of cheaters to cooperators increases significantly, cheaters will dominate the population and the cooperation between the two populations will be disrupted [36]. To reflect the impact of cheaters, the cooperative chemotactic response $\gamma_{coop}(r)$ can be refined by the cheater frequency ξ, which is defined as the ratio of the number of cheaters in the cooperative population to the total number of bacteria in the cooperative population. Then, the chemotactic term in (15) becomes $(1-\xi)n_1\chi_2(Q)\nabla Q$. $\xi = 0$ represents the case where there is no cheating while $\xi = 1$ represents the case where all cooperative bacteria became cheaters and disrupted the cooperation totally.

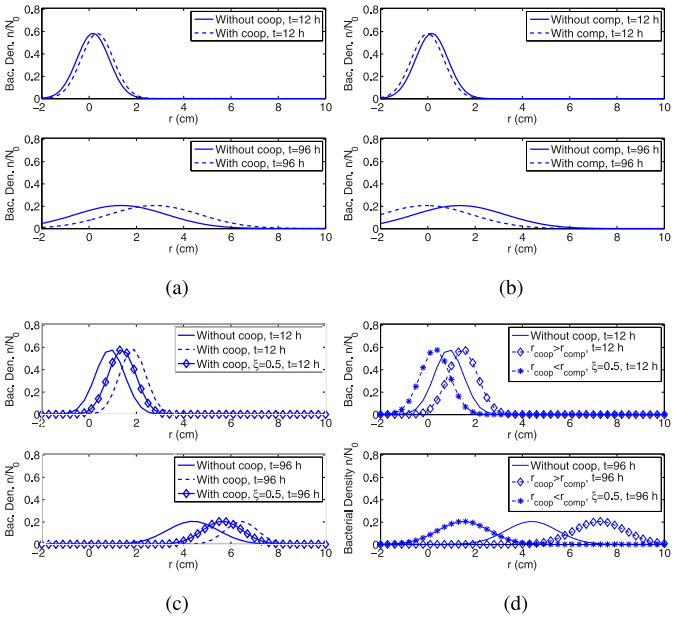

Fig. 2. (a) Bacterial density against distance in presence of a cooperative population. (b) Bacterial density against distance in presence of a competitive population. (c) Bacterial density against distance in presence of a cooperative population with cheaters. (d) Bacterial density for against distance in presence of cooperative and competitive populations.

B. Impact of Competition on Chemotaxis

When the nutrient sources are scarce, bacteria populations which are spatially close to each other compete by releasing repellent chemicals to keep the others away from the nutrient sources as shown in Fig. 1(b) [32]. The repellents only affect the other bacterial populations if they are from the same species or if they are genetically close so that the competitors identify and respond to the repellents.

Now, let's consider that we have two sibling populations where the first population is the messenger population and the second population is the competitor of the first one which was already in the environment before the release of the messenger population. The bacterial density of the messenger population is expressed as

$$\frac{\partial n_1}{\partial t} = \nabla(\mu \nabla n_1 - n_1 \chi(S) \nabla S + n_1 \chi_P(P) \nabla P), \tag{22}$$

where $\chi(S)$ is the chemotactic sensitivity for the attractant S, while $\chi_P(P)$ is the chemotactic sensitivity for the repellent P. Note that, since P is a repellent, the sign in front of the second term of the right hand side is negative. The nutrient density S is expressed as in (6).

We consider that the second population consists of non-motile bacteria and its bacterial cell density has also established a steady-state profile centered at r_{comp}. Similar to the attractant concentration in the cooperation case in (17), the repellent concentration $P(x,t)$ is expressed as follows

$$P(r) = P_0 e^{-\left(\frac{|r-r_{comp}|}{\rho_{comp}}\right)}, \tag{23}$$

where P_0 is the release rate of the repellent molecules and D_P is the diffusion coefficient for the repellents.

Then, the chemotactic response in case of competition is found as $\gamma_{comp} = \gamma - \gamma_P$, which is similar to (18). Note that

there is a negative sign representing the repellent gradient that makes the bacteria move away from the poisonous source. Then, the chemotactic response to P is found by $\gamma_P = \chi_P/\rho_{comp}$. Since γ_{comp} represents the speed of the traveling wave, we can conclude that according to the strength of competition, the speed of the traveling wave is decreasing. Since the traveling wave is slower, the bacteria will arrive to the receiver later and will diffuse more into the environment, leading to higher attenuation.

Similar to (19), we obtain the bacterial cell density for the messenger population in case of competition as

$$n_1(r,t) = \frac{1}{\sqrt{4\pi\mu_0 t}} exp\left(-\frac{(r-\gamma_{comp}t)^2}{4\mu_0 t}\right), \tag{24}$$

where basically we replaced γ_{coop} with γ_{comp}. Fig. 2(b) illustrates the slow moving bacterial density that results from the competition process.

The delay of the system in the presence of competitors can be expressed as

$$\tau_d^{comp} = \frac{r_r}{\gamma_{comp}}, \tag{25}$$

while the attenuation is expressed as

$$\Gamma^{comp} = \sqrt{4\pi\mu_0(r_r/\gamma_{comp})}. \tag{26}$$

C. The Impact of Joint Cooperation and Competition

Often bacteria live in microbiomes where there are multiple populations cohabiting the environment. When messenger bacteria is assumed to live in such an environment, there may be multiple populations that they interact with cooperatively or competitively. Each population will affect the propagation of the messenger bacteria in different strengths according to its distance to the messenger population and the diffusion properties of the chemoattractant/chemorepellent it releases. To combine the effects of every population present in the environment we can modify the bacterial density expression as follows

$$\frac{\partial n_1}{\partial t} = \nabla(\mu\nabla n_1 - n_1\chi(S)\nabla S - n_1\sum_{i=1}^{N_{coop}}\chi_{Q,i}(Q_i)\nabla Q_i + n_1\sum_{i=1}^{N_{comp}}\chi_{P,i}(P_i)\nabla P_i), \tag{27}$$

where N_{coop} is the number of cooperating populations, N_{comp} is the number of competing populations, $\chi_{Q,i}$ is the corresponding chemotactical sensitivity of i^{th} population, $\chi_{P,i}$ is the corresponding chemotactical sensitivity of i^{th} population, Q_i is the density of the i^{th} cooperative population, and P_i is the density of the i^{th} competitive population.

Following similar derivations to Sections IV-A and IV-B, the bacterial cell density for the joint cooperation-competition case with multiple populations can be expressed as

$$n_1(r,t) = \frac{1}{\sqrt{4\pi\mu_0 t}} exp\left(-\frac{(r-\gamma_j t)^2}{4\mu_0 t}\right), \tag{28}$$

where $\gamma_j = \gamma + \sum_{i=1}^{N_{coop}}\gamma_{Q_i} - \sum_{i=1}^{N_{comp}}\gamma_{P_i}$.

By substituting γ in the expression of delay given in (11) and the attenuation expression given in (13) by γ_j, the delay of the system for joint case is found by

$$\tau_d^j = \frac{r_r}{\gamma_j}, \tag{29}$$

while the attenuation is found by

$$\Gamma^j = \sqrt{4\pi\mu_0(r_r/\gamma_j)}. \tag{30}$$

Fig. 2(d) illustrates the bacterial density under the effects of both cooperation and competition.

V. Numerical Results

In this section, the analytical results obtained for the performance of bacterial nanonetwork channel as they undergo social interactions are numerically evaluated. First, we study the case of cooperation and investigate the delay and attenuation of the channel for various transmitter-receiver distances. Then, we conduct a similar study for the case of competition. For the numerical evaluations, *E. coli* is chosen to be the bacterial species for the messenger, cooperator and competitor populations due to the abundance of experimental studies on the interactions of *E. coli* populations. The parameter values are taken from [33] which studies the bacterial density of *E. coli* bacteria subject to multiple attractant/repellents environments, and from [34] for chemotactic coefficients. The random motility coefficient of bacteria is set at $\mu_0 = 1.5\times10^{-5}\text{cm}^2/\text{s}$. The chemotactic sensitivity coefficient χ_0 for the nutrient is taken as $\chi_0 = 4.1\times10^{-4}\text{cm}^2/\text{s}$ and the chemotactic sensitivity for cooperation and competition molecules are taken as $\chi_Q = \chi_P = 1.5\times10^{-5}\text{cm}^2/\text{s}$. The initial bacterial density is taken as 10^8 cells/mL and the length of the observation chamber is considered to be 4 cm as in [34]. The transmitter is located in the middle of the chamber and the receiver's location is varied from $0.01 - 0.05$ cm which limits the maximum transmitter-receiver distance to 0.05 cm.

A. Impact of Cooperation

1) Delay of The Channel: In Fig. 3(a), the impact of cooperation on the delay of the bacterial channel is illustrated. We evaluated the channel delay for $r_{coop} = 0.05$ cm and 0.1 cm and for $\chi_Q = 1.5\times10^{-5}$ cm^2/s and 4.5×10^{-5}cm^2/s. It is observed that cooperation reduces the delay of the channel significantly in all cases. It is also observed that with decreasing r_{coop} the delay is decreasing. These results can be attributed to the closeness of the transmitter to the cooperative population producing attractants with a steeper gradient. Due to the steeper gradient, the messenger bacteria are drawn faster towards the receiver based on (18). Furthermore, it is observed that the higher the chemotactic sensitivity χ_Q, the smaller is the delay. This follows from the fact that the messenger bacteria are more sensitive to cooperative molecules with higher χ_Q which increases the strength of the chemotactic response, which in turn increasing the speed of the bacterial density wave according to (18). Note that a small increase in r_{coop} causes larger deviation in delay than an increase in χ_Q due to the fact that while χ_Q is directly proportional

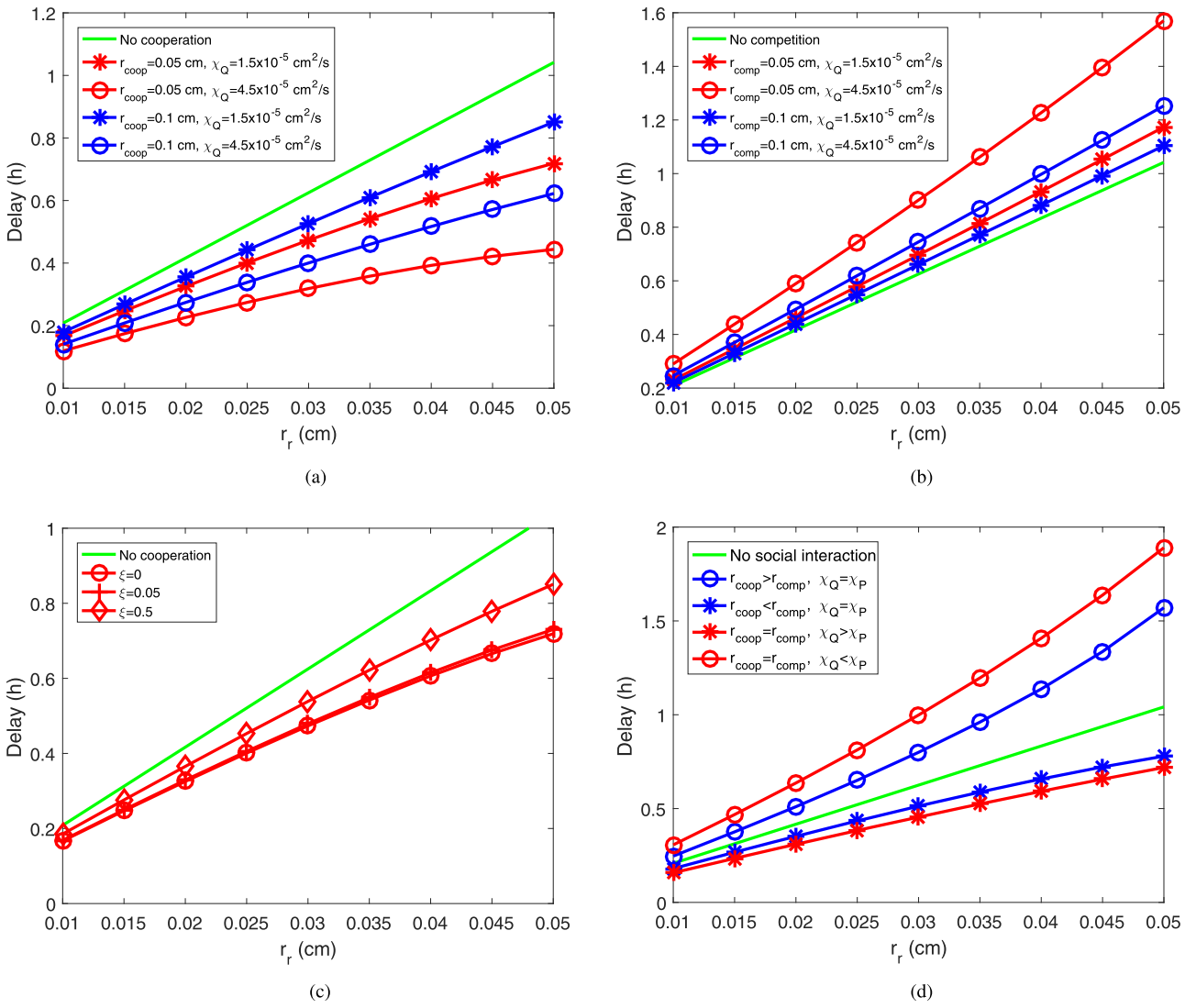

Fig. 3. Delay of the channel against the transmitter-receiver distance for: (a) Cooperation. (b) Competition. (c) Cooperation with cheating. (d) Joint cooperation and competition.

to delay, r_{coop} has a more complex effect. Firstly, with smaller r_{coop}, the cooperative population gets closer to the receiver, i.e., the nutrient source which increases their energy to use for cooperation. Secondly, due to smaller distances between the cooperative population and the messenger population, the molecule exchange gets easier.

In Fig. 3(c), the impact of cheating on delay is illustrated where $\mu_0 = 1.5 \times 10^{-5}\text{cm}^2/\text{s}$, $r_{coop} = 0.05$ cm, $\chi_Q = 4.5 \times 10^{-5}$ cm^2/s. Since cheating occurs when some of the bacteria in the population stop cooperating, it deteriorates the positive effect of cooperation. When the cheating frequency, ξ, is 0.05, i.e. there are only 5% cheaters, the delay is almost overlapping with the case without cheating, i.e., $\xi = 0$. However, when the cheating frequency rises to 0.5, the delay increases since 10% of the population is not involved in the production of cooperative molecules reducing the positive effect of cooperation.

2) Attenuation of The Channel: In Fig. 4(a), the impact of the cooperation on the attenuation of the channel is investigated. We evaluated the attenuation for $r_{coop} = 0.05$ cm and 0.1 cm and for $\chi_Q = 1.5 \times 10^{-5}$ cm^2/s and $4.5 \times 10^{-5}\text{cm}^2/\text{s}$ to reveal the effect of these two factors defining the strength of the cooperation. It is observed that when the cooperative population is closer, i.e. r_{coop} is short, the attenuation is improved. As r_{coop} decreases, the attraction between the messenger bacteria and the cooperative bacteria increases yielding a faster bacterial density wave. Since according to (9), the amplitude of the bacterial density is time-dependent, faster moving bacterial waves are less attenuated. Similarly, for higher chemotactic sensitivities χ_Q, the bacterial waves are less attenuated. As χ_Q increases, the attraction between the messenger and the cooperative bacteria increases which in turn increases the speed of bacterial density wave subject to less attenuation. Finally, Fig. 4(a) shows that cooperation improves the attenuation of the channel even if it is not as significant as in the case of delay.

In Fig. 4(c), the impact of cheating on attenuation is illustrated where $\mu_0 = 1.5 \times 10^{-5}\text{cm}^2/\text{s}$, $r_{coop} = 0.05$ cm,

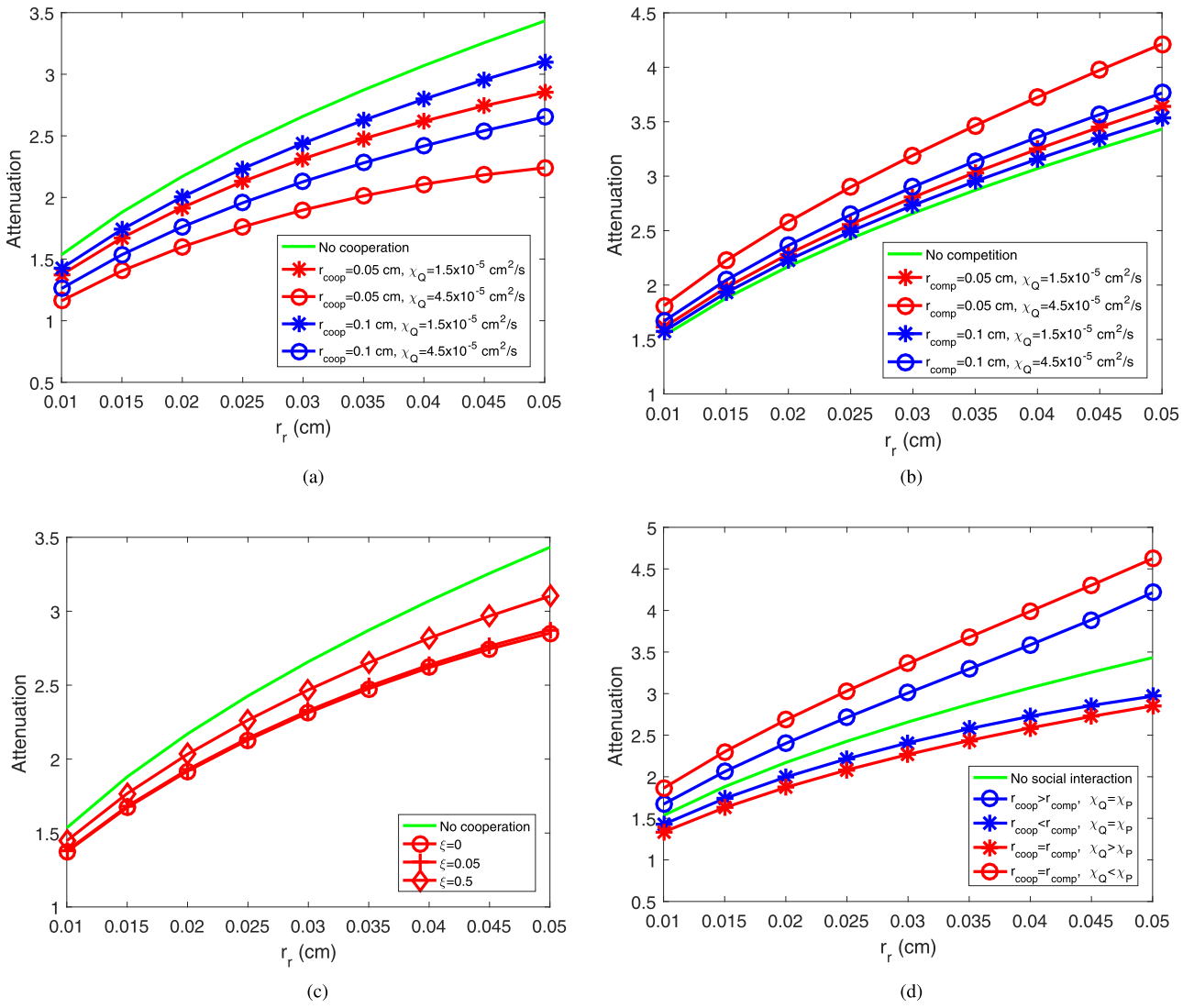

Fig. 4. Attenuation of the channel against the transmitter-receiver distance for: (a) Cooperation. (b) Competition. (c) Cooperation with cheating. (d) Joint cooperation and competition.

$\chi_Q = 4.5 \times 10^{-5}$ cm^2/s. Similar to the delay of the channel, cheating can annihilate the positive effects of cooperation when the cheating frequency is high. For the cheating frequency of $\xi = 0.05$, i.e. there are only 5% cheaters, the attenuation is not greatly affected. However, when the cheating frequency rises to 0.5, half of the population quit participating in cooperation, and this results in the attenuation becoming more severe and getting closer to the attenuation level without any cooperation.

3) Maximum Data Rate: In Fig. 5, we illustrated the effect of cooperation where $r_{comp} = 0.2$ cm, $\chi_Q = 4.5 \times 10^{-5}$ cm^2/s. It is observed that the maximum data rate is decreasing with increasing distance since the bacterial density wave is widening while traveling as shown in Fig. 2. Due to this widening effect, the previous symbol's bacterial density wave overlaps more with the current symbol's bacterial density wave requiring to slow down the rate of transmission. Furthermore, Fig. 5 shows that the cooperative behavior improves the maximum data rate. This follows from the fact cooperation lowers the delay which in turn lowers the widening of the bacterial density wave. Thus, we can transmit more frequently without overlapping waves which results in increased data rate.

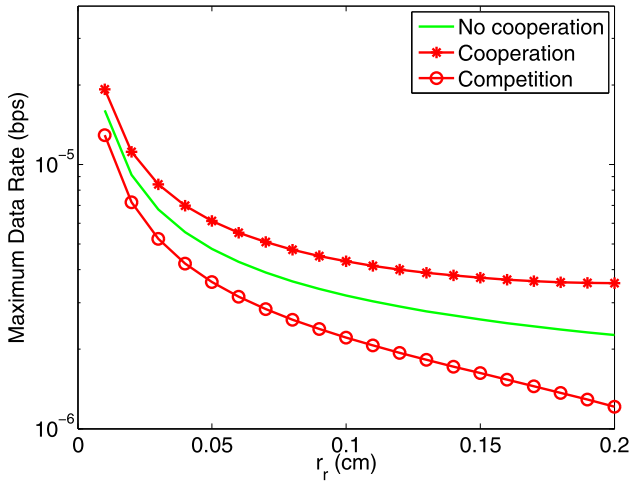

Fig. 5. Maximum data rate of the channel

B. Impact of Competition

1) Delay of The Channel: In Fig. 3(b), the impact of competition on the delay of the bacterial nanonetwork channel is illustrated. The delay of the channel is evaluated for $r_{comp} = 0.05$ cm and 0.1 cm and for $\chi_P = 1.5 \times 10^{-5}$ cm^2/s and 4.5×10^{-5}cm^2/s. It is observed that competition leads to higher delay for all the considered cases due to the negative effects on the bacterial chemotactic response as discussed in Section IV-B. Another observation is that the lower r_{comp}, i.e., the closer the competitive population to the messenger, will result in lower delay since the competitive effects driving the messenger bacteria away from the receiver are stronger when the second population gets closer. Moreover, when the chemotactic sensitivity of the messenger bacteria to the competition molecules χ_P are higher, the chemotactic response to the competition gets stronger and decreases more the speed of the bacterial density wave. Hence, the bacterial wave travels slowly causing a higher delay. Note that, since the delay is inversely related to r_{comp}, a small increase in r_{comp} causes larger deviation in delay than an increase in χ_P which is proportional to delay.

2) Attenuation of The Channel: Fig. 4(b) presents the attenuation of the channel and the effects of competition on the attenuation. The attenuation is evaluated for $r_{comp} = 0.05$ cm and 0.1 cm and for $\chi_P = 1.5 \times 10^{-5}$ cm^2/s and 4.5×10^{-5}cm^2/s. With decreasing r_{comp}, the competitive interaction between the messenger and competing population rises which leads to a stronger attenuation. This arises since strong competitive repulsion slows down the bacterial density wave whose amplitude gets attenuated by the time dependent term in (24). Similarly, for higher chemotactic sensitivities χ_P, the bacterial waves are less attenuated. As χ_P increases, the repulsion between the messenger and the cooperative bacteria increases which in turn decreases the speed of bacterial density wave subject to greater attenuation. Finally, Fig. 4(b) shows that the attenuation has worsened with competition for all cases compared to the attenuation without any competition.

3) Maximum Data Rate: In Fig. 5, we illustrated the effect of cooperation where $r_{comp} = 0.2$ cm, $\chi_Q = 4.5 \times 10^{-5}$ cm^2/s. Fig. 5 shows that the competitive behavior deteriorates the maximum data rate. This is due to the increasing effect of competition on delay which causes more widening of the bacterial density wave. Hence, the previous symbol's bacterial density wave overlaps more with the current symbol's bacterial density wave requiring to slow down the rate of transmission.

C. Impact of Joint Cooperation and Competition

To illustrate the effect of joint cooperation and competition, we considered that there are one cooperative and one competitive populations in the environment interacting with the messenger population. We considered four cases where we explore the effects of the distance and the chemotactic sensitivity of neighbor populations on the delay and attenuation.

1) Delay of the Channel: In Fig. 3(d), the joint effect of cooperation and competition on the delay is illustrated. Firstly, we consider the case where the chemotactic sensitivities of the cooperative and competitive populations are the same, i.e., $\chi_Q = \chi_P$, whereas the cooperative population is farther from the competitive population, i.e., $r_{coop} > r_{comp}$. In this case, since the competitive population is closer to the messenger population, competitive behavior is dominant which reflects as a higher delay than the no social interaction. Similarly, in the case where $\chi_Q = \chi_P$ and $r_{coop} < r_{comp}$, the cooperative behavior is dominant leading to a decreased delay.

Secondly, we consider the case where the distances of neighbor populations are the same, i.e., $r_{coop} > r_{comp}$, whereas the chemotactic sensitivity of the cooperative population is higher than the competitive one, i.e., $\chi_Q > \chi_P$. In this case, cooperative behavior is dominant since the messenger population is more sensitive to the cooperative behavior which shifts the delay in the cooperative direction to a value lower than the social interaction case. Similarly, in the case where $r_{coop} = r_{comp}$ and $\chi_Q < \chi_P$, the competitive behavior is dominant leading to an increased delay.

2) Attenuation of the Channel: In Fig. 4(d), the joint effect of cooperation and competition on the attenuation is illustrated. Firstly, we consider the case where the chemotactic sensitivities of the cooperative and competitive populations are the same, i.e., $\chi_Q = \chi_P$, whereas the cooperative population is farther from the competitive population, i.e., $r_{coop} > r_{comp}$. In this case, since the competitive population is closer to the messenger population, competitive behavior is dominant which reflects as a higher attenuation than the no social interaction case. Similarly, in the case where $\chi_Q = \chi_P$ and $r_{coop} < r_{comp}$, the cooperative behavior is dominant and the attenuation becomes lower.

Secondly, we consider the case where the distances of neighbor populations are the same, i.e., $r_{coop} = r_{comp}$, whereas the chemotactic sensitivity of the cooperative population is higher than the competitive one, i.e., $\chi_Q > \chi_P$. In this case, cooperative behavior is dominant since the messenger population is more sensitive to the cooperative behavior leading to a lower attenuation than the social interaction case. Similarly, in the case where $r_{coop} = r_{comp}$ and $\chi_Q < \chi_P$, the competitive behavior is dominant and the attenuation is higher than the no social interaction case.

VI. Conclusion

The use of bacteria has been proposed for molecular communications due to their motility property as well as the fact that DNA plasmids with encoded information can be carried by them. This MC technique is defined as bacterial nanonetworks. In this paper, we first present the Keller-Segel model that describes the dynamics of the bacterial chemotaxis process. This is followed by expressing a traveling wave solution for the density of the propagating bacteria through chemotaxis, where the delay and attenuation of the bacterial nanonetwork channel are derived. Using this traveling wave modeling approach, the social behavior of bacteria, namely, cooperation, cheating and competition, is analyzed in terms of their effects on the delay and the attenuation of the channel. The numerical results show that the social behavior have a significant effect on the channel characteristics (the species we considered is *E. coli*).

The cooperation between the bacteria improves the channel by lowering the delay and the attenuation. However, the benefits of cooperation are short-lived when the bacteria switch towards cheating behavior, and the performance worsens as the frequency of cheaters increases. Furthermore, the results show that the competition between the bacterial species deteriorates the channel by leading to higher delay and heavier attenuation. The objective of this study is to provide a model for the propagation of bacteria transferring information in the presence of other microorganism that may interact either positively or negatively depending on the environmental condition. By analyzing their interaction behavior, this will result in efficient design of bacterial nanonetworks that is realistically found in their natural environments.

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Bige D. Unluturk (S'12) received the B.Sc. and M.Sc. degrees in electrical and electronics engineering from Middle East Technical University, Turkey, in 2011 and from Koc University, Turkey, in 2013, respectively. Currently, she is working toward the Ph.D. degree in the Broadband Wireless Networking Lab at Georgia Institute of Technology, Atlanta, GA, USA, under the supervision of Prof. Dr. Ian F. Akyildiz. Her current research interests include nanoscale communications and molecular communication networks.

Sasitharan Balasubramaniam (SM'14) received the B.S. degree in electrical and electronic engineering and the Ph.D. degree from the University of Queensland, Australia, in 1999 and 2005, respectively, the M.S. degree in computer and communication engineering from the Queensland University of Technology, Australia, in 1999. Currently, he is an Academy of Finland Research Fellow with the Nano Communication Centre, Department of Electronic and Communication Engineering, Tampere University of Technology, Tampere, Finland. His research interests include bio-inspired communication networks, and molecular communications. Currently, he is an Editor for the IEEE *Internet of Things Journal*, *Nano Communication Networks*, *Swarm and Evolutionary Computation*, and *Digital Communication and Networks*.

Ian F. Akyildiz (M'86-SM'89-F'96) received the B.S., M.S., and Ph.D. degrees in computer engineering from the University of Erlangen-Nurnberg, Germany, in 1978, 1981, and 1984, respectively. Currently, he is the Ken Byers Chair Professor in Telecommunications with the School of Electrical and Computer Engineering, Georgia Institute of Technology (Georgia Tech), Atlanta, GA, USA, the Director of the Broadband Wireless Networking Laboratory and Chair of the Telecommunication Group at Georgia Tech. Since September 2012, Dr. Akyildiz is also a FiDiPro Professor (Finland Distinguished Professor Program (FiDiPro) supported by the Academy of Finland) at Tampere University of Technology, Department of Communications Engineering, Finland. He received numerous awards from IEEE and ACM. His current research interests are in nanonetworks, long term evolution (LTE) advanced networks, cognitive radio networks, and wireless sensor networks.