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Quorum Sensing-Based Multiple Access Networks

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ABSTRACT

Quorum sensing (QS) is a bacterium-to-bacterium cell communication mechanism allowing bio-cell network construction but such mechanism is not well defined yet. We construct a QS-based multiple access network (MAN) and then numerically analyse its average uplink channel capacity as well as BER performance over diffusion-based 3-D molecular communication channels.

Key Words : Molecular Communication, Quorum Sensing, Multiple Access, Capacity, BER, Autoinducer

Ⅰ.Introduction

The development of molecular communication (MC), which is a diffusion-law-based nanomachine information transmission technology, will have a great impact on future medical, industrial, military, and other bio-inspired nano-applications[1,2].

Quorum sensing (QS) is a well-known MC mechanism, where bacteria use signalling molecules (emitted from their neighbouring same bacteria cells) called autoinducers (AI), that allows network synchronization and estimation[3,4]. We construct a QS-based multiple access network (MAN) over 3-dimensional (3-D) molecular diffusion channels that consist of many artificial nanomachine nodes (or sensor cells). In this MAN, we assume that one of those nanomachine nodes might be chosen (specially designed) as an access point (AP). All transmitter nodes (TNs) encode AI with their sensing information and emits the encoded AI to the AP. Then, the AP decodes the transmit sensing information ('1' (sensed) or '0' (no sensed)) of each node from the received AI.

In the literature, until now, most of the existing work over molecular diffusion channels has focused on point-to-point transmission[5-8]. Among them, in [5], the authors address point-to-point communication using the Brownian motion based chemical signaling. The authors in [6] analyze the mutual information where information is encoded by the release of the signaling molecules. In [7], a closed form expression for the maximum achievable information rate over point-to-point diffusion-based channels is derived. In [8], the capacity over the time-slotted binary diffusion channel is derived. Recently, the authors in [9], [10] introduce a molecular ligand-binding (LB)-based channel model using defined binding and releasing rates, and construct a LB-based MAN.

In this Letter, we suggest a QS based MAN over 3-D molecular diffusion-based channels and find out an optimal solution of the proposed system model via the numerical as well as theoretical analysis. The molecular QS channel that is typically binary asymmetric[3] is assumed (approximated) to be normally-distributed[10] for simplicity. We take into account the inter-symbol interference (ISI) effect due to the MC channel propagation delay.

We numerically evaluate both the average uplink channel capacity of the proposed system and its performance in terms of bit error rate (BER) versus bit energy per noise spectral density (E_b/N_0). Especially, in this Letter, we analyze the effect of the channel contention factor k as well as the average distance d to the proposed system capacity and BER.

Ⅱ. Multiple Access Channel

Assume that for a QS-based MAN, the total

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transmitter nodes (TNs) that send a self-identifying-labelled binary signalling AI are deployed in a fluidic 3-D space. AI propagation via the MC channels is influenced by Fick's diffusion law, and then we assume that all of the AIs are distributed over a constant and relatively- large coverage area compared to their density. Consider that at every start of the symbol time t_s, a node with a transmit data sequence (whose size is $L \gg 1$) may send information bit 1 by emitting AI at a high rate (sensed; $n_X = n_1$ molecules) with the emitting probability P_A or information bit 0 by emitting AI at a low rate (no sensed; $n_X = n_0$ molecules) with the emitting probability $(1-P_A)$. If a node initially $(t=0)$ releases n_X molecules, the diffused AI concentration at the time t is defined[8] as

$$R_X(d,t) = \frac{n_X}{(4\pi Dt)^{3/2}} e^{-d^2/(4Dt)}, \tag{1}$$

where d is the distance between the node and an AP, and D is the drift velocity coefficient in the fluidic environment. The size of signalling AI, denoted as M_X^i, representing symbol X (= 0 or 1) that the AP receives from the ith (i= 1, 2, ⋯, I) node at a distance d^i during the lth symbol duration $[(l-1)t_s, lt_s)$, is

$$M_X^i = \int_{(l-1)t_s}^{lt_s} \frac{n_X}{(4\pi Dt)^{3/2}} e^{-(d^i)^2/(4Dt)} dt. \tag{2}$$

Assume that AI, once it is generated, could remain (alive) just for a two-symbol period (and then disappear immediately). The remaining portion of the previous symbol AI during the current symbol (lth symbol, $l > 1$) period, whose size is denoted as S_X^i, could interfere with the current symbol AI, which is called the inter-symbol interference (ISI). S_X^i can be given as

$$S_X^i = \int_{(l-1)t_s}^{lt_s} \frac{n_X'}{(4\pi Dt)^{3/2}} e^{-(d^i)^2/(4Dt)} dt, \tag{3}$$

where n_X' denotes the size of released AI during the previous symbol period. Multiple nodes (whose size is $I > 1$) emit their own AI to the AP and the AP receptor can identify the signalling AI from different nodes (with their own coloured labels). However, the channel contention due to the diffused AI crowdedness is not avoidable. That is, the ith node's symbol AI may interfere with the other nodes' symbol AI. Hence, in here we introduce a channel contention factor $k^i \epsilon [0,1)$ that is defined as

$$k^i = \frac{\sum_{j \neq i} \left[P_A \mu_1^j + (1-P_A)\mu_0^j\right]}{M_X^i + \sum_{j \neq i} \left[P_A \mu_1^j + (1-P_A)\mu_0^j\right]}. \tag{4}$$

We approximate $N_X^i (\geq 0) = \{M_X^i + S_X^i\} \times (1-k^i)$, indicating the size of the ith node symbol AI, as a normal random variable with the mean $\mu_X^i = E\{N_X^i\}$ and standard deviation $\sigma_X^i = \mu_X^i/3$ (where assuming $(\mu - 3\sigma) \geq 0$[9]); that is, $N_X^i \sim N(\mu_X^i, \{\sigma_X^i\}^2)$. Hence, the probability p_0^i that the ith node successfully delivers information bit 0 to the AP is derived as

$$p_0^i[N_0^i < \mu] = \int_0^{\mu} \frac{1}{\sigma_0^i \sqrt{2\pi}} e^{-\frac{(x-\mu_0^i)^2}{2(\sigma_0^i)^2}} dx, \tag{5}$$

where the threshold $\mu = (\mu_0^i + \mu_1^i)/2$. Similarly, the probability that the ith node successfully delivers information bit 1 to the AP is derived as

$$p_1^i[N_1^i \geq \mu] = \int_{\mu}^{\infty} \frac{1}{\sigma_1^i \sqrt{2\pi}} e^{-\frac{(x-\mu_1^i)^2}{2(\sigma_1^i)^2}} dx. \tag{6}$$

The MC channel transition matrix can be defined with the probability metrics P_A, p_0^i, and p_1^i. The mutual information of the ith node MI^i and the capacity per user (or average channel capacity) C between the ith node and AP over the QS-based multiple access channel are respectively represented as (where $H(\bullet)$ denotes the entropy and MI_a denotes the mutual information per user)

$$\begin{aligned} MI^i = H&\left[P_A p_1^i + (1-P_A)(1-p_0^i), P_A(1-p_1^i) + (1-P_A)p_0^i\right] \\ &- \left[P_A H(p^{i_1}, 1-p^{i_1}) + (1-P_A) H(p^{i_0}, 1-p_0^i)\right], \end{aligned} \tag{7}$$

$$C = \max(MI_a) = \max\left(\sum_{i=1}^{I} MI^i / I\right). \tag{8}$$

Ⅲ. Simulation Results

For simplicity, consider that I TNs are placed at an average distance d $(=\Sigma_i d^i/I)$ from the AP. Assume that the transmitter node i emits AI either at a low rate $(n_0=5000)$ or at a high rate $(n_1=15000)$ during $t_s=10\,ms$. Assume that D is $0.04\,nm^2$ at $310^\circ K$.

Fig. 1 shows MI_a versus P_A as d varies, where $I=15$ is assumed. The numerical results show that the average channel capacity C is 0.3457 when $P_A=0.4$ and $d=150\,nm$. We can observe that C decreases (almost) linearly due to the concentration diffusion loss when $d \geq 200nm$. However, when $d=100nm$, C decreases a little bit due to the proximity factor of the TNs (similar tendency is observed for the different I).

Fig. 2 shows MI_a versus P_A, when assuming $d=200nm$. We achieve the average capacity $C$is 0.3861, especially at $P_A=0.4$ and $I=2$. Note that due to the channel contention factor, C is degraded when $I>2$ and is converged when $I\geq 5$; it implies that in the typical environment ($I \gg 1$), C is not much affected by k.

Fig. 3 displays the proposed system BER versus E_b/N_0 (dB), with the variation of I. Assume $d=200nm$. At the AP receiver, we employ a maximum likelihood (ML) detector for the ith node signal recovery, where the threshold of the ML detector is defined as

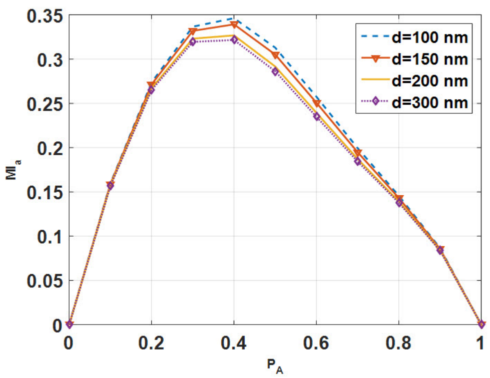

Fig. 1. Mutual information per node MI_a versus P_A with the variation of d

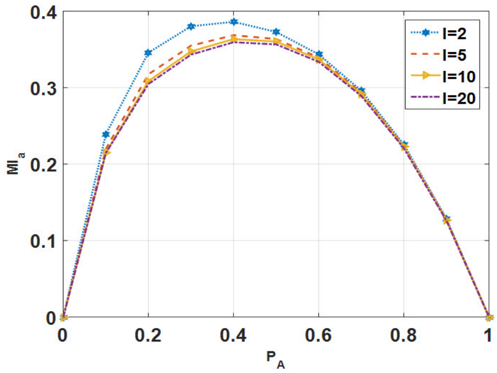

Fig. 2. Mutual information per node MI_a versus P_A with the variation of I

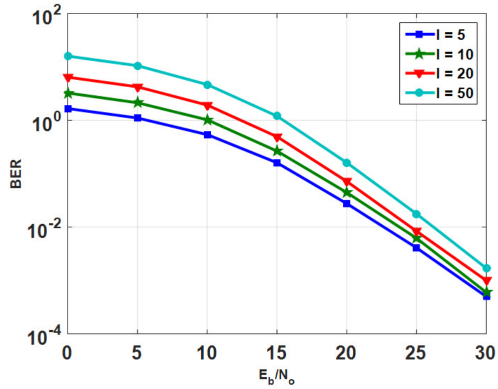

Fig. 3. BER versus E_b/N_0

$$T=2\log\left(\sigma_1^i/\sigma_0^i\right). \tag{9}$$

In the ML detector, if the size of the ith node signalling molecules sensed by the AP receptor is larger than T, then the information bit 1 is recovered. Otherwise, the information bit 0 is recovered. Fig. 3 confirms that as I increases, the BER performance is deteriorated. This indicates that the contention factor k may limit the system performance.

Ⅳ. Conclusion

We have constructed a QS-based MAN over MC channels and analyzed its average channel capacity and BER, especially focusing on the system performance effect of the channel contention factor k and average distance d.

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