Please use the complete citation as given below:
M.U. Mahfuz, D. Makrakis, and H. Mouftah, "On the Detection of Binary Concentration-Encoded Unicast Molecular Communication in Nanonetworks," in Proc. 4th International Conference on Bio-inspired Systems and Signal Processing (BIOSIGNALS-2011), Rome, Italy, 26-29 January, 2011, pp. 446-449.

ON THE DETECTION OF BINARY CONCENTRATION-ENCODED UNICAST MOLECULAR COMMUNICATION IN NANONETWORKS

Mohammad Upal Mahfuz, Dimitrios Makrakis and Hussein Mouftah
School of Information Technology and Engineering, University of Ottawa, K1N6N5 Ontario, Canada
{mmahf050, mouftah}@uottawa.ca, dimitris@site.uottawa.ca

Keywords: Molecular communication, Concentration encoding, Sampling-based detection, Energy-based detection, Nanonetworks.

Abstract: Molecular communication is a new communication technique where transmitter and receiver communicate by transmitting molecules and correspondingly modulating their specific characteristics. Molecular communication is being considered as a new physical layer (PHY) option for a vast number of communicating nanomachines that form "nanonetworks." Thus it has become a promising option for a large number of new applications, offering several benefits over conventional electromagnetic communications based on radio waves or optics at nanoscale dimension. Concentration-encoding is a simple and good technique to encode information with molecules. Incorrect detection of concentration-encoded signals makes molecular communication a real challenge. This paper has addressed sampling-based and energy-based detection approaches in detail for binary concentration-encoded molecular communication signals based on diffusion in fluidic media.

1 INTRODUCTION

Molecular communication is a new physical layer option that is being considered for communication and networking among a huge number of natural and man-made nanomachines (Akyildiz et al. 2008, Mahfuz et al. 2010a, Mahfuz et al. 2010b). A nanomachine is a tiny machine capable of performing simple tasks e.g. sensing and actuation. As shown in Fig.1 a transmitting nanomachine (TN) transmits molecules in a fluidic medium, the molecules propagate in the medium following the diffusion process, and then finally the molecules are received by the receiving nanomachine (RN). Detection of concentration-encoded molecular signals is very crucial in the sense that incorrect detection of concentration-encoded signals would result in wrong decoded bit, thus producing bit errors, and finally the effect / reaction performed by the RN would be erroneous. In this paper we have explained two detection approaches, named "sampling-based detection (SD)" and "energy-based detection (ED)," for binary concentration-encoded molecular communication in order to detect the information bits transmitted by TN and that are available at the location of RN in the form of received throughput of the molecular propagation channel. We have also shown threshold characteristics for "known-reference" and "blind-reference" cases for bit detection. In the former case, RN knows the average transmission rate used by TN (in molecules/second) beforehand, and thus RN can compute the threshold concentration as a function of known transmission rate for a given distance between TN and RN. On the other hand, in blind-reference case RN does not know the transmission rate of molecules beforehand, and so RN computes the threshold concentration as a function of available throughput at its own location. Although threshold computation is an important aspect for molecular communication, it has not been addressed in depth so far in open literature. The paper is organized as follows: section-2 briefly discusses the throughput of the channel, followed by section-3 discussing the fundamental concepts of sampling-based (SD) and energy-based (ED) detection methods for the amplitude modulated concentration-encoded signal. Finally, section-4 concludes the paper.

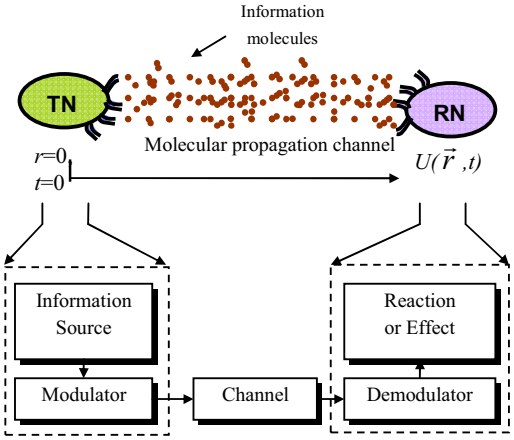


Figure 1: A generic molecular communication channel between a transmitting nanomachine (TN) and a receiving nanomachine (RN).

2 PROPAGATION OF MOLECULES

We have assumed binary amplitude modulation for the concentration-encoded signal. We assume that TN is a nanomachine or a biological entity that can emit only one kind of molecule. We consider hypothesis H_1 as the case when bit '1' is to be transmitted, and hypothesis H_0 as the case when bit '0' is to be transmitted. Correspondingly, TN transmits $Q_{average}$ molecules per second on an average for the entire bit duration of T_b seconds for H_1, while TN does not transmit any molecules at all for H_0. As shown in Fig.2, transmission stimulation protocol can be expressed as

$$Q(t) = \begin{cases} Q_{average} \; ; \; H_1 \\ 0 \;\; ; \;\; H_0 \end{cases} \tag{1}$$

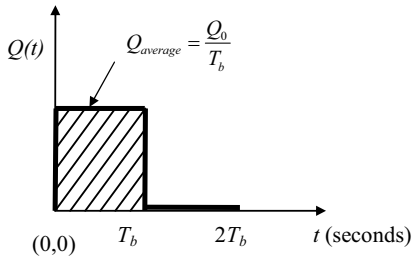
Assuming a point source type TN the concentration of molecules $U(r,t)$ in molecules per unit volume at a three-dimensional space $\vec{r} = \hat{i} \cdot x + \hat{j} \cdot y + \hat{k} \cdot z$ and at time t changes with time and space as the well-known Roberts equation (Bossert and Wilson 1963) as shown below

$$U(x,y,z,t) = \int_0^t \frac{Q(\tau)}{\{4\pi D(t-\tau)\}^{\frac{3}{2}}} \cdot e^{\frac{-\left(x^2+y^2+z^2\right)}{4D(t-\tau)}} d\tau \tag{2}$$

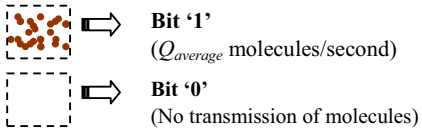
where $\vec{r}$ is the distance vector between TN and RN, τ is a dummy variable of integration, and D is the diffusion constant of information molecules in the medium in cm^2/second unit. Considering spherical symmetry Eq.(2) can be written as a function of r (in cm) as (Berg 1993).

$$U(r,t) = \int_0^t \frac{Q(\tau)}{\{4\pi D(t-\tau)\}^{\frac{3}{2}}} \cdot e^{\frac{-r^2}{4D(t-\tau)}} d\tau \tag{3}$$

where $r^2=x^2+y^2+z^2$ when a Cartesian coordinate system is assumed. In a simple manner $U(r,t)$ is also known as the throughput of the molecular propagation channel.



(a) Input stimulation protocol



(b) Binary modulation of transmission rate

Figure 2: Binary concentration-encoded molecular signalling, Q_0 representing the total number of molecules transmitted by TN during T_b.

3 DETECTION APPROACHES

3.1 Sampling-based Detection (SD)

As shown in Fig.3 with SD approach the propagation channel is excited with a random bit sequence of N bits transmitted by the TN, and correspondingly the throughput $U(r,t)$ is sampled at any suitable time instant during the bit duration T_b. However, with the assumption that TN is in time-synchronization with RN we assume that the sampling instants are at exactly the middle of any bit duration and thus can be expressed as

$$t_{\text{Samples}} = \frac{T_b}{2}, \frac{3T_b}{2}, \frac{5T_b}{2}, \ldots\ldots, \frac{(2n-1)T_b}{2}, \ldots \ldots, \frac{(2N-1)T_b}{2} \tag{4}$$

where N is the total number of bits in the bit sequence, T_b is the duration of each bit, and $n = 1, 2, 3, ..., N$ is the index of bits. As a result, the detection variable or test statistic (Kay 1998) Z_{SD} for detecting the n^{th} bit is denoted as

$$Z_{SD} = U\left[r, \frac{(2n-1)T_b}{2} \right]. \quad (5)$$

For a given data rate f, bit duration is fixed at T_b=1/f. However, since throughput $U(r,t)$ received at the location of RN largely depends on the distance r (Mahfuz et al. 2010b), Z_{SD} is a function of both distance r and diffusion constant D. For all practical reasons assuming D to remain constant over the entire observation period T, we find that Z_{SD} becomes significantly affected by r. For known-reference SD approach, RN has prior knowledge of the transmission rate of input (i.e. $Q(t)=Q_{average}$), and thus the most common threshold can be given as

$$K_{\mathrm{SD}}^{\mathrm{Known}} = \frac{Q_{average}}{2} \quad (6)$$

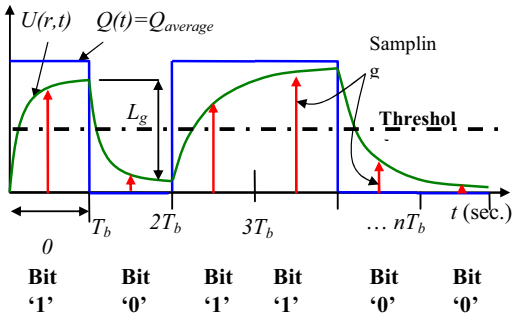


Figure 3: Sampling based (SD) detection for transmitted bits {101100}. Sampling instants are shown in red arrows, L_g denoting the level gap between maximum and minimum points of $U(r,t)$ when a bit toggles.

Since Z_{SD} is significantly affected by r, known-reference SD approach should be used in short-range molecular communication (Mahfuz et al. 2010b). Threshold for blind reference case is given below as the average throughput $U(r,t)$ over the interval from 0 to $2T_b$ seconds as shown in transmission protocol in Fig.2,

$$K_{\mathrm{SD}}^{\mathrm{Blind}} = \text{Average}\left\{U(r,t)\right\}\Big|_{\text{over time duration 0 to } 2T_b} \quad (7)$$

However, $K_{\mathrm{SD}}^{\mathrm{Blind}}$ is highly influenced by r as shown in Fig.4 below.

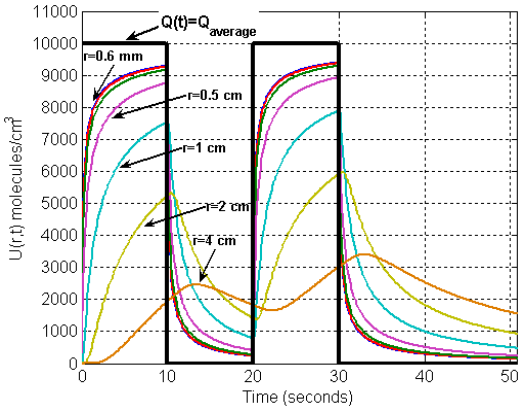


Figure 4: Distance dependence of throughput, with $Q_{average}$=10,000 molecules/sec., T_b=10 seconds, random bit sequence {10100} in air medium.

3.2 Energy-based Detection (ED)

As shown in Fig.5 with ED approach available throughput $U(r,t)$ in molecules per unit volume is integrated over any entire bit duration T_b seconds and the resulting accumulated amount of molecules is termed as the detection variable Z_{ED} for the corresponding bit and expressed as

$$Z_{ED}(n) = \int_{(n-1)T_b}^{nT_b} U(r,t)\,dt \quad (8)$$

where $n = 1, 2, 3, ..., N$ is the index of the bit and N is the total number of bits in the random bit sequence. Referring to Fig.2, in known-reference ED approach RN detects a bit when the accumulated molecules during T_b is greater than or equal to the threshold $K_{\mathrm{ED}}^{\mathrm{Known}}$ that is most commonly the half of the total transmitted energy during 0 to $2T_b$ seconds as shown below

$$K_{\mathrm{ED}}^{\mathrm{Known}} = \frac{\int_0^{2T_b} Q(t)\,dt}{2} = \frac{Q_{average}T_b}{2} \quad (9)$$

The threshold given by Eq.(9) is independent of r, however, as shown in Fig.4 the throughput $U(r,t)$ is highly influenced by the variation of distance r. As a result, this distance-dependence of throughput makes the threshold selection inappropriate for known-reference ED approach. On the other hand, in blind-reference ED approach RN does not know the transmission rate of TN. As a result, RN can compute the threshold as the average integral of throughput for the duration from 0 to $2T_b$ as shown in Fig.2.

Thus the threshold for blind-reference case can be expressed as

$$K_{\mathrm{ED}}^{\mathrm{Blind}} = \frac{\int_0^{2T_b} U(r,t)dt}{2} \tag{10}$$

as shown in the transmission protocol in Fig.2. As shown in Fig.4 since throughput *U(r,t)* varies with the varying distance, threshold in blind-reference case should vary as per the variation of the distance between TN and RN.

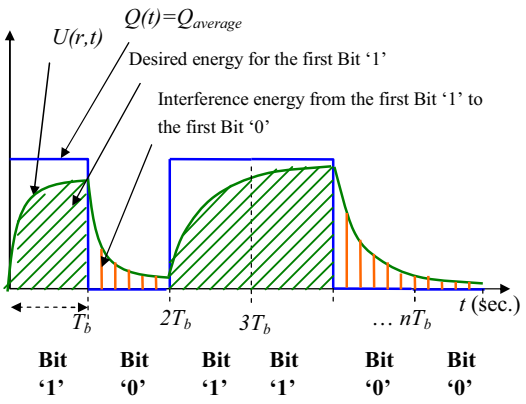


Figure 5: Concept of energy-based detection with a random bit sequence {101100}.

4 CONCLUSIONS

In this paper detection methods for binary concentration-encoded molecular communication channel has been addressed. Sampling-based and energy-based detection methods have been proposed as possible detection schemes for concentration-encoded signals. Three important factors that affect the performance of detection methods are *noise immunity*, *distance-dependence of throughput*, and *timing synchronization of TN and RN*. The SD approach detects the bit based on only one sample value of the throughput taken at the sampling instant. Thus SD approach is applicable for ideal environment and for short ranges, and so it is not recommended for most real cases where the communication is impaired with noise and/or for medium-to-long range communications. Since throughput varies with varying distance a fixed threshold for known-reference case tends to be a strict selection, whereas for blind-reference case RN has to compute the threshold from the throughput only, making the threshold highly dependent on the distance between TN and RN. Finally, timing synchronization can be achieved by correctly characterizing the propagation delay between TN and RN. While a synchronizing clock for molecular communication can be difficult, asynchronous signalling (Moore et al. 2007) can also be used for the purpose of detection of molecular signals.

ACKNOWLEDGEMENTS

The first author would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for the financial support in the form of doctoral scholarship to carry out this research work.

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