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An optimal decoding algorithm for Molecular Communications systems with noise, memory, and pulse width

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HIGHLIGHTS

- A new optimal decoding algorithm mitigates the effect of channel memory and noise.
- Channel memory, noise, and emission pulse width are considered within the model.
- Performance with regards to the bit error rate and capacity is shown.
- Distance measuring schemes are a critical part of performance analysis.

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ABSTRACT

Molecular Communications (MC) is a promising paradigm to achieve message exchange between nano-machines. Due to the specific characteristics of MC systems, the channel noise and memory significantly influence the MC system performance. Aiming to mitigate the impact of these two factors, an adaptive decoding algorithm is proposed by optimising the symbol determination threshold. In this paper, this novel decoding scheme is deployed onto a concentration-based MC system with the transmitter emission process considered. To evaluate the performance, an information theoretical approach is developed to derive the Bit Error Rate (BER) and the channel capacity. Simulations are also carried out to verify the accuracy of these formulations, to compare the performance difference against other decoding schemes, and to illustrate the performance deviation caused by different designing of relevant parameters. Furthermore, the performance of MC systems with the distance unknown is also analysed. Comparisons between distance-pre-known and distance-unknown systems are provided.

1. Introduction

Molecular communications (MC) is an increasingly attractive idea, aiming to enable the networking of nano-machines. Molecules, encoded by the transmitter nano-machine (TN), propagate to the receiver nano-machine (RN) to accomplish the exchange of information. Such information can be expressed by either the number of certain molecules or the molecular concentration. In the first case, in [1–4], researchers focused on the movement of individual molecules. There exists a certain probability for diffusing molecules to be captured by the RN, and the capture probability is utilised to describe the propagation mechanism. The RN is an active absorber, which can catch and remove the received molecules from the environment.

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By counting the number of captured molecules, the RN determines the information symbols. In the second case shown in [5–8], attention has been paid to the molecular concentration. After being released from the TN, molecules will form a certain concentration distribution in the environment. The RN is assumed as a passive observer, which can sense the surrounding concentration to decode the message symbols without affecting the molecular distribution. No matter which way is chosen to express the information, the system performance is significantly impacted by the channel noise and memory. In order to alleviate the influence of these two factors, the decoding threshold of the RN should be optimised by considering previously transmitted symbols. Thus, an adaptive algorithm will be of great benefit to enhance the MC system performance by reducing the Bit Error Rate (BER) and improving the channel capacity.

By utilising amplitude modulation schemes, the decoding strategy of the RN is to compare the received molecular signal to a pre-designed threshold to determine whether '1' or '0' was transmitted. According to the adaptivity of the threshold, research analysing the MC system performance can be sorted into two classifications. In the first category, the threshold stays constant throughout the communication process. The MC system property with a fixed threshold was characterised in [1], and expanded in [2,9] by taking the channel memory into consideration. Additionally, in [5,10–15], research that focused on modulation schemes and/or noise modelling, also provided theoretical approaches to evaluate the performance of MC systems with fixed thresholds. In these studies, messages were conveyed by the number of absorbed molecules, and the TN emission process was neglected by assuming that molecules were released simultaneously. As to the work considering the emission procedure [6,16,17], information was expressed by the molecular concentration. However, in these research, only simulations are carried out, rather than deriving mathematical expressions to study the MC system. In the second category, the decoding threshold varies depending on previously received symbols. In [4], the value of the threshold is designed to maximise a posteriori probability, but the system model should be refined by considering the emission effect. Other research such as [18,19] has taken the emission process into account, and the threshold changes with regards to the previously decoded bits. However, the threshold should be further optimised to mitigate the influence of the channel memory and noise. Moreover, the impact of the channel memory still requires further investigation.

In this paper, the following contributions are presented. First, a new decoding algorithm is proposed by optimising the threshold with the aid of previously determined symbols. The optimal threshold is derived by a mathematical approach to minimise the BER of the MC system. Accordingly, expressions of the BER and capacity are obtained. Meanwhile, the impact of the TN emission over time is considered and the influence of the channel noise and memory is also clarified. Second, the impact of the ISI is further investigated even though it has been alleviated. For theoretical deviations, ISI length is treated as an arbitrary value to maximise the generality. For simulations it is set to a length of 20 such that results are of as high a precision as is reasonably practical. Third, this is the first paper to consider the distance estimation when analysing the MC channel. Before the communication is established, the RN measures the distance between the TN and itself, so that the RN can determine the sampling time and judging conditions correspondingly. The accuracy of the distance estimation will significantly affect the system performance.

The remainder of this paper is organised as follows. In Section 2 the communication model is introduced as well as the system structure. The new decoding algorithm and channel performance are presented in Section 3. Numerical results are provided in Section 4. Finally in Section 5, the paper is concluded.

2. The concentration-based molecular communications model

As is illustrated in Fig. 1, the concentration-based MC system consists of two nano-machines, one of which, represented as Nano-machine A (NA), is viewed as the source nano-machine and the other, represented as Nano-machine B (NB), is viewed as the target nano-machine. In the first stage, before the communications between NA and NB are established, the NA emits a pulse of certain molecules (denoted as Molecule_1) to enable the NB to estimate the distance. Accordingly, the NB can adjust the sampling time and set the judging condition to determine whether '1' or '0' is transmitted. There exist several distance estimation schemes, such as those shown in [18,20,21]. In this paper, the scheme employing the peak concentration time to estimate the distance, proposed in [18], is selected for two reasons. Firstly, this scheme is implemented based on the same propagation model as the one utilised in this paper, which will be introduced later. Secondly, this scheme provides a sufficiently accurate estimation, and is easy to implement due to its simplicity.

In the second stage of the communication process, the NA encodes information symbols into the concentration of another kind of molecule (denoted Molecule_2). Two kinds of molecules are utilised so that the distribution of 'estimation' molecules will not affect that of 'message' molecules. To transmit bit '1', the NA releases a certain amount of Molecule_2; to transmit bit '0', the NA stays quiet. The NB determines incoming messages by sensing the concentration around itself to a pre-designed threshold. In contrast to existing research, the design of the threshold is optimised by considering previous decoded symbols, which will be introduced later. Similar to the work in [6–8,18,22,23], the concentration at the NB can be considered as the concentration at the centre of the sensing sphere.

The molecule concentration in a 3D environment is obtained by solving Fick's laws of diffusion, which can be regarded as the impulse response for the 3D diffusive channel [8,22]:

$$h(d,t) = \frac{1}{(4\pi tD)^{3/2}} \exp\left(-\frac{d^2}{4tD}\right), \tag{1}$$

where d is the distance between the NA and NB (in μm), t is time (in μs), and D is the diffusion coefficient (in $\mu m^2\ \mu s^{-1}$).