One Symbol Blind Synchronization in SIMO Molecular Communication Systems

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***Abstract*—Molecular communication offers new possibilities in the micro- and nano-scale application environments. Similar to other communication paradigms, molecular communication also requires clock synchronization between the transmitter and the receiver nanomachine in many time- and control-sensitive applications. This letter presents a novel high-efficiency blind clock synchronization mechanism. Without knowing the channel parameters of the diffusion coefficient and the transmitter-receiver distance, the receiver only requires one symbol to achieve synchronization. The samples are used to estimate the propagation delay by least square method and achieve clock synchronization. Single-input multiple-output (SIMO) diversity design is then proposed to mitigate channel noise and therefore to improve the synchronization accuracy. The simulation results show that the proposed clock synchronization mechanism has a good performance and may help chronopharmaceutical drug delivery applications.**

***Index Terms*—Clock synchronization, molecular communication, multiple antennas, nanomachine.**

I. Introduction

MOLECULAR communication attracts great interest from academia in recent years. It uses molecules as the carrier of information to transmit and receive message between nanomachines at the micro- or nano- scale [1]. Molecular communication has potential applications in the fields of biomedical engineering, material manufacturing, etc. For example, it can be used for drug delivery or cancer treatment, or several nanomachines can interconnect with each other, forming a nanonetwork, to monitor the quality of materials in manufacturing.

Clock synchronization is essential and necessary for molecular communication systems and control mechanisms, where sensitive feedback loops exist. For example, in a nanonetwork, the nanomachines with clock synchronization can cooperate to perform tasks such as releasing drugs to attack cancer cells at the same time. If the clocks are not synchronized, close stability between drug delivery and response in chronopharmaceutical applications may be lost [2]. In [3], based on the assumption of the synchronization, signal detections are proposed for mobile molecular communication. In [4], the nanomachines are assumed to be synchronized for distance estimation by a two-way message exchange protocol.

However, the clocks among nanomachines are not synchronized automatically. Algorithms are required to realize the clock synchronization. In [5], nanomachines release a kind of molecules called inducer. The inducer molecules can trigger other nanomachines to release the same kind molecules. When the concentration of the inducer in the environment reaches a certain threshold, the entire nanonetwork achieves the clock synchronization. A similar mechanism is proposed in [6], where the nanomachines release inhibitory molecules. These molecules inhibit the release of the same kind of molecules by other nanomachines. When the concentration of the molecules falls below a certain threshold, the molecules can be released again. The molecule releasing pulses form the clock synchronization pattern. In [7], a blind synchronization algorithm is proposed using non-decision directed maximum likelihood. The channel delay is estimated by the receiver based on the concentration samples of previous symbols, and the clock sequence is calculated. Reference [8–10] use maximum likelihood estimation to synchronize the times of two nanomachines. The time instant values are sent in one-way or two-way communications. The probability density function of the propagation delay is assumed to be known. The clock offset and/or the clock skew between the nanomachines are estimated. Reference [7–10] utilize multiple symbol transmissions, which leads to slow convergence.

In contrast to [7–10], which utilized low efficiency multiple symbol transmissions, this letter motivates the use of single symbol transmission to realize clock synchronization. The receiver samples the number of observed molecules in the symbol temporally and spatially to calculate the propagation delay and achieve the clock synchronization. Although [11] also considers synchronization problem using one symbol information, the channel parameters such as diffusion coefficient and transmitter-receiver distance have to be known in advance for the clock synchronization. The major contributions of the letter include: 1) A clock synchronization mechanism using only one symbol transmission is proposed. Without knowing the parameters of the diffusion coefficient and the transmitter-receiver distance, the receiver samples the waveform of the impulse response temporally to estimate the propagation delay and further achieve the clock synchronization. 2) Single-input multiple-output (SIMO) diversity design against channel noise

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is proposed to improve the synchronization accuracy.

The rest of the letter is organized as follows. Section II presents the system model. The clock synchronization scheme and the method of mitigating the influence of noise is proposed in Section III. The simulation results are presented and discussed in Section IV. Finally the conclusion is drawn in Section V.

II. System Model

It is supposed that there are two fixed nanomachines, one transmitter and one receiver with perfect clock frequency, in a 3-D environment as shown in Fig. 1. The receiver is assumed to have multiple spherical receiving antennas, each with a radius of ρ. The idea of molecular SIMO or multiple-input multiple-output (MIMO) systems is from [12]. There are two kinds of receiving mechanism, passive and absorbing [13]. In this paper, the receiving antenna is a passive type optical device using high frequency spectrum analysis to observe the number of molecules but does not impede the diffusion of the molecules. The distance between the two nanomachines is assumed to be large enough compared with the size of the receiver (the relationship between the radius of the receiver r_{Rx} and the transmitter-receiver distance d_{TxRx} satisfies $\frac{r_{\text{Rx}}}{d_{\text{TxRx}}} \ll 10^{-1}$), therefore the distance between the transmitter and every single receiving antenna is assumed to be the same. Then it is reasonable to assume that statistically different diffusion processes from the transmitter take place.

M-ary molecular shift keying (MoSK) in [14] is adopted to our system. Each molecule is composed of a header, a trailer, and *n* chemical bit elements. All these parts are linked using chemical bonds. Theoretically, there is no limit on the number of chemical bit elements, so we assume that the modulation order *M* can be infinite. The transmitter sends *Q* molecules at a time. The impulse response at each receiving antenna can be expressed as [15]

$$N(t) = \frac{V_R Q}{(4\pi D t)^{3/2}} \exp\left(-\frac{d^2}{4Dt}\right), \tag{1}$$

where $N(t)$ represents the average number of observed molecules at time t, d is the distance from the transmitter to the receiving antenna, D is the diffusion coefficient, $V_R = 4/3\pi\rho^3$ is the volume of the spherical receiving antenna.

In the real scenario, the molecular concentration is influenced by two kinds of noises.

1) Brownian noise: the molecules walk randomly in the environment presenting the noise to the receiver's observations. In [15, 16], it was demonstrated that the Gaussian distributed additive noise with zero mean is a reasonable approximation. In the molecular communication, the noise is non-stationary and signal dependent [17]. The noise variance is proportional to the signal amplitude which constantly changes with time. The Brownian noise can be denoted as $n_b(t) \sim \mathcal{N}(0, \sigma^2(t))$, where $\sigma^2(t)$ is the variance of $n_b(t)$.
2) Residual noise: the remaining molecules of previous transmission have an influence on the concentration distribution of the newly released molecules, which causes inter-symbol interference (ISI). The interval between two consecutive clock synchronization behaviors is usually relatively big, so the influence of the ISI can be neglected.

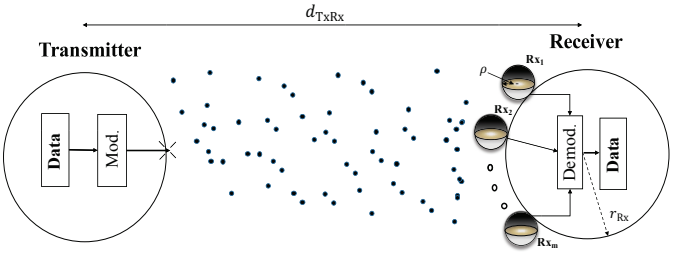

Fig. 1. System model. The fixed transmitter and receiver are located in the environment. The transmitter releases information molecules. These molecules diffuse based on Brownian motion. The receiver with multiple antennas can observe the number of molecules.

The number of observed molecules at different receiving antennas (Rx_1, Rx_2, ..., Rx_m) can be expressed as

$$\begin{bmatrix} N_1'(t) \\ N_2'(t) \\ \vdots \\ N_m'(t) \end{bmatrix} = N(t)\mathbf{1}_m^{\text{T}} + \begin{bmatrix} n_{b_1}(t) \\ n_{b_2}(t) \\ \vdots \\ n_{b_m}(t) \end{bmatrix}, \tag{2}$$

where m is the number of receiving antennas. $\mathbf{1}_m$ is the $1 \times m$ vector with all values equal to 1. Superscript T is vector transpose. $n_{b_1}(t), n_{b_2}(t), \ldots, n_{b_m}(t)$ can be considered independent and identically distributed random noise.

III. Clock Synchronization Scheme

For the clock synchronization, the transmitter encodes its clock reading T_{tx} into the molecules and releases them immediately into the channel. In conventional radio communication, signal propagation is very fast. So once the receiver obtains the clock value sent by the transmitter, it immediately updates its own clock with the received clock value. In this way, the transmitter and the receiver achieve the clock synchronization. However, in molecular communication, the information molecules propagate much more slowly. Therefore, the compensation of the propagation delay for the clock synchronization is necessary. The duration between the time instant for releasing molecule by the transmitter and the time instant of the peak concentration at the receiver is defined as the propagation delay, denoted as t_{delay}. The updated clock value at the receiver side T_{rx} should be calculated as

$$T_{\text{rx}} = T_{\text{tx}} + t_{\text{delay}}, \tag{3}$$

where T_{tx} is the molecule releasing time instant according to the clock of the transmitter. The key for the clock synchronization is to calculate t_{delay}.

A. Clock Synchronization Scheme in the Absence of Noise

As stated above, the propagation delay is the duration between the time instant for releasing molecules by the transmitter and the time instant of the peak concentration at the

receiver. In the absence of noise, to calculate t_{delay}, we take derivative of $N(t)$ in (1) with respect to t, and set it to zero. We obtain

$$t_{\text{delay}} = \frac{d^2}{6D}. \tag{4}$$

The receiver can calculate t_{delay} provided that it knows D and d. However, in the real molecular communication system, the nanomachines most probably do not know these parameters. Hence, we are motivated to take several samples of the number of observed molecules temporally to calculate the unknown parameters. For a sample $(t_i, N_i(t_i))$, it is not a solution for (1), because the transmitter and the receiver are not synchronized when sampling. Therefore, (1) is modified in the form as

$$N(t) = \frac{V_R Q}{(4\pi D(t-t_0))^{3/2}} \exp\left(-\frac{d^2}{4D(t-t_0)}\right), \tag{5}$$

where the time instant for molecule releasing is t_0. t_0 is a clock value based on the receiver's system clock.

Since there are three unknown parameters D, d, and t_0 in (5), the receiver takes three samples $N(t_1)$, $N(t_2)$, and $N(t_3)$. We have a system of equations as

$$\begin{cases} N(t_1) = \dfrac{V_R Q}{(4\pi D(t_1-t_0))^{3/2}} \exp\left(-\dfrac{d^2}{4D(t_1-t_0)}\right) \\ N(t_2) = \dfrac{V_R Q}{(4\pi D(t_2-t_0))^{3/2}} \exp\left(-\dfrac{d^2}{4D(t_2-t_0)}\right) \\ N(t_3) = \dfrac{V_R Q}{(4\pi D(t_3-t_0))^{3/2}} \exp\left(-\dfrac{d^2}{4D(t_3-t_0)}\right). \end{cases} \tag{6}$$

One can use least square method to do the approximation:

$$\{\hat{D}, \hat{d}, \hat{t}_0\} = \arg\min_{D,d,t_0} \sum_{i=1}^{3} \left(\frac{V_R Q}{(4\pi D(t_i-t_0))^{3/2}} \exp\left(-\frac{d^2}{4D(t_i-t_0)}\right) - N(t_i) \right)^2. \tag{7}$$

Then $\{\hat{D}, \hat{d}\}$ are put back into (4). t_{delay} can be obtained. Finally, the receiver updates its local clock by (3).

B. Molecular SIMO for Mitigating the Influence of Noise

As stated in Section II, the additive Gaussian noise is considered in the channel. To mitigate the influence of the noise, we use the multiple receiving antennas to get samples spatially and take average of them. According to (2), we get

$$\bar{N}(t_i) = \frac{1}{m}\sum_{j=1}^{m} N_j^{'}(t_i) = N(t_i) + \frac{1}{m}\sum_{j=1}^{m} n_{b_j}(t_i), \tag{8}$$

where $\bar{N}(t_i)$ represents the average number of observed molecules of the antennas for the *i*th temporal sample. $N_j^{'}(t_i)$ represents the number of observed molecules at the *j*th antenna for the *i*th temporal sample which is composed of $N(t_i)$ and $n_{b_j}(t_i)$. $N(t_i)$ is the theoretically molecular number at time t_i. $n_{b_j}(t_i)$ is the corresponding noise. Because $n_{b_j}(t_i)$ is independent and identically distributed Gaussian noise for $j = 1, 2, \ldots, m$, $\frac{1}{m}\sum_{j=1}^{m} n_{b_j}(t_i)$ approaches zero as the number of the antennas tends to infinity. In this way the noise is mitigated. Taking $\{(t_i, \bar{N}(t_i))\}_{i=1}^{3}$ into the scheme proposed in Section III-A, one can accurately estimate the propagation delay and achieve the clock synchronization.

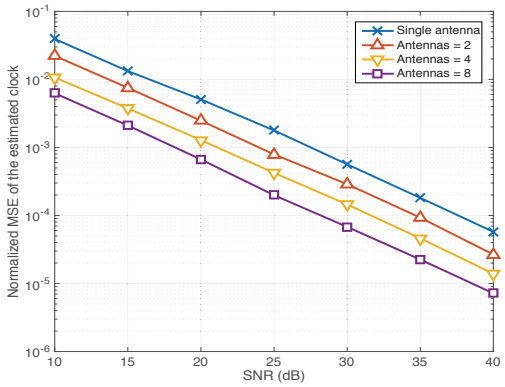

Fig. 2. The normalized MSE of the estimated clock with respect to the SNR for different numbers of antennas.

IV. Simulation Results

In this section, simulations by MATLAB are performed to evaluate the performances of the proposed scheme. In addition, the influences of different channel parameters and the number of antennas on the synchronization accuracy are analyzed.

The parameters used in the simulations are set as follows. The number of antennas is selected from 1 to 8. The average signal to noise ratio (SNR), which is related to the number of molecules released by the transmitter Q [17], is set from 10 dB to 40 dB. It is calculated by

$$\text{SNR} = \frac{P_s}{P_n} = \frac{\frac{1}{T_s}\int_0^{T_s} N^2(t)dt}{E(\sigma^2)} = \frac{\int_0^{T_s} N^2(t)dt}{\int_0^{T_s} N(t)dt}, \tag{9}$$

where P_s is the averaged signal power at the receiver which is defined as the average squared number of observed molecules. P_n is noise power. Since only one symbol transmission is used, T_s is set as a large value (10^4 ms is used in the simulations). The distance between the two nanomachines is set from 100 to 200 μm. The diffusion coefficient is set from 9 to 11 μm^2/ms [11]. The antenna radius is 5 μm. The sampling time is uniformly chosen within the time interval $(0, 5 \times t_{\text{delay}})$ for each run. Because different channels will be evaluated, we discuss the accuracy in terms of the normalized mean square error (MSE) of the estimated clock.

Fig. 2 describes the normalized MSE of the estimated clock versus the SNR for different numbers of antennas in the presence of noise. The parameters are: $D = 10\,\mu$m^2/ms, $d = 100\,\mu$m, the number of antennas $m = 1$ (single antenna), 2, 4, and 8. It is clear that as the increase of the SNR, the normalized MSE of the estimated clock decreases. This is because when the SNR increases, the noise in the channel becomes small and influences the concentration little. Therefore the accuracy improves. From the figure, larger m leads to

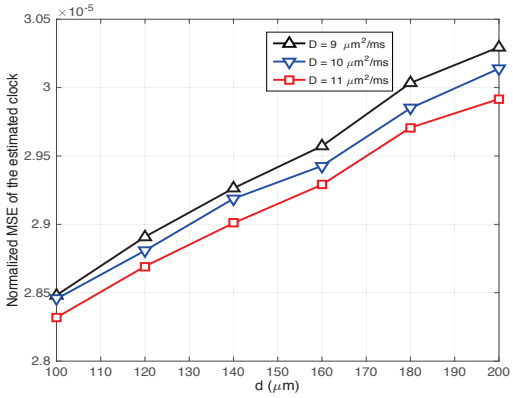

Fig. 3. The normalized MSE of the estimated clock with respect to the transmitter-receiver distance for different diffusion coefficients.

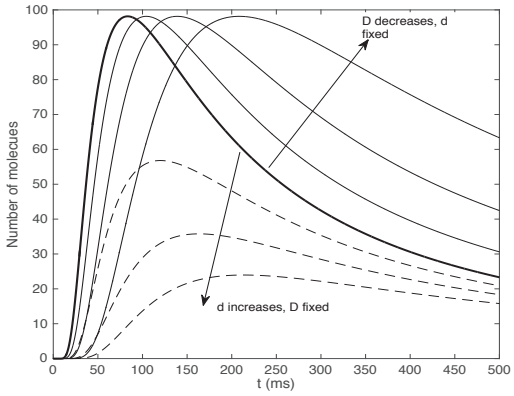

Fig. 4. Channel varying with the change of d or D.

smaller normalized MSE of the estimated clock, which proves that the SIMO scheme to mitigate the noise is effective.

In Fig. 3, the normalized MSEs of the estimated clock versus the distance between the two nanomachines for different diffusion coefficients are plotted. The parameters are: SNR = 40, $m = 2$. From the curves, the synchronization error, which is defined as the root of the normalized MSE of the estimated clock, is around 0.5%. It can be seen that as the increase of the distance, the normalized MSE of the estimated clock increases. As the increase of the diffusion coefficient, the normalized MSE of the estimated clock decreases. The reason is: if the distance is bigger or the diffusion coefficient is smaller, the impulse response becomes "flat", i.e., the channel varies more slowly, as seen in Fig. 4. Consequently, the estimations of D and d become inaccurate, and the estimation of t_{delay} becomes inaccurate. The synchronization accuracy deteriorates. In other words, a more sharply peaked curve contains more information of t_{delay}, and the estimation would be more accurate.

The proposed synchronization scheme is not compared with the existing synchronization schemes for molecular communication such as [7–10] because the fundamental system models are different. For example, in [9], the propagation delay is assumed to follow an Gaussian distribution and the probability density function is assumed to be known. However, the system model in this letter is totally different.

V. Conclusion

A blind clock synchronization mechanism using only one symbol transmission is proposed in order to improve the efficiency. Without knowing channel parameters of the diffusion channel, the receiver takes samples of the number of observed molecules from a single symbol transmission temporally and spatially with multiple receiving antennas. The samples are used to estimate the propagation delay, which is used by the receiver to update its clock. The simulation results demonstrated that the clock synchronization scheme can obtain the synchronization error of 0.5% and the SIMO diversity design is effective for mitigating the influence of the noise. It should be noted that the proposed method may be too complex for the computing ability of nanomachines. More practical approaches need to be investigated in future work.

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