Performance of Diffusion-Based MIMO Molecular Communications and Dual Threshold Algorithm

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Abstract. As the nanotechnology becomes more and more mature, the concept of molecular communication emerged and attracted lots of researchers' attention. The most widespread model for a molecular communication channel is the diffusion-based channel, where the information-carrying molecules propagate randomly in the medium based on Brownian motion. As for multi-input multi-output (MIMO) transmissions, there are not only inter-symbol interference (ISI), some molecules may arrive at the receiver after their intended time-slot, as interference. Another source of interference is the inter-link interference (ILI), which emerges when receiver receive other transmitters' molecules. In this paper, we study the bit error rate (BER) performance of a molecular communications system having two transmitters and two receiver with two receptors by considering ISI and ILI. Last, dual threshold algorithm is proposed to optimize the system BER.

Keywords: Molecular communication · Diffusion-based channel · MIMO · Dual threshold algorithm

1 Introduction

In recent years, there is more and more attention being paid to molecular communication (MC), which is defined as the molecules are used to physically carry the information [1,2]. In MC systems, nano-machines are considered as the most fundamental functional units that are able to perform simple tasks such as computation, sensing or actuation [3]. Furthermore, it proposed that The idea of forming a nanonetwork by interconnecting several nanomachines has been proposed in [4,5]. As for MC, Information can be encoded onto the molecules in different ways, such as concentration shift keying (CSK), molecular shift keying (MoSK) [6], molecular-concentration shift keying (MCSK) [7].

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Undoubtedly, multi-input multi-output (MIMO) MC system is a further study of the previous work. The performance of molecular motors in MIMO MC and result of compared with single-input single-output (SISO) MC system is proposed in [8]. Blind synchronization in SIMO molecular communication systems is studied in [9]. Reference [10] takes a summary about MIMO communications based on molecular diffusion and puts forward application of spatial multiplexing mode in MIMO firstly. Machine learning based channel modeling for molecular MIMO communications in [11] means that MIMO MC is potential to study combined with other field. And in [12], the performance of MIMO considering ISI and ILI is studied by compared with SISO, SIMO and MISO systems, where the mathematical model is established by random distribution.

In this paper, the MIMO systems model proposed in [12] is improved in being closer to reality, some of related parameters in model are studied to explain their influence to the performance with BER. Last, a dual threshold algorithm is proposed to improve the performance ulteriorly.

2 System Model

As shown in Fig. 1, the considered MIMO molecular communication system is composed of two transmitters (Tx_1 and Tx_2) and a receiver with two receptors (Rx_1 and Rx_2). Tx_1 is related to Rx_1 and unrelated to Rx_2, which means there are two interactional link. Each receptor is assumed to be spherical with radius R. The distance of related transmitter and receptor is defined as d_1, and the distance of unrelated transmitter and receptor is defined as d_2. Also, each transmitter is assumed to perfectly control the emission process of the molecules into the environment.

2.1 Fundamental Formula

CSK is the coded scheme of this system, as the two transmitters Tx_1 and Tx_2 are considered to release n_1 and n_2 molecules for transmitting the bit 1, while transmitting the bit 0 means that no molecules will be release in current slot. And in this system, transmitters are interrelated, which means transmit the same binary sequence simultaneously.

As for diffusion-based channel, due to the random motion of the released molecules in the fluid medium, the time that the molecules arrive at the receiver is probabilistic. Assuming the transmitter is located at the origin and a molecule is released at time $t = 0$, the position of the released molecule at any time t is denoted by $X(t)$, and the probability density function of $X(t)$ can be written as [12]

$$P_x(x,t) = \frac{1}{\sqrt{(4\pi Dt)^3}} exp(-\frac{x^2}{4Dt}) \tag{1}$$

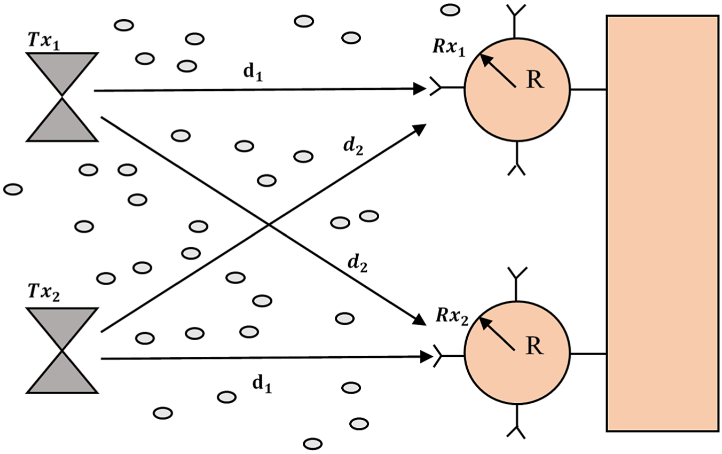

Fig. 1. Illustration of the MIMO molecular communication

where x is the distance from the transmitting node and D is the diffusion constant of information molecules in the medium in $\mu m^2/s$ unit. The probability that a molecule is absorbed by the receiver within time-slot duration t_s is also given by [12]

$$p(d, t_s) = \frac{R}{R+d} erfc(\frac{d}{\sqrt{4Dt_s}}) \tag{2}$$

where $erfc(x)$ is the complementary error function, d is the distance from the transmitter to the surface of the receiver and R is the radius of the receiver.

In view of CSK, we set that the transmitter releases n molecules into the medium for transmitting a bit 1 and no molecules to transmit a 0. Let N denote the number of molecules that are absorbed by the receiver within the time t_s. N is a random variable with binomial distribution (with n trials and $p(d, t_s)$ as a success probability) [12]; i.e.

$$N \sim B\left(n, p(d, t_s)\right) \tag{3}$$

A binomial distribution $B\left(n, p(d, t_s)\right)$ can be approximated with a normal distribution $N \sim N\left(np, np(1-p)\right)$ when p is not close to one or zero and np is large enough [12]. Under it, conditions (3) can be approximated as

$$N \sim N\left(np(d, t_s), np(d, t_s)(1 - p(d, t_s))\right) \tag{4}$$

2.2 Inter-symbol Interference

As one of interference, some of the released molecules may arrive at the receiver after their intended time-slots, which can lead to the information molecules of the subsequent transmission intervals are more than expectation, causing ISI.

A easy but faulty way of decrease ISI is setting the time slot between two transmitted bits longer. In one hand, this can effectively reduce the number of residual molecules left in the channel. On the other hand, increasing the symbol duration would also decrease transfer efficiency, which is already low compared to the classical electromagnetic channels [13]. As an alternative, signal processing and coding techniques can also be used in [14] to further mitigate the ISI.

Suppose that N_i denotes the number of molecules that were emitted i time-slots before, i.e., at $i \times t_s$ seconds before, and leak into the current time-slot. Then, according to [15], N_i is a random variable following the subtraction of two normal distributions as follows:

$$N_i \sim \frac{1}{2} N\Big(np(d,(i+1)t_s), np(d,(i+1)t_s)(1-p(d,(i+1)t_s))\Big) - \frac{1}{2} N\Big(np(d,it_s), np(d,it_s)(1-p(d,it_s))\Big) \tag{5}$$

where the factor $\frac{1}{2}$ is due to equal probability of transmission of bits 0 and 1. The first term indicates the total number of molecules that are emitted at that time-slot and absorbed by the receiver within all subsequent $i+1$ time-slots and the second term indicates those molecules that were absorbed within the subsequent i time-slots. The total ISI can be written as the sum of interference due to all previous transmissions:

$$N_{ISI} = \sum_{i=1}^{\infty} N_i \tag{6}$$

As for different accuracy requirements, we can consider a reasonable approximation for the ISI by only relating interference with k_{th} (k $= 1, 2, 3 \ldots$) time-slots as:

$$N_{ISI,1} \sim \frac{1}{2} \sum_{m=2}^{k+1} N\Big(n_1 p(d_1,(m+1)t_s), n_1 p(d_1,(m+1)t_s)(1-p(d_1,(m+1)t_s))\Big) - N\Big(n_1 p(d_1, mt_s), n_1 p(d_1, mt_s)(1-p(d_1, mt_s))\Big) \tag{7}$$

where all of these formulas only take into account when $k > 2$, as the formulas of $k \leq 2$ are easy to deduce.

2.3 ILI

As the other of interference, the molecules released from the transmitter propagate randomly in the fluid medium based on diffusion, which cause that those molecules may reach at disrelated receptor and are absorbed by it. Both transmitters are considered to transmit independent information and similar to the SISO system, and the arrival times of the molecules at receiving side follow the Brownian motion model. Since that the transmitters release the molecules simultaneously and they are identical and indistinguishable, each receptor also suffers from the ILI, which means that the interference due to all transmitted symbols of the disrelated transmitter.

Similarly, k_{th} time-slots are considered for the ILI as a reasonable approximation. However, the different way of the ISI and the ILI is that the ISI just need consider past time-slots, while one of time-slots the ILI considered is the current time-slot. Let us define $N_{ILI,0,2}$ as the distribution of the ILI from Tx_2 to Rx_1, if the current transmitted bits from Tx_2 are 0. Then, the distribution of the ILI becomes:

$$\begin{aligned} N_{ILI,0,2} \sim \frac{1}{2}\sum_{m=2}^{k} N\bigg(& n_2 p(d_2, mt_s), n_2 p(d_2, mt_s) \\ & (1-p(d_2, mt_s))\bigg) - N\bigg(n_2 p(d_2, (m-1)t_s), \\ & n_2 p(d_2, (m-1)t_s)(1-p(d_2,(m-1)t_s))\bigg) \\ & = N\bigg(\frac{1}{2} n_2 [p(d_2, kt_s) - p(d_2, t_s)], \\ & \frac{1}{2}\sum_{m=2}^{k-1} n_2 p(d_2, mt_s)(1-p(d_2, mt_s)) \\ & + \frac{1}{4} n_2 p(d_2, kt_s)(1-p(d_2, kt_s)) \\ & + \frac{1}{4} n_2 p(d_2, t_s)(1-p(d_2, t_s))\bigg) \end{aligned} \tag{8}$$

Where $p(d,t)$ as defined in (2), is the probability of success for the molecules released by Tx_2 at the current time-slot and to be absorbed by Rx_1 also at the current time-slot. Likewise, if the current transmitted symbol from Tx_2 is 1, then the distribution of the molecules arrived at Rx_1 can be written as the subtraction of two normal distributions as:

$$\begin{aligned} N_{ILI,1,2} \sim N\bigg(& \frac{1}{2} n_2 [p(d_2, kt_s) + p(d_2, t_s)], \\ & \frac{1}{2}\sum_{m=2}^{k-1} n_2 p(d_2, mt_s)(1-p(d_2, mt_s)) \\ & + \frac{1}{4} n_2 p(d_2, kt_s)(1-p(d_2, kt_s)) \\ & + \frac{5}{4} n_2 p(d_2, t_s)(1-p(d_2, t_s))\bigg) \end{aligned} \tag{9}$$

Similarly, the distribution of the ILI and the ISI from Tx_1 to the signal of Tx_2 can be easily obtained from (11) by replacing n_2 with n_1, respectively. All of these formulas only take into account when $k > 2$, as the formulas of $k \leq 2$ are easy to deduce.

3 Receptors Analysis

For the case of the MIMO system, when Tx_1 is transmitting bit 0, the number of the absorbed molecules by the first receptor within the current time-slot, denoted by $N_{0,1}$, includes both the ISI from the previous symbol transmitted by Tx_1 and ILI from Tx_2. Therefore, $N_{0,1}$ has the following normal distribution:

$$N_{0,1} = N_{ILI,0,2} + N_{ISI,1} \sim (\mu_{0,1}, \delta_{0,1}^2) \tag{10}$$

Where:

$$\begin{aligned}\mu_{0,1} =& \frac{1}{2} n_1 [p(d_1, (k+1)t_s) - p(d_1, t_s) \\ &+ \frac{1}{2} n_2 [p(d_2, kt_s) - p(d_2, t_s)\end{aligned} \tag{11}$$

And

$$\begin{aligned}\delta_{0,1}^2 =& \frac{1}{2} \sum_{m=2}^{k-1} n_2 p(d_2, mt_s)(1 - p(d_2, mt_s)) \\ &+ \frac{1}{4} n_2 p(d_2, kt_s)(1 - p(d_2, kt_s)) \\ &+ \frac{1}{4} n_2 p(d_2, t_s)(1 - p(d_2, t_s)) \\ &+ \frac{1}{2} \sum_{m=2}^{k} n_1 p(d_1, mt_s)(1 - p(d_1, mt_s)) \\ &+ \frac{1}{4} n_1 p(d_1, (k+1)t_s)(1 - p(d_1, (k+1)t_s)) \\ &+ \frac{1}{4} n_1 p(d_1, t_s)(1 - p(d_1, t_s))\end{aligned} \tag{12}$$

When Tx_1 is transmitting bit 1, it releases n_1 molecules. The number of absorbed molecules by Rx_1, in this case $N_{0,1}$, has the following normal distribution

$$\begin{aligned}N_{0,1} =& N_{ILI,0,2} + N_{ISI,1} \\ &+ N((n_1 p(d_1, t_s), n_1 p(d_1, t_s)) \\ &\sim (\mu_{1,1}, \delta_{1,1}^2)\end{aligned} \tag{13}$$

Where:

$$\begin{aligned}\mu_{0,1} = &\frac{1}{2}n_1[p(d_1,(k+1)t_s)+p(d_1,t_s)\\ &+\frac{1}{2}n_2[p(d_2,kt_s)+p(d_2,t_s)\end{aligned} \tag{14}$$

And

$$\begin{aligned}\delta_{0,1}^2 = &\frac{1}{2}\sum_{m=2}^{k-1} n_2 p(d_2,mt_s)(1-p(d_2,mt_s))\\ &+\frac{1}{4}n_2 p(d_2,kt_s)(1-p(d_2,kt_s))\\ &+\frac{5}{4}n_2 p(d_2,t_s)(1-p(d_2,t_s))\\ &+\frac{1}{2}\sum_{m=2}^{k} n_1 p(d_1,mt_s)(1-p(d_1,mt_s))\\ &+\frac{1}{4}n_1 p(d_1,(k+1)t_s)(1-p(d_1,(k+1)t_s))\\ &+\frac{5}{4}n_1 p(d_1,t_s)(1-p(d_1,t_s))\end{aligned} \tag{15}$$

Similarly, the distribution of $N_{0,2}$ and $N_{1,2}$, which are the number of absorbed molecules by Rx_2, can be easily obtained from (10), (11), (12), (13), (14), and (15) by replacing n_1 with n_2 and n_2 with n_1, respectively.

4 Bit Error Rate Analysis

In this MIMO system, single receive judgement are considered, firstly. Let Z_1 denote the number of molecules observed at Rx1. Then, the two detection hypotheses are:

$$\begin{aligned}H_0 : Z_1 \sim N(\mu_{0,1}, \delta_{0,1}^2)\\ H_1 : Z_1 \sim N(\mu_{1,1}, \delta_{1,1}^2)\end{aligned} \tag{16}$$

Applying LRT results in the following equation:

$$\begin{aligned}\frac{P(H_0|Z_1)}{P(H_1|Z_1)} &= \frac{P(H_0)P(Z_1|P_0)}{P(H_1)P(Z_1|P_1)}\\ &= \frac{\delta_{1,1}^2}{\delta_{0,1}^2} exp\{\frac{(z_1-\mu_{1,1})^2}{2\delta_{1,1}^2} - \frac{(z_1-\mu_{0,1})^2}{2\delta_{0,1}^2}\}\end{aligned} \tag{17}$$

By taking logarithm and setting to zero, the optimal decision threshold becomes:

$$\tau_1 = \frac{-B+\sqrt{B^2-4AC}}{2A} \tag{18}$$

Where:

$$\begin{aligned} A &= \frac{1}{2\delta_{1,1}^2} - \frac{1}{2\delta_{0,1}^2} \\ B &= \frac{\mu_{1,1}}{\delta_{1,1}^2} - \frac{\mu_{0,1}}{\delta_{0,1}^2} \\ C &= \frac{\mu_{1,1}^2}{2\delta_{1,1}^2} - \frac{\mu_{0,1}^2}{2\delta_{0,1}^2} \end{aligned} \tag{19}$$

The BER for the information transmitted from Tx_1 can be written as

$$P_{e_1} = \frac{1}{2}(P_{F_1} + P_{M_1}) \tag{20}$$

Where P_{F_1} and P_{M_1} are the probability of false alarm and probability of misdetection, respectively, and are derived as:

$$\begin{aligned} P_{F_1} &= P(N_{0,1} > \tau_1) = Q(\frac{\tau_1 - \mu_{0,1}}{\delta_{0,1}}) \\ P_{M_1} &= P(N_{1,1} < \tau_1) = 1 - Q(\frac{\tau_1 - \mu_{1,1}}{\delta_{1,1}}) \end{aligned} \tag{21}$$

In the case of two receptors' different result, dual threshold algorithm is proposed to choose the better result and reduce BER. As for the decisions of two receptors, we have enough confidence in their judgments and choose it as final decision, if both of decisions are same. However, if both of decisions are different like $(0, 1)$ or $(1, 0)$, the handling method is proposed to use a new threshold for the receptor, where decision is 1, and trust the new decision as final decision. New threshold τ_n and single threshold τ_s have the following relationship:

$$\tau_n = t \times \tau_s \tag{22}$$

Where t is a proportionality coefficient and $1 \leq t \leq 2$.

Further, we find that the coefficient can be adjusted dynamically, which offer better help in dual threshold algorithm. We choose the other decision to adjust it:

$$t = 2 - N_o/\tau_o \tag{23}$$

where N_o is the received molecular number of the decision "0" receptor and τ_o is its single threshold.

5 Simulation Results

In this section we present the simulation results for the error probability of the proposed MIMO transmission schemes over the diffusion channels. We consider the short-range molecular communication where communication distances are typically within tens of micrometers. Throughout the simulations, we set default parameters as: the radius of receptors $R = 10\,\mu\text{m}$; the distance of related transmitter and receptor $d_r = 30\,\mu\text{m}$;the distance of disrelated transmitter and receptor $d_d = 50\,\mu\text{m}$; the diffusion coefficient $D = 100\ \mu\text{m}^2/\text{sec}$; the number of transmitting moleculars, when the transmitter sends bit 1, is 100; the width of time slot is 30 s.

In Fig. 2, we plot the BER performance of different schemes versus the number of released molecules, which represents the transmission power, under the numerical results obtained from the number of correctly-detected bits over the total number of transmitted bits and the theoretical results obtained using derivations in (20) and (21), which show the exactness of the theoretical analysis. Three curves corresponding to various number of transmitted bit are plotted. We observe that proposed theoretical model can represent actual situation to some extent. Furthermore, we observe that simulation results are more fitting analytical result with more number of transmitted.

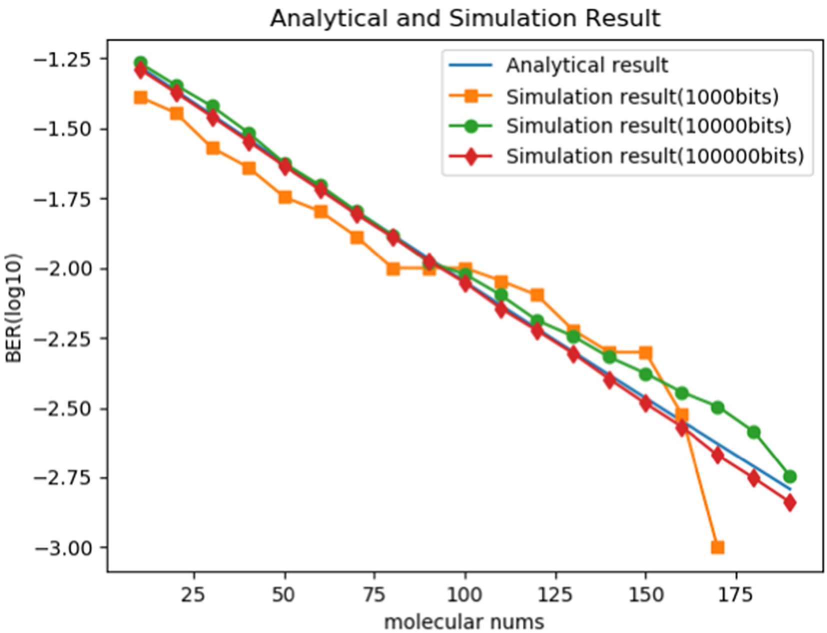

Fig. 2. Analytical and Simulation Result

In Fig. 3, we plot the BER performance versus the number of released molecules which represents the transmission power under different width of time slot between two launches. Five curves corresponding to various width of $t_s = 5\,\text{s}$, $t_s = 10\,\text{s}$, $t_s = 30\,\text{s}$, $t_s = 50\,\text{s}$ and $t_s = 100\,\text{s}$ are plotted. We observe that a lower BER can be achieved by a bigger width of time slot, while other related parameters remain unchanged. Furthermore, we observe that the BER has major change from the case of $t_s = 5\,\text{s}$ to the case of $t_s = 30\,\text{s}$ and less change from the case of

$t_s = 30\,\text{s}$ to the case of $t_s = 100\,\text{s}$. Taking transfer efficiency into consideration, we choose $t_s = 30\,\text{s}$ as default parameter.

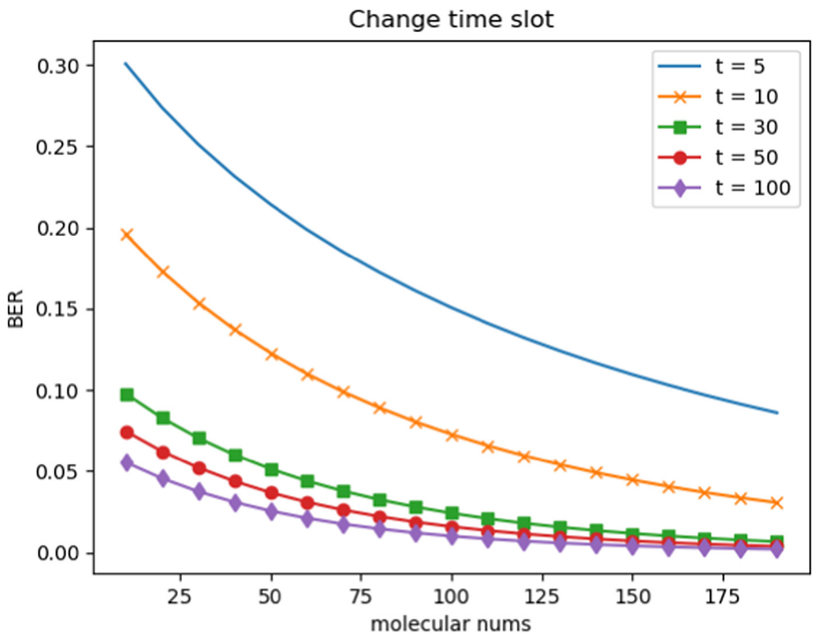

Fig. 3. Different width of time slot between two launches

In Fig. 4, we plot the BER performance versus the number of released molecules which represents the transmission power under different distance of related transmitter and receptor. Five curves corresponding to various width of $d_r = 11\,\mu\text{m}$, $d_r = 30\,\mu\text{m}$, $d_r = 40\,\mu\text{m}$, $d_r = 50\,\mu\text{m}$ and $d_r = 100\,\mu\text{m}$ are plotted. We observe that a lower BER can be achieved by a smaller distance, while other related parameters remain unchanged. Furthermore, we observe that the case of $d_r = 11\,\mu\text{m}$, which means the distance of related machines is much less than the distance of disrelated machines, is easy to reduce the BER to zero, and the case of $d_r = 100\,\mu\text{m}$, which means the distance of related machines is much more than the distance of disrelated machines, is difficult to reduce the high level BER. However, the data we need should be at normal scale, which means that the case of $d_r = 11\,\mu\text{m}$ is not necessary to discuss. As for other case, the BER will increase, if the distance increases.

In Fig. 5, we plot the BER performance versus the number of released molecules which represents the transmission power under different diffusion coefficient. Five curves corresponding to various width of $D = 50\,\mu\text{m}^2/\text{s}$, $D = 75\,\mu\text{m}^2/\text{s}$, $D = 100\,\mu\text{m}^2/\text{s}$, $D = 150\,\mu\text{m}^2/\text{s}$ and $D = 200\,\mu\text{m}^2/\text{s}$ are plotted. We observe that the BER will keep less level in bigger diffusion coefficient's circumstances.

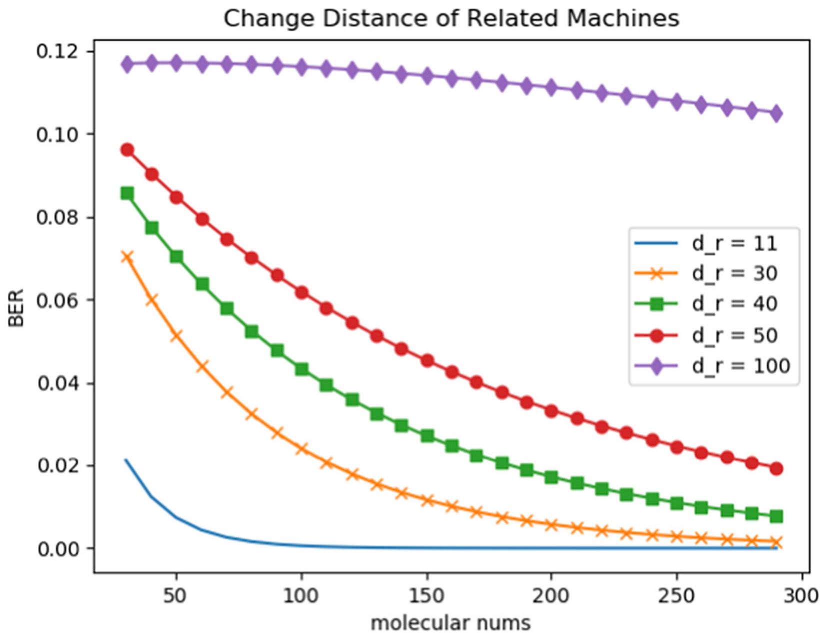

Fig. 4. Different distance of related transmitter and receptor

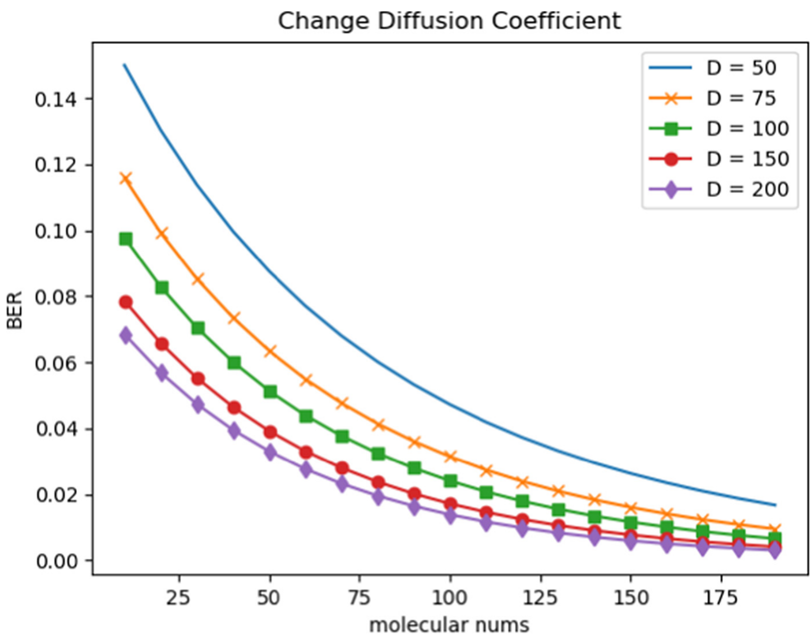

Fig. 5. Different diffusion coefficient

In Fig. 6, we plot the BER performance versus the number of released molecules which represents the transmission power under different numbers of related time slot k. In this figure, the BER is mathematically processed into its logarithm form, and five curves corresponding to various width of $k = 1$, $k = 2$, $k = 3$, $k = 4$ and $k = 5$ are plotted. We observe that more time slot are considered, more interference factors are considered and the BER level are higher, but the result is closer to reality. Furthermore, we observe that the remote time slot is less influential than the proximal time slot.

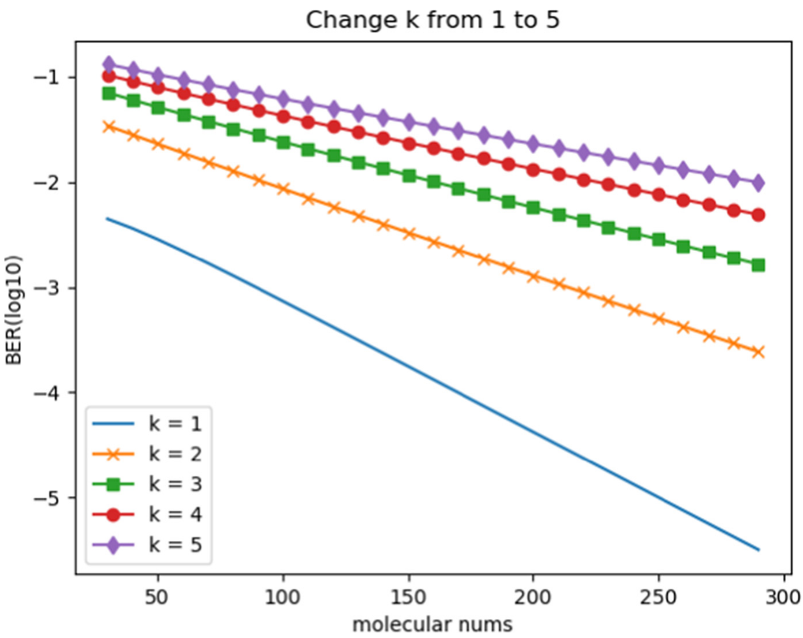

Fig. 6. Different influential time slots

In Fig. 7, we plot the BER performance versus the number of released molecules which represents the transmission power under single decision in Rx_1 and easy dual threshold decision. In this figure, the t of dual threshold is set to 1.5, which is a empirical choose. We observe that dual threshold decision plays a good improvement function in reducing BER,but the proportionality coefficient t has no rule to find and the effect may be counterproductive if t is inappropriate.

In Fig. 8, we plot the BER performance versus the number of released molecules which represents the transmission power under many kinds of ways. Firstly, this figure shows that the performance of single decision is worse than the performance of dual threshold decision. Secondly, we observe that selfadapted dual threshold decision plays a better improvement function in reducing BER than every easy dual threshold decision. Lastly, one of easy dual threshold

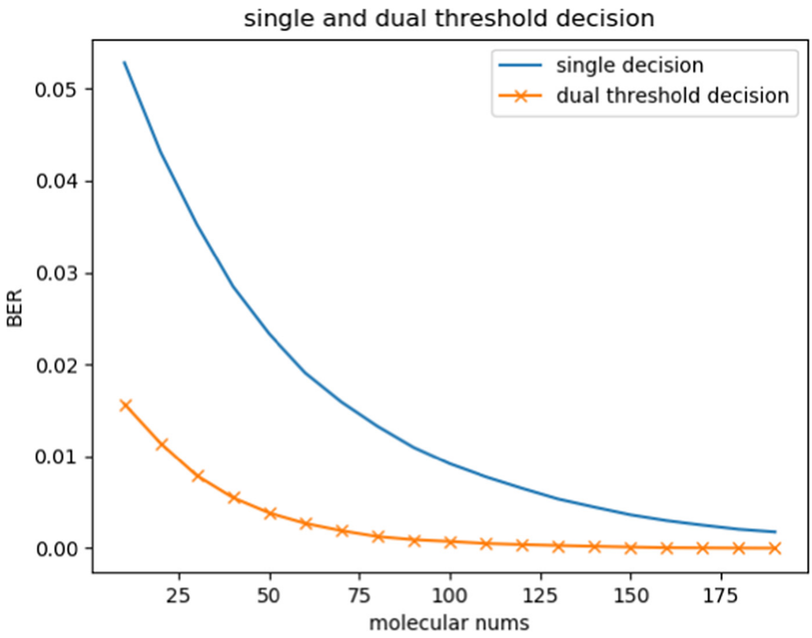

Fig. 7. Single decision of Rx_1 and dual threshold decision

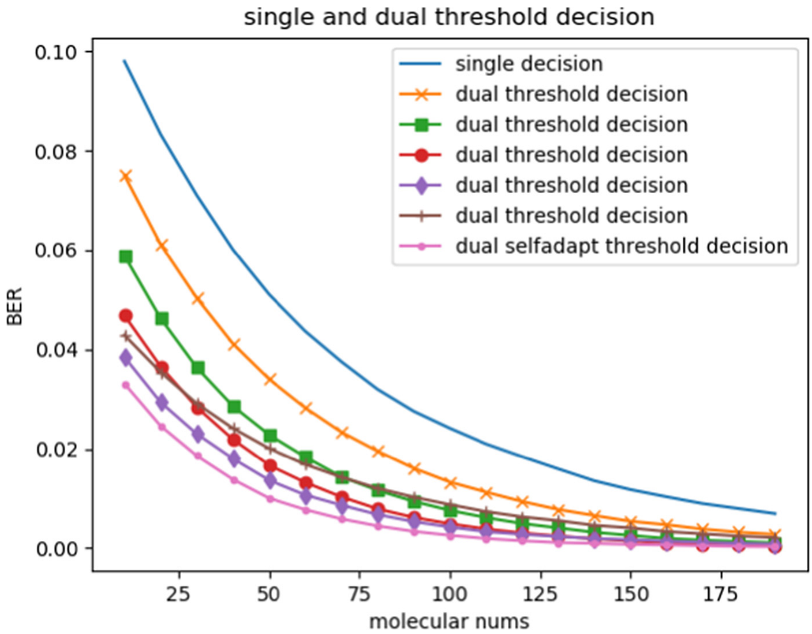

Fig. 8. Easy dual threshold and selfadapted dual threshold decision

decision is very close to selfadapt way, and we think that the associated coefficient t is appropriate in easy dual threshold decision.

6 Conclusion

In this paper, we studied the performance of a MIMO molecular communications system in a diffusion-based environment governed by the Brownian motion of molecules, and proposed two dual threshold algorithms to reduce BER. In particular, we analyzed the BER of the MIMO system in the presence of ISI and ILI. The dual threshold algorithm is considered for the case that two receptors have different decision, and a empirical threshold is set to finish final judgment. It was shown that the analytical results closely follow the simulation results. The dependency of the BER on the number of released molecules and width of time slot, distance of related machines, diffusion coefficience were studied in the simulation results. It was shown that a lower BER can be achieved by a bigger width of time slot, a more released molecules, a bigger diffusion coefficient and a shorter distance of related machines in the MIMO molecular communication system. Finally, we compared the two algorithms and analyzed the result, which show that it is true to select the appropriate parameters to adjust the coefficient dynamically.

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