Diffusion based Anti-Interference joint modulation in MIMO Molecular Communication

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***Abstract*—Molecular communication(MC) is a significant technology in the field of nano-biology, which uses molecules as message carriers to transmit information. Diffusion channel model is the most common channel model base on Brownian motion in molecular communication since molecules can diffuse to the destination without the need of extra energy supply. However, the random Brownian motion brings high delay and uncertainty to the communication process and thus modulation methods are required to improve the communication performance. The molecular communication system in the SISO (Single Input Single Output) scenario will be seriously affected by ISI (Inter Symbol Interference). In MIMO(Multi-Input Multi-Output) scenario, since there are multiple transmitters and receivers, in addition to ISI, there will be ILI (Inter Link Interference) as well. At present, most modulations are based on the concentration, type, time and space of molecules and only focus on SISO scenario. In this study, inspired by the MoSK(Molecule Shift Keying) modulation method, we proposed a new joint modulation method for MIMO communication in order to minimize the effect of ISI and ILI. Numerical results show that compared with the current modulation scheme, the proposed scheme allows the MIMO system achieve better BER(Bit error rate) performance and transmission rate.**

***Index Terms*—Molecular communication, Molecule shift keying, MIMO, Modulation, Diffusion channel.**

I. Introduction

Molecular communication is a new rising technology in recent decades, it was firstly proposed by [1]. As nanotechnology advances, it is possible to build simple nanomachines to carry out some simple tasks such as computing, sensing and actuation [2][3]. Nanomachines are gene-edited cells or bacteria and need to cooperate to perform more complicated work such as drug delivery and target tracking. As a result, communication among nanomachines is required. It has been proven that EM (ElectroMagnetic) wave-based communication is not suitable at nano-scale[1] for some reasons. In aquatic environments, the propagation of EM waves is not as straightforward as in air [4]. The presence of liquid alters the behavior of EM waves, posing challenges for their transmission and reception. Furthermore, certain EM micro-devices and waves in aquatic environments may have potential adverse effects on human health.[5]. Additionally, constructing nano-sized antennas presents significant difficulties due to their small scale. However, molecular communication is a perfect communication method for nanomachines at nano-scale for its excellent bio-compatibility and low energy consumption[6]. Although molecular communication has encountered many obstacles in practical application, it has been developing forward.

In fact, the process of molecular communication is very similar to that of EM wave based communication, including modulation and demodulation. Inspired by EM wave-based communication, molecular communication has many ways to modulate information into molecules. For example, many modulation methods in molecular communication are similar to that of traditional electromagnetic communication: CSK(Concentration Shift Keying) is similar to ASK(Amplitude Shift Keying) in electromagnetic communication. It uses the concentration of received molecules as the amplitude of signal. If the number of molecules reaching the receiver exceeds the threshold within a time slot, the receiver will decode it as "1", otherwise as "0"[6],[7]. In addition, MoSK(Molecule shift keying) is similar to FSK(Frequency Shift Keying), which uses different types of molecules as information carrier. For example, the transmitter sends M_1 molecules as bit "1" and M_2 molecules as bit "0". In diffusion-based molecular communication, there are generally two types of noise: ISI(Inter-symbol Interference) and ILI(Inter-Link Interference). Since molecule released by transmitter would diffuse freely to the receiver, not all molecules can reach the receiver during its time slot and may linger in the channel, causing ISI. If more than one transmitters and receivers are involved, there would be ILI. Both noise can cause serious problem and mitigate the performance of communication. Although CSK and MoSK are the most common modulation methods in molecular communication field, they cannot reduce the effect of noise properly and thus new anti-interference modulation methods are required.

Based on our previous work of anti-interference modulation in SISO system[8], we proposed a new joint modulation method and extended it to 2x2 MIMO molecular communication system. Our modulation method needs two transmitter to cooperate and avoid sending the same molecules at the same time slot to eliminate ILI. There are four symbols "A",

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"B", "C" and "-". "A","B" and "C" means three different types of molecules and "-" means no molecules are sent. We also proposed a concept of correlated time slot of transmitters. When a transmitter needs to choose one type of symbol as the information molecule at current time slot, it must consider its correlated time slot's circumstance to avoid ILI. We evaluated the BER(Bit Error Rate) performance of our modulation method through both simulation and theoretical derivation. Numerical results show that our proposed modulation method can effectively reduce ISI and ILI and thus improve the performance of 2x2 MIMO molecular communication.

II. Related Work

Electromagnetic waves serve as carrier signals in traditional wireless communication systems based on radio. The electromagnetic waves in wireless communication systems are sine waves, and the inherent characteristics of sine waves, such as amplitude, frequency, and phase, can serve as media for carrying information. The modulation process in molecular communication systems is very similar to the modulation methods in traditional electromagnetic communication systems, but retains some molecular characteristics.

Inspired by ASK modulation in electromagnetic wave communication, Kuran Proposed a modulation method based on molecular concentration [6] in molecular communication for the first time, and named it CSK. Its principle is to modulate the information according to the concentration change of the sending molecule. This modulation method is very similar to ASK modulation in electromagnetic wave communication, The information is loaded according to the "amplitude" change of the carrier. A modulation method based on molecular type is also proposed in [6], which is called MoSK. Transmitter sends molecule type M_1 to represents bit "0" and molecule type M_2 to represents bit "1". This modulation method is similar to FSK modulation and different frequencies are similar to different molecules. Information can also be modulated in the time dimension. A modulation based on molecular releasing time is proposed in [9], which is called TEC (time-lapse communication). It is to use the time slot between signals to modulate information. [10] proposed two different modulation methods based on molecular pulse, PAM(pulse amplitude modulation) and PPM(pulse position modulation), in which molecular pulse is realized by releasing a large number of molecules in a very short time. [11] proposed a modulation method based on characteristics of the system impulse response, such as the maximum value of the peak, the maximum delay of the peak, etc. An asynchronous modulation method is proposed in [13]. It is based on releasing time and different molecular types and can achieve higher data transmission rate.

There are some modulation methods aim to reduce the ISI in molecular communication. In [14], a new pre-equalization method for molecular communication based on diffusion channel is proposed. This method is based allows transmitter to send two different types of molecules to mitigate serious ISI interference. Noel Proposed a method to mitigate ISI interference by using biological enzymes [15]. Some enzymes are used to degrade excessive molecules in the channel to avoid ISI. [16] uses two different molecules to avoid ISI, for example, the transmitter sends molecule A and then sends molecule B to represent bit "1", and sends molecule B and then sends molecule A to represent bit "0". [7] proposed a modulation method to reduces ISI by alternately releasing two molecules at different time slots. In [18], a modulation methods is proposed by avoiding the appearance of same kind of molecules in continuous time slots.

In recent years, MIMO technologies have been introduced into molecular communication to increase the communication efficiency and reliability. In 2012, MIMO was firstly proposed in molecular communication [19]. It proposed various diversity techniques for Multi-Input Multi Output (MIMO) transmissions based on molecular diffusion to improve the communication performance in nanonetworks. In MIMO system, there is not only ISI but also ILI in different pairs of transmitters and receivers and as a result the modulation methods need more considerations. [20] proposes a spatial multiplexing mitigation modulation method based on pulse position modulation to mitigate ILI. In [21], a new modulation method for MIMO system called Molecular Space Shift Keying(MSSK) is proposed and it can combat both ISI and ILI effectively. [22] has proposed ar rising edge-based detection algorithm (RED) which can help get a better BER performance. [23] has a trained artificial neural network to acquire the channel impulse responses(CIR) of MIMO based molecular communication. Motivated from the potential of spatial diversity in classical wireless communication, it introduced different spatial coding and combining techniques to the area of MC and analyzed their performances. [24] has presented a training-based CIR estimation for diffusive MIMO (D-MIMO) channels. Maximum likelihood and least-squares estimators are derived, and the training sequences are designed to minimize the corresponding Cramer-Rao bound. In [25], it proposed a modulation method in a 4x4 MIMO system, which utilized 4 different molecules as information carriers and can help decrease BER. In addition to diffusion based MIMO system, [26] proposed a novel MIMO channel based on molecular motors and compared it with SISO channel.

III. System Model

We will introduce both SISO and MIMO system models here, including molecule diffusion model, inter-symbol interference model and inter-link interference model.

The system model is under the following assumptions:

1. The transmitter can perfectly control the releasing of molecules and is the only molecule source.
2. The information molecules are identical and mutually independent.
3. The receiver absorbs information molecules instantly.
4. The diffusion channel is an unlimited environment.

A. SISO System Model

A simple SISO molecular communication model is shown in Fig. 1. The considered model consists of a set of Transmitters (Tx) and Receivers (Rx), and the distance between them is denoted by d. The Receiver is assumed to be circular with radius R. The medium between the transmitter and the receiver is assumed to be a diffusion channel. Black dots of different shapes in Fig. 1 represent different types of molecules, which are sent from the transmitter to the channel and reach the receiver through Brownian motion.

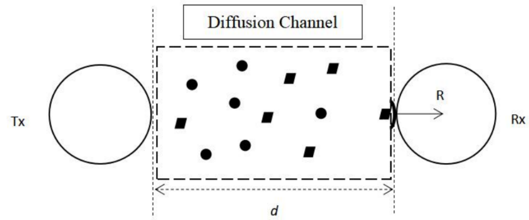

Fig. 1: SISO Molecular Communication System.

B. MIMO System Model

In molecular communication systems, it is of great significance to improve the transmission efficiency and performance of nanonetworks by increasing the number of molecule transmitting nodes and receiving nodes. Compared with the single-input single-output (SISO) molecular communication, the advantage of multiple-input multiple-output (MIMO) molecular communication lies in the increase of transmission links, which is equivalent to multiple independent SISO molecular communication systems transmitting information simultaneously, thus increasing the transmission rate. However, it also brings a significant problem which is called inter-link interference (ILI). Based on SISO model, we extend it to a 2x2 MIMO model.

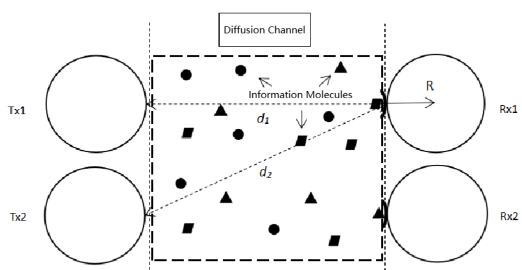

Fig. 2: 2x2 MIMO Molecular Communication System.

C. Communication Model

1) Molecule Diffusion Model: In the diffusion channel of molecular communication, the molecules generally do random diffusion motion in the fluid medium, and their arrival at the receptor is a random probability event. To facilitate mathematical modeling and research analysis, assuming that the position of the transmitter is at the coordinate axis origin and the molecules are released to the channel at t = 0, then the probability density function of the signal molecule can be written as [32]

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

where D is the diffusion coefficient of the information molecule.

Assume that the transmitter releases a single molecule at t = 0sec, which is then absorbed by the receiver after t_s (time slot), the probability of the molecule being absorbed [29] can be determined by

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

where *erfc(x)* is the complementary error function, R represents the radius of the receiver and d represents the distance between the transmitter and the receiver.

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-y^2} dy \tag{3}$$

A large number of studies and analyses show that the number of molecules N_r received by the receiver in the time slot t_s is related to the number of molecules n transmitted by the transmitter, and it follows binomial distribution [38], [41] as

$$N_r \sim \mathcal{B}(n, p_r(d,t_s)) \tag{4}$$

According to central limit theorem, a binomial distribution $\mathcal{B}(n, p(d, ts))$ can be approximated with a Gaussian distribution $\mathcal{N}(np, np(1-p))$ when p is not close to one or zero and np is large enough, then (4) can be approximated as a Gaussian distribution [29][38]

$$N_r \sim \mathcal{N}(np_r(d,t_s), np_r(d,t_s)(1-p_r(d,t_s))) \tag{5}$$

where $\mathcal{N}$ is Gaussian Distribution.

2) Inter-Symbol Interference Model: The random Brownian motion of molecules is the main cause of Inter-Symbol Interference(ISI). Due to the randomness of molecules, it is bound to lead to the residual molecules in the channel failing to reach the receiver within the corresponding time slot, thus affecting the subsequent time slot and causing ISI.

Let N_{ISIit_s} indicate the number of received molecules by the receiver at current time slot but were released i time slots before. According to [15], N_{ISIit_s} is a Gaussian random variable [35] and is shown in (6).

$$\begin{aligned} &\frac{1}{2}\mathcal{N}(np(d,(i+1)t_s), np(d,(i+1)t_s)(1-p(d,(i+1)t_s))) \\ &-\frac{1}{2}\mathcal{N}(np(d,it_s), np(d,it_s)(1-p(d,it_s))) \end{aligned} \tag{6}$$

where the factor $\frac{1}{2}$ means equal probability of transmission of bit 0 or 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. Then the number of ISI molecules received by the current time slot can be expressed as:

$$N_{ISI} = \sum_{i=2}^{\infty} N_{ISI,its} \tag{7}$$

Let N_A indicate all molecules received by the receiver at current time slot and let N_C indicate molecules released by the transmitter and received by the receiver at current time slot. N_A consists two parts which are molecules from previous time slots,N_{ISI}, and from current time slot N_C. N_C is the same as (5).

$$N_A = N_C + N_{ISI} \tag{8}$$

3) Inter-Link Interference Model: In a 2x2 MIMO system, we must consider Inter-Link interference. Since it is a symmetric model, it is safe to consider only one of the receivers. In the following analysis, Rx1 is chosen as the subject.

The molecules absorbed by Rx1 consists two parts: the ISI from Tx1 and ILI from Tx2.

Firstly we analyze ISI from Tx1:

Let d_1 indicate the distance from Tx1 to Rx1. The probability of one molecule from Tx1 being absorbed is based on (2)

$$p_r(d_1, t_s) = \frac{R}{R + d_1} erfc(-\frac{d_1}{\sqrt{4Dt_s}}) \tag{9}$$

The ISI $N_{ISI,Tx1}$ between Tx1 and Rx1 is as follows:

$$\sum_{i=1}^{\infty}(\frac{1}{2}\mathcal{N}(np(d_1,(i+1)t_s), np(d_1,(i+1)t_s)(1-p(d_1,(i+1)t_s))) \\ -\frac{1}{2}\mathcal{N}(np(d_1,it_s), np(d_1,it_s)(1-p(d_1,it_s)))) \tag{10}$$

Then we analyze ILI from Tx2:

Let d_2 be the distance from Tx2 to Rx1 and $N_{C,ILI,Tx2}$ be the molecules released by Tx2 at current time slot that were absorbed by Rx1.

$$N_{C,ILI,Tx2} \sim \mathcal{N}(np_r(d_2,t_s), np_r(d_2,t_s)(1-p_r(d_2,t_s))) \tag{11}$$

The molecules released by Tx2 in previous time slots can also add to ILI, denoted by $N_{P,ILI,Tx2}$ as follows:

$$\sum_{i=1}^{\infty}(\frac{1}{2}\mathcal{N}(np(d,(i+1)t_s), np(d,(i+1)t_s)(1-p(d,(i+1)t_s))) \\ -\frac{1}{2}\mathcal{N}(np(d,it_s), np(d,it_s)(1-p(d,it_s)))) \tag{12}$$

The total ILI from Tx2 is caused by molecules released at both current and previous time slots:

$$N_{ILI,Tx2} = N_{C,ILI,Tx2} + N_{P,ILI,Tx2} \tag{13}$$

Based on (5), (11) and (13), we can derive the total number of molecules that Rx1 absorbed at current time slot, denoted by N_A:

$$N_A = N_{c,Tx1} + N_{ISI,Tx1} + N_{ILI,Tx2} \tag{14}$$

where $N_{c,Tx1}$ is the molecules release by Tx1 and absorbed by Rx1 at current time slot.

IV. Proposed Modulation Method

A. Diffusion based Anti-interference Modulation in SISO system

The transmitter uses two types of molecules (denoted "A" and "B") for modulation. The transmitter sends "A" or "B" molecules or does not send molecule at all within a time slot. The sequence of molecules sent by the transmitter over a continuous period of time can be represented as a string of symbols,they are either "A", "B" or "-" (no transmission).

In the SISO system, ISI is the main noise. We can consider the channel as a channel with memory and we set the memory length as k time slot, which means the molecules released k time slots before still affect the current time slot. In order to avoid ISI, same type molecules should not be emitted within k time slot, which is the ISI-avoiding scheme [18]. Experiment results have shown that only the interference from one previous time slot, i.e., the ISI from the last symbol, needs to be considered [38]. This means that the receiver at current time slot is affected by the molecules released in the previous time slot only.

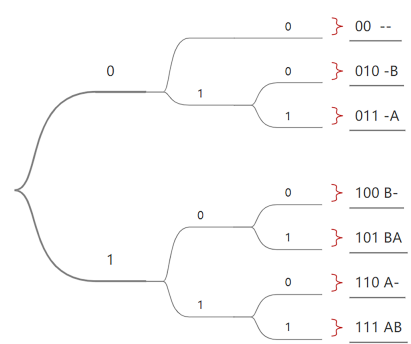

Fig. 3: Symbol set and bit sequence mapping diagram..

According to [38], the experiment results have shown that in the scenario of diffusion based molecular communication, only the interference from one previous time slot, i.e., the ISI from the last symbol, needs to be considered. Under the ISI avoidance scheme, k should be 2, that is, two adjacent symbols in the transmission sequence is not allowed be the same. For example, "A A B" is invalid, but "A B A" and "- - A" are allowed.

We make a series of combinations and each of them consists of two symbols, and they form a symbol set with an element length of 2: {A -, - A, B -, - B, AB, BA, - - }. There are in total seven elements in the set, and each element represents the combination of molecular types that the transmitter may send. It is worth noting that if an ordinary modulation method is used, that is, one type of molecule carries 1 bit of information, then this transmission sequence of 7 elements can only transmit 14 bit of information at most.

However, it is assumed that each element in the symbol set appears with equal probability. To improve the transmission rate, Huffman coding is used to map elements in the set to a longer bit sequence. The result is that the symbol set is mapped to the bit sequence set {110, 011,100, 010, 111,101,00}, and the transmission rate is increased by more than 40%.

Fig.4 shows the state diagram of the proposed modulation method, in which each edge is marked with the transmitted symbol combination and the corresponding bit sequence combination. More precisely, the left side of / represents the transmitted symbol, and the right side represents the corresponding bit sequence.

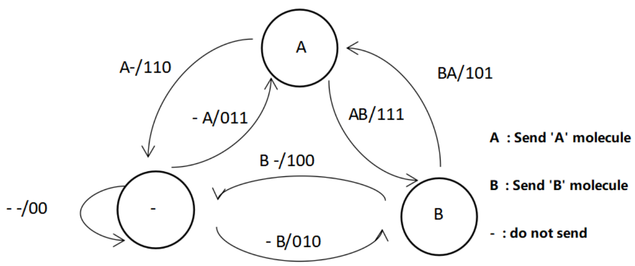

Fig. 4: State diagram of the modulation method.

B. Diffusion based Anti-Interference Joint modulation method for 2x2 MIMO System Model.

Given that the research on MIMO molecular communication systems is still in its preliminary stage, especially regarding the design of modulation methods. This section proposes a joint modulation method for diffusion-based 2x2 MIMO molecular communication systems aiming to mitigate ISL and ILI, and thus to improve the BER performance.

The purpose of this method is to effectively associate the information that multiple transmitters need to transmit during the process of modulation. A transmitter uses the its neighboring transmitter's information to jointly modulate their own information.

The modulation method is based on the following assumptions:

1. The transmitters can synthesize and release 3 types of information molecules.

2. The three types of molecules are labeled as "A", "B" and "C" , respectively.

3. The receivers can detect and receive molecules of "A", "B" and "C" .

4. Adjacent transmitters or receivers are capable of jointly performing simple functions.

Fig. 5 below shows the modulation process of two transmitters Tx1 and Tx2. The bit sequence {111101} is the bit sequence to be sent by Tx1, and the bit sequence to be sent by Tx2 is 111010. Transmitters can only send one bit with one type of molecules within a time slot. "A", "B" and "C" in each grid indicate the type of molecules that the transmitter releases within a single time slot, while "-" indicates that no molecules are released.

In addition, the Roman numeral symbol "I", "II", "III" and "IV" represent the order of modulation, specifying that the adjacent four time slots are one modulation cycle. The two time slots pointed by the double arrows are called "correlated time slots", which determine the modulation results. When the transmitter sends "0", no molecules will be released but when sending "1", the type of molecules to be sent needs to be determined according to specific conditions. The next paragraph will explain how it works.

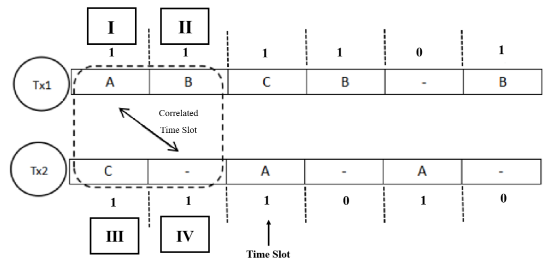

Fig. 5: Schematic diagram of modulation method.

At the beginning of modulation, the information of each time slot is modulated in the order of sequence numbers "I", "II", "III" and "IV". Firstly, it starts from "I". Within this time slot, Tx1 needs to send "1", and at this time, Tx1 can choose to release any types of molecules of "A", "B", or "C" to indicate "1". The correlated time slot of the current time slot is its diagonal time slots and the correlated time slot of "I" is "IV". If "1" is to be sent in "IV", then only "A" can be sent in the current time slot "I". After the modulation of time slot "I" is completed, the next step is time slot "II". The bit needs to be sent is still "1", Tx2 can only choose from "B" and "C" molecules because "A" have already been used. Choosing "B" or "C" in "II" is acceptable, assuming it is "C". Next it comes to the time slot "III", where "1" is still needed to be sent. However, currently only "B" are not used, so we can only choose to release "B" molecules to represent "1". In the last time slot "IV", "1" still needs to be sent. Since all types of molecules have been used, it chooses "-", which is sending no molecule, to indicate "1". At this point, a complete modulation cycle is over. Fig. 6 shows the workflow of modulation.

The modulation workflow can ensure that the same type of molecule will not appear in a single modulation cycle. That is to say, in the same communication link, it is impossible to have two identical symbols to cause ISI and in different communication links, it is also impossible to have two identical symbols to cause ILI. It can help mitigate ISI and ILI at the same time and improve the overall communication performance.

According to the modulation of MIMO system, the mathematical analysis of ISI and ILI in section II needs to be modified as well. The modified ISI formula is given in (15).

$$\begin{aligned} &\underset{i\in\mathbb{E}}{N^{m=3}_{ISI,its}} \sim \tfrac{1}{4}\mathcal{N}(np_r(d_1,(i+1)t_s),\\ &np_r(d_1,(i+1)t_s)(1-p_r(d_1,(i+1)t_s)))\\ &-\tfrac{1}{4}\mathcal{N}(np_r(d_1,it_s),np_r(d_1,it_s)(1-p_r(d_1,it_s))) \end{aligned} \tag{15}$$

where "m=3" means three different molecules are used, and *"E"* is the Even set.

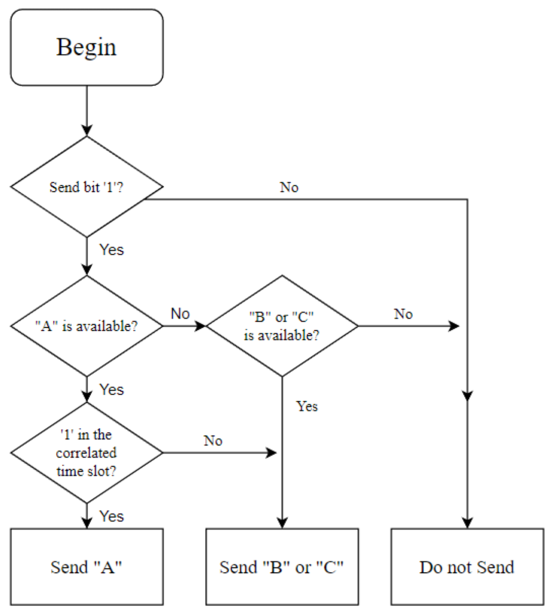

Fig. 6: Modulation Workflow.

The modified ILI formula is given in (16).

$$\begin{aligned} N_{B,ILI,Tx2}^{m=3} \sim \sum_{\substack{i=1 \\ i \in E}}^{k} \frac{1}{4} \mathcal{N} &\left(np_r \left(d_2, (i+1)t_s \right), \right. \\ & \left. np_r \left(d_2, (i+1)t_s \right) \left(1 - p_r \left(d_2, (i+1)t_s \right) \right) \right) \\ & - \frac{1}{4} \mathcal{N} \left(np_r \left(d_2, it_s \right), np_r \left(d_2, it_s \right) \left(1 - p_r \left(d_2, it_s \right) \right) \right) \end{aligned} \tag{16}$$

C. Bit Error Rate Analysis

Bit error rate (BER) is an important factor to evaluate a communication model. In this experimental model, the reason why the system generates error code is not only because of ISI interference, but also because of the selection of receiver threshold. The detection of molecules by the receiver is mainly based on the comparison between the number of molecules received in the time slot and the threshold. Therefore, the selection of receiver threshold is critical to reduce the system bit error rate [35]. There is a detection method called MAP detection, which can minimize the impact of receiver threshold on bit error. Let Z denote the number of molecules observed. Then, the two detection hypotheses are:

$$\begin{aligned} H_0 &: Z = \mathcal{N}_0 \sim (\mu_0, \sigma_0^2) \\ H_1 &: Z = \mathcal{N}_1 \sim (\mu_1, \sigma_1^2) \end{aligned} \tag{17}$$

The MAP detection is to obtain the point estimation of the quantity that is difficult to observe based on empirical data. Similar to the MLE, the MAP incorporates the prior distribution of the quantity to be estimated. Therefore, the MAP can be regarded as the regularized MLE. Applying MAP,the formula can be derived as follow:

$$\begin{aligned} \frac{P(H_0 \mid Z)}{P(H_1 \mid Z)} &= \frac{P(H_0) P(Z \mid P_0)}{P(H_1) P(Z \mid P_1)} \\ &= \frac{\sigma_1^2}{\sigma_0^2} \exp \left\{ \frac{(Z-\mu_1)^2}{2\sigma_1^2} - \frac{(Z-\mu_0)^2}{2\sigma_0^2} \right\} \end{aligned} \tag{18}$$

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

$$\tau = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{19}$$

where

$$\begin{aligned} A &= -\frac{1}{2} \left(\frac{1}{\sigma_1^2} - \frac{1}{\sigma_0^2} \right) \\ B &= \frac{\mu_1}{\sigma_1^2} - \frac{\mu_0}{\sigma_0^2} \\ C &= \ln \left(\frac{\sigma_0}{\sigma_1} \right) - \frac{1}{2} \left(\frac{\mu_1^2}{\sigma_1^2} - \frac{\mu_0^2}{\sigma_0^2} \right) \end{aligned} \tag{20}$$

The BER formula can be written as

$$\begin{aligned} P_e &= \frac{1}{2} \left(p(N_0 > \tau) + p(N_1 < \tau) \right) \\ &= \frac{1}{2} \left(Q\left(\frac{\tau - \mu_0}{\sigma_0} \right) + 1 - Q\left(\frac{\tau - \mu_1}{\sigma_1} \right) \right) \end{aligned} \tag{21}$$

V. Numerical Results

In this part, we will show the BER performance of the proposed modulation method and compare it with CSK modulation method under the same conditions in both SISO and MIMO system models.

According to experience and selection of simulation model, we set some default simulation parameters as shown in Table I. The distance between transmitter and receiver $d = 25\ \mu m$; the radius of the receiver $R = 10\mu m$; the Diffusion coefficient D = 100 $\mu m^2/s$; the symbol duration t_s = 30sec; and the related time slot $k = 2$.

TABLE I: Simulation Parameters

Parameter	**Value**
Distance in SISO(d)	10 - 100μm
Distance2 in MIMO(d_2)	10 - 60μm
Radius of Receiver(R)	10μm
Diffusion Coefficient(D)	100$\mu m^2/s$
Symbol Time Slot(t_s)	5 - 100sec
Related Time Slot(k)	2

A. SISO Simulation Results

The comparison between the simulation results of theoretical derivation and numerical simulation is shown in Fig. 7. The theoretical results are derived from (6) - (8). The simulation model used is similar to the Monte Carlo experiment, which is to simulate the communication process of the molecule

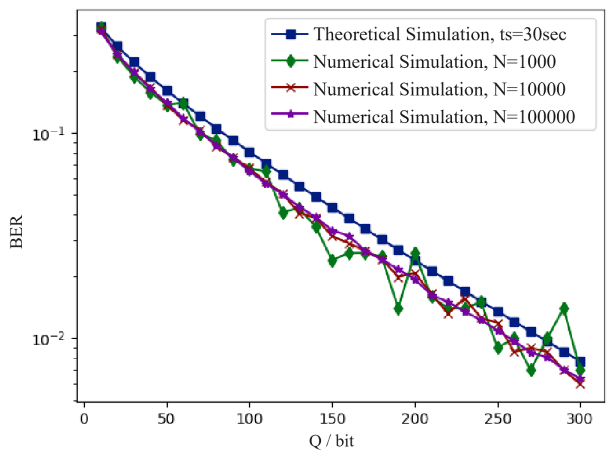

Fig. 7: Theoretical and numerical simulations.

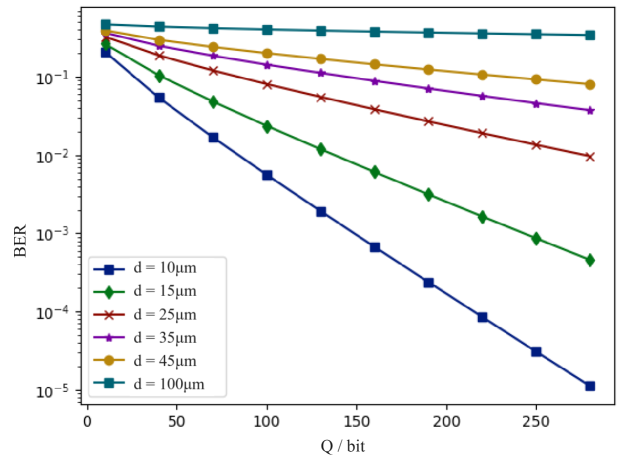

Fig. 9: BER of different distance between transmitter and receiver.

spreading from the transmitter to receiver through Brownian motion. The simulation results show that the numerical simulation results are very close to the theoretical results, and with the increase of simulation (from 1000 bit to 100000 bit), the numerical simulation curve is more smooth.

Fig. 8 shows the BER performance comparison between the proposed modulation method and other modulation methods. With the same simulation parameters, compared with CSK and MoSK modulations, the proposed modulation offers a better BER performance. With the increase of Q, the gap between curves will become more and more obvious. This also proves that the proposed modulation method can effectively reduce the negative impact of ISI and improve the system performance.

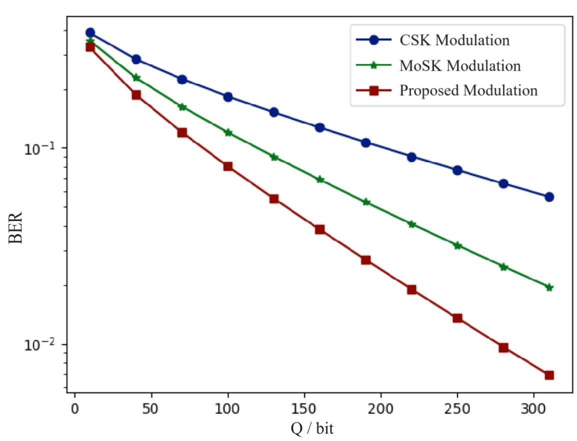

Fig. 8: BER of different modulation methods.

Fig. 9 shows how the distance between transmitter and receiver influence BER performance. With the increase of d, the BER performance of the system is getting worse. This is because the increase of distance would result in a lower probability of arrival of molecules.

Similarly, Fig. 10 shows the impact of different time slot on BER performance. We can observe that the BER performance of the system is getting better with the increase of ts. This is because the molecule has more time of diffusion and more

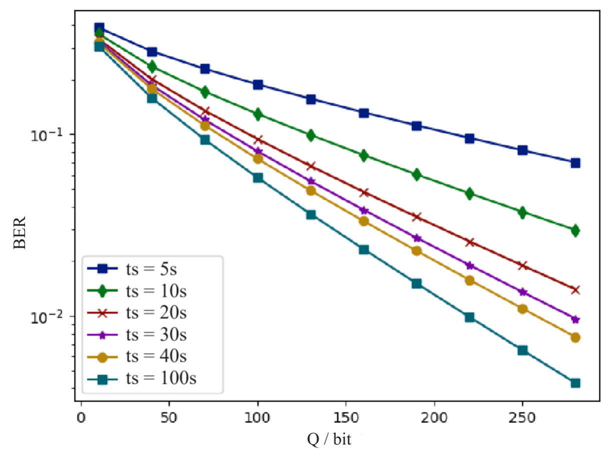

Fig. 10: BER of different time slot.

chance of arriving at the receiver. However, when ts increases to a certain extent, the BER performance of the system does not change as before. At this time, the impact of ts on the system performance is very limited.

B. MIMO Simulation Results

Fig. 11 shows the comparison between the theoretical model with the simulated experiment under the proposed modulation method. When the number of information bits in the simulation is N=1000 bits, due to the randomness of Brownian motion and the relatively small number of samples, there is a significant fluctuation. When the number increases to N=100000 bits, the results are closer to the theoretical results. It shows that with the increase of N, the influence of randomness is mitigated and the simulation curve become more smooth and close to the theoretical curve.

This also indicates that the physical model derived and analyzed in the previous text basically conforms to the characteristics of diffusion molecular MIMO communication system.

In Fig. 12, it shows comparison of BER performance of our proposed modulation method and other modulation methods. It shows that the modulation method we proposed in this paper

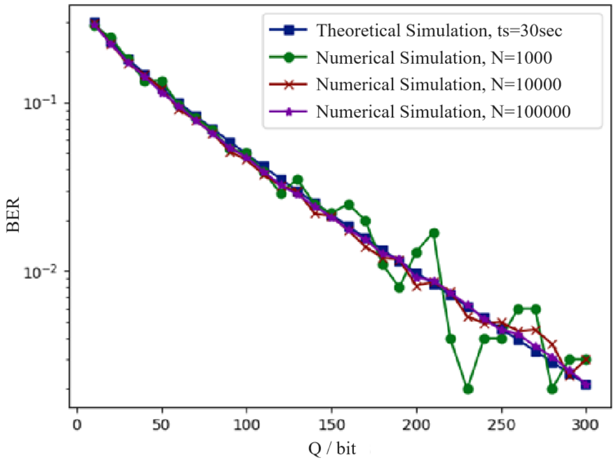

Fig. 11: Theoretical and numerical simulations.

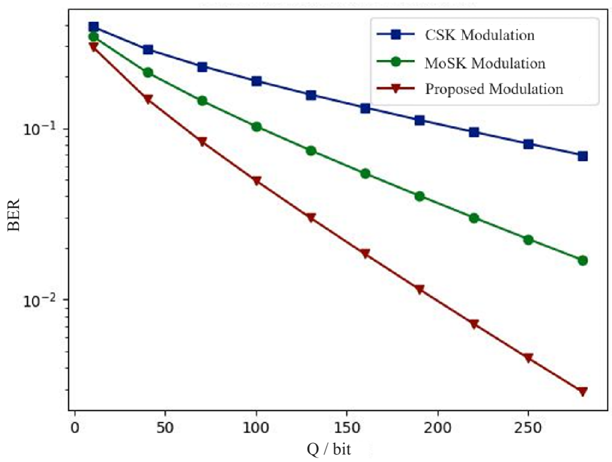

Fig. 12: BER of different modulation methods.

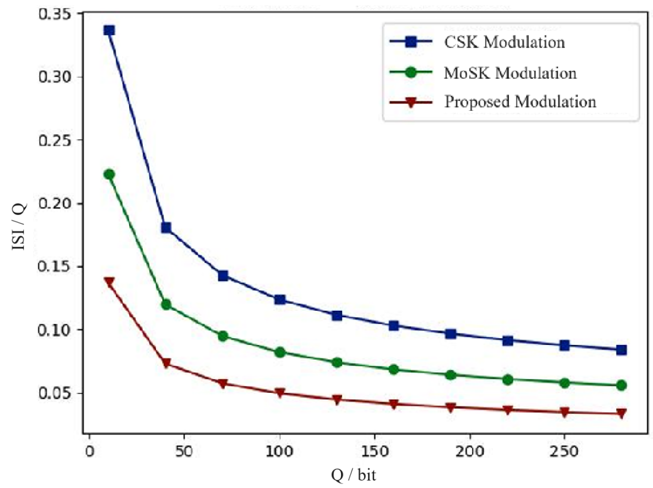

Fig. 13: ISI of different modulation methods.

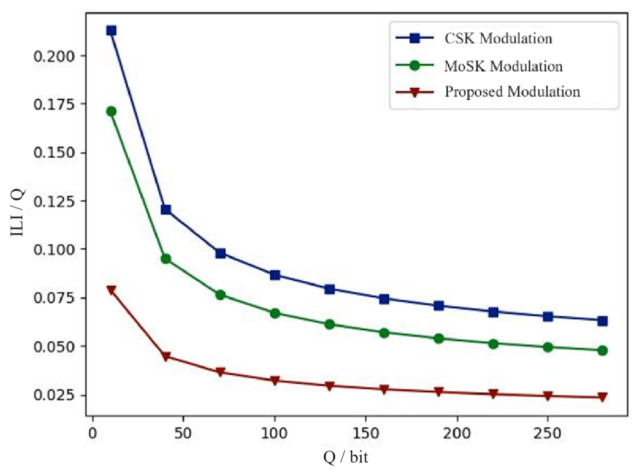

Fig. 14: ILI of different modulation methods.

can offer a better BER performance. This is because under this modulation method, the same communication link will not generate ISI during the communication process in consecutive time slots. In addition, different communication links do not generate ILI in consecutive time slots. The results of ISI and ILI are given in Fig.13 and Fig. 14 and they show that our proposed modulation has effectively mitigated ISI and ILI.

As shown in Fig. 15, the BER of different time slot ts are shown. When the transmission power is fixed and the time slot is increasing, the overall BER of the system decreases. This is because a greater time slot means the molecule has more time to diffuse to the receiver, thus reducing the system BER. In addition, it shows that when the time slot ts increases from 15s to 55s, the amplitude of BER change becomes smaller and smaller. The reason is that when the transmission power remains unchanged and the time slot interval increases to a certain threshold, most of the molecules can reach the receiver in time. Even if the slot interval is further increased, the impact on the number of molecules absorbed by the receiver is no longer significant, Therefore, the impact on the system BER is not significant.

In Fig. 16, d2 represents the distance between the transmitter and receiver in different communication links in a 2x2 MIMO communication system. When the transmission power Q is fixed, as d2 increases, the overall BER decreases. When the distance d2 between Tx2 and Rx1 increases, it takes the molecules released by Tx2 longer time to reach the distance of Rx1.

Moreover, due to the randomness of the molecules' movement, excessive distance will make most molecules deviate from their destination. This will reduce its interference to Rx1 and improve the overall error rate performance of the system.

In addition, it also shows that when d2 increases from 10μm to 60μm, the overall BER of the system does not change significantly, because the number of interfering information molecules in different links is limited.

VI. Conclusion

In this paper, we proposed a joint modulation method for a 2x2 MIMO molecular communication system based SISO molecular communication. Through the comparison of simulation results, we can draw a conclusion that the proposed modulation method can effectively reduce the impact of ISI

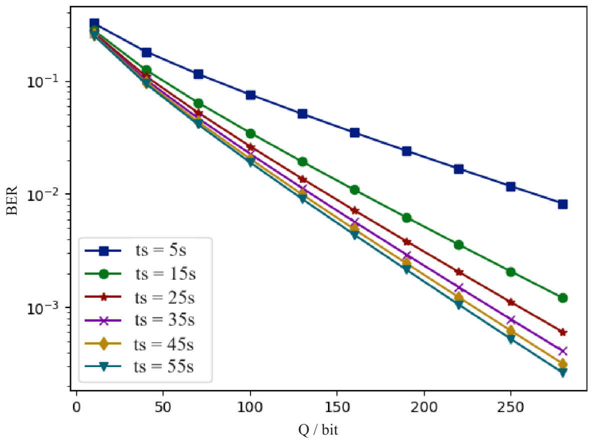

Fig. 15: BER of different time slot.

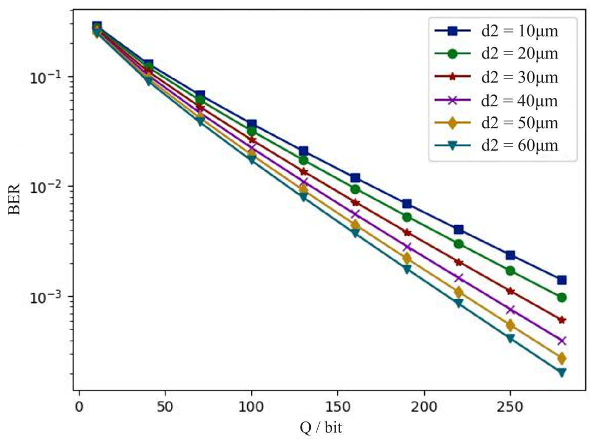

Fig. 16: BER of different distance between Tx1 and Rx2.

and ILI, and has a better BER performance than CSK and MoSK. In addition, the proposed modulation method allows the molecules to carry more information in one symbol and improve the efficiency of communication. According to the analysis above, our modulation method can improve the bps (bits per symbol) by about 40% compared with the ordinary method (1bit / symbol). In the future work, we intend to extend the MIMO system with more transmitters and receivers, and give a more universal anti-interference modulation method.

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