



# Simple ISI-Avoiding and Rate-Increasing Modulation for Diffusion-Based Molecular Communications

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**Abstract.** Molecular communication (MC) is a significant technology in the field of nanobiology, which uses molecules as message carriers to transmit information. Diffusion channel model is the most commonly channel model base on Brownian motion in molecular communication. In single-input single-output (SISO) molecular communication model, inter-symbol interference (ISI) exists due to the long tail effect. In this study, inspired by the D-MoSK modulation scheme, where different types molecules used for encoding, A new simple modulation is proposed, which can not only reduce the ISI interference effectively, but also improve the transmission rate to a certain extent. Numerical results show that compared with the current modulation scheme, the proposed scheme makes the system achieve better BER performance and the transmission rate is also improved.

**Keywords:** Molecular communication · Molecule shift keying · Transmission rate · Modulation · Diffusion channel

## 1 Introduction

Human cells can sense each other and store biological information. This magical biological structure promotes the emergence of nanomachines, which can realize simple computing and information processing functions [1]. Communication equipment in the field of nano-network is completely different from traditional communication. Communication under nano-network requires lower energy consumption, smaller size and biological compatibility [2, 3]. Molecular communication builds a bridge between engineered nanotechnology and natural Bionanotechnology, which is a new communication rule in the microenvironment [4]. The way of motion of a messenger molecule in communication of a diffusing molecule is passive and scarcely consumes any energy, which is also the most common way in molecular communication [1, 5, 17]. The most basic and simple way of communicating information to the biological environment is through free diffusion of molecules [5, 6]. Although molecular communication has encountered many obstacles in

practical application, it has been developing forward. Inspired by traditional electromagnetic communication, molecular communication has many ways to encode information into messenger molecules. Although molecular communication is a new communication mode in micro environment, practical methods in traditional communication can also be used by molecular communication. For example, most modulation methods in molecular communication come from traditional electromagnetic communication. Concentration shift keying (CSK) is similar to amplitude shift keying in traditional electromagnetic communication. It uses the concentration of the received messenger molecules as the amplitude of the signal. If the number of messenger molecules reaching the receiver exceeds the threshold  $\tau$  within a time slot, the receiver will decode to “1”, otherwise to “0” [7, 8]. Molecules shift keying (MoSK) is similar to frequency shift keying, which uses different kinds of messenger molecules to encode, and different kinds of messenger molecules are equivalent to spectrum resources [7, 9].

In this paper, we propose a simple modulation method that uses different types molecules to encode and uses a simple mapping to improve transmission rates. Mathematical calculation and simulation experiments are based on diffusion molecular communication in the hope of inspiring related research and proposing better methods. In Sect. 2, we introduce the simple SISO model of molecular communication using multiple messenger molecules in diffused channels, and the basic formula of the diffusion motion of messenger molecules is derived. In Sect. 3, a simple modulation method which can avoid ISI interference and improve transmission rate is proposed. In addition, the ISI formula and BER performance of the system under the diffusion model of the second part are derived. The numerical simulation results are in the Sect. 4 and the conclusions are in the Sect. 5.

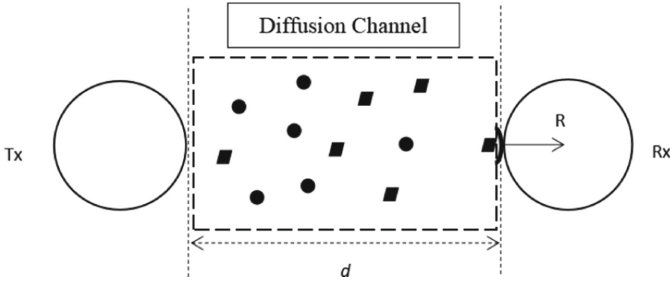
## 2 System Model

A simple SISO molecular communication model is shown in Fig. 1. The considered model consists of a set of transmitters (Tx) and receptors (Rx), and the distance between them is denoted by  $d$ . The receptor 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 messenger molecules, which are sent from the transmitter to the channel and reach the receiver through Brownian motion.

In the diffusion channel of molecular communication, the messenger 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 messenger molecules are released to the channel at  $t = 0$ , then the probability density function of the signal molecule can be written as [10]

$$p_A(d, t_s) = \frac{R}{R + d} \operatorname{erfc}\left(-\frac{d}{\sqrt{4Dt_s}}\right) \quad (1)$$

where  $\operatorname{erfc}(x)$  is the complementary error function,  $R$  represents the radius of the receiver and  $d$  represents the distance between the transmitter and the receiver.



**Fig. 1.** SISO molecular communication system

A large number of studies and analyses show that the number of messenger molecules  $N_A$  received by the receiver in the time period  $t_s$  is related to the number of messenger molecules  $n$  transmitted by the transmitter, and it follows binomial distribution as [11, 12]

$$N_A \sim B(n, p_A(d, t_s)) \quad (2)$$

A binomial distribution  $B(n, p(d, t_s))$  can be approximated with a normal distribution  $N \sim N(np, np(1 - p))$  when  $p$  is not close to one or zero and  $np$  is large enough, then (3) can be approximated as

$$N_A \sim N(np_A(d, t_s), np_A(d, t_s)(1 - p_A(d, t_s))) \quad (3)$$

### 3 Proposed Modulation Method

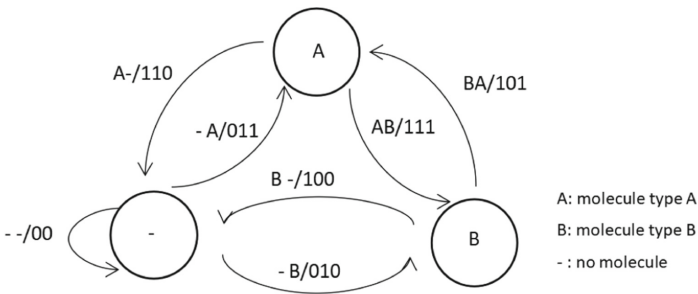
The cooperation between biological cells cannot be achieved without information and material exchange, which mainly relies on a variety of different protein carriers to transport different ions. The natural idea was to use a variety of different messenger molecules for molecular communication. Regardless of the existence of nanomachines capable of detecting multiple messenger molecules in reality, using multiple messenger molecules for modulation will inevitably simplify the structure of the transmitters and receptors.

The model of molecular communication we study is that the transmitter encodes the message only to the type of molecule, and the receiver receives the messenger molecule and decodes it into the corresponding message. In addition, the transmitter can send only one type of signal molecule or no molecule at all within a time slot  $t$ . Then 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).

The ISI in molecular communication system is mainly caused by the long tail effect. The Brownian motion of the signal molecule in the diffusion channel results in a long tail for the time probability density of the signal molecule reaching the receptor. Practically we ignore the long tail effect that leads to long memories and we replace it with finite memory. This means that the receptors in the current time slot will only be affected by the messenger molecules remaining in the previous limited time slots. The memory

length under our diffusion channel is assumed to be  $k$  time slot. In order to avoid ISI, same type messenger molecules should not be emitted within  $k$  time slot, which is the ISI-avoiding scheme [14].

For simplicity, our modulation method uses two different types of messenger molecules for analysis and simulation. One of them is A molecule and the other is B. The symbol ‘-’ means that no molecule is emitted. Under the ISI avoidance scheme,  $k$  should be 2, that is, two adjacent symbols in the transmission sequence cannot be the same. For example, ‘A, A, B’ is invalid, but ‘A, B, A’ or ‘-, -, A’ is allowed. Then the transmission sequence of the transmitter in a period of time may be ‘A, B, A, -, -, A, ...’. When we divide every two symbols into a combination, we can get a symbol set with an element length of 2: {A -, - A, B -, - B, AB, BA, -}. There are 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 can only transmit 14 bit of information at most. However, it is assumed that each element in the symbol set appears with equal probability, Then use Huffman coding to map all elements in the set to a longer bit sequence, so as to improve the transmission rate. 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. 2 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. 2.** State diagram of the modulation method.

### 3.1 Inter-Symbol Interference

Theoretically, transmitting information according to our modulation method can effectively avoid ISI, but in order to make the experimental model and simulation data more authentic, we still consider ISI [13].

The random Brownian motion of molecules is the main cause of ISI. Due to the randomness of messenger 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.

Suppose that  $N_{ISI,its}$  represents the number of molecules that were emitted  $i$  time slots before and reach the receptor at current time slot. According to [15, 16],  $N_{ISI,its}$  is a random variable, they consist of the subtraction of two normal distributions:

$$N_{ISI,its} \sim \frac{1}{2}N(np(d, (i+1)t_S), np(d, (i+1)t_S)(1-p(d, (i+1)t_S))) - \frac{1}{2}N(np(d, it_S), np(d, it_S)(1-p(d, it_S))) \quad (5)$$

where the factor  $1/2$  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. Then the number of ISI molecules received by the current time slot can be expressed as:

$$N_{C,ISI} = \sum_{i=2_{i \in E}}^{\infty} N_{ISI,its} \quad (6)$$

It can be further deduced that under our modulation method, the number of molecules of ISI received in the current time slot is:

$$N_{ISI,its}^m \underset{i \geq 2}{\sim} \frac{1}{m+1}N(np(d, (i+1)t_S), np(d, (i+1)t_S)(1-p(d, (i+1)t_S))) - \frac{1}{m+1}N(np(d, (i)t_S), np(d, (i)t_S)(1-p(d, (i)t_S))) \quad (7)$$

where  $m$  represents the number of different types of molecules.

### 3.2 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 messenger 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. 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:

$$\begin{aligned} H_0 : Z = N_0 &\sim (\mu_0, \sigma_0^2) \\ H_1 : Z = N_1 &\sim (\mu_1, \sigma_1^2) \end{aligned} \quad (8)$$

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, but with the greatest difference, 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:

$$\begin{aligned} \frac{P(H_0|Z)}{P(H_1|Z)} &= \frac{P(H_0)P(Z|P_0)}{P(H_1)P(Z|P_1)} \\ &= \frac{\sigma_1^2}{\sigma_0^2} \exp\left\{\frac{(Z - \mu_1)^2}{2\sigma_1^2} - \frac{(Z - \mu_0)^2}{2\sigma_0^2}\right\} \end{aligned} \quad (9)$$

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

$$\tau = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \quad (10)$$

where:

$$\begin{aligned} A &= -\frac{1}{2} \left( \frac{1}{\sigma_1^2} - \frac{1}{\sigma_0^2} \right) & B &= \frac{\mu_1}{\sigma_1^2} - \frac{\mu_0}{\sigma_0^2} \\ C &= \ln\left(\frac{\sigma_0}{\sigma_1}\right) - \frac{1}{2} \left( \frac{\mu_1^2}{\sigma_1^2} - \frac{\mu_0^2}{\sigma_0^2} \right) \end{aligned} \quad (11)$$

The BER for the information transmitted can be written as

$$\begin{aligned} P_e &= \frac{1}{2} (p(N_0 > \tau) + p(N_1 < \tau)) \\ &= \frac{1}{2} \left( Q\left(\frac{\tau - \mu_0}{\sigma_0}\right) + 1 - Q\left(\frac{\tau - \mu_1}{\sigma_1}\right) \right) \end{aligned} \quad (12)$$

## 4 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. According to experience and selection of simulation model, we set some default simulation parameters as shown in Table 1: the distance between transmitter and receptor  $d = 25 \mu\text{m}$ ; the radius of the receptor  $R = 10 \mu\text{m}$ ; the Diffusion coefficient  $D = 100 \mu\text{m}^2/\text{s}$ ; the symbol duration  $t_s = 30 \text{ s}$ ; and the related time slot  $k = 8$ .

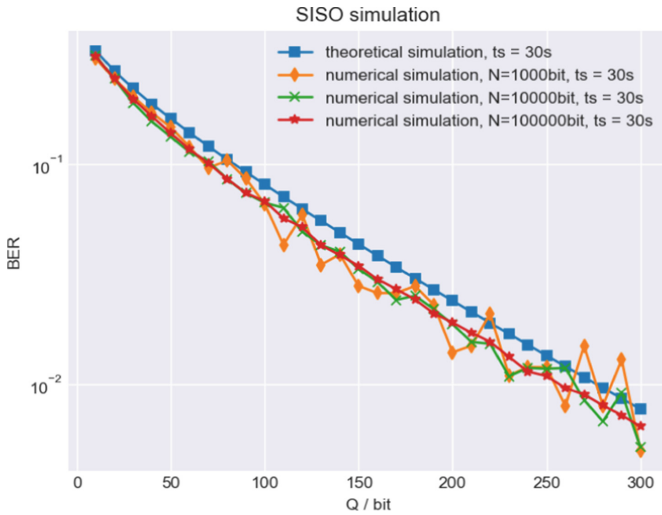
In Fig. 3, the comparison between the simulation results of theoretical derivation and numerical simulation results is shown. The theoretical simulation results are derived from Formula (5)–(7), while the numerical simulation results are obtained by

transmitting messenger molecules. The ordinate represents the BER performance, and the abscissa represents the number of messenger molecules released, that is, energy or power. The simulation results show that the numerical simulation results are very close to the theoretical analysis results on the whole, and with the increase of simulation data from 1000 bit to 100000 bit, the numerical simulation curve is more smooth, which proves the authenticity of the model.

Figure 4 shows the BER performance comparison between the proposed modulation technology and other modulation technologies. The simulation parameters use the default

**Table 1.** Simulation parameters.

Parameter	Value
Distance between transmitter and receptor ( $d$ )	25 $\mu\text{m}$
Radius of the receptor ( $R$ )	10 $\mu\text{m}$
Diffusion coefficient ( $D$ )	100 $\mu\text{m}^2/\text{s}$
Symbol duration ( $t_s$ )	30 s
Related time slot ( $k$ )	8

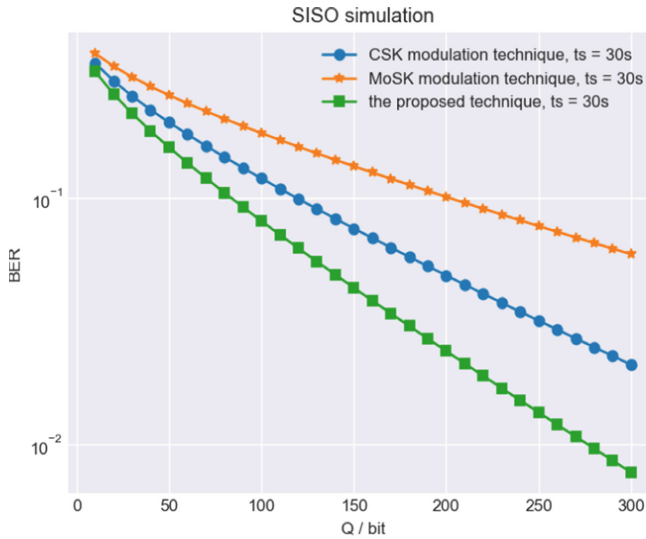


**Fig. 3.** Theoretical simulation and numerical simulation

parameters. Compared with CSK and MoSK modulation, the proposed modulations obviously have better BER performance. With the increase of  $Q$ , the gap 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.

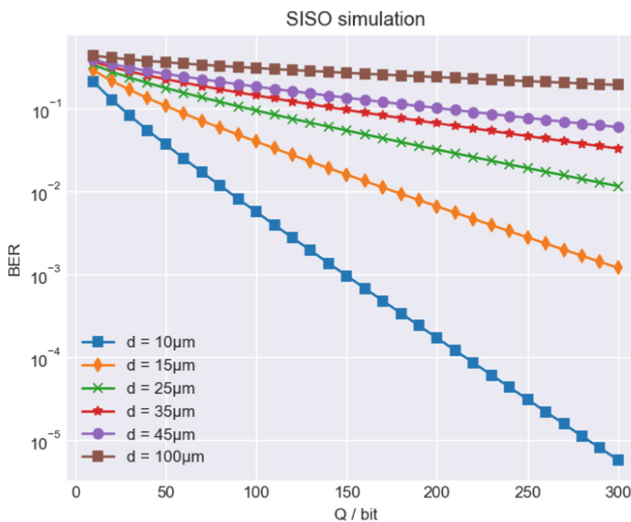
The Fig. 5 shows the distance between transmitter and receiver in relation to BER performance. The six curves respectively represent BER performance curves when  $d = 10 \mu\text{m}$ ,  $d = 15 \mu\text{m}$ ,  $d = 25 \mu\text{m}$ ,  $d = 35 \mu\text{m}$ ,  $d = 45 \mu\text{m}$ ,  $d = 100 \mu\text{m}$ . It is not difficult to find that with the increase of  $d$ , the BER performance of the system is getting worse. This is because the increase of the receiving and transmitting distance decreases the probability of the large receiver of the messenger molecule, which leads to the increase of the bit error rate and the decline of BER performance. However, when  $d$  increases to a certain extent, the BER performance degradation becomes limited. At this time, it can also be understood that too much  $d$  has less impact on the system performance.

Similarly, Fig. 6 shows the impact of different symbol duration on system BER performance. The six curves respectively represent BER performance curves when  $t_s$



**Fig. 4.** BER performance of different modulation technique

$= 5 s, t_s = 10 s, t_s = 20 s, t_s = 30 s, t_s = 40 s, t_s = 100 s$ . In addition to the change of symbol duration  $t_s$ , other simulation parameters are set by military default. We can observe that the BER performance of the system is getting better and better with the continuous increase of  $t_s$ . This is because the messenger molecule has enough time to move until the receiver is absorbed, which improves the overall probability to a large extent and reduces the bit error rate. However, when  $t_s$  increases to a certain extent, perhaps when  $t_s = 30\text{--}40 s$ , the BER performance of the system does not change much. At this time, the impact of  $t_s$  on the system performance is very limit.



**Fig. 5.** BER performance of different distance between transmitter and receptor

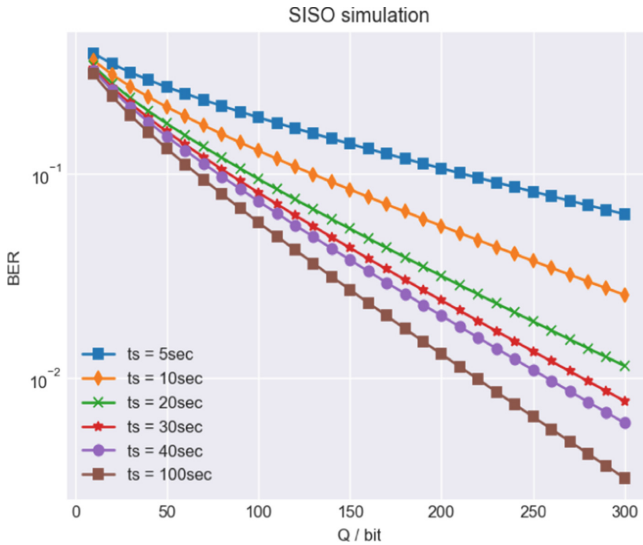


Fig. 6. BER performance of different symbol duration

## 5 Conclusion

In this paper, we propose a simple modulation scheme. Through the comparison of simulation data, we can draw a conclusion that the proposed modulation scheme can effectively reduce the impact of ISI, and has better BER performance than other modulation schemes. In addition, the proposed modulation method can enable the messenger molecules to carry more information and improve the efficiency of information transmission. According to the calculation and analysis above, this simple modulation method can improve the bps (bits per symbol) by about 40% compared with the ordinary method, and reduce the ISI effect well. To some extent, good performance needs to be achieved at the expense of the complexity of the transmitter and receptor, but this modulation scheme only uses two different types of messenger molecules. In the future work and research, we believe that with the progress of nanotechnology, relevant research will be able to achieve more remarkable results and achievements.

## References

1. Suda, T., Moore, M.J., Nakano, T.: Exploratory research on molecular communication between nanomachines. *Nat. Comput.* 1–30 (2005)
2. Yue, G., Liu, Q., Lin, L.: Directional molecular communication among nanomachines in massive bacteria-based Nanonetwork. In: 2021 International Conference on UK-China Emerging Technologies (UCET) (2021)
3. Akyildiz, I.F., Brunetti, F., Blazquez, C.: Nanonetworks: a new communication paradigm. *Comput. Netw. (Elsevier) J.* **52**(12), 2260–2279 (2008)
4. Nakano, T., Moore, M.J., Fang, W.: Molecular communication and networking: Opportunities and challenges. *IEEE Trans. Nanobiosci.* **11**, 135–148 (2012)

5. Yeh, P.C., Chen, K.C., Lee, Y.C., et al.: A new frontier of wireless communication theory: diffusion-based molecular communications. *IEEE Wirel. Commun.* **19**(5), 28–35 (2012)
6. Nakano, T., Suda, T., Okaie, Y., et al.: Molecular communication among biological nanomachines: a layered architecture and research issues. *IEEE Trans. Nanobiosci.* **13**(3), 169–197 (2014)
7. Kuran, M.S., Yilmaz, H.B., Tugcu, T., Akyildiz, I.F.: Modulation techniques for communication via diffusion in nanonetworks. In: *Proceedings IEEE International Conference Communication Kyoto, Japan*, pp. 1–5 (2011)
8. Arjmandi, H., Gohari, A., Kenari, M.N., Bateni, F.: Diffusion-based nanonetworking: a new modulation technique and performance analysis. *IEEE Commun. Lett.* **17**, 645–648 (2013)
9. Atakan, B., Galmes, S., Akan, O.B.: Nanoscale communication with molecular arrays in nanonetworks. *IEEE Trans. Nanobiosci.* **11**(2), 149–160 (2012)
10. Pierobon, M., Akyildiz, I.F.: Intersymbol and co-channel interference in diffusion-based molecular communication. In: *IEEE International Conference on Communications*, pp. 6126–6131 (2012)
11. Saeed, M., Bahrami, H.R.: Performance of MIMO molecular communications in diffusion-based channels. *Int. J. Commun. Syst.* (2017)
12. Moore, M.J., Suda, T., Oiwa, K.: Molecular communication: modeling noise effects on information rate. *IEEE Trans. Nanobiosci.* **8**(2), 169–180 (2009)
13. Jiang, C., Chen, Y., Liu, K.J.R.: Inter-user interference in molecular communication networks. In: *ICASSP*, pp. 5725–5729 (2014)
14. Arjmandi, H., Movahednasab, M., Gohari, A., Mirmohseni, M., Nasiri-Kenari, M., Fekri, F.: ISI-avoiding modulation for diffusion-based molecular communication. *IEEE Trans. Mol. Biolog. Multi-Scale Commun.* **3**(1), 48–59 (2017). <https://doi.org/10.1109/TMBMC.2016.2640311>
15. Noel, A., Cheung, K.C., Schober, R.: Improving receiver performance of diffusive molecular communication with enzymes. *IEEE Trans.* **13**(1), 31–43 (2014)
16. Liu, Q., Lu, Z., Yang, K.: Modeling and dual threshold algorithm for diffusion-based molecular MIMO communications. *IEEE Trans. Nanobiosci.* **20**(4), 416–425 (2021). <https://doi.org/10.1109/TNB.2021.3077297>
17. Liu, Q., Yang, K., Xie, J., Sun, Y.: DNA-based molecular computing, storage, and communications. *IEEE Internet Things J.* **9**(2), 897–915 (2022). <https://doi.org/10.1109/JIOT.2021.30836>