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Performance Analysis of D-Mosk Modulation in Mobile Diffusive-Drift Molecular Communication Relay System

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Abstract Molecular communication (MC) is a new wireless communication technology, which uses molecules as information carriers. Diffusion-based MC is one of the most common MC methods. With the increase of diffusion distance, the molecular signal attenuation is serious, so the traditional communication technology of relay is introduced into the MC system. In this work, a mobile diffusive-drift MC relay model is investigated, in which the depleted molecule shift keying (D-MoSK) modulation is used. The closed-form expression of symbol error rate (SER) and the channel capacity are derived, meanwhile the impacts of several crucial parameters on the performance are discussed comprehensively.

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I. INTRODUCTION

MOLECULAR communication (MC) is a new type of communication using molecules as information carriers, which can be used to its advantage in scenarios where conventional wireless communication is not suitable, such as in confined pipes, seawater or body areas. In MC systems, the molecules usually undergo Brownian motion, and as the diffusion distance increases, the molecular signal attenuates severely, making the diffusion transmission distance very limited. At the same time, the large transmission delay of freely diffusing molecules causes severe inter-symbol interference (ISI), which is an important factor affecting system performance. In order to extend the transmission distance and improve the system performance, a suitable channel transmission model is needed to study the mechanism. Because their small size and the fact that they do not easily communicate using electrons or electromagnetic waves, MC offers a new mechanism for nanometers communication by transporting molecules to represent information [1], [2]. These nanomachines have computing, storage and drive functions [3]. Due to their own limitations, they cannot perform the corresponding tasks, so they are interconnected to overcome their limitations and form a nanonetwork with certain

functions that work together in a collaborative area to accomplish specific tasks[4]–[6].

The idea that nanomachines achieve information exchange through the emission, transmission and reception of information molecules comes from the exchange of information between cells in nature [7]. Diffusion-based nanotechnology for MC has a wide range of promising applications, mainly in biomedicine. A biological system (e.g., nanomachines), each performing simple and specific operations such as the uptaking, processing and releasing of molecules, as well as cellular interactions to perform various functions of the body(e.g. , cell metabolism, molecular replication, etc.) [8].

The current demodulation algorithm applied to the received message in MC is mainly based on the detection of the number of molecules. In a fixed time slot, the transmitter sends a certain number of molecules to represent message “1”, while no molecules are sent to represent message “0”. The receiver demodulates the message to bit “1” when and only when the number of molecules received exceeds the set threshold, otherwise the message is demodulated to bit “0”. The whole communication process is based on the time slot for message transmission. This demodulation algorithm based on the number of molecules is very simple to implement. However, due to the random diffusion of molecules and ISI caused by the accumulated molecules in the medium, the recognition rate of the signal during demodulation at the receiver side is reduced, resulting in a higher BER and the reliability of the communication is greatly affected.

In order to solve the above problems, research on diffusion based MC systems has attracted a lot of academic attention. By adding relay nodes, the transmission distance of diffusing molecules can be enhanced and the system performance can be improved. By introducing relay nodes, the transmission distance of diffusion MC can be extended. Meanwhile, the system performance can be improved [9], [10]. In conventional wireless communication systems, decode-and-forward (DF) is used to enhance system performance. A point-to-point relay model based on MC can significantly improve the transmission reliability, and related on MC relay has been studied in several

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literature. In [11], diffusion-based sensory relay transmission strategies for MC systems were investigated, and although bacteria were used as information carriers, the essence of the transmission was still diffusion. The DF relay transmission model for diffusion MC systems was proposed in [12], where the channel model considers the effects of noise and channel memory, while exploring the performance of the BER in the system subject to channel fading versus the optimal relay location. Literature [12] and [13] explored the BER performance of the system in DF and amplify-and-forward (AF) transmission modes, respectively. A diffusion-based model of a reversible binding system for DF relay ligands and receptor for MC is presented in [14], where the time-varying spatial distribution of information is characterised based on the reversible binding and separation of ligands and receptors on the receiver surface. The literature [15] describes a diffusion based molecular theory system model based on the influence of molecular delivery sequences and obtains the information transmission rate of the relay channel under the influence of the sequence-based approach. In [16] the authors built an AF relay system and analysed the performance of the system under different detection schemes. In [17] the authors developed a DF relay model for MC systems based on drift diffusion, applied to the human vascular scenario, approximated the number of molecules received to a normal distribution and solved for a closed-form expression for the BER of the system. These authors after further research, proposed a DF relay system model based on energy detection in [18]. In [19], a cooperative diffusion-based MC network model is considered, which consisting of single source, single DF relay, and single destination.

However, mobile MC is needed in many envisioned applications. A static transmitter and a mobile bacterium-based receiver are considered in [20], meanwhile an adaptive ISI mitigation method and two adaptive detection schemes are proposed for the mobile scenario. In [21], authors consider a mobile MC system where the fluid medium has a fully developed homogeneous turbulence, and both the transmit and the receive nano-devices are mobile. The mobile multiuser diffusive MC system with drift which is composed of multiple mobile transmitter nanomachines and one mobile receiver nanomachine is built in [22], in which both the ISI and multiuser interference unavoidably exist in the same fluid medium. The closed-form expressions for the probabilities of detection and false alarm are derived at the cooperative and destination nanomachines considering the multiple-source interference and the ISI are obtained in [23]. The authors propose an adaptive detection scheme for mobile MC with a low computational complexity by utilizing the local convex property of the channel impulse response in [24], in which the results show that the proposed scheme achieves good detection accuracy with low

computational complexity. The mobile MC system is built in [25], in which transmitter and receiver move randomly in a free diffusion manner. The closed-form expressions of the mean and variance of the received signal are derived by considering two kinds of randomness.

In this work, a DF relay for mobile MC system is presented to improve the system performance in the long-distance scene. DF relay can reduce the accumulation noise. Meanwhile, D-MoSK modulation is used in the system. The novelties of this work are summarized as follows:

1. A DF MC relay scheme for long-distance communication is concerned, in which the source and destination are mobile, and the D-MoSK modulation is used to deduce ISI and decoding complexity.
2. The corresponding SER and capacity are characterized, and the impacts of the key factors on the performance are evaluated, such as the velocity of fluid, the coefficient of molecules and so on. The obtained results are expected to provide guidance significance for the design of a practical mobile diffusive-drift MC relay system.

The remainder of this paper is organized as follows. The mobile diffusive-drift MC relay system model, including the mobile S and the mobile D, is introduced in Section II. In Section III, we will give the mathematical derivations with respect to the detection scheme. In Section IV, numerical results and performance discussions are presented. Section V concludes the paper.

II. SYSTEM MODEL

In this work, a mobile MC relay system model is built, which considers a source node, a relay node and a destination node. They are in mobility, and the fluid medium has a certain velocity. The system model is shown in Fig. 1, where S, R and D represent the information source node, the relay node and the destination node, respectively. In this system model, the depleted molecules shift keying (D-MoSK) modulation method is utilized. It uses two different types of molecules to represent Quaternary information, that is, the emission of molecules "a" represents information "10", the emission of molecules "b" represents information "01", molecules "a" and "b" simultaneously emission represents information "11", and neither molecules "a" nor molecules "b" emission represents information "00". When the information molecules drift to the R, the R detects the signal. The R decodes the information using threshold detection. When it detects that molecules "a" exceed the threshold while molecules "b" does not, it decodes the information as "10"; otherwise, it decodes the information as "01". When both molecules "a" and "b" are detected to exceed the

threshold, the information is decoded as “11”. When neither molecules “a” nor molecules “b” exceeds the threshold, the information is decoded as “00”. The R adopts DF mode. In order to reduce the influence of ISI, the R uses different types of molecules to re-encode the decoded information. When the decoding information is “01”, the R releases a constant number of molecules “c”; when the decoding information is “10”, the R releases a constant number of molecules “d”; when the decoding information is “11”, the R releases a constant number of molecules “c” and “d”; when the decoding information is “00”, the R does not release any molecules.

Suppose that information molecules make Brownian motion in the fluid environment. That is, the information molecules have a velocity drift. The information molecules obeys the second Fick’s law of diffusion [26]. At first, we consider that the S, R and D are stationary. Then we consider the processing that information from S to R. The time slot is a random variable, which means that a molecule diffusion with drift from S to R, it defined as t , following

$$f(t) = \frac{d_0}{4\pi D t^3} e^{-\frac{(Vt-d_0)^2}{4Dp t}}, \quad (1)$$

where d_0 means the distance between S and R. Additionally, V stands for the drift velocity of the fluid medium, and Dp is the diffusion coefficient for the information molecules.

Next, we investigate a practical case, where both S and R are in mobility. Under this case, assuming the molecules are

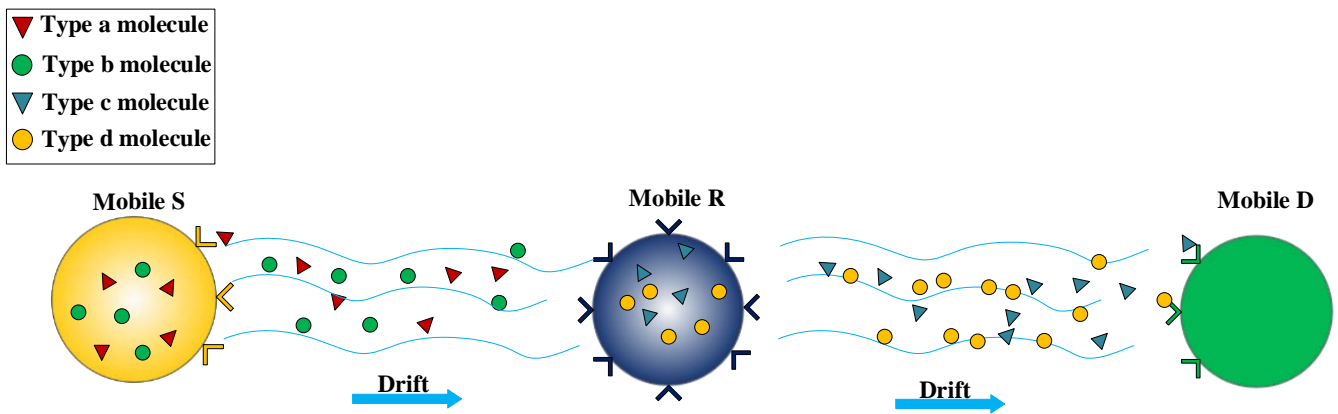


Fig. 1: The diffusive-drift molecular communication (MC) relay model with the mobile S, R and the mobile D. The red triangle represents the molecule of Type “a”; while the green circle stands for the molecule of Type “b”. The blue triangle represents the molecule of Type “c”; while the yellow circle stands for the molecule of Type “d”.

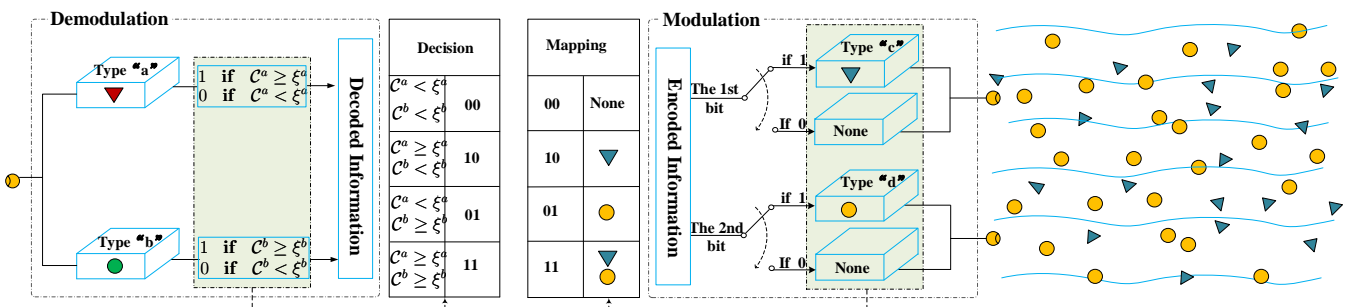


Fig. 2: Schematic diagram of the quaternary D-MoSK demodulation/modulation in a MC system at relay node. After receiving the information from the S, the R decodes it first. At the demodulator, the R captures the information molecule and decodes the data via a specially-designed decision device, in which the number of received molecules is the decision variable. C_a and C_b refer to the numbers of received molecules with Type “a” and Type “b”, respectively. Also, ξ_a and ξ_b denote the decision thresholds with respect to Type “a” and Type “b”. Then the R according to the D-MoSK modulation scheme to encode the information using molecules with Type “c” and Type “d”

transmitted by S at beginning of the i th time slot. According to the results in [27], the probability distribution function (PDF) for molecules of the first hitting time to reach R is shown in (2), where $erf(\cdot)$ denotes the standard error function. Also, DS and DR refer to diffusion coefficients of S and R, respectively. Besides, α and β are defined as $\alpha \triangleq DS + DR$ and $\beta \triangleq DR + D\rho$, respectively.

It is supposed that a molecule transmitted by S at the beginning of the first time slot and reach R after j time slots, then the probability of the molecule being captured by the R satisfies,

$$F(t; j) = \int_0^{jT_s} f(t; i) dt, \tag{3}$$

where T_s denotes the length of each time slot.

The D-MoSK modulation is used to modulate Quaternary information. We use two different types of molecules, namely Type “a” and Type “b”. In this model, it is assumed that Type “a” and Type “b” have the same diffusion coefficients. The number of molecules captured by R at n th time slot can be expressed by

$$R^{a \text{ or } b}[n] = C^{a \text{ or } b}[n] + C_I^{a \text{ or } b}[n] + C_N[n], \tag{4}$$

$$f(t; i) = \frac{\sqrt{iT_s\alpha\beta}}{\pi\sqrt{t(iT_s\alpha + \beta t)}} e^{-\frac{d_0^2}{4iT_s\alpha}} + f\left(t + iT_s\frac{\alpha}{\beta}\right) \cdot erf\left(\frac{d_0}{2\sqrt{iT_s\alpha(iT_s\alpha + \beta t)}}\right) \tag{2}$$

term in (4), i.e., $N[n]$, follows Gaussian distribution, that is $C_N[n] \sim \mathcal{N}(\mu_\omega, \sigma_\omega^2)$.

On the basis of the central limit theorem, if C_a or b is sufficiently large, the binomial distribution in Eqns. (5) and (6) will approximate to the Gaussian distribution [28]. It is found in (4) that the terms keep statistically independent, and hence the receive signal at R follows Gaussian distribution, as shown in (7), in which q_i and F are defined as $q_i \triangleq F(t; i+1) - F(t; i)$ and $F \triangleq F(t; 1)$, respectively. The conditional probability of R_a or $b[n]$ follows the Gaussian distribution as

$$\begin{cases} R^{a \text{ or } b}[n] \sim \mathcal{N}\left[\mu_0^{a \text{ or } b}, (\sigma_0^{a \text{ or } b})^2\right], & \text{if } x[n] = 0; \\ R^{a \text{ or } b}[n] \sim \mathcal{N}\left[\mu_1^{a \text{ or } b}, (\sigma_1^{a \text{ or } b})^2\right], & \text{if } x[n] = 1. \end{cases} \tag{8}$$

Define p_0 and p_1 as the probabilities with respect to transmitted bit to be “0” and “1”, respectively. Furtherly, we can have

$$\begin{cases} \mu_0^{a \text{ or } b}[n] = p_1 Q^{a \text{ or } b} \sum_{i=1}^I q_i + \mu_\omega, \\ \mu_1^{a \text{ or } b}[n] = Q^{a \text{ or } b} F + \mu_0^{a \text{ or } b}[n], \end{cases} \tag{9}$$

in which C_a or $b[n]$ stands for the number of information molecules that reach R at the n th time slot. C_a or $b / [n]$, standing for the ISI, refers to the molecules released in the previous time slots but reach R at the n th time slot. Besides, $C_N[n]$ refers to the noise.

The molecules freely diffusive and keep independence with each other, then the number of the molecules captured by R, denoted by C_a or $b[n]$, follows the binomial distribution, it follows

$$C^{a \text{ or } b}[n] \sim \mathcal{B}(Q^{a \text{ or } b} x[n], F(t; n)), \tag{5}$$

where Q denotes the released molecular number by S when the input bit is “1” as shown in Fig. 2, and $x[n]$ represents the transmitted bit by S at the n th time slot. Besides, the ISI term in (4), i.e., C_a or $I(n)$, follows

$$C_I^{a \text{ or } b}[n] \sim \sum_{i=1}^l \mathcal{B}(Q^{a \text{ or } b} x[n-i], F(t; n) - F(t; n-1)), \tag{6}$$

where l denotes as the number of ISI. Generally, the influence of ISI gradually weak over time, and hence it is reasonable to assume the number of ISI is finite. Also, $x[n-i]$ represents the transmitted bit by S at the $(n-i)$ th time slot. The noise.

in which $\mu_0^{a \text{ or } b}$ and $\mu_1^{a \text{ or } b}$ denote the means of R_a or $b[n]$ with the transmitted bit to be “0” and “1”, respectively. Besides, the variations of R_a or $b[n]$ can be calculated by

$$\begin{cases} (\sigma_0^{a \text{ or } b}[n])^2 = p_1 Q^{a \text{ or } b} \sum_{i=1}^I q_i (1 - q_i) \\ \quad + p_1 p_0 (Q^{a \text{ or } b})^2 \sum_{i=1}^I q_i^2 + \sigma_\omega^2, \\ (\sigma_1^{a \text{ or } b}[n])^2 = Q^{a \text{ or } b} F (1 - F) + (\sigma_0^{a \text{ or } b}[n])^2. \end{cases} \tag{10}$$

The R uses decode and forward scheme, so when the signal arrives R, it will be decoded, then re-encode the decoded information. The R uses different types of molecules to transmit information. It is assumed that R uses Type “c” and Type “d” to forward information.

The number of molecules captured by D at $(n+1)$ th time slot can be expressed by

$$D^{c \text{ or } d}[n+1] = C^{c \text{ or } d}[n+1] + C_I^{c \text{ or } d}[n+1] + N[n+1], \tag{11}$$

in which C_c or $d[n+1]$ stands for the number of information molecules that reach D at the $(n+1)$ th time

slot. C_c or $d / [n+1]$, standing for the ISI, refers to the molecules released in the previous time slots but reach D at the $(n + 1)$ th time slot. Besides, $N[n + 1]$ refers to the noise.

The molecules still diffusion and keep independence on each other, then the number of the molecules captured by D, denoted by C_c or $d[n+1]$, follows the binomial distribution, it follows

$$C_I^{c \text{ or } d}[n+1] \sim \sum_{i=1}^I \mathcal{B}(Q^{c \text{ or } d} x[n + 1 - i], F(t; n + 1) - F(t; n)), \quad (13)$$

where I denotes as the number of ISI. Generally, the influence of ISI gradually weakens over time, and hence it is reasonable to assume the number of ISI is finite. Also, $x[n+1]$ represents the transmitted bit by R at the $(n+1)$ th time slot. The noise term in (11), i.e., $N[n+1]$, follows Gaussian distribution, that is $N[n + 1] \sim \mathcal{N}(\mu_\omega, \sigma_\omega^2)$.

Then the information diffusion follows same distribution from R to D, the mean and variance are calculated in the same way as from S to R. According to Eqns. (9) and (10), the corresponding parameters can be changed to calculate.

III. SIGNAL DETECTION AND DATA DECODING

The maximum likelihood (ML) detection method is used in signal detection at R, and the likelihood ratio test (LRT) scheme satisfies

$$\begin{aligned} H_0 : \quad & \xi = N_I^{a \text{ or } b}[n] + C_N[n], \\ H_1 : \quad & \xi = R^{a \text{ or } b}[n], \end{aligned} \quad (14)$$

$$\frac{1}{\sqrt{2\pi}\sigma_1^{a \text{ or } b}} e^{-\frac{(\xi - \mu_1^{a \text{ or } b})^2}{2(\sigma_1^{a \text{ or } b})^2}} = \frac{1}{\sqrt{2\pi}\sigma_0^{a \text{ or } b}} e^{-\frac{(\xi - \mu_0^{a \text{ or } b})^2}{2(\sigma_0^{a \text{ or } b})^2}} \quad (18)$$

$$R^{a \text{ or } b}[n] \sim \mathcal{N}(Q^{a \text{ or } b} F + \sum_{i=1}^I Q^{a \text{ or } b} x[n - i] q_i + \mu_\omega, Q^{a \text{ or } b} F(1 - F) + \sum_{i=1}^I Q^{a \text{ or } b} x[n - i] q_i (1 - q_i) + \sigma_\omega^2) \quad (7)$$

$$\begin{aligned} & \left[(\sigma_1^{a \text{ or } b})^2 - (\sigma_0^{a \text{ or } b})^2 \right] \xi^2 - \left[2\mu_0^{a \text{ or } b} (\sigma_1^{a \text{ or } b})^2 - 2\mu_1^{a \text{ or } b} (\sigma_0^{a \text{ or } b})^2 \right] \xi + \mu_0^{2a \text{ or } b} (\sigma_1^{a \text{ or } b})^2 \\ & - \mu_1^{2a \text{ or } b} (\sigma_0^{a \text{ or } b})^2 - 2(\sigma_1^{a \text{ or } b})^2 (\sigma_0^{a \text{ or } b})^2 \ln \frac{\sigma_1^{a \text{ or } b}}{\sigma_0^{a \text{ or } b}} - 2(\sigma_1^{a \text{ or } b})^2 (\sigma_0^{a \text{ or } b})^2 \ln \frac{p_0}{p_1} = 0. \end{aligned} \quad (19)$$

Then, according to calculate we can get the conclusion which is shown in (19). Further, the detection threshold, i.e., ξ , can be calculated by

$$\xi = \text{round} \frac{B + \sqrt{B^2 - AC}}{A}, \quad (20)$$

$$N^{c \text{ or } d}[n + 1] \sim \mathcal{B}(Q^{c \text{ or } d} x[n + 1], F(t; n + 1)), \quad (12)$$

where Q_c or d denotes the released molecular number by R when the input bit is "1", and $x[n+1]$ represents the transmitted bit by R at the $(n + 1)$ th time slot. Besides, the ISI term in (11), i.e., C_c or $d / (n + 1)$, follow

where H_0 and H_1 represent the ML conditions. So the detection threshold function follows

$$f(\xi) = \frac{p(\xi|H_1)}{p(\xi|H_0)} = \frac{f_\xi^{(1)}(\xi)}{f_\xi^{(0)}(\xi)} \stackrel{<}{>} \frac{p_0}{p_1} \quad (15)$$

in which $f_\xi^{(0)}(\xi)$ and $f_\xi^{(1)}(\xi)$ represent the probability density function (PDF) of ξ in terms of H_0 and H_1 , respectively, defined as

$$\begin{aligned} f_\xi^{(0)}(\xi) & \triangleq \frac{1}{\sqrt{2\pi}(\sigma_0^{a \text{ or } b})^2} e^{-\frac{(\xi - \mu_0^{a \text{ or } b})^2}{2(\sigma_0^{a \text{ or } b})^2}}, \\ f_\xi^{(1)}(\xi) & \triangleq \frac{1}{\sqrt{2\pi}(\sigma_1^{a \text{ or } b})^2} e^{-\frac{(\xi - \mu_1^{a \text{ or } b})^2}{2(\sigma_1^{a \text{ or } b})^2}}. \end{aligned} \quad (16)$$

According to Eqns. (15) and (16), we can get the likelihood-ratio function,

$$\lambda(\xi) \triangleq \frac{f_\xi^{(0)}}{f_\xi^{(1)}} \quad (17)$$

It is assumed that the transmission of "0" and "1" are equal probability, let $\lambda(\xi) = 1$, and we can have,

where A , B and C are defined as

$$\begin{aligned} A & \triangleq (\sigma_1^{a \text{ or } b})^2 - (\sigma_0^{a \text{ or } b})^2, \\ B & \triangleq \mu_0^{a \text{ or } b} (\sigma_1^{a \text{ or } b})^2 - \mu_1^{a \text{ or } b} (\sigma_0^{a \text{ or } b})^2, \\ C & \triangleq (\mu_0^{a \text{ or } b} \sigma_1^{a \text{ or } b})^2 - (\mu_1^{a \text{ or } b} \sigma_0^{a \text{ or } b})^2 \\ & - 2(\sigma_0^{a \text{ or } b} \sigma_1^{a \text{ or } b})^2 \left(\ln \frac{p_0}{p_1} - \ln \frac{\sigma_0^{a \text{ or } b}}{\sigma_1^{a \text{ or } b}} \right). \end{aligned}$$

Using the transfer probability, the symbol error rate (SER) of from S to R is derived by (21), in which $Q(\cdot)$ refers to the well-known Q-function. Then, the SER of from R to D is derived by (22). So the BER of from S to D can be calculated as

$$P_e = 1 - (1 - P_{e_{s,r}})(1 - P_{e_{r,d}}). \tag{23}$$

Based upon Shannon’s information theory, the channel capacity is defined as the maximum of the mutual information, which is denoted by $I(X; Y)$, between the transmitted symbol X and the received symbol Y . Let X_n represent the signal transmitted by S in the n th time slot, and Y_n represent the signal received by R at the n th time slot. Thus, the channel capacity of from S to R can be expressed by

$$C_{s,r} = \max I(X_n, Y_n) \text{ bit/slot}. \tag{24}$$

The mutual information can be calculated by (25), where $p_x = \Pr(X_n = x)$ and $\Pr(Y_n = y|X_n = x)$ refer to the *priori* probability and conditional probability, respectively. while the channel capacity of from R to D can be expressed by

$$C_{r,d} = \max I(X_{n+1}, Y_{n+1}) \text{ bit/slot}. \tag{26}$$

in which X_{n+1} represent the signal transmitted by R in the $(n+1)$ th time slot, and Y_{n+1} represent the signal received by D at the $(n + 1)$ th time slot.

So all the channel capacity of from S to D is expressed as

$$C = \min(C_{s,r}, C_{r,d}) \text{ bit/slot}. \tag{27}$$

IV. NUMERICAL RESULTS AND PERFORMANCE ANALYSIS

In this section, the numerical results in (23) to evaluate the SER performance of D-MoSK modulation in a mobile diffusive-drift DF communication system are presented. The parameters used in the evaluations are summarized in Table I.

It can be found in Fig. 3 that D-MoSK exhibits a much better SER performance than MoSK in the decode-and-forward communication system. Here we need to point out that the D-MoSK modulation employs much fewer molecular types than MoSK modulation. Thus, the D-MoSK modulation is considered to have the capability to reduce the decoding complexity, as well as the hardware complexity. In this work, we use the number of molecular types that the R and D need to identify to evaluate the decoding complexity. Take the quaternary modulation as an example. For MoSK, the D needs to identify four types of molecules; while for D-MoSK, the D only needs to identify two types of molecules. For general comparisons, we investigate the ratio of decoding complexity between MoSK and D-MoSK, that is $M = \log_2 M$, in which M stands for the modulation order. It can be accessible that along with the increase of modulation order, the advantage of D-MoSK modulation in terms of complexity performance will become more evident. Also, as mentioned above, four types of molecules are needed for quaternary MoSK modulation to form a symbol; while only two types are needed for quaternary D-MoSK modulation. Assume that S can release Q molecules within a bit time. For the MoSK modulation, the number of released molecules is $n_{\text{MoSK}} = 4 \times 2 \times Q$. For the D-MoSK modulation, the number of released molecules is $n_{\text{D-MoSK}} = 2 \times 2 \times Q$. We can conclude that for the quaternary modulation, the number of molecules released in D-MoSK is half of that for MoSK.

In Fig. 4, we investigate the SER performances versus of the ISI length with different Q . From Fig. 4, we can find that SER curves go up along with the ISI length increases. The ISI refers to the information molecules transmitted by the previous time slot arrive in the current time slot. As can be seen from Fig.4, the closer the slot is to the current slot, the greater the impact of ISI. With the increase of time slot distance, the influence of ISI is smaller. When the length of ISI in more than 10, the influence on the system is basically unchanged. That is to say, the current time slot will be affected within 10 slots before the current time slot. In addition, the impact of ISI on the current time slot can be ignored. Therefore, the length of ISI is set to 10 in this paper.

$$P_{e_{s,r}} \triangleq p(00) [p(01|00) + p(10|00) + p(11|00)] + p(01) [p(00|01) + p(10|01) + p(11|01)] + p(10) [p(00|10) + p(01|10) + p(11|10)] + p(11) [p(00|11) + p(01|11) + p(10|11)] = \frac{1}{4} \left\{ 4 - \left[1 - Q \left(\frac{\xi - \mu_0^a}{\sigma_0^a} \right) \right] \left[1 - Q \left(\frac{\xi - \mu_0^b}{\sigma_0^b} \right) \right] - \left[1 - Q \left(\frac{\mu_1^a - \xi}{\sigma_1^a} \right) \right] \left[1 - Q \left(\frac{\xi - \mu_0^b}{\sigma_0^b} \right) \right] - \left[1 - Q \left(\frac{\mu_1^b - \xi}{\sigma_1^b} \right) \right] \left[1 - Q \left(\frac{\xi - \mu_0^a}{\sigma_0^a} \right) \right] - \left[1 - Q \left(\frac{\mu_1^a - \xi}{\sigma_1^a} \right) \right] \left[1 - Q \left(\frac{\mu_1^b - \xi}{\sigma_1^b} \right) \right] \left[1 - Q \left(\frac{\mu_1^a - \xi}{\sigma_1^a} \right) \right] \right\} \tag{21}$$

$$\begin{aligned}
 P_{e_{r,d}} &\triangleq p(00) [p(01|00) + p(10|00) + p(11|00)] + p(01) [p(00|01) + p(10|01) + p(11|01)] \\
 &\quad + p(10) [p(00|10) + p(01|10) + p(11|10)] + p(11) [p(00|11) + p(01|11) + p(10|11)] \\
 &= \frac{1}{4} \left\{ 4 - \left[1 - Q \left(\frac{\xi - \mu_0^c}{\sigma_0^c} \right) \right] \left[1 - Q \left(\frac{\xi - \mu_0^d}{\sigma_0^d} \right) \right] - \left[1 - Q \left(\frac{\mu_1^c - \xi}{\sigma_1^c} \right) \right] \left[1 - Q \left(\frac{\xi - \mu_0^d}{\sigma_0^d} \right) \right] \right. \\
 &\quad \left. - \left[1 - Q \left(\frac{\mu_1^d - \xi}{\sigma_1^d} \right) \right] \left[1 - Q \left(\frac{\xi - \mu_0^c}{\sigma_0^c} \right) \right] - \left[1 - Q \left(\frac{\mu_1^d - \xi}{\sigma_1^d} \right) \right] \left[1 - Q \left(\frac{\mu_1^c - \xi}{\sigma_1^c} \right) \right] \right\} \tag{22}
 \end{aligned}$$

$$I(X_n; Y_n) = \sum_y \sum_x p_x \Pr(Y_n = y | X_n = x) \log_2 \frac{\Pr(Y_n = y | X_n = x)}{\sum_x p_x \Pr(Y_n = y | X_n = x)} \tag{25}$$

Table 1: Parameters Used in the Numerical Results

Definition	Symbol	Value
Diffusion coefficient of information molecules	D_a, D_b, D_c, D_d	$[1, 50] \times 10^{-10} \text{ m}^2/\text{s}$
Diffusion coefficient of S	D_S	$[1, 100] \times 10^{-14} \text{ m}^2/\text{s}$
Diffusion coefficient of R	D_R	$[1, 100] \times 10^{-13} \text{ m}^2/\text{s}$
Initial distance between S and R	d_0	$10 \text{ }\mu\text{m}$
Symbol time	T_s	$[0, 0.2 \text{ s}]$
Number of molecules transmitted by S	Q_a, Q_b, Q_c, Q_d	$(0, 800]$
Velocity of fluid medium	V	$[0.1, 1] \times 10^{-3}$
Mean of noisy molecule	μ_ω	0
Variance of noisy molecule	σ_ω^2	300
Length of ISI	I	10

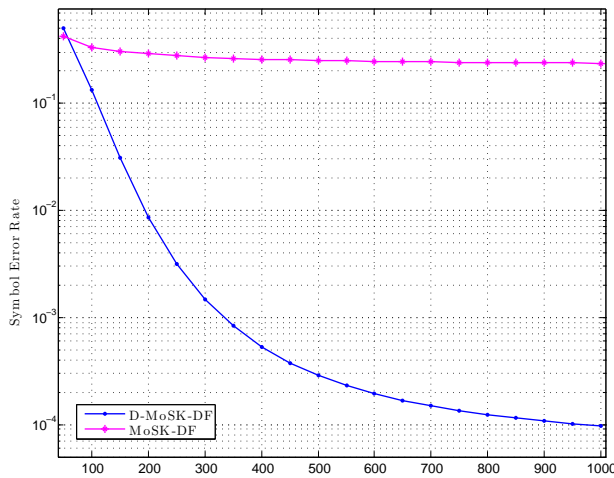


Fig. 3: Comparisons of SER performances between MoSK and D-MoSK.

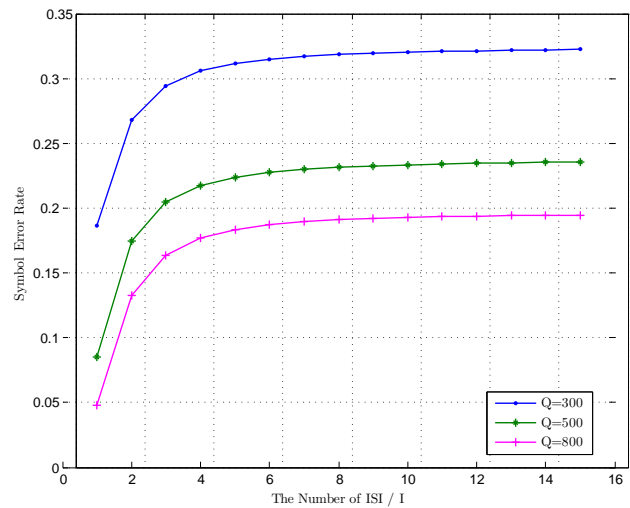


Fig. 4: SER performance versus length of ISI with different Q.

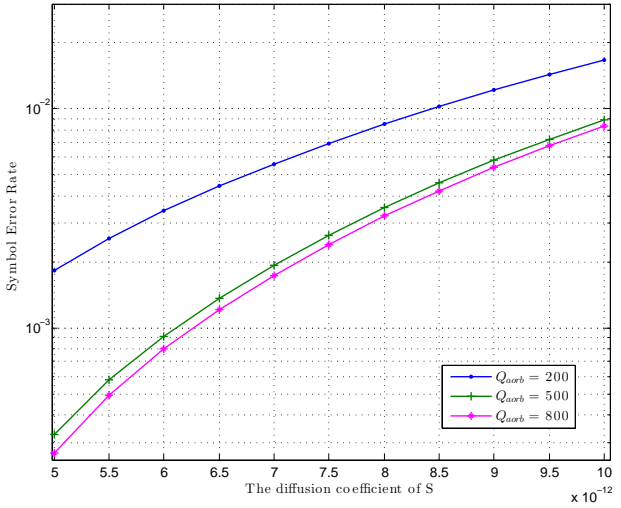


Fig. 5: SER performance versus diffusion coefficient of S. Here Q refers to the number of molecules transmitted by S.

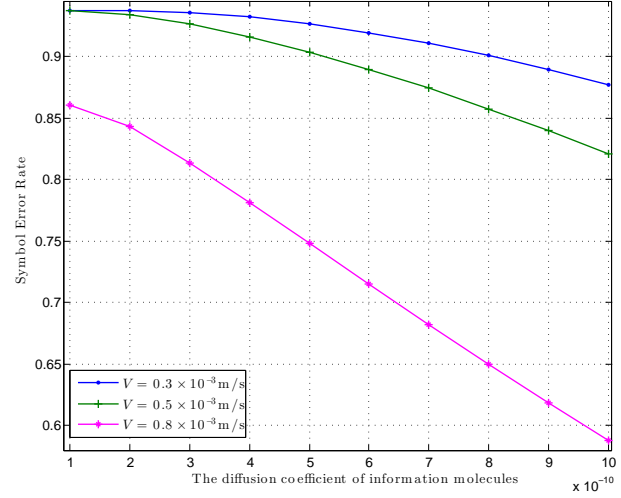


Fig. 7: SER versus different diffusion coefficient of information molecules with different V .

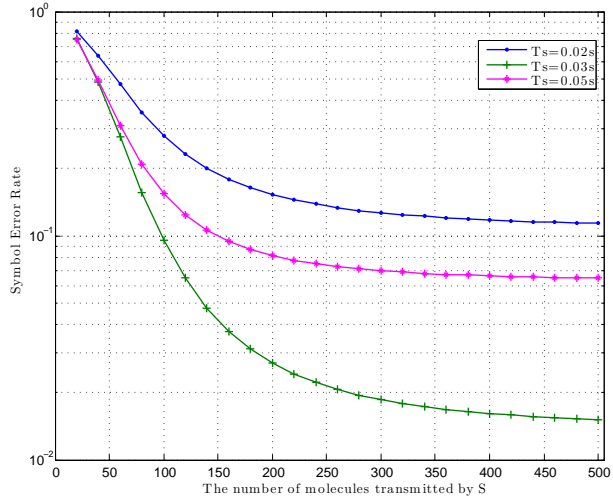


Fig. 6: SER performance versus number of information molecules, i.e., Q transmitted by S with different Ts.

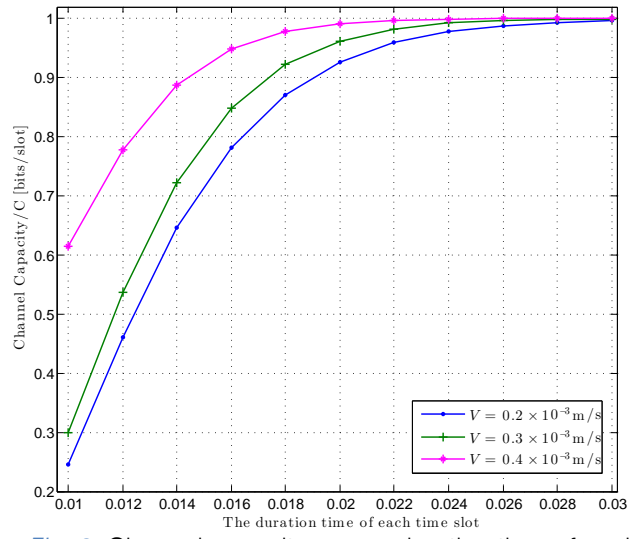


Fig. 8: Channel capacity versus duration time of each time slot with different V . Here V denotes the drift velocity.

From Fig. 5, it can be concluded that with the increase of the diffusion coefficient of S, the SER of system increases. The diffusion coefficient of S means the moving speed. The speed increases will bring much uncertainty, it causes channel fading. Then the molecules captured by R or D will decrease. So from Fig. 5, we can see that SER becomes decrease with larger diffusion coefficient. The increase of the number of molecules can make up for part of the channel fading, so the number of molecules increases and the SER decreases.

In Fig. 6 , we explore the SER performance versus the number of transmitted molecules with different Ts. It can be seen from Fig. 6 that SER decreases as the number of transmitted molecules increases, since more information molecules will be captured by R or D within a time slot. Additionally, we can find that with the same number of transmitted molecules, prolonging the time slot will decrease the SER.

In Fig. 7, we investigate the SER performance versus the Fig. 8. Channel capacity versus duration time of each time slot with different V . Here V denotes the drift velocity. diffusion coefficient of information molecules with different V . With the increase of diffusion speed of information molecules in the channel is accelerated, which directly leads to the decreases of the time for molecules to arrive the destination, and the probability of being captured by the receiver in the same time increases, which makes the SER decrease. In addition, the increase of liquid velocity also accelerates the speed of information molecules. Therefore, the faster the liquid flow rate, the smaller the SER.

From Fig. 8, we can see that channel capacity along with the time duration of each time slot increase. With the increase of slot length, the number of information molecules captured at destination increases which can reduce the SER. Along with the increase of liquid velocity, the velocity of molecular diffusion is also

increased, and the number of captured information molecules increase, and the SER decrease.

From the previous discussion, we can draw the following conclusions: with the increase of liquid flow velocity, the molecular movement speed is accelerated, which makes the number of molecules captured in the per time slot increase, and the system performance is improved. It can be seen from the Fig. 9 that the simulation results are consistent with the previous conclusions. Meanwhile, with the increase of slot length, the number of molecules captured in the same time slot increases, which can also improve the system performance.

V. CONCLUSIONS

In this work, a diffusive-drift MC relay system model with mobile S and mobile D was investigated. The D-MoSK modulation is employed to this system model and the performance is analyzed. In order to reduce the decode complicated, the R uses DF scheme and different types of molecules. We introduce the ML criterion at R and D to decode the information. Meanwhile, the analytical results in terms of SER and capacity are derived. The numerical results show that D-MoSK exhibits better SER performances than the MoSK modulation.

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