

A Novel Pre-Equalization Method for Molecular Communication via Diffusion in Nanonetworks

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Abstract—In this letter, a novel pre-equalization method in the context of molecular communication via diffusion (MCvD) is proposed. Our method is based on the emission of two types of messenger molecules (MMs) from the transmitter in order to mitigate the high intersymbol interference (ISI), which critically hinders the performance of any MCvD system. In this approach, the difference between the number of received molecules of each MM type is considered as the actual signal at the receiver side. We model the underlying diffusion channel, and conduct an analysis on the error performance of the proposed method. We compare the proposed method with other modulation and ISI mitigation techniques in the literature, such as concentration shift keying, molecular shift keying, molecular concentration shift keying, and minimum mean squared equalization. Simulation results show that, by tuning the delay value between the emissions of the two MM types and their respective molecule counts, the proposed pre-equalization method outperforms the aforementioned methods and reduces the bit error rate of the MCvD system significantly.

Index Terms—Communication via diffusion, molecular communication, nanonetworks, equalization, signal shaping, ISI mitigation.

I. INTRODUCTION

WITH the recent advent of techniques enabling cheaper and smaller electronic designs, there is a growing interest for communication between nano- and micro-scale devices for a variety of applications [1]. Over the last couple of years, several different systems have been proposed in this context, ranging from electromagnetic systems like terahertz signaling [2] to molecular communication systems [3]. Among various molecular communication systems proposed in the literature, molecular communication via diffusion (MCvD) is a particularly effective and energy-efficient method for exchanging information [4].

The MCvD system consists of two nanomachines, called the transmitter and the receiver, both of which reside in a liquid communication medium. The transmitter constitutes the transmitted signal by encoding the information onto some physical property (concentration, type, etc.) of the messenger molecules (MMs), and releases them to the medium. Due to the very small

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sizes (i.e., 1–10 nm in diameter) of MMs, their movement in this medium is governed by Brownian motion. As shown in [5], due to the internal dynamics of the diffusion channel, the transmitted signal is transformed in the medium and the resulting received signal exhibits a shape that resembles a power-law function with a long tail, which causes intersymbol interference (ISI) and significantly reduces the system performance.

In the literature, several methods have been proposed to shape the received signal and mitigate the aforementioned shortcomings of the MCvD system. Inducing an impulse signal at the receiver side via deriving the inverse channel characteristics is proposed in [6]. Although this is a very elegant solution, the derived composite transmit pulse contains a negative element (poison signal), which is a continuous function of time. This means that the transmitter must *continuously* release a *varying* number of molecules into the communication medium. Furthermore, the poison signal is also a function of the distance between the transmitter and the receiver. This means that its amplitude will increase proportional to this distance. These factors, especially the fact that the signal is continuous rather than discrete, make the implementation of this mechanism very hard in a realistic environment. Another modulation technique, Zebra-CSK, for shaping the signal via using inhibitor molecules is proposed in [7]. While this method significantly reduces the ISI, its performance strongly relies on the inhibition efficiency β , which is quite low in a 3-D liquid medium. Additionally, the symbol error probabilities are obtained considering the effect of only one previous symbol, not a continuous transmission. Another modulation technique, molecular concentration shift keying (MCSK), which utilizes two types of molecules for even and odd time slots, is proposed in [8]. This method also reduces ISI significantly, and is also implemented for a comparison with the proposed method.

In contrast to these works, in this letter, we consider a pre-equalization method in which the transmitter utilizes two types of MMs, type-*A* and type-*B*, and the receiver interprets the difference between the received quantities of these two types of molecules as the received signal. By doing so, the resulting received signal is shaped such that the interference is significantly reduced. We analyze the performance of this equalized MCvD system and show that the performance is significantly improved compared to the other ISI mitigation techniques proposed in the literature.

The remainder of this letter is organized as follows: in Section II, the intricacies of the diffusion channel are reviewed. In Section III, we present the proposed pre-equalization method in order to mitigate the adverse effects of the diffusion channel. In Section IV, a performance analysis of the proposed system is given and comparisons with conventional modulation and equalization techniques are provided. Finally, Section V concludes the letter.

II. THE DIFFUSION CHANNEL

In an MCvD system, MMs propagate through the diffusion channel where the overall communication is divided into time slots of equal duration that allow a single symbol to be sent. These time slots are called symbol durations and denoted by t_s . Since the number of molecules induced at the receiver in a given time slot constitutes the received signal, the diffusion channel can be discretized in time and modeled as a finite impulse response (FIR) filter. In this work, we consider a single-transmitter, single-receiver MCvD system where the transmitter is a point source and the receiver is spherical. The distance from the point source to the center of the receiver is denoted by r_0 and the radius of the receiver is denoted by r_r .

A. Modulation Techniques in Communication via Diffusion

The basic modulation technique that is proposed in the literature is concentration shift keying (CSK), which utilizes different number of molecules for different symbols and applies a basic thresholding mechanism at the receiver side [9]. The most basic incarnation of the CSK modulation is binary CSK (BCSK), where a symbol represents one bit of information. In BCSK, the receiver counts the number of MMs it receives within a symbol duration. If this number exceeds a certain threshold, the receiver decodes the symbol as bit-1, otherwise as bit-0. An alternative modulation technique proposed for the MCvD system is molecular shift keying (MoSK) [9]. This technique suggests using different types of molecules for each different symbol in order to reduce the amount of ISI. Similar to CSK, binary MoSK (BMoSK), where the transmitter emits molecules of type-A for a bit-0, and emits molecules of type-B for a bit-1, constitutes the most basic realization of this method.

In order to distinguish how many and which type of molecules are emitted for a bit, let $M_0(x)$ and $M_1(x)$ denote the number of type- x molecules emitted for a bit-0 and bit-1, respectively. Considering the BCSK and BMoSK implementations, the MM emission strategy of both modulation techniques can be summarized as

- BCSK:
 - $M_0(A)$: number of type-A molecules emitted for bit-0
 - $M_1(A)$: number of type-A molecules emitted for bit-1
 - $M_0(A)$ is generally chosen as $M_0(A) = 0$.
- BMoSK:
 - $M_0(B)$: number of type-B molecules emitted for bit-0
 - $M_1(A)$: number of type-A molecules emitted for bit-1
 - $M_1(B) = M_0(A) = 0$.

B. Modeling the Channel

In order to model the diffusion channel, the probabilistic nature of the Brownian motion must be considered. Let $F_{\text{hit}}(t)$ denote the expected value of the fraction of molecules absorbed by the receiver until time t , calculated as [5]

$$F_{\text{hit}}(t) = \frac{r_r}{r_0} \operatorname{erfc} \left[\frac{r_0 - r_r}{\sqrt{4Dt}} \right]. \quad (1)$$

By using $F_{\text{hit}}(t)$, the probability of a single molecule to hit the receiver in a given time slot can be calculated. Let p_k denote

the hitting probabilities, where p_1 is the hitting probability in the current symbol duration and p_k for $k \geq 2$ denote the hitting probabilities in the consecutive symbol durations. Hitting probabilities for a given system model can be calculated as

$$p_k = F_{\text{hit}}(kt_s) - F_{\text{hit}}([k-1]t_s). \quad (2)$$

Hitting probabilities are sufficient to describe the channel response and the received signal completely.

Let $\mathbf{b}_1^n = \{b_1, b_2, \dots, b_n\}$ denote the binary message sequence, and b_i denote the message symbols sent from the transmitter in the i th time slot for $i = 1, 2, \dots, n$, respectively. We consider BCSK and assume $M_0(A) = 0$, i.e., the transmitter does not send any molecules to transmit bit-0. Let C_i denote the number of molecules induced at the receiver in the i th time slot due to the transmission of \mathbf{b}_1^i . The probability model for C_i can be defined as

$$b_i \sim \mathcal{BE}(P[b_i = 1]), \quad (3)$$

$$C_i | \mathbf{b}_1^i \sim \text{Poisson}(\mu^{(i)}), \quad (4)$$

where $\mathcal{BE}(\cdot)$ and $\text{Poisson}(\cdot)$ denote the Bernoulli and Poisson probability distributions, and $P[b_i = 1]$ and $P[b_i = 0]$ denote the probabilities of occurrences for bit-1s and bit-0s in the message sequence, respectively. The distribution parameter of C_i is defined as

$$E[C_i] = \mu^{(i)} = \mu_0 + M_1(A) \sum_{k=1}^i p_k b_{i-k+1}, \quad (5)$$

where μ_0 denotes the mean of the environment noise independent of the source signal [8], which may represent the counting noise at the receiver, or noise due to the molecule reactions in the environment. Equation (5) indicates that $\mu^{(i)}$ is dependent on the previously transmitted bits, as well as the current transmission.

Notice that (5), which is frequently used in the literature [10], is indeed a discrete convolution, and can be used to derive the coefficients of the FIR filter that models the diffusion channel. Let h_k denote the coefficients of this FIR filter of length K , which can be calculated as

$$h_k = M_1(A)p_k \quad \text{for } k = 1, 2, \dots, K. \quad (6)$$

In order to quantify the amount of ISI in terms of channel coefficients, a signal-to-interference (SIR) measure is defined as

$$\text{SIR} = \frac{h_1}{\sum_{k=2}^K |h_k|}. \quad (7)$$

At high data rates, i.e., when t_s is small, SIR decreases significantly due to the high amount of ISI in the diffusion channel, hence the communication quality is significantly reduced. The pre-equalization method proposed in the following section aims to increase the SIR, thus allow higher communication quality with high data rates.

III. PROPOSED PRE-EQUALIZATION METHOD

If equalization at the receiver side is intended, it must be employed in an adaptive manner, since the variance of the

received signal varies with i , as in (5). Examples of receiver side equalizers can be found in [11], including minimum mean squared error (MMSE) or decision feedback equalizers (DFE), where the equalizer taps are updated for each sample. These equalizers employ complex operations which makes them inefficient in terms of energy and computational complexity.

Equalization can also be performed at the transmitter side by sending a secondary signal that will interfere with the primary signal destructively to reduce the ISI. Since negative molecules do not exist, destructive interference can be imitated by employing a subtraction operation at the receiver side. In order for the receiver to distinguish the primary signal from the secondary one, different types of molecules must be utilized.

In the case of BCSK, if $M_0(A) = 0$, the primary signal is formed of the type- A molecules sent for each bit-1. On average, $p_1 M_1(A)$ of these molecules out of $M_1(A)$ hit the receiver in the first time slot, and the residual ones cause ISI. In order to reduce the effects of ISI, a second type of molecule (type- B) can be sent for each bit-1, which targets the residual type- A molecules in the channel. This can be achieved by emitting type- B molecules with some delay after type- A molecules are emitted, and subtracting the number of received type- B molecules from the number of received type- A molecules at the receiver at each time slot. *This subtraction operation imitates the destructive interference between the primary and the secondary signals.*

Since the receiver performs a subtraction operation, the received signal can be defined as the difference between two random variables as $C_i = C_i(A) - C_i(B)$, where $C_i(A)$ and $C_i(B)$ denote the number of received type- A and type- B molecules, respectively.

Hitting probabilities for type- A and type- B molecules can then be defined as

$$p_k(A) = F_{\text{hit}}(kt_s) - F_{\text{hit}}([k-1]t_s), \quad (8)$$

$$p_k(B) = F_{\text{hit}}(kt_s - \tau) - F_{\text{hit}}([k-1]t_s - \tau), \quad (9)$$

where τ denotes the amount of delay that type- B molecules encounter.

It is important to note that $C_i(A)$ and $C_i(B)$ do not contain any information individually whereas their difference, $C_i = C_i(A) - C_i(B)$, constitutes the received signal. After the subtraction is performed, the receiver does not need to store $C_i(A)$ and $C_i(B)$ separately. Consequently, the resulting channel response can be defined as

$$h_k = M_1(A)p_k(A) - M_1(B)p_k(B). \quad (10)$$

Channel responses before and after pre-equalization are illustrated in Fig. 1. Note that SIR is significantly increased after pre-equalization is employed.

A. Optimizing the Pre-Equalizer Parameters

In a classical communication scenario, one of the main objectives is to minimize the bit error rate (BER) subject to the constraint that the signal has an average power of \bar{P} . For BCSK with $M_0(A) = 0$, the average power per symbol can be defined as $\bar{P} = M_1(A)P[b_i = 1]$. This constraint must also be satisfied for the proposed pre-equalization method, such that $\bar{P} = M_1(A)P[b_i = 1] + M_1(B)P[b_i = 1]$, indicating that the av-

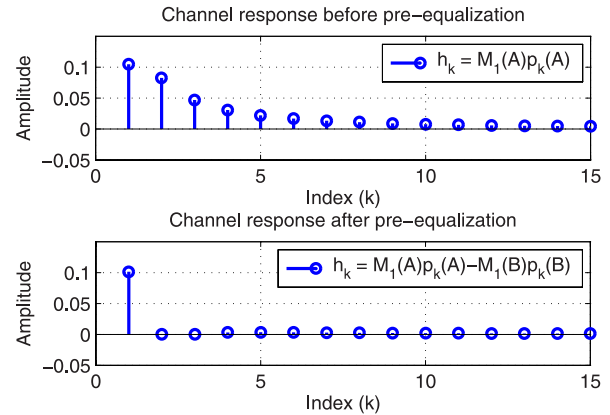


Fig. 1. Channel responses before and after pre-equalization for $t_s = 100$ ms, $\tau = 76$ ms, $M_1(A) = 100$, and $M_1(B) = 66$.

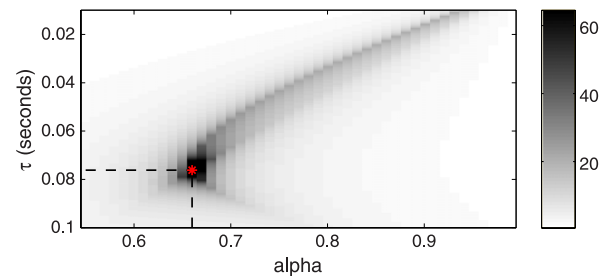


Fig. 2. SIR for different τ and α values where $t_s = 100$ ms, $K = 3$, $P[b_i = 0] = 0.5$, $r_r = 5 \mu\text{m}$, $r_0 = 10 \mu\text{m}$, and $D = 79.4 \mu\text{m}^2/\text{s}$.

erage power per symbol must be portioned out between the primary and the secondary signals. Let α denote the fraction of the average signal power dedicated to the primary signal, such that $M_1(A) = \alpha \bar{P}/P[b_i = 1]$, and $M_1(B) = (1 - \alpha) \bar{P}/P[b_i = 1]$. Rewriting SIR explicitly by using (10) leads to

$$\text{SIR} = \frac{\alpha (p_1(A) + p_1(B)) - p_1(B)}{\sum_{k=2}^K |(\alpha (p_k(A) + p_k(B)) - p_k(B))|}, \quad (11)$$

which indicates that the amount of SIR for the proposed method is a function of τ and α . Since it is desirable to have the SIR as large as possible, optimal values for τ and α , τ^* and α^* , can be calculated by maximizing the SIR subject to the constraint that the signal has an average power of \bar{P} .

In order to calculate τ^* and α^* , derivative of (11) with respect to τ and α should be set to zero and should be solved simultaneously. For $K > 2$, this calculation becomes intractable due to the increasing number of additive terms in the denominator, hence the optimal values cannot be calculated analytically. In order to show that there exists a global maximum, heuristic techniques are used for various numbers of parameter sets. Heat map of SIR utilizing $K = 3$ for a given parameter set is presented in Fig. 2.

As seen in Fig. 2, there is a global maximum. Note that, for different values of t_s , this computer search must be repeated in order to find τ^* and α^* .

IV. NUMERICAL RESULTS AND PERFORMANCE EVALUATION

In order to evaluate the performance of the proposed method, Monte Carlo simulations are employed. Results for BCSK,

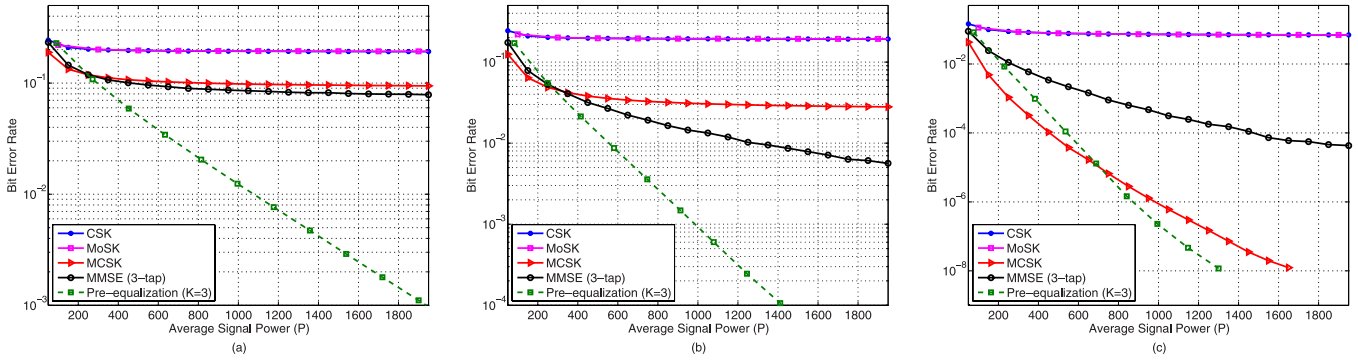


Fig. 3. (a) BER curves of CSK, MoSK, MCSK, MMSE and proposed method where $t_s = 80$ ms. (b) BER curves of CSK, MoSK, MCSK, MMSE and proposed method where $t_s = 100$ ms. (c) BER curves of CSK, MoSK, MCSK, MMSE and proposed method where $t_s = 150$ ms.

BMoSK, MCSK proposed in [8], and 3-tap adaptive MMSE equalizer proposed in [11] are also included in the plots. Briefly, MCSK utilizes different types of molecules for odd and even time slots with the same signal power. BER curves for $t_s = 80$ ms, $t_s = 100$ ms, and $t_s = 150$ ms are given in Fig. 3(a)–(c), respectively. Note that the choice of symbol duration determines the channel coefficients, which depend on r_r , r_0 , and D . Environmental noise is assumed to have $\mu_0 = 2$, and system parameters are chosen as $P[b_i = 0] = 0.5$, $r_r = 5 \mu\text{m}$, $r_0 = 10 \mu\text{m}$, and $D = 79.4 \mu\text{m}^2/\text{s}$. Binary messages of length 10^2 bits are employed and 10^5 replications are performed in order to obtain an average. A maximum likelihood (ML) decoder is implemented for the receiver side for all modulation and equalization techniques.

As seen in Fig. 3(a)–(c), BER decreases significantly when pre-equalization is employed. Furthermore, due to the increasing SIR, error floor vanishes and error rate decreases very fast with increasing signal power. Notice that pre-equalization outperforms MCSK for higher data rates, whereas for higher symbol durations, MCSK outperforms the pre-equalization at small signal power values. On the other hand, although MCSK reduces ISI significantly, it will always lead to an error floor due to the residual molecules in the channel, unlike the proposed pre-equalization method.

V. CONCLUSION

In this letter, a pre-equalization method is proposed to mitigate ISI for BCSK-modulated sequences in a single-transmitter single-receiver MCvD system. The transmitter utilizes type-*A* and type-*B* molecules to modulate the primary and the secondary signals, respectively. Afterwards, the transmitter emits the secondary signal with a certain amount of delay, and the receiver performs a subtraction operation in order to imitate the destructive interference between the primary and the secondary signals. Optimal values for the amount of delay and secondary signal power are calculated numerically, and Monte Carlo simulations are employed to evaluate the system performance.

The proposed method decreases the interference, hence increases the SIR significantly. Furthermore, since the proposed method does not have an adaptive nature, it does not increase the system complexity compared to the other equalization techniques. We compare the proposed method with MCvD systems utilizing BCSK and BMoSK modulation as well as the MMSE equalizer and show that it significantly outperforms all of these methods, especially for high data rates.

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