A Generalized Strength-Based Signal Detection Model for Concentration-Encoded Molecular Communication

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ABSTRACT

In this paper, a generalized strength-based signal detection model for Concentration-Encoded Molecular Communication (CEMC) has been presented. The generalized strength-based signal detection problem in diffusion-based CEMC system has been investigated in the presence of both diffusion noise and intersymbol interference (ISI). Amplitude-shift keying (ASK)-modulated CEMC system has been considered with impulsive transmission scheme. The receiver for optimum signal detection has been developed theoretically and explained with both analytical and simulation results of binary signal detection. It is found that the receiver thus developed can detect the CEMC symbols; however, the performance of the receiver is influenced by two main factors, namely, communication range and transmission data rate. Correspondingly, the bit error rate (BER) performance of the receiver thus developed is further evaluated under various communication ranges and transmission data rates through extensive simulation experiments.

Categories and Subject Descriptors

E.4 [**Coding and Information Theory**]: Formal models of communication.

General Terms

Algorithms, Performance, Design.

Keywords

Molecular communication, concentration-encoding, strength-based signal detection, optimum receiver, inter-symbol interference, nanonetworks.

1. INTRODUCTION

In recent years, the knowledge and tools of nanotechnology have brought about a remarkable progress in the research of communicating nanomachines [1-7]. Molecular communication (MC) is one of the promising techniques suitable for communication among bionanomachines [7]. In MC, a transmitting nanomachine (TN) communicates with a receiving nanomachine (RN) with information molecules by modulating several features of the information molecules, e.g. specific type [8], concentration [9], and transmission order [10] of information molecules. In diffusion-based MC, the molecules released by the TN perform random walk-based diffusion [11] mechanism and reach the RN probabilistically [12]. In Concentration-Encoded Molecular Communication (CEMC), the TN uses only a *single* type of information molecules in order to encode information, and modulates the amplitude of the transmitting rate of molecules. Correspondingly, the RN decodes the information symbols by observing the *intensity* [13, 14] or the *strength* [13, 15] of the concentration of molecules at the location of its receptors, the detection schemes being known as *sampling-based* [14] and *strength-based* [15] detections respectively. In CEMC, the *intensity* and the *strength* respectively mean the instantaneous amplitude of the concentration of the information molecules at the RN at any time instant [9] and the total number of accumulated information molecules in the entire symbol duration [9]. While in sampling-based detection the RN senses the intensity of the concentration at one or more temporal instants during the signal interval and decides based on the sample value(s) of concentration intensity, in strength (i.e. energy)-based signal detection the RN accumulates the total number of received information molecules during the entire symbol interval and decides based on its strength. However, in both cases the RN uses a threshold for the detection variable to be compared with. Since strength of concentration is represented in terms of the total number of accumulated molecules, strength-based detection can also be equivalently termed as energy-based detection (ED)[1] in CEMC [16], with the distinction that, unlike electromagnetic (EM) wave-based communication [17], ED in CEMC does not require squaring the concentration intensity, and requires only summing the number of molecules during a symbol duration [16].

Diffusion-based propagation of molecules causes residual molecules originating from the previous symbols to become available at the current symbol, thereby causing intersymbol interference (ISI) [18]. In CEMC, the information molecules representing different transmitted symbols are of *single* type and so the RN fails to distinguish between molecules intended for the current symbol and those for the previous symbols. Due to the temporal spreading of the impulse response of the molecular channel [19], the effects of ISI become severe when the RN is farther apart from the TN [18]. In addition, the effect of ISI

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[1] We use the term ED to denote strength-based detection in short and the subscript "$_{\text{ED}}$" to denote the quantities related to strength-based signal detection in the later sections of this paper.

increases with the increase of transmission data rate. As a result, signal detection in CEMC becomes very challenging.

In this paper, a particular focus has been given to generalized strength-based signal detection in CEMC. The main contributions of the paper are as follows: 1) A generalized model of CEMC signal detection in the presence of diffusion noise and ISI has been presented in detail. 2) A receiver model for the ED scheme has been provided and its receiver operating characteristics (ROC) curves are explained. 3) Finally, the bit error rate (BER) performance of the proposed receiver in terms of communication range and transmission data rate is presented.

The paper is organized as follows: Section 2 provides the related works, followed by Section 3 describing the strength-based optimum CEMC signal detection in detail. Analytical results of the detection performance are provided in Section 3. Numerical results obtained from simulation experiments are shown in Section 4. Finally, Section 5 concludes the paper with a summary of the findings and possible future works.

2. RELATED WORK

Strength-based signal detection was first conceptualized in [13] where the authors first proposed ED technique as a means to determine the effective communication ranges in CEMC between a pair of nanomachines. Later on, the idea of ED scheme was further investigated in [16] that provided *threshold*-based ED schemes in CEMC. On the other hand, taking into the effects of stochastic ligand-receptor binding based on *chemical Langevin equation* [20], the ED scheme with mean concentration of molecules at the RN was later investigated in [15] in terms of performances depending on communication ranges and transmission rates. However, the works presented in [13, 15, 16] were based on mean signal intensity only and did not consider diffusion-based noise [14] at the RN while developing the ED scheme.

Apart from these, other related works include finding the optimum threshold-based detection with a prior signal transmission probability and without considering the diffusion noise as reported in [21], and in a noiseless scenario as in [21] but from the microscopic perspective with only one molecule transmitted as shown in [22]. In addition, optimum molecule-shift keying (MoSK) receiver was presented in [23], where the TN encodes information symbols in different types of information molecules. A signal detection scheme based on multiple amplitude modulation dealing with the diffusion channel from microscopic perspective, where the molecule with drift velocity is removed from the system once it hits the RN, has been shown in [24]. In [34], the noise in diffusion-based propagation of molecules is identified as *particle-counting noise* where the authors developed the expression of the concentration signal perturbed by the diffusion noise at the location of the RN. However, the work in [34] did not provide a separate signal and noise models of the concentration signal at the RN, as mentioned in [23].

Our work presented in this paper is different from the works presented in [21-24] in the sense that we consider the CEMC system from the macroscopic perspective dealing with the *concentration* of a large number of transmitted molecules, all of which are of a *single* type all through, where the molecules propagate in an unbounded three-dimensional propagation medium and none of the molecules is removed from the system upon its first hit at the RN, thereby providing an ideal (i.e. free) diffusion-based propagation environment. In addition, we also consider both diffusion noise and ISI while developing the ED scheme in CEMC, which to the best of our knowledge were not incorporated in any of the available open literature including ours.

3. STRENGTH-BASED DETECTION

3.1 Receiver Model

As shown in Fig. 1, the TN and the RN communicate with a single type of information molecules that bind with a single type of receptors located on the surface of the RN. The TN is assumed to be a point source type of transmitter, located at the origin (0,0,0), that emits $Q_m\delta(t)$ information molecules[2] in impulsive fashion at the beginning of each symbol[3] duration T_{sym}, where $m \in \{0,1\}$, $Q_m \gg 1$, and $\delta(t)$ denotes the *Dirac delta function* [25]. As a result, the TN transmits Q_0 and Q_1 molecules at the beginning of each T_{sym} when it wants to transmit a bit 0 and a bit 1 respectively. Therefore, $\sum_{j=0}^{N_b} Q_m\delta(t - jT_{\text{sym}})$ represents the transmitted signal, where $b_j \in \{0,1\}$, $j=\{1,2,\ldots,N_b\}$, is the bit to be transmitted, N_b being the total number of bits. The RN is assumed to be located at the centre of a small volume known as the *virtual receive volume* (VRV) [26]. The TN and the RN are assumed to be in time-synchronization [4] and not move in space. The concentration of molecules at the location of the RN varies with time and space as below [12]

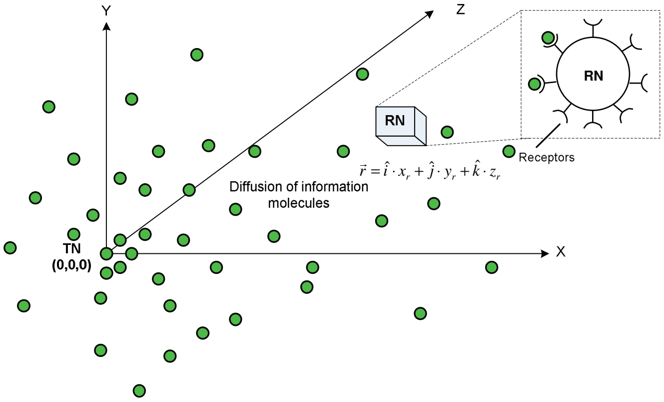

Figure 1. Ideal (i.e. free) diffusion of information molecules, shown as green circles, in the propagation medium. The receptors are shown in the inset.

$$\frac{\partial U}{\partial t} = D\nabla^2 U \tag{1}$$

where *U(r,t)* denotes the mean concentration signal intensity at location of the RN. In response to an impulsive transmission $Q_m\delta(t)$, *U(r,t)* can be defined as the *channel impulse response* (CIR) expressed as $G(r,t)$ shown below.

$$U(r,t) = \frac{Q_m}{(4\pi Dt)^{\frac{3}{2}}} e^{\frac{-r^2}{4Dt}} \triangleq G(r,t)\cdot \tag{2}$$

Here $r^2 = x_r^{\,2} + y_r^{\,2} + z_r^{\,2}$ and $G(r,t)$ is known as the CIR of the CEMC channel. Figure 2 shows the mean CIR of the molecular

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[2] In the remainder of the paper, a "molecule" would mean an "information molecule" unless otherwise specified.

[3] In binary system, each bit (0 or 1) represents each symbol. However, in M-ary scheme, each symbol consists of $\log_2 M$ bits, M being the alphabet size [33].

channel. Within the small sensing volume VRV, the mean concentration of the information molecules available to the RN can be expressed as [14]

$$s_m(r,t) = \iiint_V G(r,t)dV = \iiint_V \frac{Q_m}{(4\pi Dt)^{\frac{3}{2}}} e^{\frac{-(x_r{}^2+y_r{}^2+z_r{}^2)}{4Dt}} dXdYdZ = Q_m p(r,t) \tag{3}$$

where $dV = dXdYdZ$ is the differential volume in the VRV and $p(r,t)$ is the *probability of getting one molecule* [12] in the receiver sensing volume. Since each of $Q_m \gg 1$ transmitted molecules travels independently in the unbounded three-dimensional space, the number of molecules available at the RN at any time instant due to diffusion only is a random variable $y(t)$ and, based on the *normal*-approximation to the *binomial* distribution, can be expressed as below [14].

$$\begin{gathered} y(t) \sim \mathcal{N}\left(s_m(t), s_m(t)\left(1-p(t)\right)\right) \\ \Rightarrow y(t) = s_m(t) + n_{\text{samp}}(t) \text{ where } n_{\text{samp}}(t) \sim \mathcal{N}\left(0, s_m(t)\left(1-p(t)\right)\right) \end{gathered} \tag{4}$$

Here $n_{\text{samp}}(t)$ denotes the diffusion noise at the sample taken at the t-th time instant. For simplicity, at a given r, the functional dependences of $s_m(r,t)$ and $p(r,t)$ on r are omitted and so hereafter the respective quantities are shown as functions of t only.

In ED scheme, after the RN has sensed the molecules available at its receptors at regular time intervals of t_s seconds, it accumulates all the molecules that become available at the RN during that symbol. As a result, the output variable (test statistic) of ED scheme in diffusion noise only can be expressed as below.

$$y_{\text{ED}} = \sum_{n=0}^{N_{\text{samp}}} t_s y(nt_s) \Rightarrow y_{\text{ED}} \sim \mathcal{N}\left(s_{\text{ED}}, \sigma^2_{\text{S(ED)}}\right) \text{ where} \tag{5}$$

$$s_{\text{ED}} = \sum_{n=0}^{N_{\text{samp}}} t_s s_m(nt_s) \text{ and } \sigma^2_{\text{S (ED)}} = \sum_{n=0}^{N_{\text{samp}}} t_s^2 s_m(nt_s)\left(1-p(nt_s)\right)$$

Here, N_{samp} denotes the number of samples per symbol. Therefore,

$$y_{\text{ED}} = s_{\text{ED}} + n_{\text{ED}}^{\text{Noise}} \quad \text{where } n_{\text{ED}}^{\text{Noise}} \sim \mathcal{N}\left(0, \sigma^2_{\text{S (ED)}}\right) = \sigma_{\text{S (ED)}} \mathcal{N}(0,1) \tag{6}$$

In the accumulated molecules during the i-th symbol, in addition to the molecules that were intended for the i-th symbol only, the RN would also receive some of the molecules that were not intended for the i-th symbol. This means some of the molecules that were transmitted during the first to the (i-1)-th symbols would become available at the RN during the i-th symbol, causing ISI to the i-th symbol. Therefore, the intensity $z(t)$ and the strength z_{ED} of the CEMC signal including the effects of ISI can be written respectively as

$$z(t) = y(t) + n_{\text{ISI}}(t) \tag{7a}$$

$$\Rightarrow z_{\text{ED}} = s_{\text{ED}} + n_{\text{ED}}^{\text{Noise}} + n_{\text{ED}}^{\text{ISI}} \tag{7b}$$

where $n_{\text{ED}}^{\text{Noise}}$ is as shown in Eq. (6) and $n_{\text{ED}}^{\text{ISI}}$ denotes the accumulated number of residual molecules causing ISI and can be expressed as $n_{\text{ED}}^{\text{ISI}} \sim \mathcal{N}\left(\mu_{\text{ISI (ED)}}, \sigma^2_{\text{ISI (ED)}}\right)$. Figure 3 shows the input signal and υ-th realization $z_v(t)$ of the output signal $z(t)$. Therefore, strength-based binary detection problem in CEMC can be formally written as below, where hypotheses H_1 and H_0 denote the cases when bits 1 and 0 are to be transmitted respectively.

$$z_{\text{ED}} = \begin{cases} \mathcal{N}\left(s_{\text{ED}}^{(1)} + \mu_{\text{ISI (ED)}}, \sigma^{2(1)}_{\text{S (ED)}} + \sigma^2_{\text{ISI (ED)}}\right); & \text{H}_1 \\ \mathcal{N}\left(s_{\text{ED}}^{(0)} + \mu_{\text{ISI (ED)}}, \sigma^{2(0)}_{\text{S (ED)}} + \sigma^2_{\text{ISI (ED)}}\right); & \text{H}_0 \end{cases} \tag{8}$$

An optimum receiver gives the minimum probability of error in detecting the transmitted bits. Therefore, we consider Neyman-Pearson theorem [27] and calculate the logarithm of the likelihood ratio under the *minimum probability of error criterion* using equal prior probabilities $\Pr(\text{H}_0) = \Pr(\text{H}_1)$ in order to derive the test statistic $T(z_{\text{ED}})$ as shown below

$$\frac{\ell\left(z_{\text{ED}} \mid \text{H}_1\right)}{\ell\left(z_{\text{ED}} \mid \text{H}_0\right)} > 1 \Rightarrow \ln \frac{\ell\left(z_{\text{ED}} \mid \text{H}_1\right)}{\ell\left(z_{\text{ED}} \mid \text{H}_0\right)} > 0 \tag{9}$$

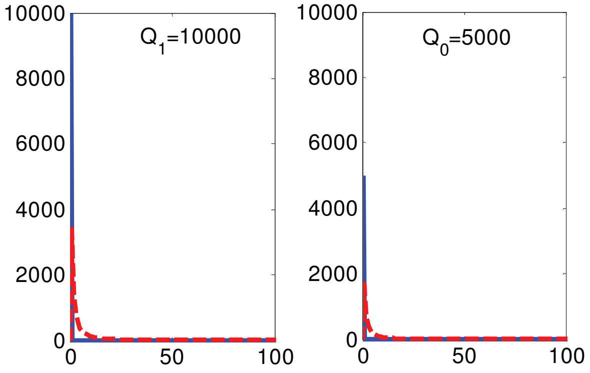


Figure 2. Mean concentration signal intensity *U(r,t)* at *r*=10 μm in response to impulse transmissions $Q_1\delta(t)$ and $Q_0\delta(t)$ when bits 1 and 0 are transmitted respectively.

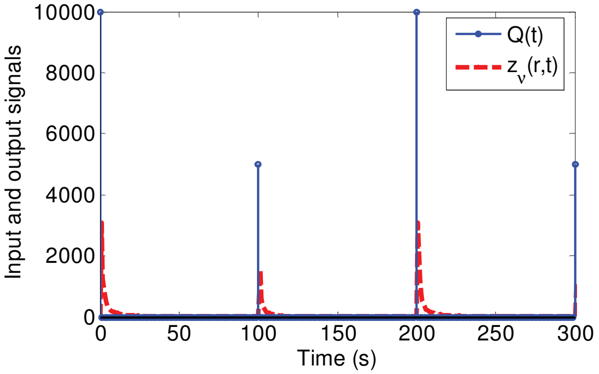
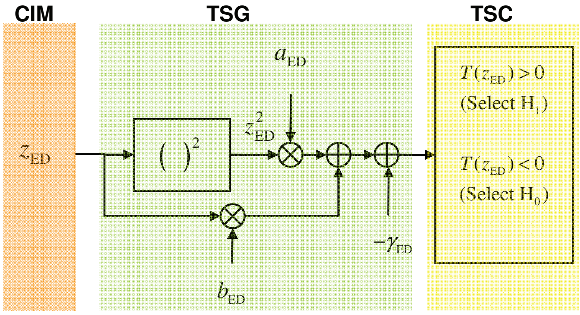


Figure 3. Input ($Q(t)$) and one realization $z_\upsilon(t)$ of the output concentration signal at *r*=10 μm in binary ASK CEMC system with diffusion noise and ISI.



CIM – Concentration Intensity Measurement
TSG – Test Statistic Generator
TSC – Test Statistic Comparator

Figure 4. Strength-based receiver architecture in binary CEMC system with diffusion noise and ISI.

where the conditional probabilities can be expressed as shown in Eq. (10).

$$\ell\left(z_{\text{ED}}\,|\,\text{H}_1\right)=\frac{1}{\sqrt{2\pi\left(\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}}\exp\left[-\frac{\left\{z_{\text{ED}}-\left(s^{(1)}_{\text{ED}}+\mu_{\text{ISI (ED)}}\right)\right\}^2}{2\left(\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}\right] \tag{10}$$

$$\ell\left(z_{\text{ED}}\,|\,\text{H}_0\right)=\frac{1}{\sqrt{2\pi\left(\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}}\exp\left[-\frac{\left\{z_{\text{ED}}-\left(s^{(0)}_{\text{ED}}+\mu_{\text{ISI (ED)}}\right)\right\}^2}{2\left(\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}\right]$$

The strength-based detector computes the test statistic $T(z_{\text{ED}})$ at the end of symbol duration after the RN has accumulated all the molecules during that symbol. Therefore, in each symbol duration the detection processing unit of the RN would generate one observation of $T(z_{\text{ED}})$ and the detection of the symbol would be based on that observation. Combining Eqs. (9) and (10) and simplifying yields the test statistic as follows.

$$T\left(z_{\text{ED}}\right)=a_{\text{ED}}z^2_{\text{ED}}+b_{\text{ED}}z_{\text{ED}}-\gamma_{\text{ED}}\;\underset{\text{Select H}_0}{\overset{\text{Select H}_1}{\gtrless}}\;0,\ \text{where}$$

$$a_{\text{ED}}=\left\{\frac{1}{2\left(\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}-\frac{1}{2\left(\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}\right\}$$

$$b_{\text{ED}}=\left\{\frac{\left(s^{(1)}_{\text{ED}}+\mu_{\text{ISI (ED)}}\right)}{\left(\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}-\frac{\left(s^{(0)}_{\text{ED}}+\mu_{\text{ISI (ED)}}\right)}{\left(\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}\right\}$$

$$-\gamma_{\text{ED}}=\left\{\frac{1}{2}\ln\frac{\left(\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}{\left(\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}-\frac{\left(s^{(1)}_{\text{ED}}+\mu_{\text{ISI (ED)}}\right)^2}{2\left(\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}+\frac{\left(s^{(0)}_{\text{ED}}+\mu_{\text{ISI (ED)}}\right)^2}{2\left(\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\right)}\right\} \tag{11}$$

As a result, the strength-based receiver can be shown in Fig. 4. The main difference between a conventional energy-detector in EM wave-based signals and the strength-based detector in CEMC signals is that in CEMC the number of diffusion noise and ISI-producing molecules depend on the signal value itself under the specific hypothesis. This makes the strength-based detection of CEMC signals and its receiver implementation quite challenging. However, the generalized detection model is able to provide the theoretical performance of the detector, the simulation results that describe the performance of such a detector in CEMC systems as well as the effects of any suitable simplifications that may be possible in the detection signal processing unit.

3.2 Receiver Operating Characteristics

3.2.1 *Generalized ASK Detection*

Using Eq. (8) ROC curves have been analytically found for the generalized ASK-modulated signal detection scheme with diffusion noise and ISI. Eq. (8) yields the *probability of false alarm* (P_{FA}) and the *probability of detection* (P_D) of the generalized detector as below.

$$P_{\text{FA}}=\Pr\left\{z_{\text{ED}}>\gamma'_{\text{ED}};\text{H}_0\right\}=Q\left(\frac{\gamma'_{\text{ED}}-s^{(0)}_{\text{ED}}-\mu_{\text{ISI (ED)}}}{\sqrt{\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}}\right) \tag{12}$$

$$P_{\text{D}}=\Pr\left\{z_{\text{ED}}>\gamma'_{\text{ED}};\text{H}_1\right\}=Q\left(\frac{\gamma'_{\text{ED}}-s^{(1)}_{\text{ED}}-\mu_{\text{ISI (ED)}}}{\sqrt{\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}}\right)$$

Expressing the threshold γ'_{ED} in terms of P_{FA} yields the P_{D} as shown below.

$$P_{\text{D}}=Q\left(\frac{\sqrt{\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}}{\sqrt{\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}}Q^{-1}(P_{\text{FA}})-\frac{\left(s^{(1)}_{\text{ED}}-s^{(0)}_{\text{ED}}\right)}{\sqrt{\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}}\right) \tag{13}$$

Here $s^{(1)}_{\text{ED}}>s^{(0)}_{\text{ED}}$ and $Q(\cdot)$ is the *right tail probability* [27] expressed as below.

$$Q(x)=\int_x^\infty\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{1}{2}\xi^2\right)d\xi \tag{14}$$

For equiprobable bits transmitted by the TN, $\Pr(\text{H}_0)=\Pr(\text{H}_1)=1/2$, and so BER can be expressed as

$$\text{BER}=\frac{(1-P_{\text{D}})+P_{\text{FA}}}{2}. \tag{15}$$

For a given P_{FA}, BER decreases as P_{D} increases and vice versa. Therefore, keeping P_{FA} unchanged a detector that maximizes P_{D} would be highly desired. The most noteworthy feature of the detection performance of the generalized ASK receiver (Eq. (13)) is that the terms $\sqrt{\sigma^{2(0)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}\Big/\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}$ and $\left(s^{(1)}_{\text{ED}}-s^{(0)}_{\text{ED}}\right)\Big/\sqrt{\sigma^{2(1)}_{\text{S (ED)}}+\sigma^2_{\text{ISI (ED)}}}$ impact the detection performance significantly, which is different from the detection performance found in many traditional AWGN-affected communication signals, e.g. see [27]. In addition, it is important to note that the variances of the diffusion noise in both H_1 and H_0 hypotheses are functions of the signal values themselves respectively (see Eq. (4)), which ultimately yield the complicated structure of the detection performance shown in Eq. (13).

3.2.2 *A Simple Receiver for ASK Detection*

Using Eq. (13) the performance of any detector that detects ASK-modulated CEMC signals can be obtained. However, in this paper, the detection performance of a generalized binary CEMC receiver is investigated, where the TN transmitted Q_0 and Q_1 molecules respectively, and $Q_1=2Q_0$. As shown in Figs. 2 and 3, assuming that the TN encodes bits 1 and 0 by sending $Q_1=10000$ and $Q_0=5000$ molecules respectively, from Eq. (3), (5), and (8), the mean and the variance of z_{ED} can be expressed as below.

$$s_1(t)=Q_1p(t),\ s_0(t)=Q_0p(t),\ \text{where } Q_1=2Q_0 \tag{16}$$
$$\Rightarrow s_1(t)=2s_0(t)\ \text{which gives}\ s^{(1)}_{\text{ED}}=2s^{(0)}_{\text{ED}}\ \text{and}\ \sigma^{2(1)}_{\text{S (ED)}}=2\sigma^{2(0)}_{\text{S (ED)}}$$

In this simple detection model, the receiver is not capable of estimating the exact number of ISI-producing molecules in the current symbol and assumes that a minimum ISI is present in the system. Under this scenario the receiver is simple in terms of functional complexity required to detect the information symbols. This can be considered acceptable in view of the extremely limited tasks and capabilities of a nanomachine [5] such that the RN may not have the ability to compute the ISI-producing molecules at all. In this particular scenario, the RN assumes that there occurs minimum one ISI-producing molecule on average such that $n_{\mathrm{ED}}^{\mathrm{ISI}} \sim \mathcal{N}\left(\mu_{\mathrm{ISI\,(ED)}}, \sigma_{\mathrm{ISI\,(ED)}}^{2}\right) = \mathcal{N}(1,1)$. From the system designer's point of view, it would be possible to design a CEMC transmitted signal such that $T_{\mathrm{sym}} \gg T_{\mathrm{DS}}$, where T_{DS} is the delay spread [28] of the CEMC channel [19], which would ensure that minimum or no ISI-producing molecules are present in the current symbol. As a result, $\sigma_{\mathrm{S\,(ED)}}^{2(0)} \gg \sigma_{\mathrm{ISI\,(ED)}}^{2}$ and $\sigma_{\mathrm{S\,(ED)}}^{2(1)} \gg \sigma_{\mathrm{ISI\,(ED)}}^{2}$. Correspondingly, using Eq. (13) the detection performance of the detector based on Eq. (16) can be derived as below.

$$P_{\mathrm{D}} = Q\left(\frac{Q^{-1}\left(P_{\mathrm{FA}}\right)}{\sqrt{2}} - \frac{1}{2}\left(\frac{s_{\mathrm{ED}}^{(1)}}{\sigma_{\mathrm{S\,(ED)}}^{(1)}}\right)\right) \tag{17}$$

The analytical detection performance and the ROC of the detector based on Eqs. (16) and (17) are shown in Figs. 5 and 6 respectively. Note that the term $\left(s_{\mathrm{ED}}^{(1)} / \sigma_{\mathrm{S\,(ED)}}^{(1)}\right)$ can be thought of as the *signal to noise ratio* (SNR) when H_1 is true, where $\left(\sigma_{\mathrm{S\,(ED)}}^{(1)} / s_{\mathrm{ED}}^{(1)}\right)$ is known as the *coefficient of variation* (c_{V}) of z_{ED} when H_1 is true.

As shown in Fig. 5, when SNR is kept unchanged, P_{D} can be increased by choosing a higher P_{FA}. Alternatively, for a chosen P_{FA} increasing the SNR gives a higher P_{D}. As shown in Fig. 6, for this particular detector, a family of ROCs can be obtained when SNR varies. When SNR is 9 dB, an ideal ROC can be achieved meaning that the particular detector would provide $P_{\mathrm{D}} = 1$ for any P_{FA}. When SNR is unchanged each point on the ROC represent a value of (P_{FA}, P_{D}) for a given threshold γ'_{ED}. As expected when γ'_{ED} increases, both P_{FA} and P_{D} decrease and vice versa. By adjusting the threshold the system designer can obtain any point on the ROC. However, it is possible to adjust the system settings in order to obtain an operating point close to the ideal detector point (0,1) located at the upper left-hand corner in Fig. 6. Note also that using the same approach shown above, the detection performance and the ROC for $Q_1 = \alpha Q_0$, $\alpha > 1$, can be obtained, which would allow the system designer to choose the value of α and thereby adjust the difference between the transmitted numbers of molecules in H_1 and H_0 hypotheses based on the particular CEMC system under examination. In addition, it should be noted that, unlike this particular scenario, a detailed analysis of the impact of ISI-producing molecules at the RN is also possible, which belongs to our on-going research.

4. SIMULATION RESULTS

4.1 Simulation Setup

The purpose of simulation experiments used here is to test the functionality of the strength-based receiver model thus developed at various system settings with transmitted bits. Based on Eq. (11) optimum receiver for CEMC system has been implemented in software platform and tested at several scenarios using simulation experiments. We explain the optimum receiver in terms of two main factors, namely, communication range (r) and transmission data rate (f). The receiver is evaluated by using simulations with 100,000 randomly generated bits at each setting of the experiment and BER results are thus obtained. Information molecules having a diffusion constant of 10^{-6} cm^2/s in water medium has been assumed [29]. An observation time up to 10,000,000 simulated seconds (≈ 2777 simulated hours) is considered. D is assumed to remain unchanged over the entire observation time. Communication ranges from 400 nm up to 100 µm [18] covering short, medium, and long-range CEMC in water medium are considered with transmission data rates of 0.01 bits per second (bps) up to 0.1 bps [30]. The TN emits 5000 and 10000 molecules when it wants to send bits 0 or 1 respectively. Each transmitted bit is tested by using 30 different randomly generated CIR realizations such that the probability that the sample mean of the CIR at the RN differs from the true mean by less than one standard deviation is 0.96 [31]. The RN is assumed to sense the occupancy of its receptors uniformly at intervals of 1 second (s) [18].

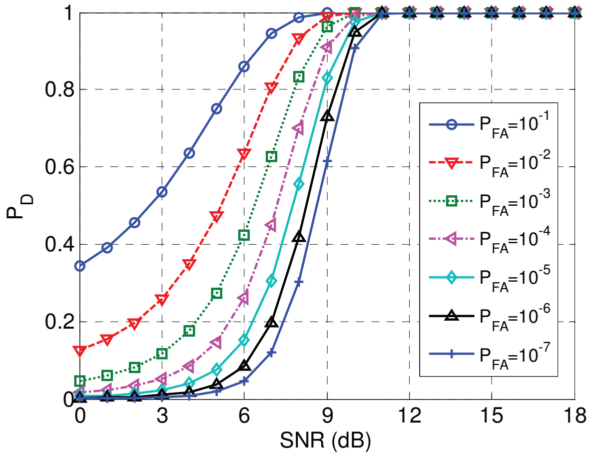


Figure 5. Detection performance of the simple ASK receiver shown in Eq. (17).

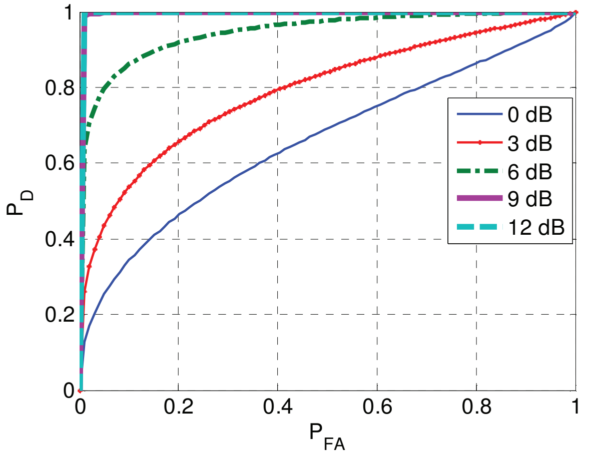


Figure 6. ROC of the simple ASK receiver shown in Eq. (17)

4.2 BER Performance

The receiver has been found to detect the CEMC bits quite effectively. Figure 7 shows that for data rates of 0.01 bps and 0.05 bps, the receiver can detect all the bits correctly (BER=0) up to 30 µm and 10 µm respectively, and beyond this range the BER increases as r increases, while the higher transmission data rate suffers from higher BER. The reason of the increasing BER with the increase of data rate is that at higher data rates, the symbol duration becomes shorter, and the effect of ISI becomes dominant. Since the receiver model is not able to estimate the ISI accurately, as a result of the effects of the ISI the BER increases.

For example, when the transmission rate increases to 0.1 bps, being closer to the TN does not help the RN to recover from the higher BER, and the performance degrades significantly causing ~22% bits to be erroneously detected when *r*=800 nm. The degraded BER performance at *f* = 0.1 bps is clearly seen from the results shown in Fig. 7. BER performance is found to depend significantly on communication range and transmission data rate.

On the other hand, the impact of increasing data rate on the BER has also been shown in Fig. 8 for two different communication ranges, namely, 800 nm and 10 μm. As expected as the data rate increases the BER increases at both values of *r*; however, the effects at *r*=10 μm is more severe than that at *r*=800 nm. This is due to the fact that at higher data rates, the effect of the ISI is comparatively more severe than that at lower data rates, and in addition, the CIR of the channel becomes temporally spread as the communication range increases. However, at data rates of 0.05 bps or lower the receiver is found to detect all the bits correctly at both *r*=800 nm and *r*=10 μm cases, thus providing BER=0 at these two scenarios. We believe that the communication ranges of 800 nm and 10 μm are reasonable enough to be used in numerical experiments because they represent the border lines between short, medium, and long range diffusion-based CEMC in water medium [18].

5. CONCLUSIONS

In this paper, we have developed a generalized strength-based optimum signal detection scheme for CEMC system. The architecture of optimum receiver is first presented, followed by its performance analysis in terms of analytical investigations in the form of detection probability and the ROC. Finally, the BER performance of the receiver thus developed is shown on the basis of various simulation experiments. Although the current focus of the paper is mainly on impulse-based modulation, the receiver model developed in this paper can be applied to detect multi-level (M-ary) and pulse amplitude modulated (PAM) CEMC signaling by properly modifying the signal processing blocks of the receiver. Our on-going work with this generalized CEMC detection model includes a detailed investigation into the effects of ISI and signal strength on the performance of the detector.

Although it is already known that bionanomachines, e.g. biological cells, can sense the concentration of information molecules continually at their receptors [32] and biological cells can be engineered in order to do required tasks [7], the actual implementation of the strength-based detector at the cell level still requires a considerable amount of interdisciplinary research at the crossroads of molecular and synthetic biology, information theory, and communication engineering. Therefore, we strongly believe that the strength-based detection model presented in this paper mainly from the information theory aspects should be useful in the study of the design of CEMC system in greater details.

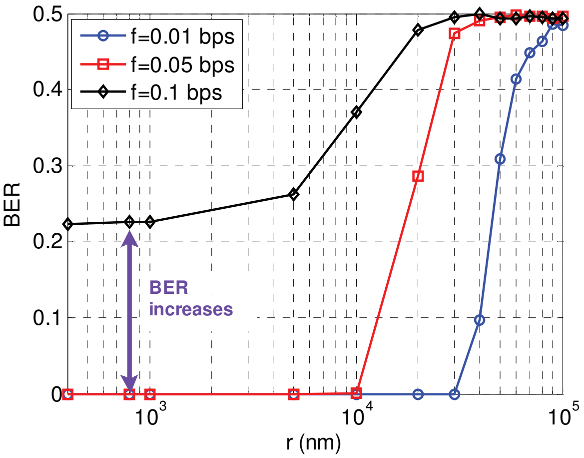


Figure 7. Range-dependent BER characteristics at various transmission data rates

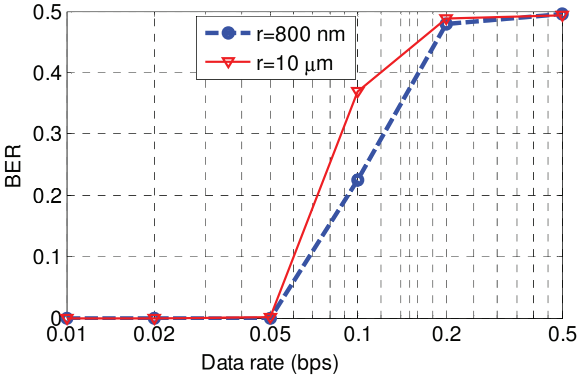


Figure 8. BER performance at various data rates when *r*=800 nm and *r*=10 μm

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