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Interference effects on modulation techniques in diffusion based nanonetworks

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ABSTRACT

Currently, Communication via Diffusion (CvD) is one of the most prominent systems in nanonetworks. In this paper, we evaluate the effects of two major interference sources, Intersymbol Interference (ISI) and Co-channel Interference (CCI) in the CvD system using different modulation techniques. In the analysis of this paper, we use two modulation techniques, namely Concentration Shift Keying (CSK) and Molecule Shift Keying (MoSK) that we proposed in our previous paper. These techniques are suitable for the unique properties of messenger molecule concentration waves in nanonetworks. Using a two transmitting couple simulation environment, the channel capacity performances of the CvD system utilizing these modulation techniques are evaluated in terms of communication range, distance between interfering sources, physical size of devices, and average transmission power.

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1. Introduction

Nanonetworking is a new communication paradigm that covers various communication methods that can be used to transmit information between micro- and/or nano-scale machines [1]. Molecular communication (MC) is envisioned as a promising method as an alternative to traditional approaches such as electromagnetic wave or acoustic wave based systems. Also these systems can be used as a transmission solution for communication between nanomachines and actual living cells, which are crucial for certain applications like interaction between prosthetic smart limbs and nervous system.

In MC, the information is carried via so-called messenger molecules. Motivated by the cellular biological communication systems, various communication methods for MC systems have been proposed in the literature [1]. These systems can be categorized by their effective ranges as short range, (e.g., molecular motors [4], Fluorescence Resonance Energy Transfer [8]), short to medium range, (e.g., ion signaling [14], Communication via Diffusion (CvD) [17]), and long range molecular communication systems, (e.g., bacterium based communication [10], pheromone signaling [9]).

Among these systems, we focus on short and medium range CvD systems in nanonetworks. The main idea behind the CvD system is the usage of certain molecules, called messenger molecules, as the information carriers between two nanomachines residing in close-to-medium proximity to each other in a fluid environment (Fig. 1). The system is composed of five key processes as encoding, transmission, propagation, reception, and decoding [1,17]. First, data is encoded upon one or several properties (e.g. concentration level) of a molecule wave. Then, based on the selected encoding technique and the bit sequence, the transmitter releases a number of molecules in a time slotted fashion. These messenger molecules scatter in the medium following the probabilistic diffusion dynamics in the environment. Some of these released molecules are received into molecule via receptors in the cell membrane.

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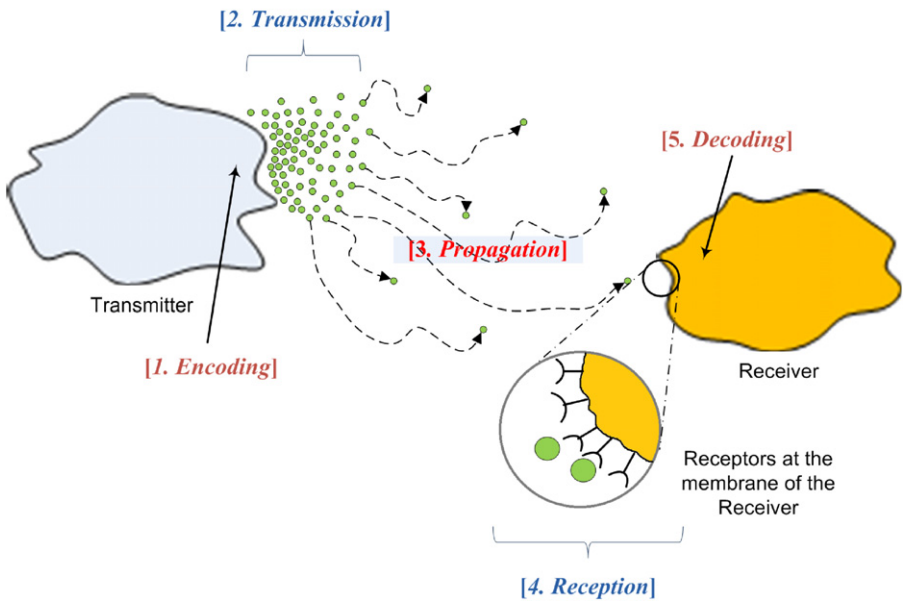

Fig. 1. The transmission model.

Finally, based on the properties of the received molecule wave, the information is decoded and understood by the receiver.

In the recent years, some elements of this aforementioned five process structure have found place in the literature. Most of these studies focus on the channel capacity and propagation dynamics of the CvD medium [15,2,12,3,13]. Some of these propagation process studies consider the probabilistic behavior of the channel as the transfer function of the system while others model it as a unique noise source inherent to a diffusion medium. According to the aforementioned studies on channel capacity and our own results in [18], it is shown that the reliability of the transmission diminishes exponentially with increasing transmission range while the average end-to-end delay increases exponentially. These results limit the effective communication range of the CvD systems to a few tens of micrometers; making it a solution for short-to-medium range inter-nanomachine communication.

Most of these studies on the CvD system focus on a single transmitter single receiver systems. However, when there are more communicating couples in the environment, additional issues arise and change the workings of the communication system. Thus, in order to develop a fully capable system for the CvD system in MC, we need to address these issues and design our communication system with these concerns in mind. An important one among these issues is the interference between closely placed transmitting couples in the same medium. When two or more transmitting pairs try to communicate simultaneously using the same technique and same type of messenger molecules, their signals affect each other and reduce/increase the signal to noise and interference ratio (SINR) of all nearby transmissions.

Apart from the interference issues, other studies show the effects of different modulation techniques on the overall performance of the system. Most of the studies in the literature use the received molecular concentration as the information carrying property of the wave, similar to the Amplitude Shift Keying (ASK) technique in classical communication literature [2,15,16]. Other modulation techniques have also been investigated in the literature. Garralda et al. describe the usage of Pulse Position Modulation (PPM) [6], Mahfuz et al. study the effects of Frequency Shift Keying (FSK) [13], and we have developed a new modulation technique called Molecular Shift Keying (MSK) unique to the CvD medium while formalizing the ASK based techniques as Concentration Shift Keying (CSK) [11].

In this paper, we study the effects of co-channel interference (CCI) over the modulation techniques proposed in [11] with respect to several system parameters and evaluate the molecular reuse distance similar to the established frequency reuse range in the wireless electromagnetic communication literature.

The remainder of the paper is organized as follows. In Section 2, we describe the interference sources that affects a communication system and explain how these sources appear in the CvD system. In Section 3, the two modulation techniques whose performances regarding interference sources are explained briefly. The channel model is explained in Section 4. In Section 5, we present analysis of intersymbol interference (ISI) and CCI effects over these modulation techniques and conclude the paper with Section 6.

2. Interference analysis

In communication systems, a given signal is affected by various sources while it propagates in the medium. All elements that affect a given signal are called interference to the signal. These effects can either be beneficial (constructive interference) or harmful (destructive interference) to the signal in question. The most important sources

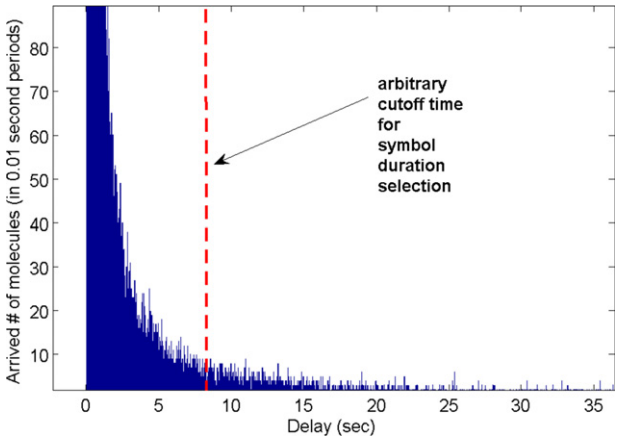

Fig. 2. Molecule arrival delay distribution at the receiver in CvD system.

of interference are the intersymbol interference (ISI), adjacent channel interference (ACI), and co-channel interference (CCI). In any transmission, the signal is composed of a sequence of symbols, which upon aggregation form the whole data. ISI is defined by the interference effect of a symbol onto the successor symbols. When the transmitter sends a sequence of symbols in waveform, due to numerous reasons (e.g., multipath propagation, non-linear response from the channel, etc.), the signal representing a given symbol can affect the subsequent symbols. ACI is the result of imperfect filtering in the transmitter, which results in the signal also having some components in the adjacent frequencies. Ideally, a transmitter should only transmit the signal at a given frequency, however due to wave forming limitations of filters, this property cannot be properly attained by a real-life transmitter circuit. Thus, a signal unavoidably causes interference to its adjacent channels. The last major interference source, the CCI, is the effect of concurrent transmissions onto each other in a given physical environment utilizing the same frequency. Since a signal propagates freely through the environment, when there are more than one transmitting couples in close proximity, some parts of a given transmitter's signal reach the other receivers. In addition to these interference sources, the signal is also affected by environmental background effects. However, these effects are not considered as a type of interference and are called noise. We have analyzed the effects of ISI in the CvD system in our previous work [18]. In this paper, while retaining the ISI effects, we focus on the CCI effects in the CvD system.

The prevalent force that affects the propagation of a signal in MC is the probabilistic behavior of the Brownian motion. While this behavior is fundamentally different from the well-known and well-studied deterministic medium of the electromagnetic wave based communication, the concept of interference still applies to MC.

As seen in Fig. 2, the concentration amount based received signal has a log-normal like distribution in MC. The amplitude of the signal is affected by the number of molecules released, and the variance is affected by the diffusion coefficient. Since the MC medium is inheritably slow in terms of propagation delay, the symbol duration (t_s) should be selected to the left as much as possible in this distribution graph while including the spike part of the signal but leaving out some part of the long tail. However, the molecule arrival in this left out part of the tail affects the decoding process of the next symbol, and thus forms the ISI in the MC [18]. In addition to the molecules arriving to the receiver, the rest of the molecules released from the transmitter wander around in the environment and in time will be received by other devices. Considering these devices using the same type of molecule for transmission purposes, these stray molecules is the cause of the CCI effect in MC.

In electromagnetic communication, since the power of a signal diminishes with increasing range, the most common method in eliminating (or reducing) CCI among neighboring transmission couples is to utilize a reuse distance between the communicating pairs. The relationship between range and signal power also occurs in MC. Therefore, in this work we analyze the effects of the distance between two transmitters, h, over the channel capacity of the signal to see if the reuse distance method is also applicable to this communication system and show how it should be selected.

3. Modulation techniques

In the CvD system, the information is sent using a sequence of symbols spread over sequential time slots (t_s) as one symbol in each slot. The symbol sent by the transmitter is called the "intended symbol" and the symbol received at the receiver is called the "received symbol". A variety of modulation techniques can be used for the mapping between messenger molecule reception and the received symbol, in other words, symbol detection. The symbol can be modulated over various "messenger molecule arrival properties" at the receiver, (e.g., concentration, frequency, phase, molecule type), to form a signal.

3.1. Concentration shift keying (CSK)

In this technique, the concentration of the received messenger molecules is used as the amplitude of the signal. The receiver decodes the intended symbol as "1" if

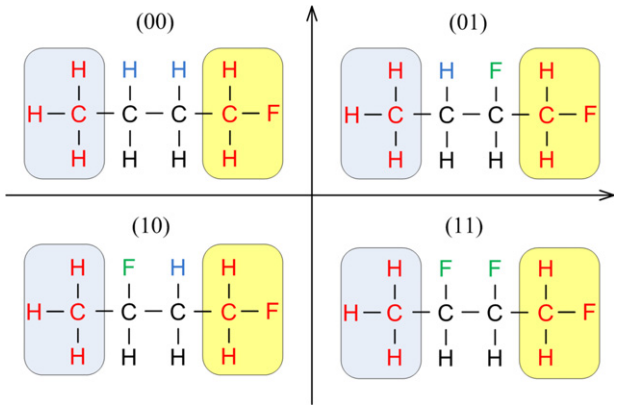

Fig. 3. Constellation of QMoSK using hydrofluorocarbon based messenger molecule.

the number of messenger molecules arriving at the receiver during a time slot exceeds a threshold (τ), "0" otherwise. In order to represent different values in symbols, the transmitter releases different number of molecules for each value the symbol can represent: for "0" the transmitter releases n_0 molecules whereas for "1", n_1 molecules are released.

CSK is analogous to Amplitude Shift Keying (ASK) in classical communication. Instead of using two n values, e.g., n_0 and n_1, and a single threshold, the symbol can be tailored to represent b bits by using 2^b different n values with $2^b - 1$ threshold levels.

We use the classical modulation naming convention based on the number of bits per symbol. CSK can be implemented in practice as BCSK (Binary CSK) or QCSK (Quadruple CSK), depending on the bits per symbol rate.

- If $b = 1$, CSK is called Binary CSK (BCSK)
- If $b = 2$, CSK is called Quadruple CSK (QCSK).

As explained in our previous work, ISI has significant detrimental effects on this modulation technique. Similar to ISI, CCI also cause attenuation on the signal using this modulation technique. In case of several transmitting couples in close proximity to each other, stray molecules from each transmitter will increase the amplitude of other signals in the vicinity which may lead to decoding errors in the receivers. Following a similar pattern to the ISI effect, as the b value increases, so does the CCI's harmful effect over all the transmissions in a region.

3.2. Molecular shift keying (MoSK)

MoSK utilizes the emission of different types of messenger molecules to represent information. For the transmission of n information bits in one symbol, 2^n different molecules are utilized, each representing a combination of the 2^n different n-bit sequences. The transmitter releases one of these molecules based on the current intended symbol. The receiver decodes the intended symbol based on the type and the concentration of the molecule received during a time slot. If the concentration of a single molecule type exceeds the threshold τ at the receiver, the symbol is decoded based on the bit sequence corresponding to this molecule type. On the other hand, an error is assumed, if the concentration of any molecule types does not exceed the threshold or the concentration of more than one molecule type exceeds the threshold.

Inspired by Freitas [5], hydrofluorocarbons can be used as the messenger molecule structure for systematically designing 2^n different molecules for n bit logical information representation. Based on the message to be transmitted, a special messenger molecule is synthesized using three parts: header, trailer, and the chemical bit element. A single header and a single trailer are present in each molecule representing the start and the end of the message. For each bit of information, a chemical bit element is synthesized. This chemical bit element has two forms: one for representing "0" and another one representing "1". All of these parts are linked to each other using chemical bonds to form a single messenger molecule. In Fig. 3, we depict a 2-bit constellation realization of this modulation technique called Quadruple MoSK (QMoSK).

A signal using MoSK is more resilient to the ISI effects compared to a signal that uses CSK technique [11]. Signals emitted from transmitters that are close to each other can only affect other transmissions that are sending exactly the same bit value at the same symbol duration since for each bit value a different molecule type is utilized in MoSK. Thus, following the ISI case CCI is expected to have less detrimental effect over a signal using the MoSK modulation technique, even the b value is high.

4. Communication model

In order to evaluate the effect of ISI and CCI over different modulation techniques, we develop a communication model where time is divided into equal sized slots (called symbol durations-t_s) in which a single symbol can be sent. The model incorporates two transmitting couples in a 3D environment each is compromised of one transmitter and one receiver biological cell-like nanomachine. Each nanomachine is modeled with a spherical body with a radius of r_{cell} and has a fixed position in the topology. In each couple, the transmitter is separated from the receiver by a distance of d nanometers. The two transmitters are placed h nanometers apart from each other and so are the receivers (Fig. 4). A transmitter releases a given number of molecules depending on the bit value of the symbol

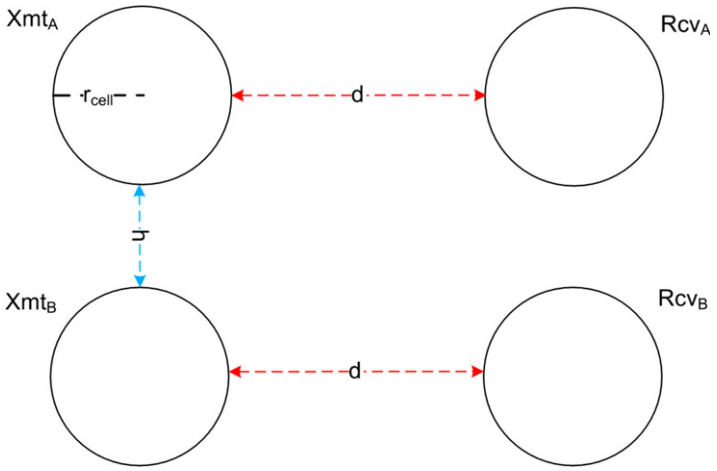

Fig. 4. Communication model topology.

(e.g. n_0 for "0", and n_1 for "1"). Instead of a classical omni-directional antenna used in EM communication, the whole nanomachine acts as the antenna in MC. Hence, the release points of two cell-like nanomachines, each with a radius of r_{cell}, has a minimum distance of $2 \times r_{cell}$ in between due to the volume of the devices. Thus, in addition to h, r_{cell} is also an important factor for the severity of CCI since it also affects the distance between the release points of the messenger molecules.

We assume each molecule has a spherical size with a radius of $r_{molecule}$ and propagates in the medium according to the Brownian motion whose diffusion coefficient is given as D. If a molecule collides with a receiver, we say "the molecule hit the receiver", and the molecule is removed from the system since the ligand receptor at a receiver forms a chemical bond with the messenger molecule and the molecule is absorbed by the receiver [2]. It is assumed that the whole surface of the receiver is composed of receptors, which are able to bind with the messenger molecules. If a molecule hits a transmitter it bounces back from the transmitter since a transmitter does not have the same ligand receptors on their outer shell. The messenger molecules in this system operate in the low Reynolds number domain. Thus, they do not and cannot have any inertia. Following this property, we model the bouncing molecule as canceling an illegal movement as if it did not happen at all [7].

After the molecules are released to the environment, some of them hit to a receiver fairly quickly while others hit after a long period of time and few wander around. Theoretically, if we wait indefinitely, every released molecule eventually hits a receiver. However, as stated in the previous section, in a communication system the information is encoded on a number of symbols and is expected to arrive at the receiver within a given duration, called symbol duration (t_s). According to our previous work, the selection of this symbol duration is heavily dependent on several parameters such as d and D. While a detailed analysis of symbol duration should be utilized, for the sake of simplicity we follow our previous method for choosing the symbol duration in this work. For each combination of d, r_{cell}, and h values used in the simulations, we take 100,000 independent trials for the propagation of a single molecule. Among these trials we take the ones that hit the correct receiver and select the time required for α% of them to hit the correct receiver as the symbol duration. According to our trials, we find out that the α value should be chosen close to 60, which enables reasonable values for both the symbol duration length and the number of unwanted surplus molecules to the subsequent symbol.

After finding out the appropriate t_s value, we re-run the molecule propagation trials for this duration and calculate the hitting probabilities of a single molecule to both of the receivers (P^R_{hit}, as hitting probability to the correct receiver and P^W_{hit} as the hitting probability to the wrong receiver). Then, we calculate the distribution of number of hitting molecules ($N^R_{c(n)}$) when a given number of molecules (n) are released from the same point at the same time as

$$N^R_{c(n)} \sim Binomial(c(n),\ P^R_{hit}(d, t_s)). \tag{1}$$

In addition to the molecules originating from the transmitter, other molecules may hit the receiver. Some of these molecules belong to the previous symbol of the signal while others originate from the current and previous symbols of the other transmitter. These sources act as ISI and CCI to the intended transmission, respectively. The number of molecules causing the ISI is denoted as N^R_p and follows a distribution as

$$N^R_{p(n)} \sim Binomial(p(n),\ P^R_{hit}(d, 2t_s)) - Binomial(p(n),\ P^R_{hit}(d, t_s)). \tag{2}$$

The molecules causing the CCI is denoted as $N^W_{c(n)}$ and $N^W_{p(n)}$ for molecules belonging to the current and previous symbol of the other transmitter. Molecules coming from the other transmission follow similar distributions as the molecules from the main transmission as

$$N^W_{c(n)} \sim Binomial(c(n),\ P^W_{hit}(d, t_s)) \tag{3}$$

and

$$N^W_{p(n)} \sim Binomial(p(n),\ P^W_{hit}(d, 2t_s)) - Binomial(p(n),\ P^W_{hit}(d, t_s)). \tag{4}$$

Combining these four molecular arrival distributions in one symbol, the total number of molecules hitting the

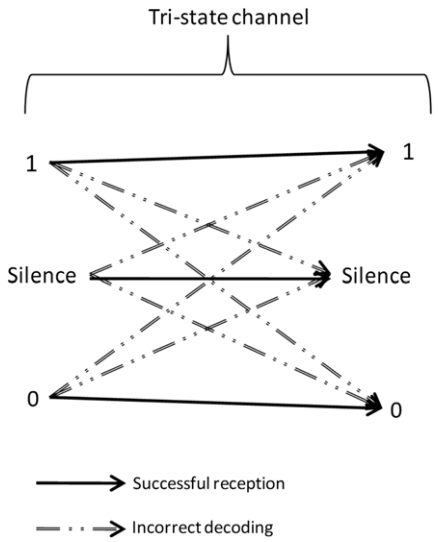

Fig. 5. Silence Aware channel model.

receiver in a t_s can be calculated as the summation of these sources

$$N = N^R_{c(n)} + N^R_{p(n)} + N^W_{c(n)} + N^W_{p(n)}. \tag{5}$$

We only utilize the binary variations of CSK and MoSK techniques (i.e. BCSK and BMoSK) for the sake of simplicity. Using a tri-state channel model that differentiates between a signal and silence (s), the symbol is decoded as silence if $N < \tau_0$, as "0" if $(N > \tau_0)\,\&\,(N < \tau_1)$, and as "1" if $(N > \tau_1)$.

Being a tri-state channel, the current symbol of the main transmission (s^R_c) and the other three symbols (previous symbol of the main transmission (s^R_p), previous symbol (s^W_p), and the current symbol (s^W_c) of the other transmission) can each take three values (Fig. 5).

4.1. Probabilities for the BCSK technique

Using the N value and different thresholds (Fig. 6) for each case, the probabilities for the BCSK case can be found as follows if the current symbol (s^R_c) is "0"

$$\begin{aligned} P_{R(s^R_p, s^W_p, s^R_c=0, s^W_c)} &= P(A_0 < \tau_{s^R_p,1}) - P(A_0 < \tau_{s^R_p,0}) \\ P_{X_1(s^R_p, s^W_p, s^R_c=0, s^W_c)} &= P(A_0 > \tau_{s^R_p,1}) \\ P_{X_S(s^R_p, s^W_p, s^R_c=0, s^W_c)} &= P(A_0 < \tau_{s^R_p,0}), \end{aligned} \tag{6}$$

if s^R_c is "1"

$$\begin{aligned} P_{R(s^R_p, s^W_p, s^R_c=1, s^W_c)} &= P(A_1 \geqslant \tau_{s^R_p,1}) \\ P_{X_0(s^R_p, s^W_p, s^R_c=1, s^W_c)} &= P(A_1 < \tau_{s^R_p,1}) - P(A_1 < \tau_{s^R_p,0}) \\ P_{X_S(s^R_p, s^W_p, s^R_c=1, s^W_c)} &= P(A_1 < \tau_{s^R_p,0}), \end{aligned} \tag{7}$$

and if s^R_c is silence (s)

$$\begin{aligned} P_{R(s^R_p, s^W_p, s^R_c=s, s^W_c)} &= P(A_1 < \tau_{s^R_p,0}) \\ P_{X_0(s^R_p, s^W_p, s^R_c=s, s^W_c)} &= P(A_1 < \tau_{s^R_p,1}) - P(A_1 < \tau_{s^R_p,0}) \\ P_{X_1(s^R_p, s^W_p, s^R_c=s, s^W_c)} &= P(A_1 \geqslant \tau_{s^R_p,1}) \end{aligned} \tag{8}$$

where $A_i = N^R_{p(n_{s^R_p})} + N^W_{p(n_{s^W_p})} + N^R_{c(n_i)} + N^W_{c(n_{s^W_c})}$, $P_{R(s^R_p, s^W_p, s^R_c, s^W_c)}$ is the successful reception probability of s^R_c, and $P_{X_j(s^R_p, s^W_p, s^R_c, s^W_c)}$ is the incorrect decoding probability of s^R_c as "j".

4.2. Probabilities for the BMoSK technique

In the BMoSK case, the probabilities are calculated considering the type of the molecules based on the bit values of the four molecular arrival sources. If the current symbol (s^R_c) is "0" or "1"

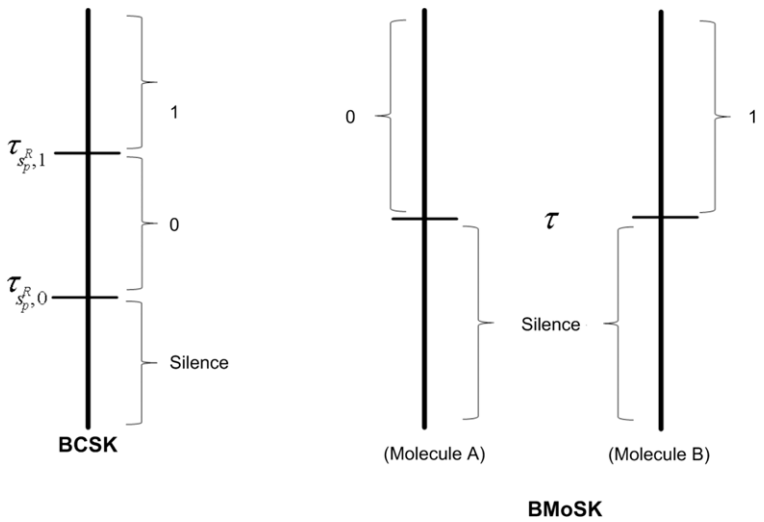

Fig. 6. Threshold values for modulation techniques.

$$P_{R(s_p^R, s_p^W, s_c^R, s_c^W)} = P(N_c^R + \delta_p^R N_p^R + \delta_p^W N_p^W + \delta_c^W N_c^W \geqslant \tau) \times P(\beta_p^R N_p^R + \beta_p^W N_p^W + \beta_c^W N_c^W < \tau) \quad (9)$$

$$P_{X_{\sim s_c^R}(s_p^R, s_p^W, s_c^R, s_c^W)} = P(N_c^R + \delta_p^R N_p^R + \delta_p^W N_p^W + \delta_c^W N_c^W < \tau) \quad (10)$$

$$\times P(\beta_p^R N_p^R + \beta_p^W N_p^W + \beta_c^W N_c^W \geqslant \tau) \quad (11)$$

$$P_{X_S(s_p^R, s_p^W, s_c^R, s_c^W)} = 1 - P_R - P_{X_{\sim s_c^R}}$$

$$\delta_k^l = \begin{cases} 1, & \text{if } s_k^l = s_c^R \\ 0, & \text{otherwise} \end{cases} \quad (12)$$

$$\beta_k^l = \begin{cases} 1, & \text{if } s_k^l = \sim s_c^R \\ 0, & \text{otherwise} \end{cases} \quad (13)$$

where $(\sim s_c^R)$ represents the opposite bit value of the current symbol. If the current symbol (s_c^R) is "s"

$$P_{R(s_p^R, s_p^W, s_c^R = s, s_c^W)} = 1 - P_{X_0} - P_{X_1}$$

$$P_{X_0(s_p^R, s_p^W, s_c^R = s, s_c^W)} = P(\alpha_p^R N_p^R + \alpha_p^W N_p^W + \alpha_c^W N_c^W \geqslant \tau) \quad (14)$$

$$\times P(\gamma_p^R N_p^R + \gamma_p^W N_p^W + \gamma_c^W N_c^W < \tau) \quad (15)$$

$$P_{X_1(s_p^R, s_p^W, s_c^R = s, s_c^W)} = P(\alpha N_p^R + \alpha_p^W N_p^W + \alpha_c^W N_c^W < \tau) \quad (16)$$

$$\times P(\gamma_p^R N_p^R + \gamma_p^W N_p^W + \gamma_c^W N_c^W \geqslant \tau) \quad (17)$$

$$\alpha_k^l = \begin{cases} 1, & \text{if } s_k^l = 0 \\ 0, & \text{otherwise} \end{cases} \quad (18)$$

$$\gamma_k^l = \begin{cases} 1, & \text{if } s_k^l = 1 \\ 0, & \text{otherwise.} \end{cases} \quad (19)$$

4.3. Calculation of channel capacity

After substituting 0, 1, and s according to symbol values s_c^R, s_p^R, s_c^W, and s_p^W, the decoding probabilities and conditional channel capacities are calculated in all possible 81 cases. Summing up these conditional channel capacities with equally likely symbol values (each symbol has the same probability of being 0, 1, and s), we calculate the overall channel capacity of the system using the well-known channel capacity formulation below

$$C = \max_{\tau} \sum_{y \in \{S,0,1\}} \sum_{x \in \{S,0,1\}} \mathbf{P}_{X,Y}(x, y) \log_2 \frac{\mathbf{P}_{X,Y}(x, y)}{\mathbf{P}_X(x)\mathbf{P}_Y(y)}. \quad (20)$$

5. Performance evaluation

Based on the communication model above, we evaluate the effect of CCI in the CvD system with respect to different h values over two performance metrics, the probability of hitting to the receivers and the overall channel capacity. We run the simulations assuming a water-like environment in average body temperature with insulin hormone-sized messenger molecules. For precision in calculation, we choose the step time in the diffusion model as 0.001 s. The symbol durations are chosen based on $\alpha = 60$, and varying values of d. We use the average number of molecules emitted for each symbol $(n_0 + n_1)/3$ as the transmitter power since the channel is a tri-state channel (a symbol can either represent 0, 1, or silence). The simulation parameters are given in Table 1.

Table 1
Simulation parameters.

Parameter	Value
Radius of messenger molecule ($r_{molecule}$)	2.5 nm[5]
Viscosity of the fluid (η)	0.001 $\frac{kg}{s\,m}$
Temperature (T)	310 °K
Drag constant (b)	5.391 10^{-11} $\frac{kg}{s}$
Diffusion coefficient (D)	79.4 $\frac{\mu m^2}{s}$
Step time (Δt)	0.001 s
Symbol duration (t_s) $d = 4\,\mu m$	0.213 s
Symbol duration (t_s) $d = 8\,\mu m$	0.949 s
Symbol duration (t_s) $d = 16\,\mu m$	4.064 s
Symbol duration (t_s) $d = 32\,\mu m$	17.391 s

First, we analyze the effect of h parameter over the hitting probabilities for different d values while setting r_{cell} to a moderate value (5 μm). As seen in Fig. 7, with the increase in h, P_{hit}^W decreases and eventually converges to zero while P_{hit}^R increases only slightly. Compliant to our previous works and other findings in the literature, P_{hit}^R decreases with increasing transmission range (d). However, P_{hit}^W does not show the same behavior. This is due to the fact that, when $d = 4\,\mu m$, the molecules have little space to move and most of them either hit the correct receiver or dissipate in the environment. When d increases, the molecules move more freely in the environment and they have a higher chance of hitting the wrong receiver albeit the detrimental effect of increased range. As d further increases, both hitting probabilities decrease since the transmission range becomes the prevalent factor affecting the hitting probabilities.

Using these hitting probabilities, in Figs. 8 and 9 we depict the channel capacities with varying h and d values for both modulation techniques while the average transmission power per symbol is 333 molecules (i.e. $n_0 = 300$ and $n_1 = 700$ in BCSK, $n = 500$ in BMoSK). For both modulation techniques when $d = 4\,\mu m$, the low P_{hit}^W values do not affect the overall channel capacity. Thus, increasing h has little benefit to the system. However, as d increases, CCI starts to affect the performance of the system, and increasing h becomes a good solution to mitigate CCI as in the electromagnetic wave-based wireless communication case. As the d value increases, the channel capacity difference between BCSK and BMoSK techniques also increases. This is due to the fact that different bit values in the environment does not effect the channel in BMoSK since a different molecule is used for each bit value. On the other hand, in the BCSK case regardless of the bit value, each transmission causes CCI to the other. Similar to the ISI case as depicted in our previous work [11], BMoSK is also more resilient to CCI.

6. Conclusion

Nanonetworks is a promising field that aims to develop communication systems between micro- and nano-scale

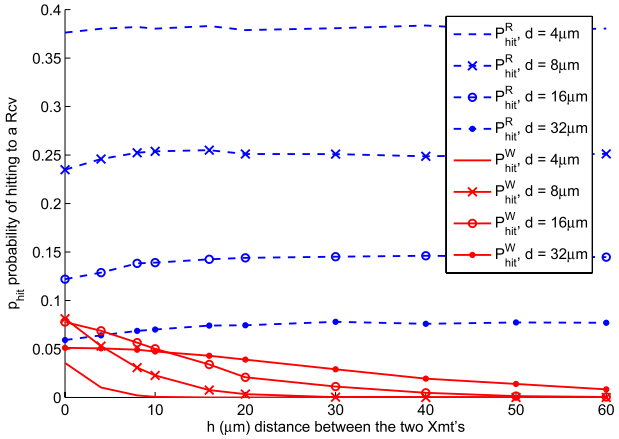

Fig. 7. Effect of *h* over the hitting probabilities with varying *d*.

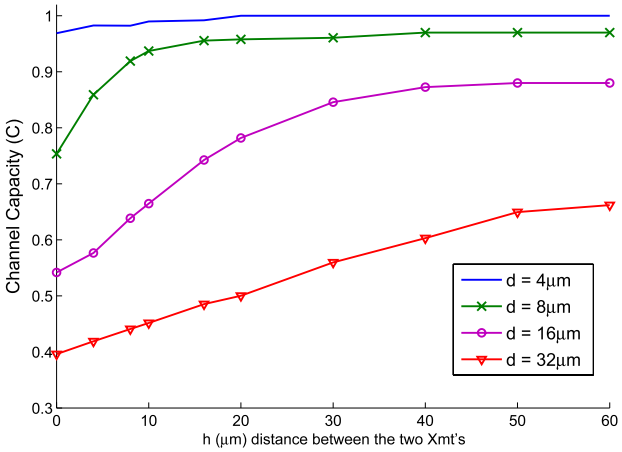

Fig. 8. Effect of *h* over channel capacity with varying *d* using BCSK.

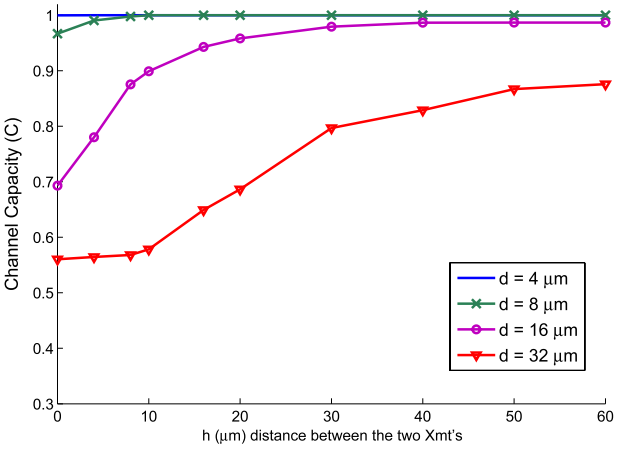

Fig. 9. Effect of *h* over channel capacity with varying *d* using BMoSK.

machines. Currently, one of the prominent nanonetwork systems studied in the literature is the CvD system. In this paper, we explain two major interference sources (i.e. ISI and CCI) that can affect the performance of the CvD system. Using a two transmitting couple simulation topology, we develop a channel model and compare the performances of two modulation techniques (CSK and MoSK) under these two interference sources. As seen from the results, compared to CSK modulation technique, using the MoSK technique, a CvD system can become more resilient to the potential interferences from nearby transmitting pairs. This issue can be quite important when there are several

to many communicating pairs in a given topology using the CvD system. As the future work, we plan to extend our work by including other modulation techniques proposed for the CvD system in the literature. Also, we aim to test the harmful effects of CCI under a more dense topology where more than one interfering communication pairs are available in the network.

Acknowledgments

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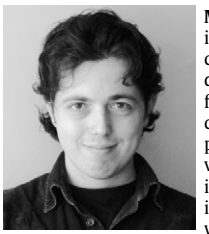
References

[1] I.F. Akyildiz, F. Brunetti, C. Blazquez, Nanonetworks: a new communication paradigm, Computer Networks (Elsevier) Journal 52 (12) (2008) 2260–2279.
[2] Baris Atakan, Ozgur Akan, On channel capacity and error compensation in molecular communication, Transactions on Computational Systems Biology *X* (2008) 59–80.
[3] Baris Atakan, Ozgur B. Akan, Deterministic capacity of information flow in molecular nanonetworks, Nano Communication Networks (Elsevier) (ISSN: 18787789) 1 (1) (2010) 31–42. doi:10.1016/j.nancom.2010.03.003.
[4] Akihiro Enomoto, Michael Moore, Tadashi Nakano, Ryota Egashira, Tatsuya Suda, A molecular communication system using a network of cytoskeletal filaments, in: Proceedings of the 9th Nanotechnology Conference (NANOTECH), vol. 1, pp. 725–728, May 2006.
[5] Robert A. Freitas, Nanomedicine, Vol. I: Basic Capabilities, first ed., Landes Bioscience, 1999.
[6] Nora Garralda, Ignacio Llatser, Albert Cabellos-Aparicio, Massimiliano Pierobon, Simulation-based evaluation of the diffusion-based physical channel in molecular nanonetworks, in: Workshop on Molecular and Nano Scale Communications (MoNaCom'11), in: IEEE International Conference on Computer Communications (INFOCOM'11), IEEE, ISBN: 978-1-4577-0249-5, 2011, pp. 443–448. doi:10.1109/INFCOMW.2011.5928854.
[7] Shlomo Havlin, Daniel Ben-Avraham, Diffusion in disordered media, Advances in Physics 36 (6) (1987) 695–798. doi:10.1080/00018738700101072.
[8] M. Kuscu, O.B. Akan, A nanoscale communication channel with fluorescence resonance energy transfer (FRET), in: Workshop on Molecular and Nano Scale Communications (MoNaCom'11), in: IEEE International Conference on Computer Communications (INFOCOM'11), IEEE, ISBN: 978-1-4577-0249-5, 2011, pp. 425–430. doi:10.1109/INFCOMW.2011.5928851.
[9] Llu'ıs, P. Giné, F. Ian, Akyildiz, Molecular communication options for long range nanonetworks, Computer Networks (Elsevier) Journal 53 (16) (2009) 2753–2766.
[10] Luis C. Cobo, Ian F. Akyildiz, Bacteria-based communication in nanonetworks, Nano Communication Networks (Elsevier) (ISSN: 18787789) 1 (4) (2010) 244–256. doi:10.1016/j.nancom.2010.12.002.
[11] Mehmet S. Kuran, Huseyin B. Yilmaz, Tuna Tugcu, Ian F. Akyildiz, Modulation techniques for communication via diffusion in nanonetworks, in: Communications (ICC), 2011 IEEE International Conference on, IEEE, ISBN: 978-1-61284-232-5, 2011, pp. 1–5. doi:10.1109/icc.2011.5962989.
[12] Michael J. Moore, Tatsuya Suda, Kazuhoro Oiwa, Molecular communication: modeling noise effects on information rate, NanoBioscience, IEEE Transactions on 8 (2) (2009) 169–180.
[13] Mohammad U. Mahfuz, Dimitrios Makrakis, Hussein T. Mouftah, On the characterization of binary concentration-encoded molecular communication in nanonetworks, Nano Communication Networks (Elsevier) (ISSN: 18787789) 1 (4) (2010) 289–300. doi:10.1016/j.nancom.2011.01.001.
[14] Tadashi Nakano, Tatsuya Suda, Michael Moore, Ryoto Egashira, Akhiro Enomoto, Kayo Arima, Molecular communication for nanomachines using intercellular calcium signaling, Nanotechnology, (IEEE-NANO'05), 5th IEEE Conference on 2 (2005) 478–481.
[15] M. Pierobon, I.F. Akyildiz, A physical end to end model for molecular communication in nanonetworks, IEEE Journal on Selected Areas in Communications (JSAC) 28 (4) (2010) 602–611.
[16] K.V. Srinivas, Raviraj S. Adve, Andrew W. Eckford, Molecular communication in fluid media: the additive inverse Gaussian noise channel, December 2010, URL: http://arxiv.org/abs/1012.0081.
[17] Tatsuya Suda, Michael Moore, Tadashi Nakano, Ryota Egashira, Akihiro Enomoto, Exploratory research on molecular communication between nanomachines, in: Genetic and Evolutionary Computation Conference, (GECCO'05), ACM, 2005.
[18] Mehmet Sukru Kuran, H. Birkan Yilmaz, Tuna Tugcu, Bilge Özerman, Energy model for communication via diffusion in nanonetworks, NanoCommunication Networks (ISSN: 18787789) 1 (2) (2010) 86–95.



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