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On

PERFORMANCE OF MOLECULAR COMMUNICATION SYSTEMS USING NETWORK CODING

BY

AMPATI RAJA VISHWANATH

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Submitted by

AMPATI RAJA VISHWANATH

Guided by

Dr. PRABHAT KUMAR UPADHYAY

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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DECLARATION OF AUTHORSHIP

I hereby declare that the project entitled "PERFORMANCE OF MOLECULAR COMMUNICATION SYSTEMS USING NETWORK CODING" submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Electrical Engineering completed under the supervision of Dr. Prabhat Kumar Upadhyay, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

_____

CERTIFICATE

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Signature of BTP Guide(s) with dates and their designation

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Preface

This report on "Performance of Molecular Communication Systems Using Network Coding" is prepared under the guidance of Dr. Prabhat Kumar Upadhyay.

In this report we have tried to give a detailed analysis of a relay assisted molecular communication system for improving the error performance of the system and optimization. The parameters under investigation are distances between the nodes and relay, size of the relay, concentrations of the signal molecules and diffusion coefficients.

AMPATI RAJA VISHWANATH
B.Tech. IV Year
Discipline of Electrical Engineering
IIT Indore

PERFORMANCE OF MOLECULAR COMMUNICATION SYSTEMS USING NETWORK CODING

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ABSTRACT

The performance of a molecular communication system depends on various parameters of the system like diffusion coefficients of the messenger molecules, the distance between the two communicating nanomachines, the volume of the nanomachines, the time taken for molecules to reach the receiver, concentrations of molecules for different signals**,** etc. Even after optimizing the adjustable parameters**,** sometimes nanomachines need to communicate with distances between them being comparably large than their optimal distances, where communication becomes difficult. Hence, we introduce a third nanomachine called Relay to assist the communication process. We use Network Coding to improve the performance of the system by reducing the time taken by the signals and improving the error performance of the system. The numerical results will help to choose reliable parameters for the considered relay based model of the molecular communication system.

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Abbreviations

1. **MC ---** Molecular Communications
2. **ISI ---** Inter Symbol Interference

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1. INTRODUCTION

1.1 BACKGROUND

Molecular communication (MC) is the beginning of a new type of communication. It is a model of communication with molecules as the information carriers [1]-[4]. It is not new to us and this type of communication can easily be observed in everyday life. For example, many glands in our body take some hormones as the received signal and release their hormones into the body. The pituitary gland releases various set of hormones each having its effect on one particular gland of the body as a signal to release its hormones. Some plants release Gibberillens as a signal for promoting fruit ripening, plant growth, and other functions.

As the name suggests, in MC the signal transmission is achieved by using molecules as the information carriers. These signal carrying molecules can be transmitted and received by microscopic devices called nanomachines [5]-[8]. A simple system can be formed by taking two nanomachines into consideration. Nanomachine that emits the molecular encoded signal can be seen as a transmitter. Moreover, Nanomachine that receives the molecules and decodes it to get the information of the signal is seen as the receiver. As such, when both nanomachines mutually communicate with each other, then each nanomachine will act as both transmitter and receiver depending on the instant what function it is performing.

The field of MC can have a great influence in the medical domain. Many biological processes occurring in nature use MC. For example, biological processes like respiration and even food, energy distribution in some single cellular organisms use MC. The relatively small size of nanomachines compared to any other devices and their biocompatible nature makes their usage in the medical field possible. They can be used to do simple tasks like targeted drug delivery or specific time-based release of the drug into the body. Further, they could also be used to do complex tasks like analyzing different concentrations present in the medium in real time and in case of any detected abnormalities, sending warning signals to the patient or even taking action by sending necessary signals or releasing the necessary medicine into the diffusive medium.

Based on how the molecules reach the receiver, MC can be divided into two types [9]. If the signal carrying molecules travel to the receiver simply by diffusing then it is called passive transport and if they travel to the receiver using some directional chemical energy then it is called active transport. In passive type of communication the molecules simply diffuse in all possible directions making them dynamic and unpredictable, hence it will be the best choice to use them in environments where we cannot use a properly connected infrastructure. However, the time taken by molecules to reach the receiver varies with square of the communication distance. Hence, the diffusion for longer destinations takes longer time and large no of signaling molecules would be needed for proper detection of the signal. Hence passive transport is only effective for small distances. In active transport, the signal molecules can travel over large distances by use of external means like microtubules guiding it to the receiver, molecular motors which carry the signaling molecules to the receiver. Thus, active transport needs smaller no of molecules to be sent for a particular signal. However, the energy required to transport the molecules must be replenished continuously.

1.2 MOTIVATION

The type of MC in which we are mostly interested is the passive transport because it uses diffusion for the transport of signaling molecules. Diffusion is a naturally occurring process found in everyday life. We can see numerous examples of diffusion processes in action both in biological domains and at environmental scale. Diffusion rates are faster over small distances. Diffusion needs no extra energy, hence it can be the best process to choose especially when we need to communicate in the environment where we cannot form proper infrastructure between the components.

The attenuation of molecular concentration in MC system limits the communication range along with the reduction in the transmission rate and fidelity. Moreover, the propagation time increases with the square of the distance [10]. Hence it necessitates the use of a relay for MC with distant receivers. Several works have studied relaying and network coding in MC system to alleviate the above problem. For instance, see [11]–[13] for decode and forward relaying, [12] for sense and forward relaying, [14] for amplify and forward relaying, and [15], [16] for network coded MC. Different detection techniques have been covered in the literature

for MC systems such as amplitude and energy detection in [17], maximum likelihood detection in [18] and weighted sum detection in [10], [14], [18]–[20].

In [15], authors have calculated probability of error using energy detection for network coded MC system with an arbitrary threshold. However, in this paper, we calculate the probability of error for optimal network coded MC system with weighted sum detector since it is physically more reliable [19]. The proposed error model explicitly considers diffusion noise [21] and inter-symbol interference (ISI) effects.

2. NETWORK CODING USING NANO RELAY

As the distance between nanomachines increases, the communication using diffusion becomes hard to implement. Hence, we use another nanomachine called relay to aid the communication between the required nanomachines. For a simple case, to improve the communication between the nanomachines A and B we can use the nanorelay as the signal repeater. In such a case, the total steps involved in the communication process would be four.

1. Nanorelay receiving and analyzing the signal from A.
2. Nanorelay transmitting the signal from A into the medium to B.
3. Nanorelay receiving and analyzing the signal from B.
4. Nanorelay transmitting signal from B into the medium for A.

Now, we can actually code how the nanorelay responds to the incoming signals and make it send a desired output. This method is called network coding. Instead of sending the messages to A and B separately, it sends a message that has the information of both the signals A and B, and the combined signal is transmitted into the medium. The nanomachines A and B are coded in such a way that they can extract the required signal from the combined signal of the nanorelay.

Hereby, the number of steps involved would be three.

1. Nanorelay receiving and analyzing the signal from A i.e., x_A.
2. Nanorelay receiving and analyzing the signal from B i.e., x_B.
3. Nanorelay transmitting a combined signal to be received by both A and B.

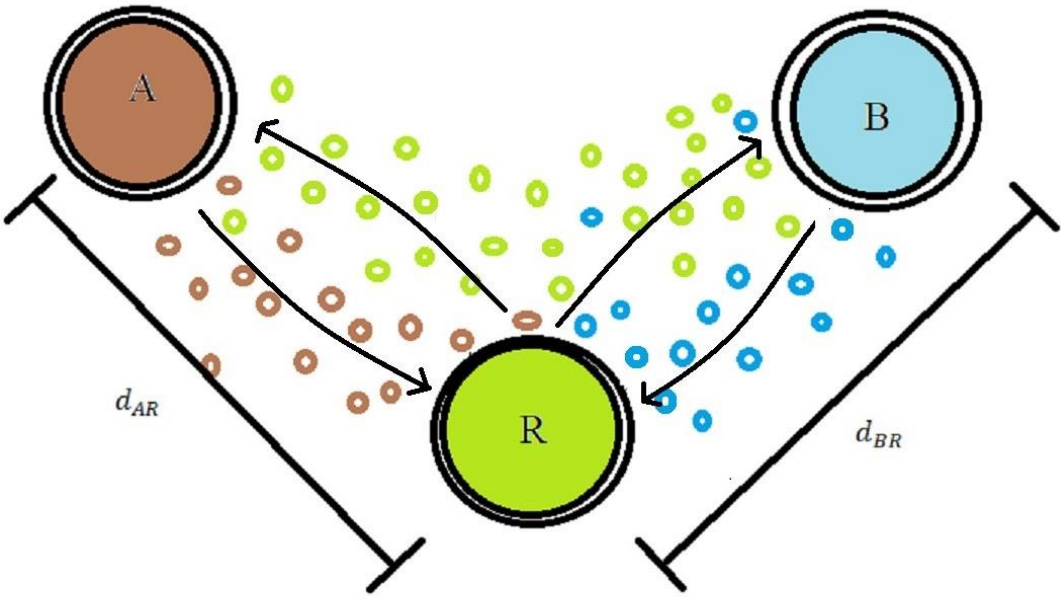

Fig.1 Molecular communication using network coding.

As such, we use XOR logic to reduce the number of communication time slots. The nanorelay is coded to apply XOR function on the incoming signals and transmit the resulting signal. Hence, the combined transmitted signal would be $x_A \oplus x_B$. Now, the nanomachines A and B are coded to apply XOR function on the received signal and their own signal to get the intended one as follows.

Received signal at A, $x_A \oplus (x_A \oplus x_B) = x_B$ (1)

Received signal at B, $x_B \oplus (x_A \oplus x_B) = x_A$ (2)

Hence, by using network coding, intended signal can be decoded at the respective nanomachines in less time slots.

3. SYSTEM MODEL

In this work, we employ three nanomachines namely A, B and R for the performance analysis of a network coded MC system. Nanomachines A, B release different type of signaling molecules as shown in Fig.1. The nanomachine R (nanorelay) is placed in between and equidistant from the nanomachines A and B. We assume a three-dimensional medium having a fixed diffusion coefficient D. The released number of molecules corresponding to information bits 0 and 1 are N_0 and N_1 respectively. The distance between nanomachines A and R is 'r', which is also the distance between nanomachines R and B. Further, the radius of nanomachines are taken as ρ. Moreover, T denotes the time taken by molecular signal to arrive at the nanorelay. More importantly, signals from A and B take same time to reach the nanorelay and vice-versa.

4. ERROR PERFORMANCE ANALYSIS

The molecular concentration corresponding to bit 0 at time t and distance r can be expressed as

$$C^0(r,t) = \frac{N_0}{(4\pi Dt)^{\frac{3}{2}}}.e^{\frac{-r^2}{4Dt}}. \quad (3)$$

Consequently, the received number of molecules for information bit 0 can be given as

$$N^0(r,t) = C^0(r,t).V, \quad (4)$$

where

$$V = \frac{4}{3}.\pi\rho^3, \quad (5)$$

is the volume of spherical reception region.

Since $C^0(r,t)$ and $N^0(r,t)$ give instantaneous values, receiving nanomachine takes L number of samples and adds them to be compared with the detection threshold τ, i.e.,

$$T_s = \frac{T}{L}, \quad (6)$$

where T_s is the sampling duration.

Thus, the observed number of molecules when information bit 0 was transmitted can be written as

$$N_{obs}^{0} = \sum_{k=1}^{L} N^{0}(kT_s) \quad (7)$$

Similarly, the observed signal when information bit 1 was transmitted can be calculated as

$$N_{obs}^{1} = \sum_{k=1}^{L} N^{1}(kT_s)\ , \quad (8)$$

where

$$N^{1}(r,t) = C^{1}(r,t).V\ , \quad (9)$$

is the instantaneous received number of molecules at time t and distance r when information bit 1 was transmitted.

Herein, $C^{1}(r,t)$ is the molecular concentration corresponding to information bit 1, and can be represented as

$$C^{1}(r,t) = \frac{N_1}{(4\pi Dt)^{\frac{3}{2}}}.e^{\frac{-r^2}{4Dt}}\ . \quad (10)$$

Now, we calculate the statistics of Brownian or counting noise for large N_1, N_0. As such, variance of counting noise, $n^{o}(t)$, corresponding to information bit 0 can be expressed as

$$\sigma_0^2 = \sum_{k=1}^{L} N^{0}(kT_s)\ . \quad (11)$$

Likewise, variance of counting noise, $n^{1}(t)$, corresponding to information bit 1 can be expressed as

$$\sigma_1^2 = \sum_{k=1}^{L} N^{1}(kT_s)\ . \quad (12)$$

Hereby, average probability of error when $\hat{x}_A$ is in error can be written as

$$P_e^A = P_E^{x_A=0}P(x_A = 0) + P_E^{x_A=1}P(x_A = 1)$$

$$= 0.5\ (P_E^{x_A=0} + P_E^{x_A=1}),\ \text{for equally likely symbols.}$$

$P_E^{x_A=0} = P[\ N_{obs}^{o} + n_{ob}^{o}\ > \tau]$, where $n_{ob}^{o} = \sum_{k=1}^{L} n^{0}(KT_s)$

$$= P[n_{ob}^{o} > \tau - N_{obs}^{0}]$$

$$= \frac{1}{\sqrt{2\pi\sigma_0^2}} \int_{\tau - N_{ob}^{0}}^{\infty} e^{\frac{-(n_{ob}^{o})^2}{2\sigma_0^2}} d(n_{ob}^{o})$$

Hence, $P_E^{x_A=0} = \frac{1}{2} erfc(\frac{\tau - N_{obs}^{0}}{\sqrt{2\sigma_0^2}})$ (13)

Similarly, $P_E^{x_A=1} = P[n_{ob}^{1} \leq \tau - N_{obs}^{1}]$, where $n_{ob}^{1} = \sum_{k=1}^{L} n^{1}(KT_s)$

Therefore, $P_E^{x_A=1} = \frac{1}{2} erf(\frac{\tau - N_{obs}^{1}}{\sqrt{2\sigma_1^2}})$ (14)

Eventually,

$$P_e^A = \frac{1}{4}[erfc\left(\frac{\tau - N_{obs}^{0}}{\sqrt{2\sigma_0^2}}\right) + erf\left(\frac{\tau - N_{obs}^{1}}{\sqrt{2\sigma_1^2}}\right)] \quad (15)$$

Now, we calculate the probability of observing ISI causing molecules as

$$p(t) = \frac{V}{(4\pi D(T+t))^{\frac{3}{2}}} . e^{\frac{-r^2}{4D(T+t)}} \quad (16)$$

Then, we calculate ISI statistics as

$n_{ISI} = N(\mu, \sigma_{ISI}^2)$,

where

$$\mu = 0.5 \sum_{k=L+1}^{2L} \{N^{1}(kT_s) + N^{0}(kT_s)\} , \quad (17)$$

and

$$\sigma_{ISI}^2 = 0.5\left(N^{0} + N^{1}\right). \sum_{k=L+1}^{2L} p(kT_s).(1 - p(kT_s)) .$$

Further, average probability of error when $\hat{x}_B$ is in error can be written as

$P_e^B = P_E^{x_B=0} P(x_B = 0) + P_E^{x_B=1} P(x_B = 1)$.

$P_E^{x_B=0} = P \ \ [n_{ob}^0 + n_{ISI} > \tau - N_{obs}^0]$

$$= \frac{1}{\sqrt{2\pi\sigma_{t0}^2}} \int_{\tau - N_{obs}^0}^{\infty} e^{-\frac{(n_{t0} - \mu_{t0})^2}{2\sigma_{t0}^2}} d(n_{t0}), \text{ where } n_{t_0} \sim N(\mu_{t_0}, \sigma_{t_0}^2) ,$$

$\sigma_{t_0}^2 = \sigma_0^2 + \sigma_{ISI}^2$,

$\mu_{t_0} = \mu$.

$$P_E^{x_B=0} = \frac{1}{2} erfc(\frac{\tau - N_{obs}^0 - \mu}{\sqrt{2}\sigma_{t0}}) \qquad (18)$$

Similarly,

$$P_E^{x_B=1} = \frac{1}{\sqrt{2\pi\sigma_{t1}^2}} \int_{0}^{\tau - N_{obs}^1} e^{-\frac{(n1 - \mu_{t1})^2}{2\sigma_{t1}^2}} d(n_{t1}) , \text{ where } n_{t_1} \sim N(\mu_{t_1}, \sigma_{t_1}^2) ,$$

$\sigma_{t_1}^2 = \sigma_1^2 + \sigma_{ISI}^2$,

$\mu_{t_1} = \mu$.

$$P_E^{x_B=1} = \frac{1}{2}[erf(\frac{\mu}{\sqrt{2}\sigma_{t1}}) + erf(\frac{\tau - N_{obs}^1 - \mu}{\sqrt{2}\sigma_{t1}})] \qquad (19)$$

Thereafter,

$P_e^R = P_e^A + P_e^B$, when x_R is in error.

$P_e^{\hat{R}} = \frac{1}{2}(P_E^{\hat{x}_R=0} + P_E^{\hat{x}_R=1})$, when $\hat{x}_R$ is in error.

$P_e^{\hat{R}} = P_e^A$, since $\hat{x}_R$ is not affected by ISI.

Finally, the overall probability of error in network coded MC can be given as

$$P_e = P_e^R + 2P_e^{\hat{R}} = 3P_e^A + P_e^B \tag{20}$$

$$P_e = \frac{3}{4}[erfc(\frac{\tau - N_{obs}^0}{\sqrt{2}\sigma_0}) + erf(\frac{\tau - N_{obs}^1}{\sqrt{2}\sigma_1})] + \frac{1}{4}[erfc(\frac{\tau - N_{obs}^0 - \mu}{\sqrt{2}\sigma_{t0}}) + erf(\frac{\mu}{\sqrt{2}\sigma_{t1}}) + erf(\frac{\tau - N_{obs}^1 - \mu}{\sqrt{2}\sigma_{t1}})] \tag{21}$$

5. OPTIMUM DETECTION THRESHOLD, τ_{opt}

Increasing detection threshold τ enhances the probability of miss detection. However, decreasing τ increases the probability of false alarm. Hence, we are interested in finding the optimal detection threshold, τ_{opt}, that minimizes P_e.

Since τ is a continuous function the min value of the function P_e would be at certain value of τ such that

$$\frac{\partial P}{\partial \tau} = 0$$

Now, using $erfc(x) = 1 - erfc(x)$,

and $\frac{d}{dx} erfc(x) = \frac{-2}{\sqrt{\pi}} e^{-x^2}$,

one can arrive at

$$\Rightarrow \frac{3}{4}\left[\frac{-\sqrt{2}}{\sqrt{\pi}} e^{-\left(\frac{\tau-N}{\sqrt{2}\sigma}\right)^2}\right] - \frac{3}{4}\left[\frac{-\sqrt{2}}{\sqrt{\pi}} e^{-\left(\frac{\tau-N}{\sqrt{2}\sigma}\right)^2}\right] + \frac{1}{4}\left[\frac{-\sqrt{2}}{\sqrt{\pi}\,\sigma} e^{-\left(\frac{\tau-N-\mu}{\sqrt{2}\sigma}\right)^2}\right] - \frac{1}{4}\left[\frac{-\sqrt{2}}{\sqrt{\pi}\,\sigma} e^{-\left(\frac{\tau-N-\mu}{\sqrt{2}\sigma}\right)^2}\right] = 0$$

$$\Rightarrow \frac{3}{\sigma} e^{-\left(\frac{\tau-N}{\sqrt{2}\sigma}\right)^2} - \frac{3}{\sigma} e^{-\left(\frac{\tau-N}{\sqrt{2}\sigma}\right)^2} + \frac{1}{\sigma} e^{-\left(\frac{\tau-N-\mu}{\sqrt{2}\sigma}\right)^2} - \frac{1}{\sigma} e^{-\left(\frac{\tau-N-\mu}{\sqrt{2}\sigma}\right)^2} = 0 \tag{22}$$

Finally, one can numerically get $\tau_{opt} = \lfloor \tau \rfloor$ such that $N_{obs}^0 < \tau < N_{obs}^1$.

6. NUMERICAL RESULTS

TABLE I

VALUES OF THE SYSTEM PARAMETERS

Parameters	Notation	Values
# molecules for sending bit 0	N_0	{500, 600}
# molecules for sending bit 1	N_1	1000
Diffusion coefficient	D	{1, 5-12}x10^{-10} m^2/s
Distance between R and {A, B}	r	{325-350} nm
Radius of A, R, B	ρ	{45, 50} nm
# samples	L	10
Sampling duration	T_s	20 μs

In this section, we conduct numerical investigations to evaluate the performance of the proposed system using MATLAB. The simulation parameters are listed in Table I.

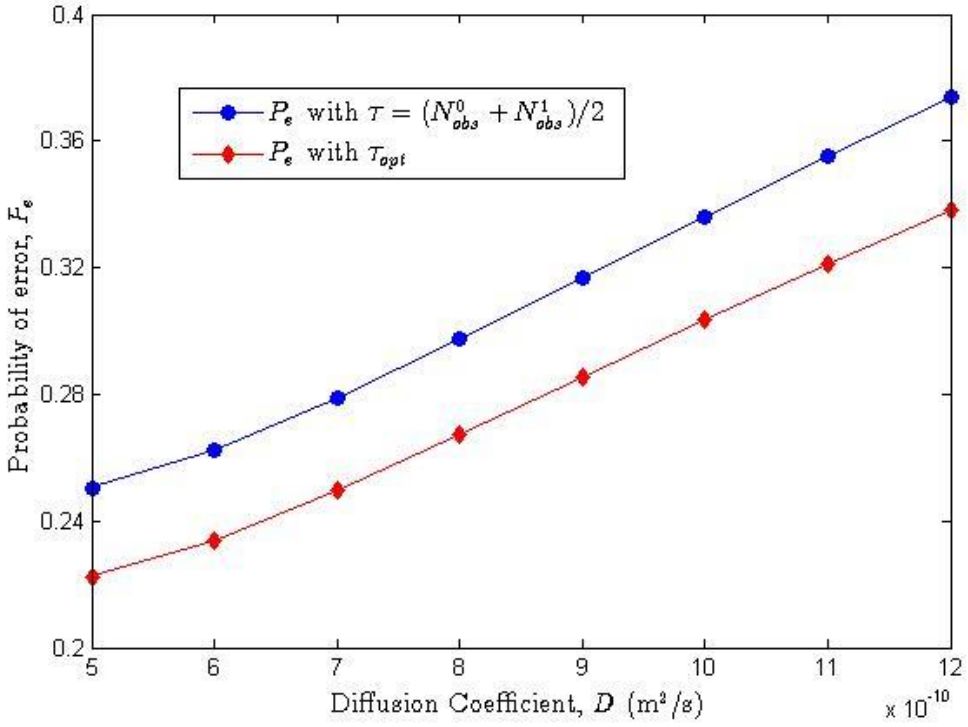

Fig.2 Probability of error as a function of diffusion coefficient.

In Fig. 2, the error probability of a network coded diffusive molecular communication system is evaluated as a function of diffusion coefficient D, with $\tau = (N_{obs}^{0} + N_{obs}^{1})/2$ and τ_{opt}, for system parameters N_0 = 500, r = 350 nm, and ρ = 45 nm. Evidently, one can observe that the error probability increases as diffusion coefficient increases. This is because the molecular pulse decays more quickly as value of diffusion coefficient increases. Moreover, one can see that the optimal detection threshold τ_{opt} minimizes the error probability significantly.

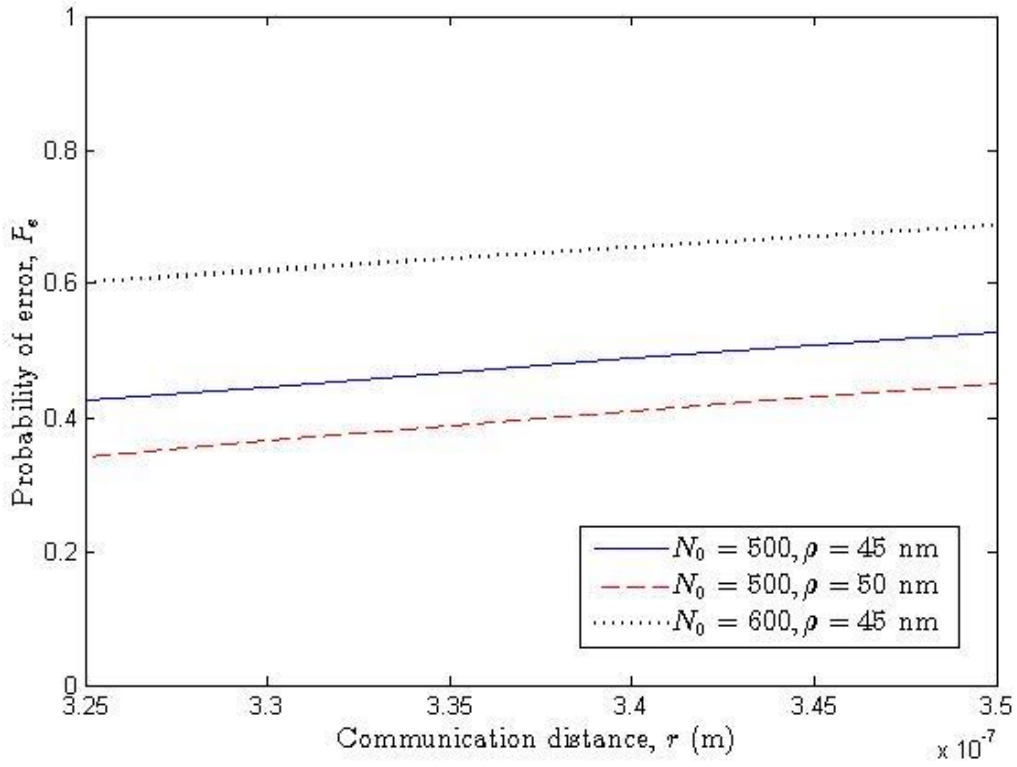

Fig.3 Probability of error as a function of communication distance r.

In Fig. 3, the error probability of the considered system is evaluated as a function of communication distance r, with $\tau = (N_{obs}^{0} + N_{obs}^{1})/2$, for system parameters N_0 = {500, 600}, ρ = {45, 50} nm, and D = 1x10^{-10} m^2/s. One can notice that the error probability reduces as the radius of receiver nanomachine increases due to reduced variance of diffusion noise. Intuitively, the error probability increases as the distance between nanomachines and the nanorelay increases.

Moreover, for a fixed value of N_1, error probability increases with increasing value of N_0 due to the reduced constellation distance.

7. CONCLUSIONS

We calculated the probability of error for a network coded molecular communication system with physically more realizable weighted sum detector. Moreover, we optimized the detection thresholds of the considered system to minimize the error probability. Eventually, we demonstrated the effect of several parameters on the error performance.

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