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Optimal relaying in molecular communications[☆]

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ABSTRACT

Molecular communication via diffusion (MCvD) schemes are limited to short distances between the nanomachines due to the transmitted signal becoming rapidly weaker as the distance increases. Additionally, these schemes are very often affected by high inter-symbol interference, which makes them prone to errors, thus leading to unreliability. In this paper, a novel system is proposed, which aims to enhance the received signal shape and the overall performance of MCvD schemes over longer distances. A relay nanomachine is introduced between the transmitter–receiver pair, which collects the first portion of the molecules emitted from the transmitter and keeps them for some delay time τ, then releases them towards the receiver, such that the delayed and non-delayed portions of the molecules arrive almost at the same time. In this way, the signal's strength is enhanced by pointing more molecules towards the intended direction, that is, the receiver node. An analytical model for the optimal relaying scheme is proposed, alongside with an optimization problem to find the most advantageous τ value. Comparison between the proposed scheme and the conventional single-input single-output scenario is provided by means of analytical and computer simulation results, showing a promising improvement in error rates when the relay is introduced.

1. Introduction

Molecular communication (MC) has received great attention in recent years in regard to numerous small scale applications, for which electromagnetic communication is impractical due to the constraints that characterize these applications [1]. One such constraint is the requirement of the antennas' sizes in the nano scale [2]. Moreover, MC offers characteristics such as biocompatibility and lowest level of invasion, which make it preferable for health-related applications [3]. Inspired by biological systems, MC paradigm is based on transmitting the information using molecules that diffuse through a fluid environment from the source to the destination. MC offers promising results in medical treatments and human health. For instance, nanomachines can be used to find and fight against pathogens, mimicking and carrying out similar functions of immune systems. Additionally, they can reach critical and sensitive locations of the human body, for which traditional solutions fail to do so [4]. Due to its simplicity and energy efficiency, molecular communication via diffusion (MCvD) is amongst the most preferred and practical methods for MC [5].

In its simplest form, a MCvD system consists of a transmitter and a receiver nanomachine [6]. The information is conveyed on properties of the molecular wave that is emitted from the transmitter side, such as the number of molecules, type, emission time, etc. [7]. These molecules propagate through the medium following a pattern that depends on the molecules and on the properties of the medium. A fraction of the transmitted molecules is received through the receptors of the receiver, and the information is decoded accordingly [8]. From the communication system's perspective; encoding, propagation, and decoding of the information signal can be designed and altered for enhancing the performance of the system in accordance with its purpose and attributes [9,10].

1.1. Literature review

A considerable number of studies in the literature focus on the mitigation of the heavy-tailed channel response that characterizes MC systems. The heavy tail nature of the received signal is caused by the molecules received during the following unintended symbol times, and it leads to inter-symbol interference (ISI) [11]. The alleviation of ISI is directly related to the performance of communication systems. Several enhancements and

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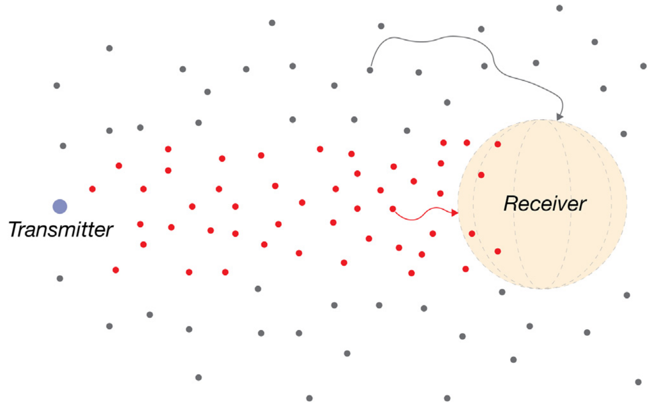

Fig. 1. A rough illustration of the emitted molecules from the transmitter, where the red molecules are the LoS molecules and the gray ones are the NLoS molecules. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

modifications towards ISI mitigation are proposed in [12–16]. These solutions include using more than one type of molecules for encoding the signal, novel modulation techniques and/or algorithms that soothe the ISI effect. The multiple-input multiple-output (MIMO) setting is introduced to MCvD systems as well. In this case, the diffusive characteristic of the molecules causes inter-link interference (ILI), which is another source of error for the MCvD systems. The authors of [17] propose a novel modulation scheme for the purpose of ILI mitigation. Zero-forcing detection is discussed in [18] for the cases when ILI is large.

Apart from the ISI and ILI issues, the reliability of a MCvD system decreases with increasing distance between the transmitter and receiver nodes. In other words, these systems are restricted to short distances, otherwise the communication is highly unreliable. Relaying in MCvD systems has been proposed as one of the prominent solutions to this issue [19]. For instance, the authors of [20] propose the utilization of time-dependent molecular concentrations for encoding the information. The relay decodes and forwards the information by using the same or different types of molecules than those used by the transmitter. Furthermore, multi-hop networks with several relays are considered in [21]. Full-duplex and half-duplex modes of transmission are analyzed, and it is found that ISI can be mitigated if the decision threshold for decoding is selected in an adaptive manner. Moreover, closed-form expressions for the error probability of the overall network are provided as well. Similarly, multi-hop MC is investigated for applications concerned with target detection in [22]. A throughput improvement by incorporating cooperative relaying in MC is demonstrated by the experimental results of [23], whereas its augmentation in the gain is proven by the analytical and simulation results in [24]. Other works also consider finding the optimal position of the relay. For instance, the authors of [25] approach the solution of optimal positioning by formulating a joint optimization problem with the objective being the minimization of the error rate. Similarly, the authors of [26] study several aspects of the MCvD relaying-based scheme, including optimal relay location. Different strategies for the implementation of relaying, such as decode-and-forward, estimate-and-forward, and amplify-and-forward are investigated in the literature as well [27–30].

1.2. Contributions of the proposed model

Most of the works in the literature consider molecular relaying with the purpose of extending the communication range between nanomachines, and thus simultaneously decreasing the error rates. Stimulated by the principle of relaying and by the fact that interfering molecules arrive at the receiver later than the non-interfering molecules, this paper proposes an optimal MC relaying scheme that aims to enhance the overall performance of the communication link. Considering a basic MC scheme that consists of a point transmitter and a spherical receiver, the received non-interfering molecules can be roughly thought of as line-of-sight (LoS) molecules, whereas the interfering ones as non-line-of-sight (NLoS) molecules, as roughly illustrated in Fig. 1. If examined separately, each of those two components has its own peak time of arrival, which can be calculated as explained in [31]. In this paper, we propose a novel relay-based system that aims to isolate these two components. The main idea is to introduce a relay to this basic scheme somewhere between the transmitter and receiver, which will collect the LoS molecules until a time τ and release them afterwards towards the receiver, such that LoS and NLoS molecules arrive almost at the same time at the receiver. Although there is a slight communication delay by doing so, this scheme can improve the error rate as well as extend the communication range by enhancing the received signal shape. The concept is inspired by the recent research on reconfigurable intelligent surfaces (RIS) in wireless networks, which aims to enhance the performance of the network by optimally modifying the propagation environment [32]. Thus, since the proposed scheme is based on manipulating the received signal's shape, we address it as optimal relaying scheme. The received signal gets stronger with the introduction of the relay, since the majority of the molecules arrive at the receiver almost at the same time. To better illustrate this concept, we can draw an analogy between this scheme and the optical lens: the relay aims to collect the molecules in time, just as the lens collects the beams of parallel rays [33].

In order to obtain the parameters of the most advantageous scheme, an optimization problem is introduced to find the optimum τ value for which the minimum bit error rate (BER) is achieved. This optimization problem is based on the optimization function proposed by the authors of [34], known as signal to interference difference (SID), whose global maximum corresponds almost to the global minimum of BER. SID is basically the difference between the first channel tap and the summation of all the consequent taps. The validation of this approach is done by comparing the results of the analytical model of the proposed system with the results obtained from the simulations. The BER comparison between the optimal relaying scheme and the conventional single-input single-output (SISO) model shows the improvement that this scheme provides.

In summary, the main contributions of this work are given as follows:

- The design of a novel optimal relaying system,
- The analytical modeling of this scheme for achieving the delay (τ) optimization,
- The performance analysis of the proposed solution and its comparison with the conventional system.

The remainder of this paper is organized as follows. In Section 2, the topology of the optimal relaying scheme is introduced. The analytical model and its validation are described in Section 3, followed by the optimization problem. In Section 4, we provide the overall results obtained from this study. Finally, the conclusion of this paper is summarized in Section 5.

2. System model

The conventional MCvD scheme consists of a transmitter–receiver pair in a fluid environment and molecules that convey the information. The transmitter is a point source, whereas the receiver is a sphere with radius r_0. The distance between the

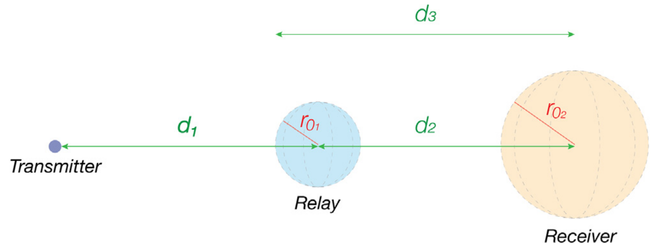

Fig. 2. Optimal relay-based proposed system, where the relay is between the transmitter–receiver pair.

transmitter and the center of the receiver is denoted by r_r. When the molecules are emitted in an unbounded 3-D environment without drift, they propagate following the Brownian motion, which is a random position change with a normal distribution of mean 0 and variance $2\,D\,dt$, defined by $\mathcal{N}(0, 2\,D\,dt)$, where D is the diffusion coefficient that depends on the fluid and the molecules and dt is the time step. The portion of molecules absorbed until time t is modeled as

$$F_{hit}(r_0, r_r, t) = \frac{r_r}{r_0}\operatorname{erfc}\left(\frac{r_0 - r_r}{\sqrt{4\,D\,t}}\right), \tag{1}$$

which is the cumulative fraction of absorbed molecules (CFAM) by the receiver [31]. The proposed scenario is similar to the aforementioned one, the only difference being that a spherical relay is placed between the transmitter and the receiver, as shown in Fig. 2. Let us denote the radii of the relay and the receiver by r_{0_1} and r_{0_2}, respectively. The distance from the transmitter to the center of the relay is denoted by d_1, the distance from the center of the relay to the center of the receiver by d_2, and $d_3 = d_2 + r_{0_1}$.

Assuming that the molecules are emitted from the transmitter at time $t = 0$, the relay absorbs the arriving molecules until $t = \tau$. In the meantime, the receiver absorbs few NLoS molecules. After a specified delay τ, the relay releases the absorbed molecules simultaneously from the closest point to the receiver. This means that the receiver will be receiving NLoS molecules until time τ, and then molecules arriving from both the transmitter and the relay. It is noteworthy to mention that the relay is assumed to be reflective after time τ, such that if the emitted molecules hit back to the surface of the relay, they are reflected back. Considering the transmission of a single bit, the received molecules can be divided into groups for a better understanding of the optimization problem, which will be introduced in the following section. These groups are listed below:

- N - the molecules emitted from the transmitter,
- $M_{Tx}^{Rx}(0, T_s)$ - the molecules received by the receiver released from the transmitter during the first symbol duration (T_s),
- $M_{Tx}^{Rx}(T_s, t)$ - the molecules received by the receiver released from the transmitter after the first symbol duration, for any time $t > T_s$,
- $M_{Tx}^{Rel}(\tau)$ - the molecules absorbed by the relay until time τ,
- $M_{Rel}^{Rx}(\tau, T_s)$ - the molecules absorbed by the receiver released from the relay during the first symbol duration,
- $M_{Rel}^{Rx}(T_s, t)$ - the molecules absorbed by the receiver released from the relay after the first symbol duration, for any time $t > T_s$.

In other words, the components corresponding to the desired received molecules are $M_{Tx}^{Rx}(0, T_s)$ and $M_{Rel}^{Rx}(\tau, T_s)$, whereas $M_{Tx}^{Rx}(T_s, t)$ and $M_{Rel}^{Rx}(T_s, t)$ constitute the ISI.

The analytical derivation of these terms, as well as the optimization problem, are described in the following section.

3. Parameter optimization

In this section, we first propose the analytical approach for obtaining the received signal by deriving the aforementioned components. Then, we introduce the optimization function that is utilized to find the optimum τ value. It is noteworthy to mention that apart from the τ value, the position of the relay is another crucial parameter that has a direct impact on the performance of the system, since it is directly related to the fraction of the molecules that the relay directs towards the receiver. Joint optimization of both τ and d_1 can be considered in future works.

3.1. Analytical modeling of the system

The time until which the relay delays the LoS molecules (τ) is a crucial parameter for the optimal relaying scheme. If the delay time is very short, the signal is not sufficiently manipulated. On the other hand, if the delay is long, the tail becomes very heavy.

The optimization of τ aims to solve this trade-off and determine the delay for which BER is at minimum. An initial approach for finding τ, based on the relay delaying its release time by the peak times of the LoS and NLoS components (peak times derived as in [31]), did not yield the global maximum of SID; thus, BER is not at its minimum. As an alternative approach, SID optimization was considered. In order to obtain the SID optimization function, the previously mentioned signal components should be derived.

The number of molecules absorbed by the relay, released from the transmitter at $t = 0$, can be calculated by

$$M_{Tx}^{Rel}(\tau) = N\frac{r_{0_1}}{d_1}\operatorname{erfc}\left(\frac{d_1 - r_{0_1}}{\sqrt{4\,D\,\tau}}\right), \tag{2}$$

assuming that the receiver does not interfere with the molecules between the transmitter and the relay in the first τ seconds of the transmission. In other words, the very small fraction of molecules that might be absorbed by the receiver during this time is considered insignificant. Similarly, the number of molecules absorbed by the receiver from the relay can be calculated using

$$M_{Rel}^{Rx}(\tau, T_s) = M_{Tx}^{Rel}(\tau)\frac{r_{0_2}}{d_2 - r_{0_1}}\operatorname{erfc}\left(\frac{d_2 - r_{0_1} - r_{0_2}}{\sqrt{4\,D\,(T_s - \tau)}}\right), \tag{3}$$

$$M_{Rel}^{Rx}(T_s, t) = M_{Tx}^{Rel}(\tau)\frac{r_{0_2}}{d_2 - r_{0_1}}\operatorname{erfc}\left(\frac{d_2 - r_{0_1} - r_{0_2}}{\sqrt{4\,D\,t}}\right). \tag{4}$$

Although these expressions are due to (1), the spherical shape of the relay does not match the point transmitter assumption of (1), and this leads to an approximation.

The expression in (3) is used to calculate the received molecules during the first symbol time, whereas in the expression (4), $t > T_s$, so this expression stands for any time interval after the first symbol time. The validity of these expressions are shown in Figs. 3 and 4, where the CFAM and hitting rate of molecules curves of the analytical model and the simulation results are shown, respectively. It is observed that the absorbed portion of molecules whose source is the relay is modeled quite accurately. Moreover, the reflective characteristic of the relay does not become an impediment towards modeling these components, because its impact is not tremendous. This is because the relay has a finite surface, thus it does not act as an infinite mirror for the molecules that hit the relay back. The values of the parameters of the system for which these graphs are obtained are given in Table 1. The selected value of τ in Figs. 3 and 4 is not the optimized one, as the purpose of this section is validating the proposed system model.

The expressions derived so far dealt with the transmitter-relay and relay-receiver links, which were not heavily affected by the existence of the third body (receiver and transmitter,

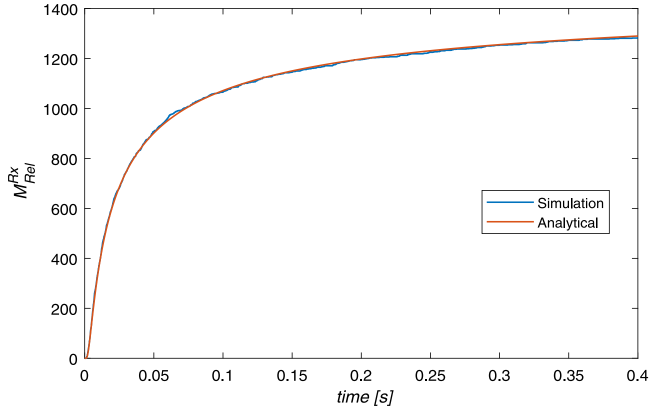

Fig. 3. Simulation and analytical CFAM curves for the absorbed molecules by the receiver released from the relay.

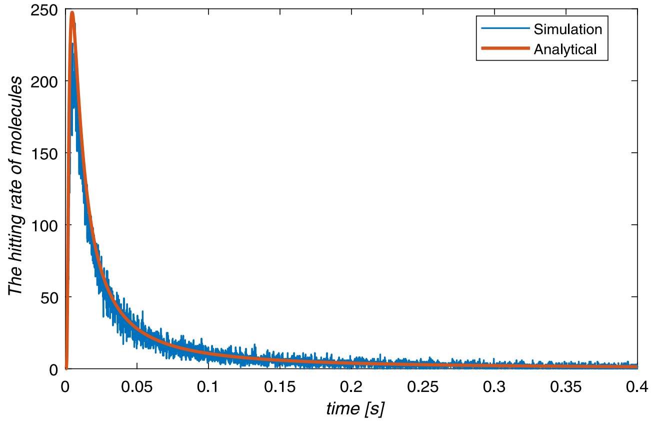

Fig. 4. Simulation and analytical curves for the hitting rate of the absorbed molecules by the receiver released from the relay.

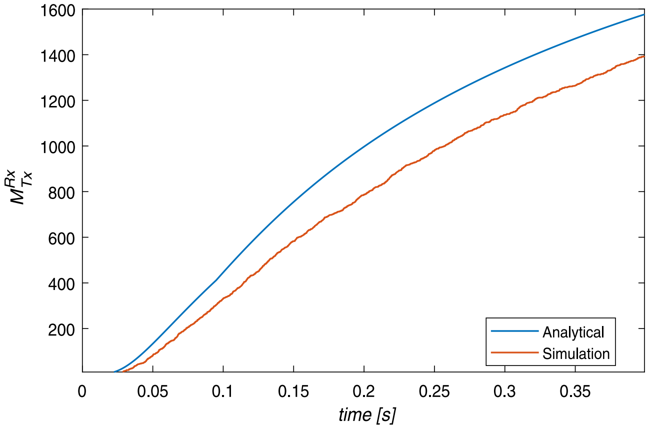

Fig. 5. Simulation and analytical CFAM curves for the absorbed molecules by the receiver released from the transmitter.

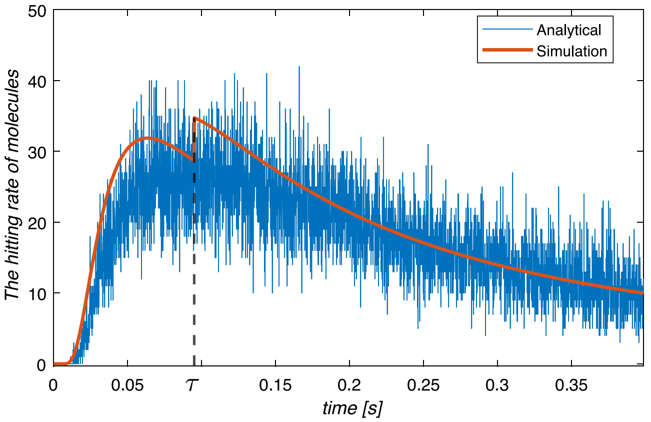

Fig. 6. Simulation and analytical curves for the hitting rate of the absorbed molecules by the receiver released from the transmitter.

respectively). On the other hand, the derivation of the expressions for the received molecules whose source is the transmitter is not straightforward. This is due to the shadowing effect that originates from the presence of the relay. The authors of [33] propose an analytical expression for the received molecules for a single-input multiple-output (SIMO) topology, based on the original SISO response. However, the proposed expressions and approximations are heavily affected by the shadowing effect. Since τ is strictly smaller than T_s, consequently being a rather short time, the equations derived in [35] hold for our scheme reasonably. Based on these expressions, the closest point of the relay to the receiver is considered to be the "virtual" release point, whose distance is included in the $f(t)$ function (d_3). The expression for calculating the number of molecules received from the transmitter during any time interval is given as

$$M^{Rx}_{Tx}(0,t) = N\left(\frac{r_{0_2}}{d_1+d_2}\operatorname{erfc}\left(\frac{d_1+d_2-r_{0_2}}{\sqrt{4Dt}}\right) - f(t)\right), \tag{5}$$

where

$$f(t) = \begin{cases} \frac{r_{0_1}}{d_1}\operatorname{erfc}\left(\frac{d_1-r_{0_1}}{\sqrt{4Dt}}\right) * \frac{r_{0_2}}{d_3}\operatorname{erfc}\left(\frac{d_3-r_{0_2}}{\sqrt{4Dt}}\right), & 0 < t \le \tau, \\ \frac{r_{0_1}}{d_1}\operatorname{erfc}\left(\frac{d_1-r_{0_1}}{\sqrt{4D\tau}}\right) * \frac{r_{0_2}}{d_3}\operatorname{erfc}\left(\frac{d_3-r_{0_2}}{\sqrt{4Dt}}\right), & \text{otherwise.} \end{cases}$$

For instance, considering any time interval after the first symbol duration, the number of molecules received is calculated as

$$M^{Rx}_{Tx}(T_s,t) = N\left(\frac{r_{0_2}}{d_1+d_2}\operatorname{erfc}\left(\frac{d_1+d_2-r_{0_2}}{\sqrt{4Dt}}\right) - \frac{r_{0_1}}{d_1}\operatorname{erfc}\left(\frac{d_1-r_{0_1}}{\sqrt{4D\tau}}\right) * \frac{r_{0_2}}{d_3}\operatorname{erfc}\left(\frac{d_3-r_{0_2}}{\sqrt{4Dt}}\right)\right), \tag{6}$$

for $t > T_s$.

The corresponding CFAM and hitting rate of molecules curves are shown in Figs. 5 and 6, respectively. Although there is a distinguishable offset between the curves, the preceding approximations fit sufficiently good with the simulation results.

3.2. SID optimization function

The next step in our analysis is obtaining the SID function. According to [34], SID is calculated as

$$SID = h[1] - \sum_{n=2}^{L} h[n], \tag{7}$$

where $h[n]$ is the channel tap for the nth symbol duration and L is the channel memory. The computation of the first channel tap for the considered scenario is given as

$$h_\tau[1] = \frac{M^{Rx}_{Rel}(\tau,T_s) + M^{Rx}_{Tx}(0,T_s)}{N + M^{Rel}_{Tx}(\tau)}. \tag{8}$$

Table 1
System parameters.

r_{0_1}	1 μm
r_{0_2}	4.5 μm
d_1	3 μm
d_2	7 μm
T_s	0.35 s
D	79.4 μm^2/s
τ	0.095 s

The other channel taps are obtained in a similar manner. For calculating the channel taps, the overall number of transmitted molecules is considered in order to fairly evaluate this scheme. When $L \rightarrow \infty$, SID can be rewritten as

$$\begin{aligned} SID(\tau) &= h_\tau[1] - \sum_{n=2}^{\infty} h_\tau[n] \\ &= 2h_\tau[1] - \frac{M_{Rel}^{Rx}(T_s,\infty) + M_{Tx}^{Rx}(T_s,\infty)}{N + M_{Tx}^{Rel}(\tau)} \end{aligned} \tag{9}$$

The above SID function is the objective function, which needs to be maximized to obtain the optimal τ value. The τ value for which SID reaches its maximum value is found by simulations. The following section summarizes the obtained results and points out the advantages of this scheme compared to a simple MCvD scenario.

4. Simulation results

The validation of the model is done by comparing the results obtained from the analytical SID expression with the ones acquired from computer simulations. The analytical model considers infinite channel memory, whereas the simulations are performed for $L = 50$, which is a quite accurate representation of the infinite MCvD channel. The following results correspond to the evaluation of the optimal relaying scheme for the parameters listed in Table 1.

Firstly, the two curves shown in Fig. 7 are the analytical and simulation results of the computation of the SID function. Although there is a difference between the two curves, their maximum values are achieved for the same value of $\tau = 0.11$ s. The reason behind the difference between these curves might come as a result of the slight separation shown in Fig. 5. Apart from that, the minimum BER value is also obtained for the same τ value, as shown in Fig. 8. This curve is obtained from the simulation results, for a fixed transmitted number of molecules, $M_{Tx} = 10^6$. As can be seen, the SID-simulation curve and the BER curve are almost mirroring each other, which once again demonstrates that SID function maximization corresponds to the BER function minimization.

The overall BER performance of this scheme is shown in Fig. 9. First of all, the improvement that the optimal relaying scheme provides compared to the conventional SISO setting is clear. For any τ value around the optimized one, the achieved BER values are lower compared to the SISO case. Additionally, the optimized value gives the best BER performance amongst them. It should be mentioned that, when plotting these curves, we both count the molecules transmitted from the transmitter and the relay, to make the comparisons with the SISO case fair. The T_s value is also an important one in order to provide significant improvement of the received signal.

5. Conclusion

In this work, a novel optimal relaying MCvD scheme has been proposed in order to enhance the overall performance of MC systems. A relay has been placed between the transmitter and the receiver with the purpose of collecting LoS molecules until time τ. Thus, the collected molecules are emitted towards the receiver with some delay. The signal strength at the receiver side is significantly boosted, improving the error rates considerably. The delay parameter is crucial, as it leads to a trade-off between signal improvement and ISI level. In order to find the best τ value, an optimization problem based on the SID function has been proposed. An analytical model for the optimal relaying has been

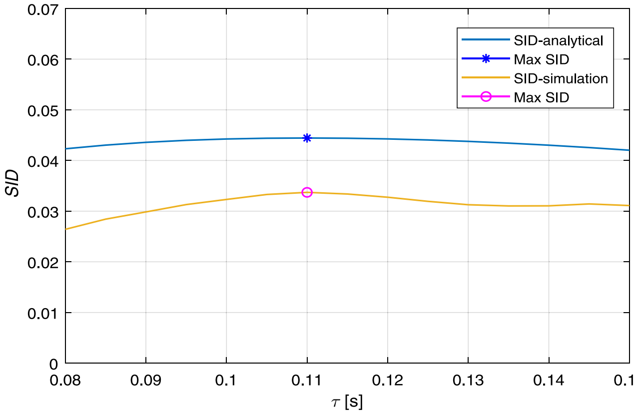

Fig. 7. SID curves obtained from the analytical model and computer simulations, with both maximum values are reached for $\tau = 0.11$ s.

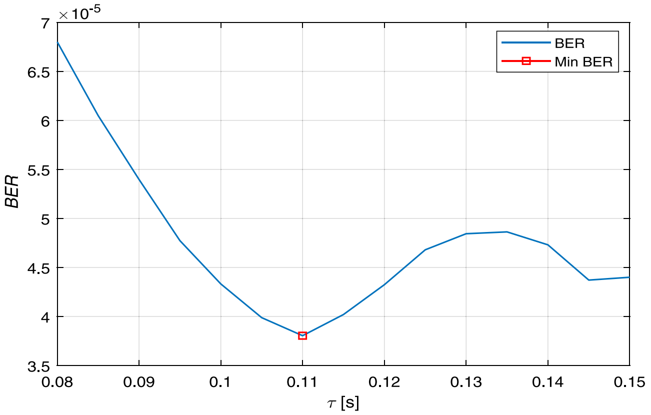

Fig. 8. BER curve obtained for $M_{Tx} = 10^6$ emitted molecules for the optimal relaying scheme with its minimum value at $\tau = 0.11$ s.

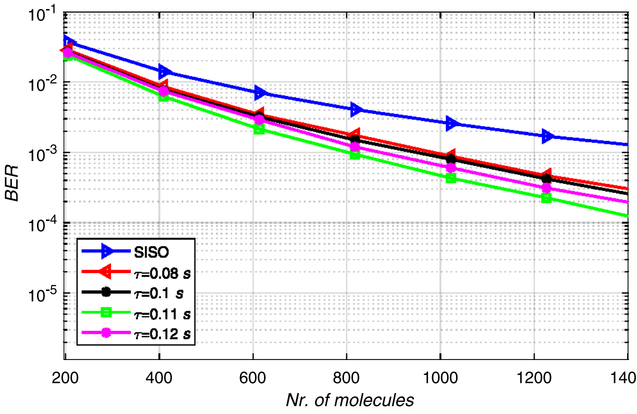

Fig. 9. Comparison of BER between the optimal relaying scheme with different τ values and the conventional SISO setting.

introduced, in order to optimize the SID function. Comparisons between the proposed model and simulation results have been drawn, as well as BER analysis for the proposed scheme. Lastly, the improvement in BER values as a result of this scheme is observed.

As the next step, the optimal relaying scheme can be also introduced to more complex scenarios, such as MIMO setting. Moreover, as this study considers that the location of the nanomachines is fixed, later works may consider the mobility effect and possible solutions for the case when these positions are not fixed. Additional future work might include amplification of the fraction of the molecules absorbed by the relay in order to further improve the overall performance. Optimization of other parameters, such as relay positioning might be jointly studied with τ optimization as well.

CRediT authorship contribution statement

Joana Angjo: Software, Validation, Formal analysis, Conceptualization, Writing – original draft. **Ali E. Pusane:** Conceptualization, Methodology, Supervision. **H. Birkan Yilmaz:** Conceptualization, Writing – review & editing. **Ertugrul Basar:** Conceptualization, Supervision, Writing – review & editing. **Tuna Tugcu:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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