Relay Analysis in Molecular Communications with Time-Dependent Concentration

Xiayang Wang, Matthew D. Higgins, *Member, IEEE,* and Mark S. Leeson, *Senior Member, IEEE*

***Abstract*—Molecular Communications (MC) is a promising paradigm which enables nano-machines to communicate with each other. Due to the severe attenuation of molecule concentrations, there tends to be more errors when the receiver becomes farther from the transmitter. To solve this problem, relaying schemes need to be implemented to achieve reliable communications. In this paper, time-dependent molecular concentrations are utilised as the information carrier, which will be influenced by the noise and channel memory. The emission process is also considered. The relay node (RN) can decode messages, and forward them by sending either the same or a different kind of molecules as the transmitter. The performance is evaluated by deriving theoretical expressions as well as through simulations. Results show that the relaying scheme will bring significant benefits to the communication reliability.**

***Index Terms*—Molecular Communications, Decode-and-Forward Relaying Scheme, Bit Error Rate.**

I. Introduction

Molecular Communications (MC) is an emerging technology that utilises molecules to accomplish the information exchange between nano-machines. To evaluate the MC system reliability, information theoretical approaches have been well developed to obtain the Bit Error Rate (BER) [1]–[3], where also, intuitively, it is observed that the BER increases with the rising distance due to the attenuation of the molecules concentration around the receiver (Rx). Thus, reliable communications still remains a key challenge over longer distance.

The first attempt to solve this problem was shown in [4], and further expanded to investigate the performance improvement of Decode-and-Forward (DF) relaying schemes in [5], [6] and Sense-and-Forward (SF) relaying schemes in [7], [8]. However, these schemes were implemented in an MC system with steady-state concentrations. For each symbol transmitted, the Tx had to keep emitting molecules continuously and the theoretical period must be infinite. Consequently, this is undesirable, as not only is the transmission rate lowered, but the idea of a continuous, infinitely-lasting emission, raises practical concerns. Conversely, the only publication on relay systems with the time-dependent concentrations can be found in [9]. However, the transmission model needs re-enhancing by considering the emission process and clarifying the noise influence. A decoding method to mitigate the Inter-Symbol Interference (ISI) can also be utilised.

The authors are with the School of Engineering, University of Warwick, Coventry, CV4 7AL, UK.
E-mail: {xiayang.wang;m.higgins;mark.leeson;}@warwick.ac.uk
Manuscript version: 11th Sept. 2015

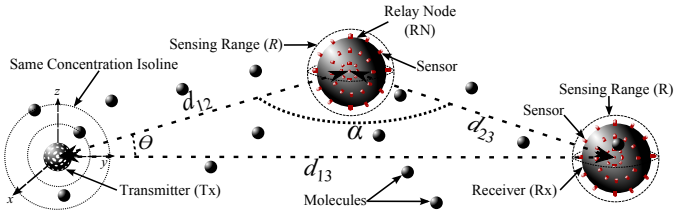

Fig. 1. The structure the relay MC system.

In this letter, following contributions are presented. Firstly, when implementing relaying schemes, the transmission model is enhanced. The molecules concentrations, encoded with messages, are regarded to change over time and are influenced by both noise and channel memory. Meanwhile, for the first time, the emission duration is considered. Secondly, when the Rx determines transmitted symbols, the ISI is mitigated by taking remaining concentrations of previous symbols into consideration. Based on the Mean Square Error (MSE) obtained, the Rx makes better decisions. Thirdly, it is the first research to investigate the impact of positions of the RN on relay systems performance. Optimal positions are obtained in different cases.

The remainder of this paper is organized as follows. In Section II, the enhanced transmission model is introduced. The system performance is studied in Section III. Simulation description and numerical results are provided in Section IV. Finally in Section V, the paper is concluded.

II. The Diffusive Molecules Transmission Model

In the MC system, the transmitter nano-machine (Tx) encodes binary messages into molecular concentrations. To transmit bit '1', the Tx releases certain amount of molecules; to transmit bit '0', the Tx releases nothing. The DF relay node (RN) senses the surrounding concentration, determines the information bits correspondingly, and forwards these bits to the receiver (Rx) at the destination end. In this MC system, the size of the Tx is negligible compared with the relative distance between nano-machines. Similar to previous work [9], [10], the concentration at the RN or Rx can be considered as the concentration at the centre of the sphere. Referring to Fig. 1, the distances between the Tx, RN, and Rx are respectively d_{12}, d_{13} and d_{23}. The angle between d_{12} and d_{13} is represented by θ, and the angle between d_{12} and d_{23} is represented by α.

The emission process is modeled as a rectangular pulse with an emission rate A (in number/μs), emission duration T_e (in μs) and emission period T_{pd} (in μs). $m = A \times T_e$ is denoted as the number of molecules released per pulse. The distance between nano-machines is denoted as d (in μm). Considering

the impulse response, $h(d,t)$, derived by solving Fick's laws of diffusion [11], the concentration per pulse in a 3D environment can be obtained via convolution with regards to time t (in μs):

$$u(d,t) = A \cdot \text{rect}\left(\frac{t - T_e/2}{T_e}\right) * h(d,t) = \begin{cases} \frac{A}{4\pi dD}\text{erfc}(\frac{d}{\sqrt{4tD}}), & t \le T_e \\ \frac{A}{4\pi dD}[\text{erfc}(\frac{d}{\sqrt{4tD}}) - \text{erfc}(\frac{d}{\sqrt{4(t-T_e)D}})], & t > T_e \end{cases} \quad (1)$$

where D is the diffusion coefficient (in $\mu\text{m}^2\,\mu\text{s}^{-1}$). The sampling time of the Rx, t_s, is the peak time of the theoretical concentration $u(d,t)$. t_s can be derived by solving [12]:

$$d^2 = \frac{6D}{T_e} \cdot (t_s - T_e) \cdot t_s \cdot \ln\left(\frac{t_s}{t_s - T_e}\right). \quad (2)$$

The concentration is also influenced by the ISI and the noise $n(t)$. The ISI length, I, represents the 'affecting' time of newly emitted molecules. Specifically, the channel with finite I is called the Memory Limited Channel [13]. It is further denoted that the set $\{a_{k-i}, i = 0,1,2,...,I\}$ is the binary message sequence within the ISI length, where the element a_{k-i} represents the binary value of each symbol, and k represents the k^{th} symbol from the beginning of transmission. Thus, the sampled concentration is:

$$r(d,t) = u(d,t) + n(t) = \sum_{i=0}^{I} a_{k-i} u(d, t = t_s + iT_{pd}) + n(t) = \sum_{i=0}^{I} a_{k-i} u_i + n(t), \quad (3)$$

where $n(t)$ obeys normal distribution, given as [2], [11], [14]:

$$n(t) \sim \mathcal{N}\{0, 3r(d,t)/(4\pi R^3)\}. \quad (4)$$

where R is the radius of the RN and Rx.

III. Relay Channel Analysis

Information bits are decoded by calculating the Mean Square Error (MSE) [14]. If r represents the sampled concentration, the judgment condition L is expressed as:

$$L = \text{MSE}_1 - \text{MSE}_0 = [r - l_1]^2 - [r - l_0]^2, \quad (5)$$

where l_1 and l_0 are pre-designed criteria for the RN (or Rx) to determine the message bits. The design of l_1 and l_0 has considered the influence of previous symbols, which is a method to mitigate the ISI. Specific values for l_1 and l_0 will be introduced later. When $L \ge 0$, '0' is decided; and otherwise, '1' is decided. When forwarding information, the RN can emit the same kind of molecules as the TX does, denoted as 'Relay-1', or emit a different kind of molecules, denoted as 'Relay-2'.

With d_{12}, d_{23} pre-known, the sampling time of the RN and Rx, respectively denoted as $t_s^{(12)}$ and $t_s^{(23)}$, can be derived via (2). Within the i^{th} period, where $i = 0,1,2,...,I$, RN-sampled noiseless concentrations of molecules from the Tx is denoted as $u_i^{(12)} = u(d = d_{12}, t = t_s^{(12)} + i \times T_{pd})$, and Rx-sampled noiseless concentrations of molecules from the RN and Tx are respectively denoted as $u_i^{(23)} = u(d = d_{23}, t = t_s^{(23)} + i \times T_{pd})$ and $u_i^{(13)} = u(d = d_{13}, t = t_s^{(12)} + t_s^{(23)} + t_{proc} + i \times T_{pd})$, where t_{proc} is the time for the RN to process the relay function. Herein, it is assumed that $t_{proc} = 0$.

A. BER for Relay-2

First, the transmission from the Tx to RN is considered. Molecules from the RN will not affect the distribution of molecules from the Tx. Thus, the sensed concentration of the RN and the pre-designed criteria of the RN are respectively:

$$r_{RN}^{(2)} = \sum_{i=0}^{I} u_i^{(12)} a_{k-i} + n(t), \quad (6)$$

$$l_{RN1}^{(2)} = \sum_{i=1}^{I} u_i^{(12)} \hat{a}_{k-i} + u_0^{(12)}, \quad (7)$$

$$l_{RN0}^{(2)} = \sum_{i=1}^{I} u_i^{(12)} \hat{a}_{k-i}. \quad (8)$$

where $\{\hat{a}_{k-i}, i = 1,2,...,I\}$ is previously decoded symbols, and the superscript '(2)' represents 'Relay-2'. If errors are assumed to occur independently, then $\hat{a}_{k-i} = a_{k-i}$ for $i = 1,2,...,I$. By substituting (6) through (8) into (5), the judging condition for the RN can be obtained as:

$$L_{RN}^{(2)} = -2u_0^{(12)}[n(t) + (a_k - \frac{1}{2})u_0^{(12)}]. \quad (9)$$

Errors occur when the Tx emits '0' but '1' is received (named as a_k=0 but $\hat{a}_k$=1), or when '1' is transmitted but '0' is received (named as a_k=1 but $\hat{a}_k$=0). At the RN, when a_k=0 but $\hat{a}_k$=1, the judging condition should satisfy:

$$L_{RN}^{(2)} < 0 \Leftrightarrow n(t) > \frac{u_0^{(12)}}{2}. \quad (10)$$

Due to the existence of the ISI, different permutations of values of previous symbols within the ISI length, $\{a_{k-i}, i = 1,2,...,I\}$, will result in different error patterns. Each error pattern will be corresponding to a certain permutation of values of $\{a_{k-i}, i = 1,2,...,I\}$. With the ISI length equal to I, there will be 2^I error patterns. Thus, for a certain error pattern 'j', where $j = 1,2,..,2^I$, the error probability can be derived by calculating the probability of (10). Given $n(t)$ expressed in (4), the BER can be obtained as:

$$P_{RN0j}^{(2)} = \int_{\frac{u_0^{(12)}}{2}}^{\infty} \frac{1}{\sqrt{2\pi}} \frac{1}{\sigma_{RN0j}^{(2)}} \exp[-\frac{1}{2}(\frac{v}{\sigma_{RN0j}^{(2)}})^2]dv = 1 - \Phi(\frac{u_0^{(12)}}{2\sigma_{RN0j}^{(2)}}), \quad (11)$$

where $\sigma_{RN0j}^{(2)} = \sqrt{\frac{3}{4\pi R^3}\sum_{i=1}^{I} a_{k-i} u_i^{(12)}}$, and $\Phi(\cdot)$ is the cumulative distribution function of standard normal distribution.

When a_k=1 but $\hat{a}_k$=0, the judging condition should satisfy:

$$L_{RN}^{(2)} \ge 0 \Leftrightarrow n(t) \le -\frac{u_0^{(12)}}{2}. \quad (12)$$

Thus, similarly, the BER for error pattern 'j' is derived as:

$$P_{RN1j}^{(2)} = 1 - \Phi(\frac{u_0^{(12)}}{2\sigma_{RN1j}^{(2)}}), \quad (13)$$

where $\sigma^{(2)}_{RN1j} = \sqrt{\frac{3}{4\pi R^3}(\sum_{i=1}^{I} a_{k-i}u_i^{(12)} + u_0^{(12)})}$.

The probability of '1' or '0' transmitted is assumed to be $\frac{1}{2}$. Thus, the BER at the RN can be derived as:

$$P^{(2)}_{RN} = \frac{1}{2^{I+1}}\sum_{j=1}^{2^I}[2 - \Phi(\frac{u_0^{(12)}}{2\sigma^{(2)}_{RN0j}}) - \Phi(\frac{u_0^{(12)}}{2\sigma^{(2)}_{RN1j}})]. \quad (14)$$

Second, the transmission process from the RN to Rx is considered, which can be viewed as the same process from Tx to RN but with different parameters. Thus, the BER from the RN to Rx can be derived as:

$$P^{(2)}_{Rx} = \frac{1}{2^{I+1}}\sum_{j=1}^{2^I}[2 - \Phi(\frac{u_0^{(23)}}{2\sigma^{(2)}_{Rx0j}}) - \Phi(\frac{u_0^{(23)}}{2\sigma^{(2)}_{Rx1j}})], \quad (15)$$

where $\sigma^{(2)}_{Rx0j} = \sqrt{\frac{3}{4\pi R^3}\sum_{i=1}^{I} a_{k-i}u_i^{(23)}}$, and $\sigma^{(2)}_{Rx1j} = \sqrt{\frac{3}{4\pi R^3}(\sum_{i=1}^{I} a_{k-i}u_i^{(23)} + u_0^{(23)})}$.

Throughout the system, an error occurs if the detection is erroneous in either the first or the second transmission process. Given (14) and (15), the overall error probability is given as:

$$P^{(2)} = (1 - P^{(2)}_{RN})P^{(2)}_{Rx} + P^{(2)}_{RN}(1 - P^{(2)}_{Rx}). \quad (16)$$

B. BER for Relay-1

First, the transmission from the Tx to RN is considered. Molecules emitted by the RN will also form the concentration around itself. At the RN sampling time, the propagation time for molecules from the RN is $t = i * T_p$, where i presents the i^{th} period after the mission. Thus, the concentration of molecules from the RN within the i^{th} period can be viewed as the average concentration over the sphere, that is:

$$\bar{u}_i = \frac{3}{4\pi R^3}\int_0^R u(d = w, t = iT_{pd}) \cdot 4\pi w^2 dw. \quad (17)$$

Specifically, $\bar{u}_0 = 0$. Thus, for the RN, the sensed concentration and the pre-designed criteria are respectively given as:

$$r^{(1)}_{RN} = \sum_{i=0}^{I} u_i^{(12)}a_{k-i} + \sum_{i=1}^{I}\bar{u}_i a_{k-i} + n(t), \quad (18)$$

$$l^{(1)}_{RN1} = \sum_{i=1}^{I} u_i^{(12)}\hat{a}_{k-i} + \sum_{i=1}^{I}\bar{u}_i\hat{a}_{k-i} + u_0^{(12)}, \quad (19)$$

$$l^{(1)}_{RN0} = \sum_{i=1}^{I} u_i^{(12)}\hat{a}_{k-i} + \sum_{i=1}^{I}\bar{u}_i\hat{a}_{k-i}, \quad (20)$$

where superscript '(1)' denotes 'Relay-1'. Substituting (18) through (20) into (5), the judging condition of the RN is:

$$L^{(1)}_{RN} = -2u_0^{(12)}[n(t) + (a_k - \frac{1}{2})u_0^{(12)})]. \quad (21)$$

Thus, similar to the situation shown in III-A, the BER from the Tx to RN can be derived as:

$$P^{(1)}_{RN} = \frac{1}{2^{I+1}}\sum_{j=1}^{2^I}[2 - \Phi(\frac{u_0^{(12)}}{2\sigma^{(1)}_{RN0j}}) - \Phi(\frac{u_0^{(12)}}{2\sigma^{(1)}_{RN1j}})], \quad (22)$$

where $\sigma^{(1)}_{RN0j} = \sqrt{\sum_{i=1}^{I} u_i^{(12)}a_{k-i} + \sum_{i=1}^{I}\bar{u}_i a_{k-i}}$,$\sigma^{(1)}_{RN1j} = \sqrt{\sum_{i=1}^{I} u_i^{(12)}a_{k-i} + u_0^{(12)} + \sum_{i=1}^{I}\bar{u}_i a_{k-i}}$.

TABLE I
SIMULATION PARAMETERS

1.	The radius of the Rx and RN	R	$0.5\,\mu\text{m}$
2.	The distance between Tx and Rx	d_{13}	$5\,\mu\text{m}$
3.	The diffusion coefficient	D	$1 \times 10^{-3}\mu\text{m}^2\,\mu\text{s}^{-1}$
4.	The emission duration	T_e	$1000\,\mu\text{s}$
5.	The pulse period	T_{pd}	$5000\,\mu\text{s}$
6.	The number of molecules per pulse	m	2×10^5
7.	The ISI length	I	10

Second, the transmission from the RN to Rx is considered. Molecules from both the Tx and RN will form concentration distribution around the Rx, Thus, similar to the explanation in III-A, the sensed concentration and the pre-designed criteria of the Rx will be respectively expressed as:

$$r^{(1)}_{Rx} = \sum_{i=0}^{I} a_{k-i} \times (u_i^{(13)} + u_i^{(23)}) + n(t), \quad (23)$$

$$l^{(1)}_{Rx1} = \sum_{i=1}^{I} \hat{a}_{k-i} \times (u_i^{(13)} + u_i^{(23)}) + u_0^{(13)} + u_0^{(23)}, \quad (24)$$

$$l^{(1)}_{Rx0} = \sum_{i=1}^{I} \hat{a}_{k-i} \times (u_i^{(13)} + u_i^{(23)}). \quad (25)$$

By substituting (23) through (25) into (5), the judging condition of the Rx can be re-written as:

$$L^{(1)}_{Rx} = -2(u_0^{(13)} + u_0^{(23)})[n(t) + (a_k - \frac{1}{2})(u_0^{(13)} + u_0^{(23)})]. \quad (26)$$

Thus, similar to the situation shown in III-A, the error probability from the RN to Rx can be derived as:

$$P^{(1)}_{Rx} = \frac{1}{2^{I+1}}\sum_{j=1}^{2^I}[2 - \Phi(\frac{u_0^{(13)} + u_0^{(23)}}{2\sigma^{(1)}_{Rx0j}}) - \Phi(\frac{u_0^{(13)} + u_0^{(23)}}{2\sigma^{(1)}_{Rx1j}})], \quad (27)$$

where $\sigma^{(1)}_{Rx0j} = \sqrt{\frac{3}{4\pi R^3}\sum_{i=1}^{I} a_{k-i} \times (u_i^{(13)} + u_i^{(23)})}$, and $\sigma^{(1)}_{Rx1j} = \sqrt{\frac{3}{4\pi R^3}[\sum_{i=1}^{I} a_{k-i} \times (u_i^{(13)} + u_i^{(23)}) + u_0^{(13)} + u_0^{(23)}]}$. Thus, the overall BER for 'Relay-1' can be calculated by:

$$P^{(1)} = (1 - P^{(1)}_{RN})P^{(1)}_{Rx} + P^{(1)}_{RN}(1 - P^{(1)}_{Rx}). \quad (28)$$

IV. NUMERICAL RESULTS

In this section, both theoretical derived and simulated results are presented. During simulations, molecular concentrations, encoded with messages, are simulated to change with time and distance in the environment. The RN and Rx sense the concentrations at the pre-designed sampling time, and determine messages correspondingly. The channel herein is assumed to be Memory Limited Channel with $I = 10$. The times of the simulation trials are based on theoretical results. For example, if the theoretical BER is 10^{-7}, then 10^{11} successive bits are correspondingly simulated. All results are presented with a common set of parameters assigned in Table I. These values agree with the research in [10], [12], [14].

Fig. 2 shows the minimum error probability that can be achieved for each angle θ when the distance between the

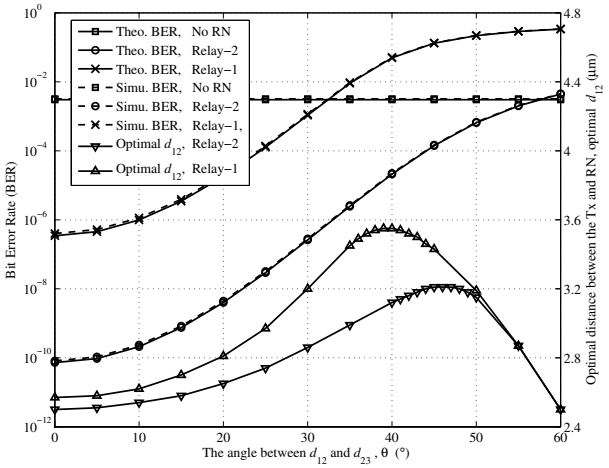

Fig. 2. The optimal BER and corresponding d_{12} for different angle θ. 'Theo.' represents theoretical results, 'Simu.' represents simulated results, and 'No RN' represents the BER without any relay node.

Tx and RN is optimised. At each angle, the values of BER are obtained versus different values of d_{12} for both 'Relay-1' and 'Relay-2', and then the optimal distance is selected with the BER minimized for this given angle. It is clearly illustrated that the quality of the communication between the Tx and Rx can be significantly improved by deploying a relay node. Furthermore, performance of Relay-2 is superior than that of Relay-1. The main reason is that for Relay-2, the self-interference is eliminated by using different kinds of molecules, which help the RN and Rx to make better decisions when determining transmitted symbols.

Another intuitive feature is that with θ rising, the relay system tends to suffer from more errors. This is mainly due to the increase of relative distances from the RN to the Tx and Rx, respectively d_{12} and d_{23}. With θ getting larger, it is easy to prove the RN accordingly becomes farther away from the Tx and Rx, leading to a higher error rate. Especially, when θ is quite large (about 30° for Relay-1, and about 60° for Relay-2), the relay system may not bring in any benefit.

Fig. 2 also presents optimal locations of the RN at different angles. The optimal d_{12} for both 'Relay-2' and 'Relay-1' first increases and then starts to decrease. When θ is small, the RN should be placed around the point where $d_{12} \approx d_{23}$; when θ increases to around 40°, the RN should be placed around the position where $\alpha \approx 90^\circ$. Moreover, it is also shown that the optimal d_{12} for Relay-1 is larger than that for 'Relay-2'. If d_{12}=d_{23}, it can be deduced from (17) through (27) that $P_{RN}^{(1)} < P_{Rx}^{(1)}$ for 'Relay-1'; while given (11) through (15), $P_{RN}^{(2)} = P_{Rx}^{(2)}$ for 'Relay-2'. Thus, the optimal position of the RN for 'Relay-1' should be closer to the Rx, which makes the optimal d_{12} of 'Relay-1' is larger than that of 'Relay-2'.

It should be also noticed that simulated results show agreement with theoretical values, even though the simulated BER appears slightly higher due to the *error burst*. When deriving the theoretical BER, errors are assumed to occur independently, which means previously decoded bits will not affect the determination of the current bit. In other words, when decoding the bit a_k, it is assumed $\hat{a}_{k-i} = a_{k-i}$ for $i = 1, 2, ..., I$. However, when carrying out simulations, this assumption no longer holds. One wrongly decoded bit will affect the decoding of next several symbols. Errors therefore occur in succession, which is called the *error burst*. Thus, the existence of the *error burst* leads to a higher BER for simulations.

V. Conclusions

In this paper, a relaying scheme is introduced in a diffusive MC system based on the enhanced transmission model. The impact of emission process has been considered and the concentration changes over time and is influenced by the channel noise and memory. Both theoretical derivations and simulations are provided to show the BER significant decrease due to the implementation of the relay node. Results also present that if molecules from the Tx and RN are of different species, the relay system will provide a better performance. It can be further deduced that when t_{proc} is not negligible, the superiority of the relay system will be more distinct. Moreover, the decoding method utilised in this paper can mitigate the ISI as remaining concentrations of previous symbols within the ISI length have been considered when decoding messages.

References

[1] K. V. Srinivas, A. W. Eckford, and R. S. Adve, "Molecular Communication in Fluid Media: The Additive Inverse Gaussian Noise Channel", in *IEEE Trans. Inf. Theory*, Jul. 2012, pp. 4678-4692.

[2] Y. Chahibi, and I. F. Akyildiz, "Molecular Communication Noise and Capacity Analysis for Particulate Drug Delivery Systems", in *IEEE Trans. on Commun.*, Nov. 2014, pp. 3891-3903.

[3] T. Nakano, Y. Okaie, and J.-Q. Liu, "Channel Model and Capacity Analysis of Molecular Communication with Brownian Motion", in *IEEE Commun. Lett.*, Jun. 2012, pp. 797-900.

[4] B. Atakan and O. B. Akan, "On Molecular Multiple-Access, Broadcast, and Relay Channels in Nanonetworks", in *Proc. 3rd Int. Conf. Bio-Inspired Models Netw. Inform. Comput. Syst.*, Nov. 2008, pp. 16:1-16:8.

[5] A. Einolghozati, M. Sardari, and F. Fekri, "Relaying in diffusion-based molecular communication", in *IEEE Int. Symp. on Inform. Theory Proc. (ISIT)*, Jul. 2013, pp. 1844-1848.

[6] A. Einolghozati, M. Sardari, and F. Fekri, "Decode and forward relaying in diffusion-based molecular communication between two populations of biological agents", in *IEEE Int. Conf. on Commun. (ICC)*, Jun. 2014, pp. 3975-3980.

[7] T. Nakano, and J.-Q. Liu, "Design and Analysis of Molecular Relay Channels: An Information Theoretic Approach", in *IEEE Trans. on NanoBioscience*, Sept. 2010, pp. 213-221.

[8] T. Nakano, and J. Shuai, "Repeater design and modeling for molecular communication networks", in *IEEE Conf. on Comput. Commun. Workshops*, Apr. 2011, pp. 501-506.

[9] A. Ahmadzadeh, A. Noel, and R. Schober, "Analysis and design of two-hop diffusion-based molecular communication networks", in *IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2014, pp. 2820-2825.

[10] H. ShahMohammadian, G. G. Messier, and S. Magierowski, "Optimum receiver for molecule shift keying modulation in diffusion-based molecular communication channels", in *Nano Commun. Netw.*, Sept. 2012, pp. 183-195.

[11] I. Llatser, A. Cabellos-Aparicio, M. Pierobon, and E. Alarcon, "Detection Techniques for Diffusion-based Molecular Communication", in *IEEE J. Sel. Areas Commun.*, Dec. 2013, pp. 726-734.

[12] X. Wang, M. D. Higgins, and M. S. Leeson, "Distance Estimation Schemes for Diffusion Based Molecular Communication Systems", in *IEEE Commun. Lett.*, Mar. 2015, pp. 399-402.

[13] G. Aminian, H. Arjmandi, A. Gohari, M. N. Kenari, and U. Mitra, "Capacity of LTI-Poisson Channel for Diffusion based Molecular Communication", in *IEEE Int. Conf. on Commun. (ICC)*, Jun. 2015.

[14] D. Kilinc, and O. B. Akan, "Receiver Design for Molecular Communication", in *IEEE J. Sel. Areas Commun.*, Dec. 2013, pp. 705-714.