ISSN 2349-7815

International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE)
Vol. 6, Issue 1, pp: (1-13), Month: January - March 2019, Available at: www.paperpublications.org

An Analysis of Molecular Communication with Different Error Correcting Codes

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Abstract: **The molecular communication presents a relatively newer concept in field of communication, this involves the use of molecules to encode and transmit information among nanoscale devices (nanomachines) to form nano-communication network. The close bonding of this field with biology will eventually open up the new possibilities in the area of bio-engineering. However there are many types of molecular communication are proposed, in this paper we focused on diffusion-based molecular communications. In such type of systems the carrier molecule propagates through the channel by obeying diffusion process. Because of randomness involved in diffusion process the system suffer from molecule crossovers, i.e., the molecules received at different order than the order they transmitted, which eventually leads to higher symbol error rate. In this paper, we presented a study on the impact of different error correcting codes on molecular communication based on the simulation model. The presented analysis can help in better understanding of the behavior of such communication systems as well as can helps in the future development of different applications based on such models.**

Keywords: **Molecular communication, communication via diffusion, hitting time distribution, error correcting codes.**

I. INTRODUCTION

The recent development in nanotechnology, enables the development of nanomachines which are the machines designed at the scales between $0.1\mu m$ to $100\mu m$. These machines have a lots of applicability in the biological systems. Because of its scale the single nanomachine has very limited computational capabilities, to overcome such limitations a group of nanomachines are configured to perform the specific task, which can only be done after establishing proper communications between those nanomachines. Communications between nanomachines is a challenging task-the traditional method of communication through electromagnetic waves is pretty much impractical and is afflicted by significant attenuation in liquid channel conditions [9]. Molecular communications, using molecules as an information carrier, has been regarded as a promising solution [8]. Unlike traditional technologies, molecular communication works on a completely different environment, which needs innovative solutions, including the recognition of existing molecular communication mechanisms, the development of the fundamentals of molecular information theory, and the development of communication protocols for nanomachines. Currently, molecular communications has been studied by many researchers from diverse disciplines, including nanotechnology, biotechnology, and communication theory [9]. Research initiatives on analyzing and finding possible details on channel capacity, of molecular communications according to different system designs have already been conducted in [9, 10, 11]. The present abilities of molecular communication are quite limited. In fact, the first ever molecular communication system with the capacity of sending a text has a volume of roughly $100cm^3$.Comparable to spectral efficiency, the operational system has a chemical efficiency of 0.3 bits/s/chemical substance over a free-space distance of a few meters [1]. To get a significant impact, these systems will have to shrink and boost their data speeds by factor of two. The enhance of data rate may be accomplished by: developing specially designed modulation and error correcting coding techniques [7], and increasing the amount of orthogonal chemical substances [12] or carrier frequencies [16] used to transport information. Drawing on the existing connection with designing radio-wave communication systems, in molecular communication also the significant improvement in data rate could be exhibited with signal processing and error correcting codes.

In this paper we analyzed the impact of the different parameters such as length of the channel, radius of the receiver node and different error correcting codes on the molecular communication performance using the mathematical modeling.

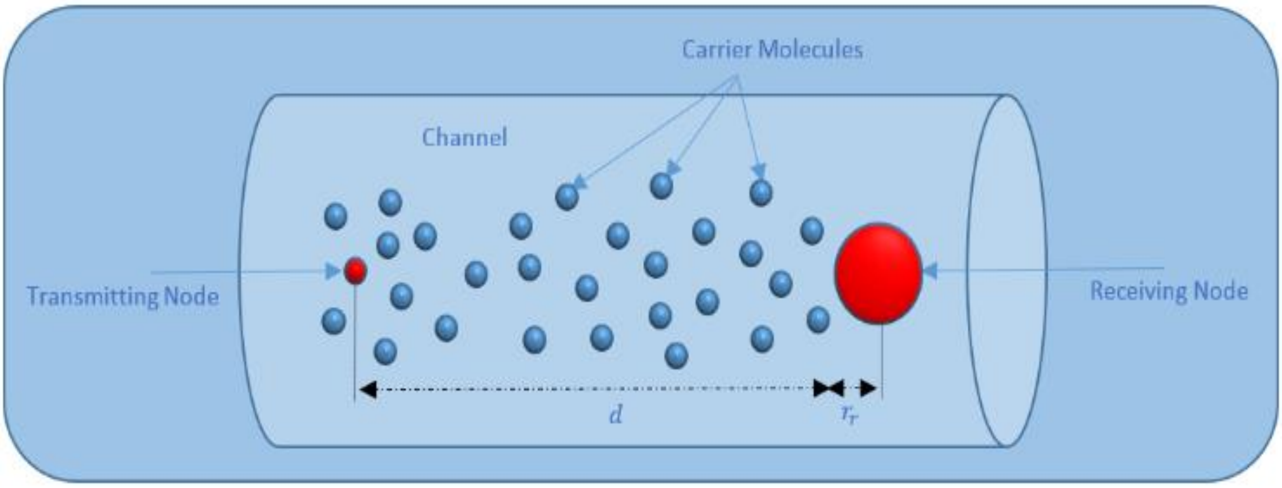


Figure 1: Illustrative diagram of Molecular Communication via Diffusation

II. LITERATURE REVIEW

A number of literatures are already published addressing the problems faced with molecular communication and proposals to overcome these problems. In this section we presented some of those most related to this work. Among the early surveys that regarded the idea of nanonetworks was [23], where both Molecular and electromagnetic-based communication using novel substances like carbon nanotubes are considered. Long-range Molecular communication propagation schemes had been proposed in [24]. The first study on general microscale Molecular communication was presented in [25]. A more recent survey was presented by Nakano et al. in [26]. In [27], a study of Molecular communication based on microtubules and physical contact was provided, and [28] presented some helpful information about some of the experimental concerns faced with Molecular communication. The authors in [2], [13] studied thoroughly the basic principles of molecular communication via diffusion. In [2], authors explored an innovative energy model to discover how much energy is essential to transmit messenger molecules and [13] introduced concentration-centered and molecular-type-centered modulation techniques. The researchers also compared the achievable data rate, by using a straightforward binary symmetric channel model. In examining their modulation methods, however, [2], [13] did not evidently recommend concrete structures for the messenger molecules. They looked at insulin-based nano networks, but it is usually unclear how these could possibly be employed in practice. In [12], in order to maximize the feasible data rate with considerably less transmit power/energy, authors propose using isomers as messenger molecules. They also proposed a new ratio-based modulation method. From the beginning the error correcting codes development, the error rate performance has been the primary focus, and decent error correcting codes usually necessitate complex decoding. Although some low complexity decoding algorithms, like the syndrome decoding of some linear block codes (e.g., BCH codes) [4], the Viterbi decoding of convolutional codes [4], the iterative decoding of Turbo codes [14], [5] and graph-based codes (e.g., low-density parity-check (LDPC) codes) [17], [18], and the Berlekamp-Massey algorithm [4] and the list decoding [15] of Reed-Solomon codes, have already been developed. The model of Brownian motion with drift to illustrate this physical propagation process of molecules is discribed in [7], [8]. Diverse diffusion-based molecular communication strategies have already been proposed by carrying information on the number, the type, the inter-transmission duration of molecules, and the combinations of the above strategies [6], [20], [21], [22].

III. MOLECULAR COMMUNICATION SYSTEM

In our simulation model we consider a nano-communication system that, for simplicity, is made up of single point transmitter and a single spherical receiver, as illustrated in Fig. 1. The information-encoded molecules are called carrier molecules, and they can propagate through the medium (channel) from transmitter node towards the receiver node using diffusion-based propagation, so the carrier molecules diffuse through the medium (i.e., liquid). In this model we also assumes that no collisions take place among the propagating carrier molecules.

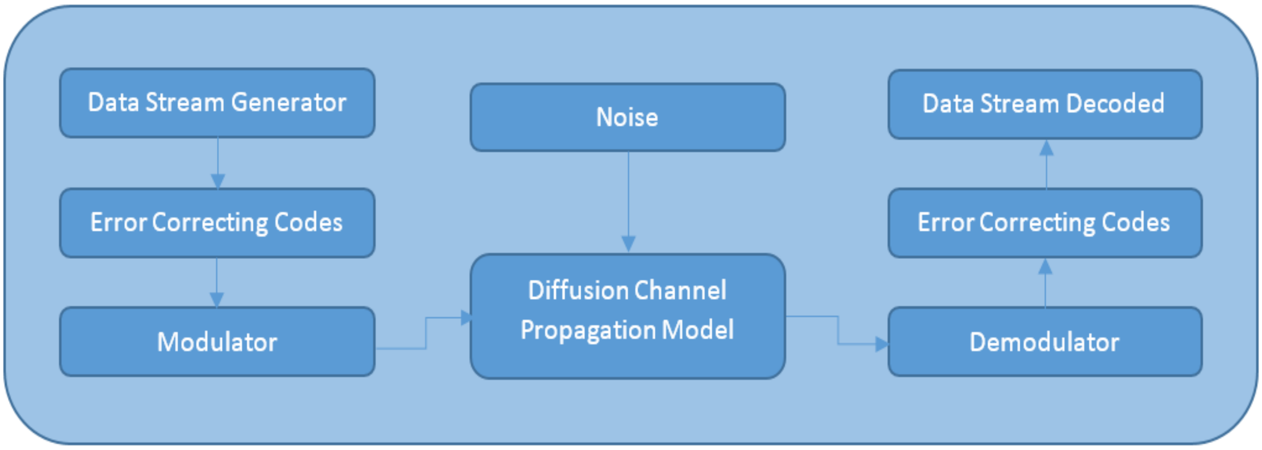


Figure 2: Basic Blocks of the system used for simulation.

3.1. *Hitting Distribution*

In nature, whenever a carrier molecule hits the receiver, the molecule is received and removed from the channel. If the in case the receptors do not remove carrier molecules from the channel, hence, after the hitting molecule cannot move further and constitutes the signal only once. This process is referred to as first passage or the hitting process. So we can call the hitting distribution as the probability of a diffusing carrier molecule to reaching the specific point at specific time. Considering the carrier molecules movement in the channel as the a simple random walk process, a common equation for such probability density function $h(d,t)$,of emitted molecule from a true point source hitting a point in space. In fact, the equation determines the important communication aspects of the channel for a distance d, time t, and diffusivity D. The hitting distribution for 1-D environment is usually given as

$$h^{1D}(d,t) = \frac{d}{\sqrt{4\pi D t^3}} e^{-d^2/4Dt} \tag{1}$$

The first hitting probability in a 1-D environment is inversely proportional to $t^{-\frac{3}{2}}$. In a 3-D environment, the first hitting probability for a point source is

$$h(d,t) = \left(\frac{r_{\mathrm{RN}}}{r_{\mathrm{RN}} + d}\right) \frac{d}{\sqrt{4\pi D t^3}} e^{-d^2/4Dt} \tag{2}$$

Where, r_{RN} is the radius of the receiver node. First hitting probability in a 3-D environment exhibits the same behavior with a normalization factor.

The equation (2) can be used for the estimation of the received molecules at given interval as follows:

$$\Delta M^{Rx}_{t,t+\Delta t} = M^{Tx}_{t_0} \times (h(d,t+\Delta t) - h(d,t)) \tag{3}$$

Where, $\Delta M^{Rx}_{t,t+\Delta t}$ is the number of molecules received in between time t to $t + \Delta t$, and $M^{Tx}_{t_0}$ is the number of molecules transmitted at time t_0.

3.2. *Experimental System Configuration*

As the block diagram in figure 2 shows, the complete system consists of five blocks, which is common for any communication system, however what differs is the technique used to perform the operations stated in the blocks, which depends upon the type of the communication system i.e. RF, Optical, Molecular etc. In other words it can be said that the implementation of each block is completely depends upon the type of the information carriers used for the communication and the property of the channel (medium) through which these information carrier propagate.

Since in this paper we are studying about molecular communication, hence the implementation of these blocks are also specific to molecular communication. The details about the implementation of these blocks are as follows:

3.3. *Modulation*

As in general it is used to represent the method by which information is encoded into the carriers. Since in molecular communication these carriers are molecules a number of techniques have been proposed to encode the information into these molecules, these techniques also shows the analogy with electrical communication systems.

3.4. ***Molecular Concentration Shift Keying (MoCSK):*** as the name suggest the technique switches the concentration of the molecules injected by the transmitter node, depending upon the information is to be transmitted, for example to transmit a bit '1' the transmitter node may inject a specific amount of carrier molecules into the diffusion channel. On the other hand to transmit a bit '0' the transmitting node may stop the injection of molecules in the channel.

This method is similar to the amplitude modulation technique used with electrical communication such as ASK (amplitude shift keying) or in binary form OOK (on off keying). The CSK method used with the molecular communication has two variants named as pulsed CSK and square CSK.

In pulsed CSK the molecules are injected during a small portion of the symbol duration, mostly when signal changes from '0' to '1' state, hence the molecules injected into the channel at the transition event, on the other hand in the square CSK the molecules injected during the whole symbol duration. Here it must be noted that the total number of molecules transmitted for same symbol remains the same in the both techniques, therefore the pulsed CSK looks like an impulse as it injects all the molecules at single event.

The above discussion about the CSK is for binary CSK, where only one bit information is encoded at a time hence only two concentration levels are required. Hoverer, the same concept can be extended for QCSK (quadrature concentration shift keying) and M-CSK (M-ary concentration shift keying), although analyzing the characteristics of the molecular communication these techniques could lead to significant drop in performance.

Molecular Frequency Shift Keying (MoFSK): unlike the concentration shift keying where the molecular injection rate for symbols are kept constant throughout the symbol duration in this technique the molecular emission rate for symbols follows the sinusoidal rate change throughout the symbol duration, however to differentiate between the symbols the frequency of the governing sinusoid is changed for each symbol.

Although this technique seems similar to the FSK used with the electrical communication, the way channel behaves in molecular communication ruins its advantages of orthogonality as it got in electrical communication, which results in inferior performance then CSK.

Molecular Shift Keying (MoSK): this technique utilizes the different types of molecules for different symbols for example in this technique the bit '0' information can be transmitted using $\alpha - D - glucopyranose$, while the bit '1' information could be transmitted using $\beta - D - glucopyranose$.

The application of different molecules reduces the chances of inter symbol interference (ISI) which results in better symbol detection and higher data transfer rates. However to get the full benefits of molecular shift keying the minimization of the false molecular type detection must achieved. Overall we can say that MoSK is capable of providing higher data rate communication by utilizing the orthogonality between the different molecules, however, the reliable and cost effective detection technique is required.

3.5. *Demodulation*

This is a process of recovering the original transmitted symbol from the carrier received. These methods are specific to the modulation technique used the transmitter. In present work we used the following demodulation techniques.

Threshold Detection: this demodulation technique compares the concentration of the received carrier molecules against the predefined threshold value and the received symbol is estimated on the basis of the comparison result. This method is found to be most suitable for CSK as the molecular concentration in this technique are predefines for each symbols.

Synchronous Detection: in this technique the received molecular concentration during the whole symbol duration is stored then the dot product of this stored information with the all possible symbols is performed one by one. Finally the symbol resulted the maximum value for dot product is selected as received symbol. Since this technique relies on the orthogonality of the symbols in the time domain. Hence provide best results for the orthogonal symbols, which in our case is MoFSK. So we use this method to demodulate the MoFSK symbols.

3.6. *Diffusion Channel Propagation Model*

Like any communication system channel modeling is model important aspect to correctly estimate its impact on carriers. In our work we use the same model discussed in section 3 of this paper.

3.7. *Error Correcting Codes*

Since the communication channel may corrupt the information transmitted through it. Hence to maintain the reliable communication through a channel a special type of codes are used which can correct the errors up to certain limit depending upon it configuration. There are many types of error correcting codes has been developed, however in this paper we only the following codes.

- Hamming Codes.
- Cyclic Codes.
- Convolution Codes.

Hamming Codes: It was invented by the Richard Hamming in year 1940, which led to development of the 1-error correcting codes, and further extended to, 1-error correcting and 2-error detecting codes. Hamming Codes are found applications in many fields like telecommunication and computing and are still used extensively. These codes are also utilized with Data compression, puzzle games and Block Turbo Codes.

Generator Matrix: for an $[n, k]$ linear code, it is a $k \times n$ matrix for which the row space is the given code.

Check Matrix: an $(n - k) \times k$ matrix M for which $Mx = 0$ for all x in the code.

Code Generation: for a given r, form an $r \times 2^r - 1$ matrix M, the columns of which are the binary representations (r bits long) of $1, \ldots, 2^r - 1$. The linear code for which this is the check matrix is a $[2^r - 1, 2^r - 1 - r]$ binary Hamming Code $= \{x = (x_1\ x_2\ \ldots\ x_n) : MxT = 0\}$.

Syndrome Decoding: let $y = (y_1\ y_2 \ldots y_n)$ be a received codeword. The syndrome of y is $S := L_r y^T$. If $S = 0$ then there was no error. If $S \neq 0$ then S is the binary representation of some integer $1 \leq t \leq n = 2^r - 1$ and the intended code word is $x = (y_1 \ldots y_{r+1} \ldots y_n)$.

Cyclic Codes: Cyclic codes belongs to subclass of linear block codes and were first presented by Prange in 1957. These codes has two main advantages: first, they perform very effectively for error detection/correction and second, they hold many algebraic properties which simplifies the implementation of encoder and the decoder. Other properties of the cyclic codes as follows:

- A cyclic code is a linear block code where if c is a codeword, so are all cyclic shifts of c e.g., {000,110,101,011} is a cyclic code.
- Cyclic codes can be dealt with in the very same way as all other linear block code's i.e. the generator and parity check matrix can be found.

- A cyclic code can be completely described by a generator string G. All codewords are multiples of the generator string.
- In practice, cyclic codes are often used for error detection (CRC), i.e. when an error is detected by the received, it may requests retransmission.

Convolution Codes: It was first proposed by Elias in 1955 as an alternative to block codes. The convolutional codes differ from block codes in that the encoder contains memory and the n encoder outputs at any time unit depend not only on the k inputs but also on m previous input blocks. An (n, k, m) convolutional code can be implemented with a k input, n output linear sequential circuit with input memory m. Typically, n and k are small integers with k.

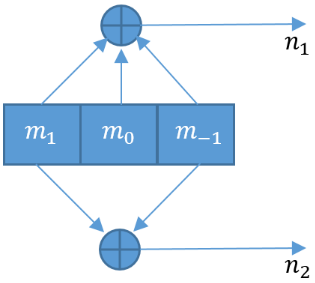


Figure 1: Convolution Coder Structure.

Encoding process: Convolutional codes k number of bits shifted into the encoder at one time $k = 1$ is usually used, n number of encoder output bits corresponding to the k information bits $R_c = k/n$ code rate K constraint length, encoder memory. Each encoded bit is a function of the present input bits and their past ones.

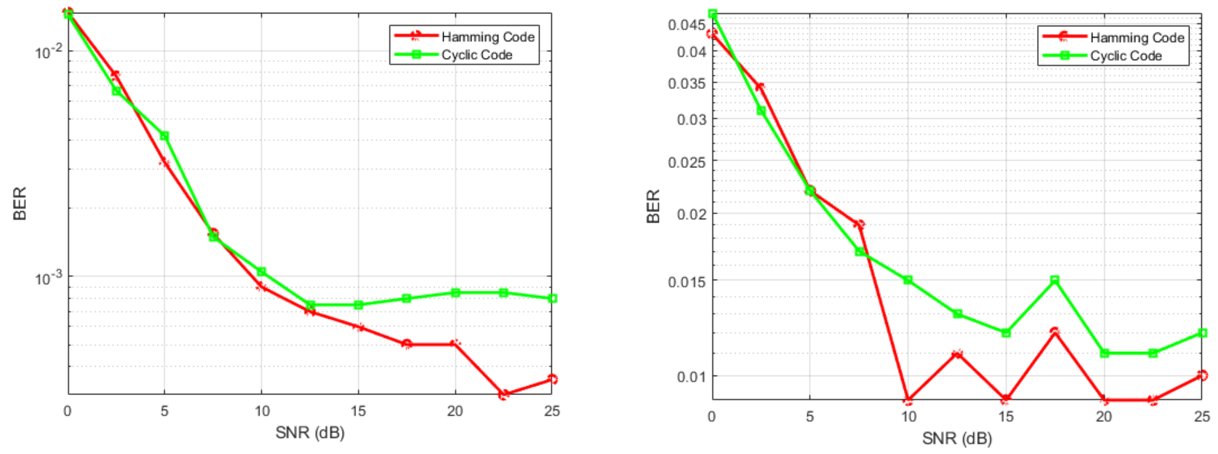
Decoding process: A sequential decoding as an efficient decoding scheme for convolutional codes was proposed by Wozencraft. In 1963, Massey proposed a less efficient but simpler to implement decoding method called threshold decoding. Then in 1967, Viterbi proposed a maximum likelihood decoding scheme that was relatively easy to implement for cods with small memory orders. This scheme, called Viterbi decoding, together with improved versions of sequential decoding. This is the most commonly used method used for decoding of convolution codes.

IV. SIMULATION RESULTS

This section presents the results obtained by simulating the molecular communication via diffusion with different error correcting code configurations. To obtain the most accurate results and avoid any uncertainties each simulation is repeated for five times and then the averaged values of all results are used to present the final result.

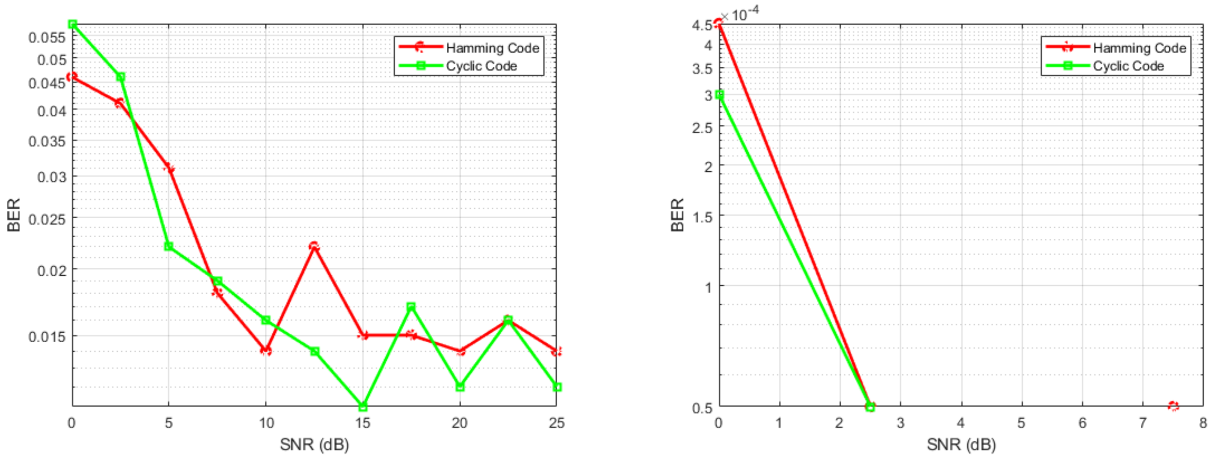
Table 1: Molecular Communication System Configuration used during Simulation.

Transmitter Node Type	Point
Receiver Node Type	Sphere
Receiver Node Radius	$5\mu m$
Distance between Nodes Center to Center	$2\mu m$
Number of Molecules per Symbol	100
Diffusion Constant	$100\mu m^2/s$
Symbol Duration	$25ms$
Sampling Rate	$1ms$
Symbols Transmitted	10000



(a) BCSK Pulse

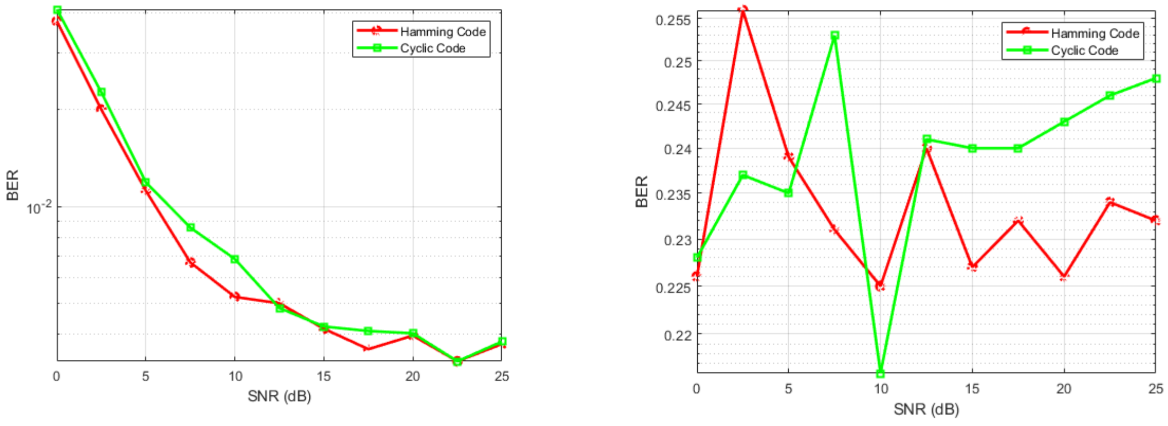
(b) BCSK Square.



(c) BFSK

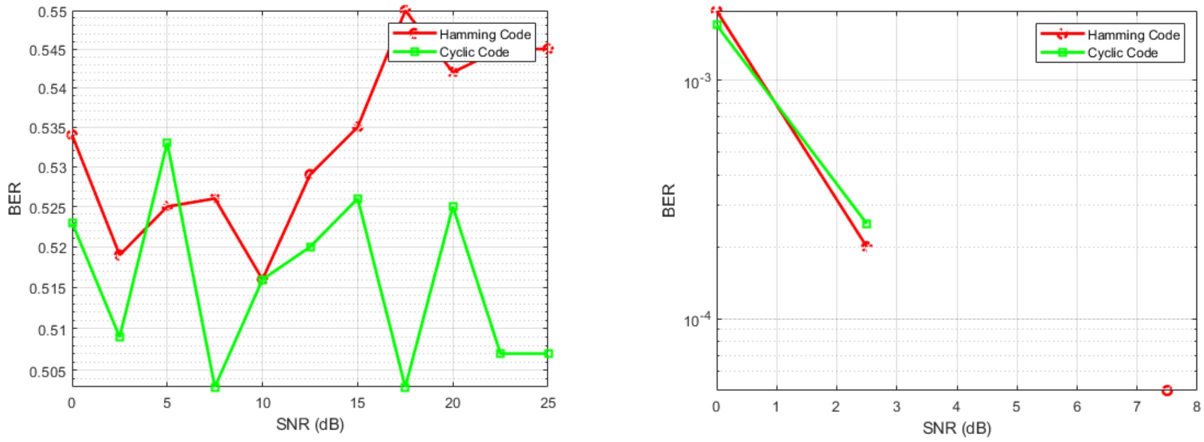
(d) BMoSK

Figure 2: the plot when block codes of n=3, k=1, which is equivalent to code rate of 1/3. The plot shows that even the Hamming and Cyclic Codes belongs to same class (linear block codes), the Hamming codes performs better at higher SNR values.



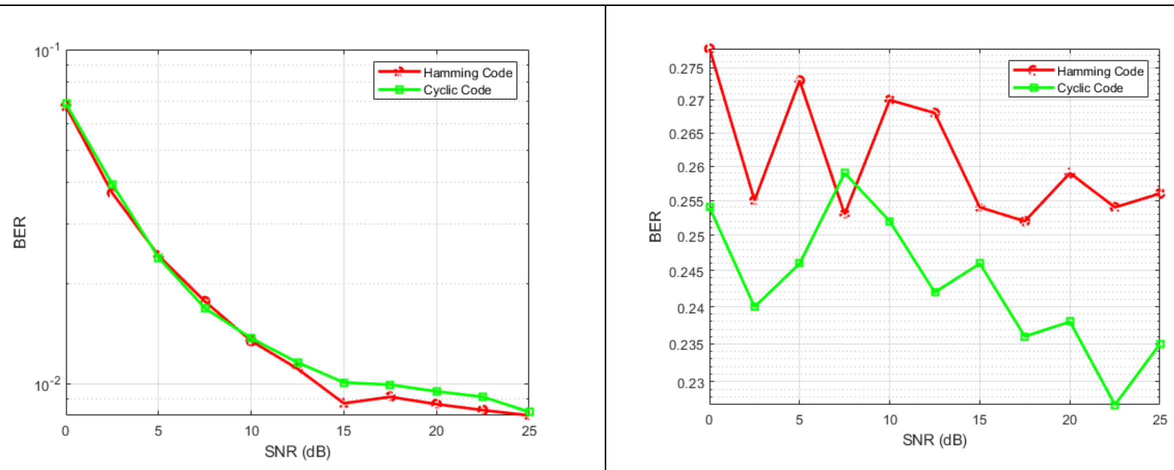
(a) BCSK Pulse.

(b) BCSK Square.

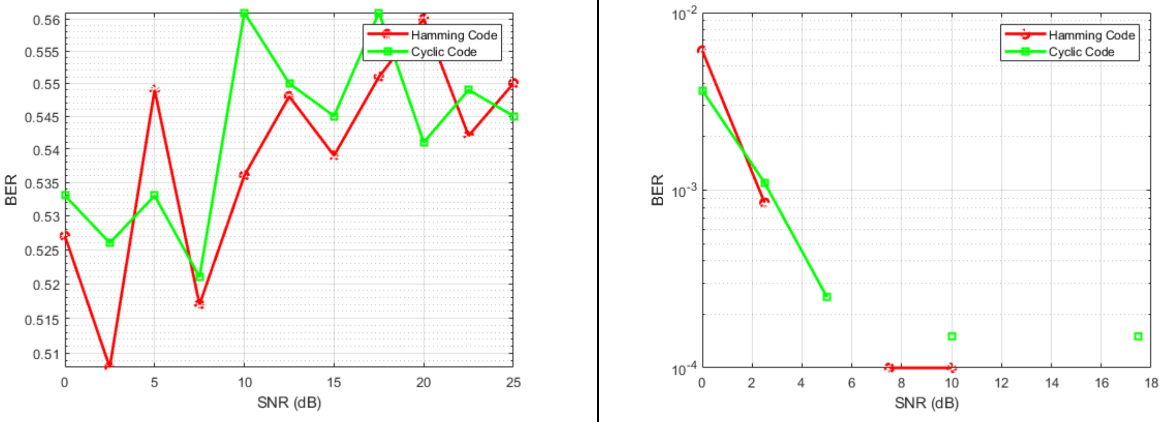


(c) BFSK. **(d) BMoSK.**

Figure 3: the plot when block codes of n=7, k=4, which is equivalent to code rate of 4/7≈0.57. The plot shows that the both codes perform equally.

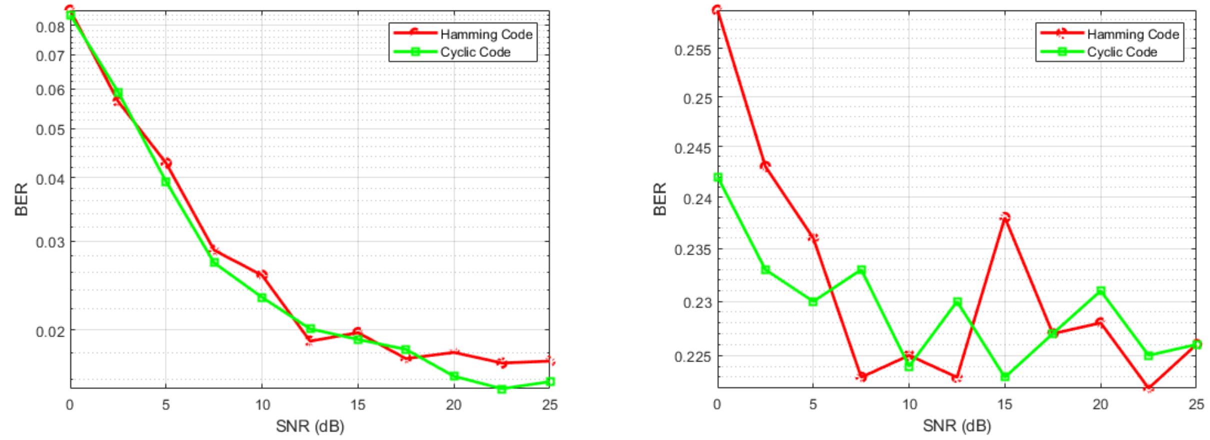


(a) BCSK Pulse. **(b) BCSK Square.**



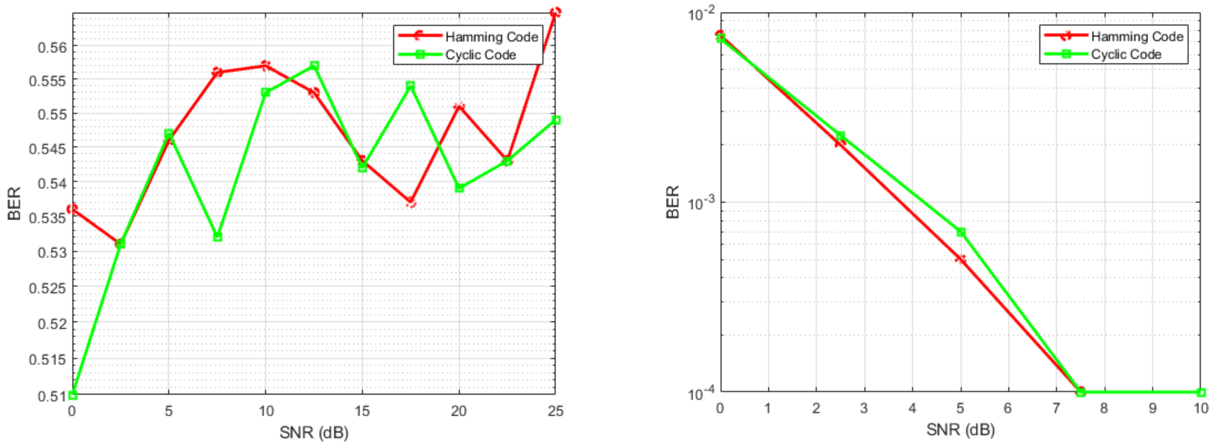
(c) BFSK. **(c) BMoSK.**

Figure 4: the plot when block codes of n=15, k=11, which is equivalent to code rate of 11/15≈0.73. The plot shows that Hamming codes performs a bit better at higher SNR values.



(a) BCSK Pulse.

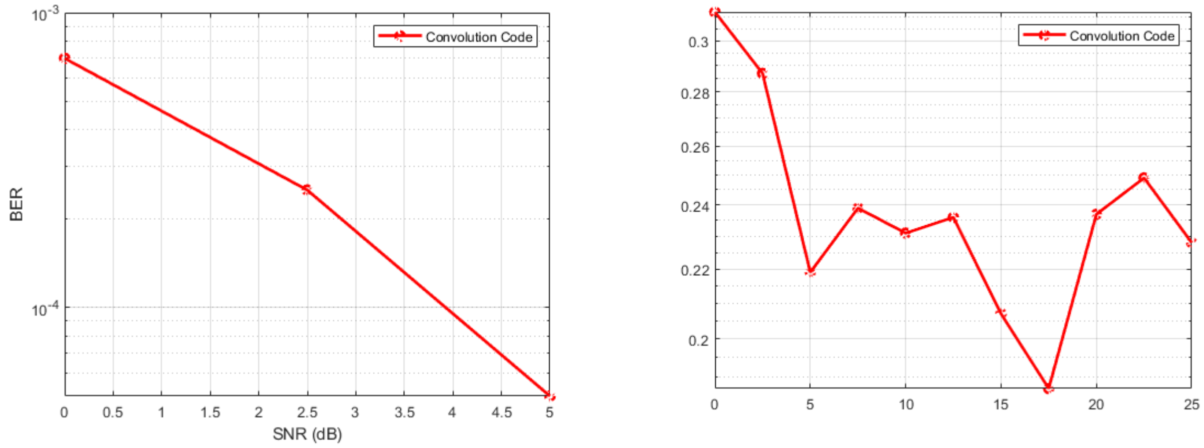
(b) BCSK Square.



(c) BFSK.

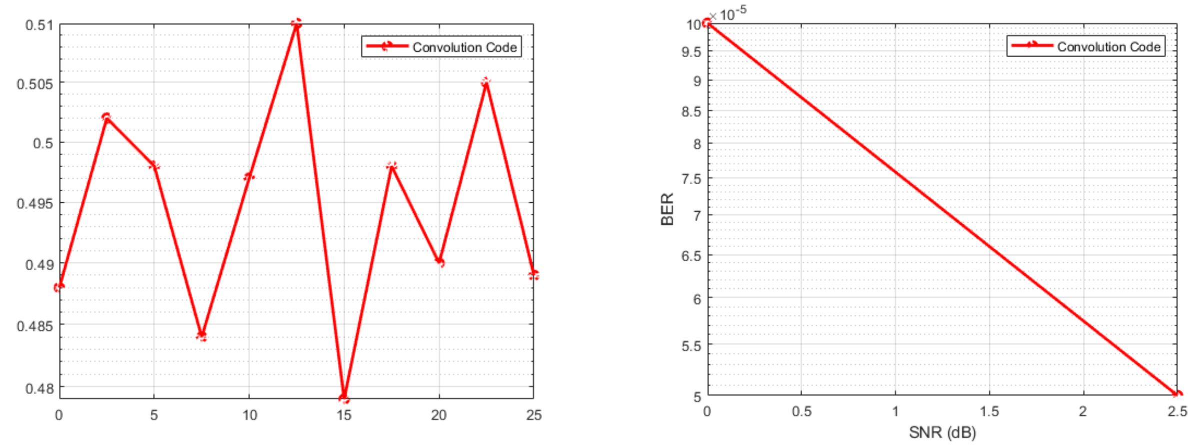
(d) BMoSK.

Figure 5: the plot when block codes of n=31, k=26, which is equivalent to code rate of 26/31=0.84. The plot shows that Cyclic Codes performs better at all SNR values, furthermore it performs much better at higher SNR values.



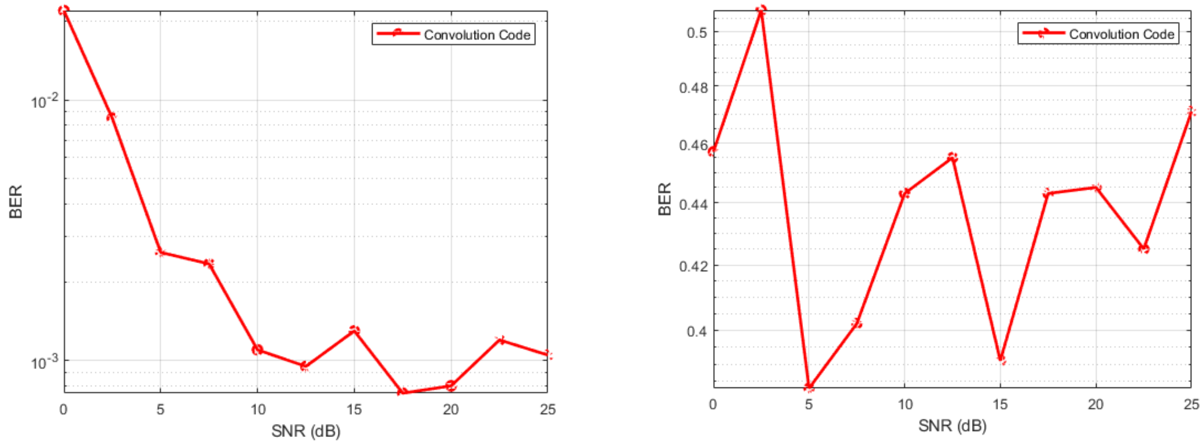
(a) BCSK Pulse.

(b) BCSK Square.

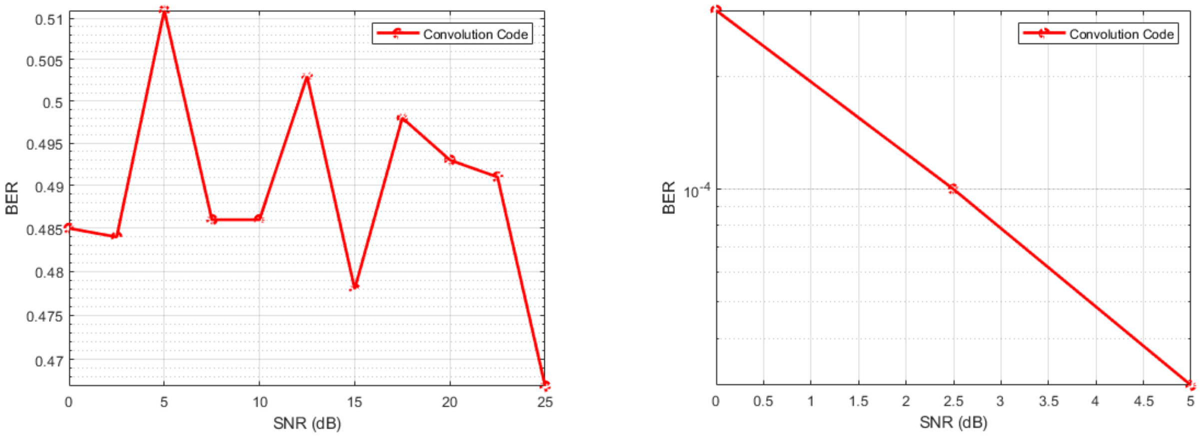


(c) BFSK. **(d) BMoSK.**

Figure 6: the plot when convolution codes of n=3, k=1, and m=3, which is equivalent to code rate of 1/3. The plot shows the drastic improvement by convolution codes over the block codes as it reaches to zero BER at only 5dB of SNR.

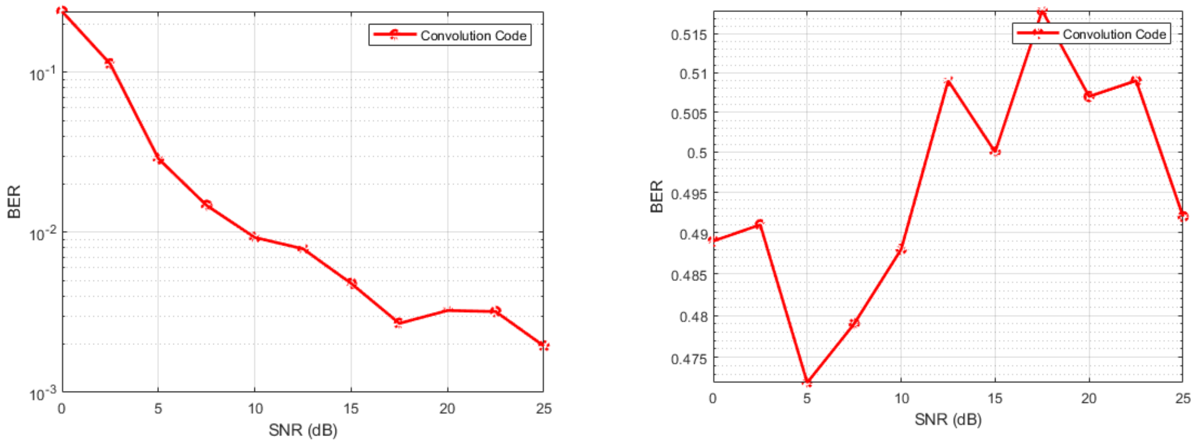


(a) BCSK Pulse. **(b) BCSK Square.**

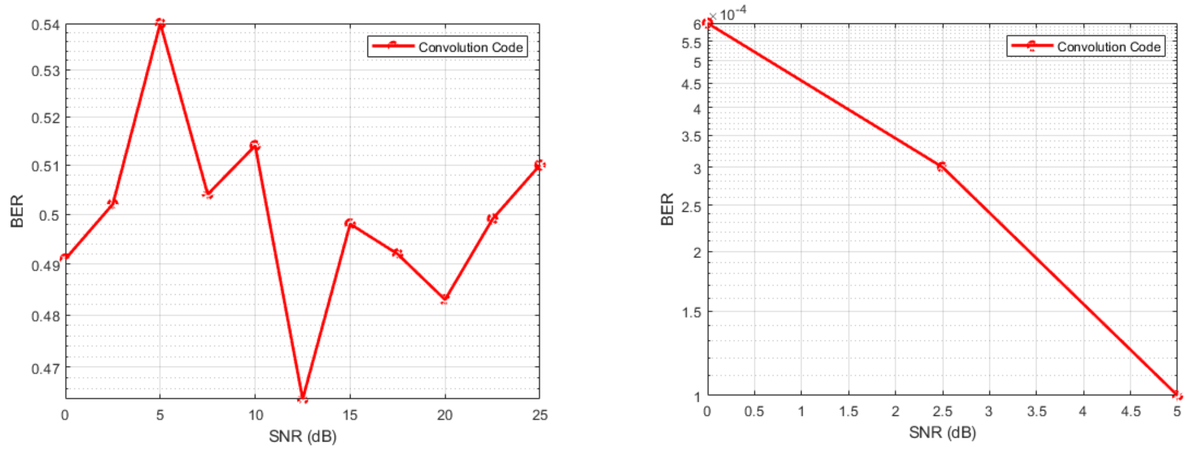


(c) BFSK. **(d) BMoSK.**

Figure 7: the plot when convolution codes of n=2, k=1, and m=3, which is equivalent to code rate of 1/2. The convolution codes still perform better.



(a) BCSK Pulse. **(b) BCSK Square.**



v

(c) BFSK. **(d) BMoSK.**

Figure 8: the plot when convolution codes of n=15, k=10, and m=5,4, which is equivalent to code rate of 2/3. The convolution code performs better.

V. CONCLUSION

This paper presented an analysis of molecular communication with different error correcting codes using mathematical simulation. The error correcting codes used here are of two types block codes and convolution codes. For the analysis four different modulation techniques are also taken. The simulation results obtained for each configuration are presented in figures from 4 to 10. The results depicts that the convolution encoder provide the many folds better results than the block coders for both the BCSK pulsed and BMoSK. However none of the error correcting technique works for BCSK Square and BFSK modulation techniques and both of them gives worst performance. For lower coding rate the convolution cods reaches to almost zero error rate at even 3dB of SNR. Hence from the results it can be concluded that the convolution encoder is an preferable choice for molecular communication as it can outperform the block codes for any coding rate with large margin.

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