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## Research Article

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# Performance Analysis for Molecular Communication under Feedback Channel using Multipath and Single path Technique

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**Abstract:** Nanomachines that can run tasks and molecular communication (MC) for interconnecting nanomachines have been made possible by advances in nanotechnology. Different techniques of Automatic Repeat Request (ARQ) protocols have been devised in MC for acquiring the necessary molecules, although retransmission of duplicate copies requires special attention. This work presents a diffusion-based MC with a feedback loop to improve MC performance. Based on the received ACK(s) or NACK(s), the Channel state determines if the state is good (G) or bad (B), and then single path or multipath procedures are used to the 'G' and 'B' states. The results of the MATLAB simulation illustrate how the systems compare in terms of communication rate, the possibility of complete transmission of the desired molecules, and energy consumption. When the channel state is bad, the multipath approach performs better, but when the channel state is perfect in MC, the single path strategy performs better.

*Keywords:* ARQ, MC, Feedback Channel, Diffusion Coefficient.

## 1. Introduction

Over the past few years, Molecular communication (MC) has received a lot of attention among network scientists and engineers. MC is a new nature-inspired network communications paradigm with the potential to realize internetworking nanomachines at nanoscale<sup>1</sup>. In MC, molecules are information carriers between the transmitter (TX) and the receiver (Rx). Essentially, the transmitter encodes information to be communicated to the receiver into the properties of the molecules and releases them. The molecules travel through the environment and reach the intended receiver where the information is decoded and used. With the capability to mimic the signaling mechanisms deployed between the living cells, MC has great potential to address the shortcomings of standard communications systems. Furthermore, it is expected that MC will enable a wide variety of novel applications that include biomedical applications (e.g., monitoring target substances in biotechnology<sup>2</sup>), healthcare applications (e.g., monitoring and drug delivery<sup>3,4</sup>, industrial applications (e.g., monitoring oil and gas pipelines)), and smart

homes applications (e.g., interconnecting household devices).

Different signaling methods such as diffusion<sup>5,6</sup>, active transport<sup>7</sup>, bacteria, and calcium signaling can be used to achieve signal propagation in MC but still lacking of obtaining the optimum number of molecules to be transmitted also to limit the number of duplicate copies sent back and forth between sender and receiver. Thus, in order to find the channel states either good or bad in MC, considering the feedback channel based on received ACK(s) or NACK(s) is also one of the importance parameters to achieve higher. A simple block diagram of MC is portrayed in Fig. 1.

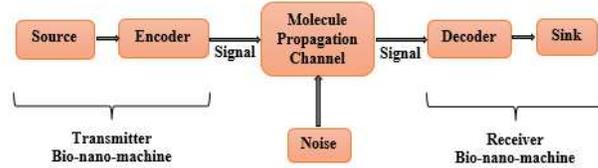


Fig.1. A simple model of MC

This paper's contribution can be summarized: It is neither any reason nor logic to apply the same technique in diffusion-based MC. Thus, the channel is decided into two states i.e., good and bad states by considering the channel Probability of Error (PE) with a value ranging from 0.1 to 0.9. If the PE value ranges from 0.1 to 0.4 then the channel state is good and the bad state if the value of the P.E ranges from 0.5 to 0.9. It is also detailed in the manuscript that the rate of communication is higher but lesser in energy consumption in multipath as compared to the single path technique when the PE of the channel is higher.

In the rest of the paper, the problem overview is discussed in section 2. The related works are described in Section 3. In Section 4, we elaborate on how to take the decision state of the channel under the consideration of feedback symbols of ACK(s) or NACK(s). Simulation results and conclusions are discussed in Section 5 and section 6.

## 2 Problem Overview

In the same way that ARQ is used in traditional wireless networks, it is also used in MC. It is expected that the first encoded molecules (S1) are transported from Tx to Rx, as shown in Fig. 2. After successfully receiving S1 molecules, the Rx will release S2 molecules to prevent the Tx from releasing previous molecules. As a result, encoded molecules (such as S3 or S4) will begin to transmit from Tx to Rx. The medium between Tx and Rx is likewise determined to be a diffusing channel, therefore the capture probability (CP) of the encoded molecules at the Rx is also provided by eq. (1).

$$CP(r_0, t) = \frac{R}{r_0} \operatorname{erfc} \left\{ \frac{r_0 - R}{2\sqrt{Dt}} \right\} \quad (1)$$

where R denotes the radius of Tx or Rx which is in spherical shape such that  $R < r_0$  and  $r_0$  is the distance from Tx to Rx and D is the diffusion coefficient of the molecules.

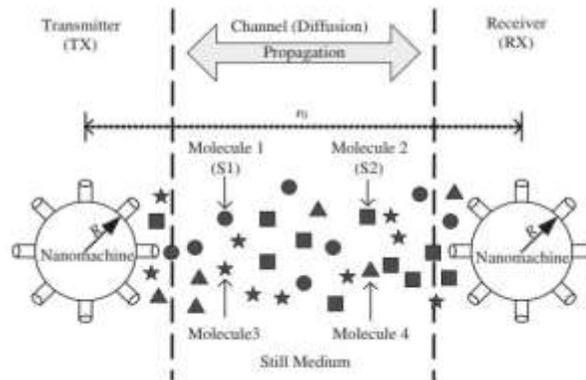


Fig. 2. ARQ in diffusion-based MC <sup>8,9</sup>

Many academics have presented novel concepts and ideas based on the ARQ in MC, but the channel state has yet to be discovered. According to the literature, increasing the number of molecules transmitted from Tx can likewise increase the number of interferences between molecules, lowering MC performance. As a result, in a diffusion-based MC, we build this manuscript to improve performance by utilizing both multipath and single path strategies in the determined channel states in order to achieve higher communication rates while also consuming less energy.

### 3. Related Works

Brownian motion causes encoded molecules to disperse in a fluidic medium, causing out-of-order delivery and frequent packet mistakes. Chang<sup>8,9</sup> proposed ARQ after seeing it in use in older wireless networks to ensure packet delivery from Tx to Rx. Many researchers have developed different ARQ procedures in MC, which are also mentioned and discussed here. Three novel molecular communication mechanisms were proposed by Wang et al<sup>10</sup>. The proposed methods are based on Stop and Wait (S/W) ARQ, which is diffusion-based. These strategies are numerically simulated and evaluated to see how well they perform in terms of average time and energy consumption. The first S/W-ARQ system functions similarly to the regular S/W-ARQ system. The Tx sends a packet and then waits for the Rx to acknowledge it (ACK). In the second technique, Rx sends back  $k$  copies of the corresponding ACK at the same time as the packet is received. When the Tx receives one of the  $k$  ACKs, another packet is sent. The third strategy focuses on the receiver's ability to catch molecules. As soon as at least one copy of the current packet is received, Tx sends out  $n$  copies of it, along with  $n$  copies of the accompanying ACK. As a result, the Tx will send the next packet in  $n$  copies. As a consequence of the data, the third scheme is found to be more efficient in terms of average time and energy use.

In addition, ARQ approaches for bacterial quorum communication were investigated<sup>11</sup>. The use of quorum sensing to communicate among bacterial cells is known as quorum communication. Various ARQ protocols are thought to improve the performance of communication. The findings show that the Selective Repeat-ARQ method outperforms the other methods in bacterial communication networks. It is also regarded as the MC that uses packet combining techniques to reduce duplicate copy transmission<sup>12</sup>.

Nakano et al<sup>13</sup> investigated the constraints and opportunities of molecular networking and communication. He's also talked about communication protocols and networking systems. Several researchers<sup>14,15</sup> have worked on channel and capacity analysis with ISI mitigation using Brownian motion and modulation, as well as its application<sup>16,17</sup>. Energy is a key aspect to consider when determining the performance of a communication system since it impacts the channel capacity and data rate. Many approaches are also discussed, with the most effective being MC via diffusion. However, inter-symbol interference causes various problems in MC when using the diffusion technique. Tepekule et al<sup>18</sup> provided an analytical method for determining the best threshold value. ISI mitigation strategies based on the optimum threshold are also offered on the transmitter and receiver sides. According to the findings, fixing the thresholding issue is an essential step before suggesting ISI mitigation strategies. MC systems with an absorbing receiver were simulated by Yilmaz and Chae<sup>19</sup>. They demonstrated a bespoke end-to-end MC simulator for MC in 1-D, 2-D, and 3-D environments using diffusion and reinforcement. The ISI mitigation approaches have been addressed and studied after assessing the outcomes.

Determining the distance between sender and receiver is one of the most important parts of optimum communication in an MC. By analyzing the RTT or Signal Attenuation of the sent feedback signal, it uses a single spike feedback signal to determine the distance from source to destination<sup>20</sup>. A one-dimensional diffusion-based channel is used to offer two one-way communication options<sup>21,22</sup>. Without synchronization with the transmitter, the receiver determined the peak concentration of the broadcast molecules. Another option was to employ double spikes and have the receiver directly monitor the difference in time between the peak concentrations. Sanjit et al<sup>23</sup> discussed the effective distances between T and B cells in the immune system in order to increase the likelihood of desired molecules being captured.

### 4. Decision States Under Feedback Channel for Proposed Work

This section describes the proposed work. We describe the three states of transition of proposed work and the two transition stages of proposed work in the following discussions in order to determine if the proposed work is in a good or bad state. Fig. 3 shows the flow chart of the suggested technique for determining if the decision state is good (G) or bad (B). The

communication rate is compared and assessed in the later part of this section when the channel status is good or bad. From Fig.4, we assume that the symbol '0' denotes the NACK and the symbol '1' denotes the ACK. Since the Rx transmits ACK symbol through feedback channel when molecules are successfully received and also reached the threshold value ( $\tau$ ). If the received molecules fail to obtain the threshold value, then NACK symbol will be transmitted back. Thus, from the received symbols we elaborate the decision of the channel into two and three states and it is explained in the following.

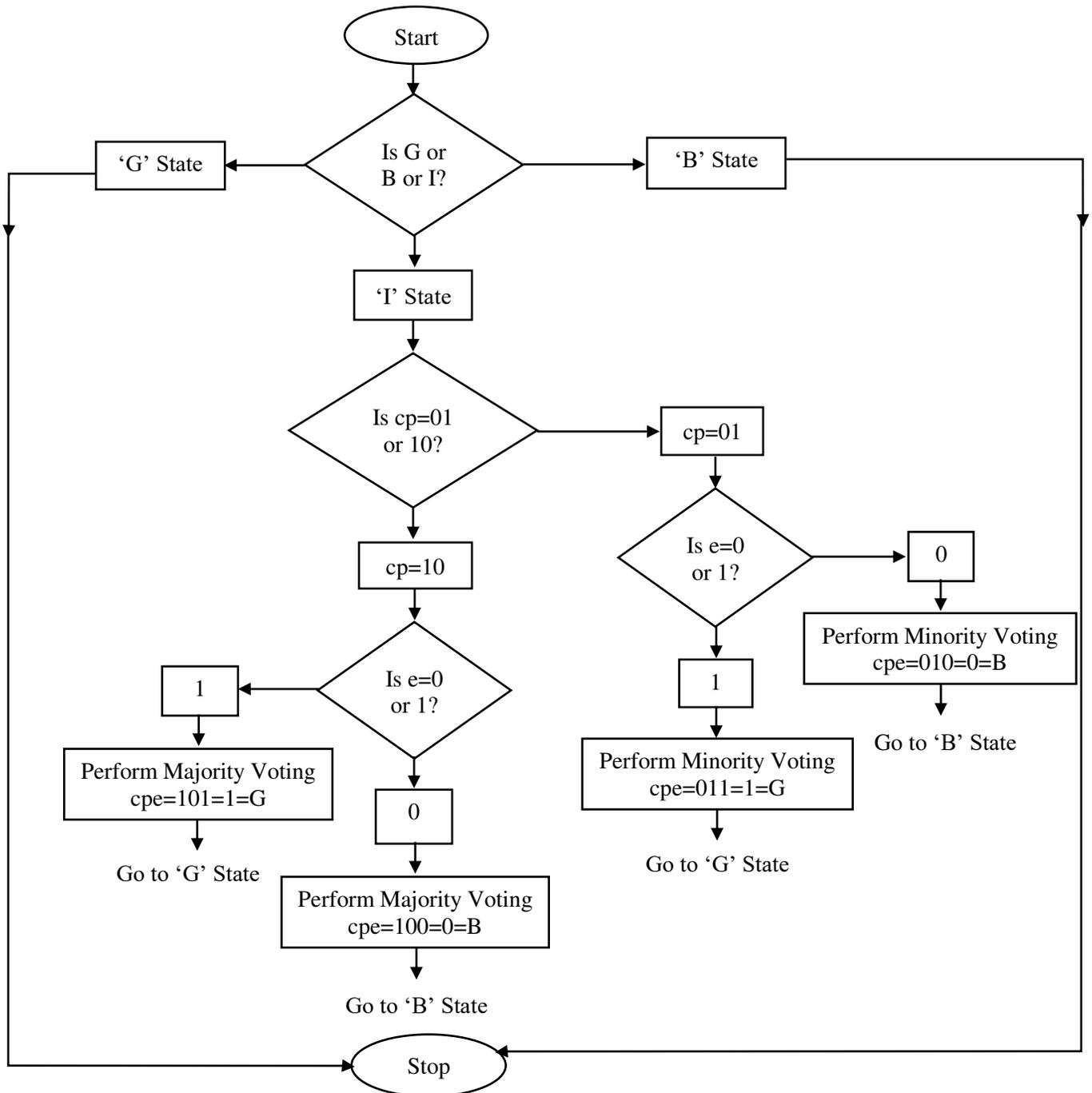


Fig. 3. Proposed scheme's flow chart

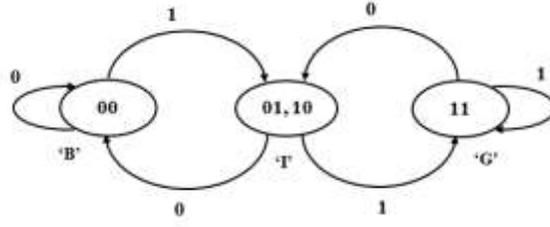


Fig. 4. Proposed scheme's transition states

*Case 1:* Tx gets consecutive symbols of 0 with a probability of  $P(S0) = P(00)$ . The symbols on the left and right indicate the previous and current NACK received ( $s$ ). As a result, it is presumed that the channel is in a bad state in the proposed design.

*Case 2:* The probability  $P(S1) = P(01)$  is defined as the Rx failing to receive the prior molecules but receiving the present molecules successfully. Tx receives the feedback symbols '01' as a result. As a result, Eq. (2) is used to define *Case 2*.

$$P(0,1) = \sum_{j=\tau}^n \binom{n}{j} P_1^j (1 - P_1)^{n-j} \quad (2)$$

where  $n$  is the total number of molecules transferred, is the threshold value, and  $P_1$  is the probability of receiving the current molecules successfully. As a result of the symbols of '01' *Case 2* is presumed to be an Intermediate state (I).

*Case 3:* The probability  $P(S2) = P(10)$  indicates that Rx received the prior molecules successfully but did not receive the present molecules. As a result, Tx receives the symbols '10'. Eq. (3) is now used to formulate *Case 3*.

$$P(1,0) = 1 - Q \left( \frac{\tau - n(P_2 - P_1)}{\sqrt{n[P_2(1 - P_2) + P_1(1 - P_1)]}} \right) \quad (3)$$

where  $P_2$  is the probability that molecules from the previous time ( $t$ ) are successfully accepted by Rx in the current time ( $2t$ ). As a result of the received '10' symbols, the Tx determines that the channel is in the 'I' state.

*Case 4:* The probability  $P(S4) = P(11)$  indicates that the Tx receives a contiguous symbol of '1'. It assesses if Rx has successfully accepted both the previous and current molecules. As a result, the Tx determines that the channel is in a 'good' state. As a result, Eq. (4) can be used to calculate the chance of success in *Case 4*.

$$P(1,1) = Q \left( \frac{\tau - nP_2}{\sqrt{n[P_2(1 - P_2) + 2P_1(1 - P_1)]}} \right) \quad (4)$$

The generalized transition of two states is depicted in Fig. 5 to decide the channel into two states, namely bad (B) and good (G) states.

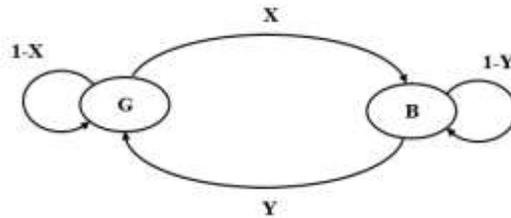


Fig. 5. Proposed schemes minimized to two states

The following steps illustrate how to decide the channel into two states by performing XOR operation and majority voting.

*Step 1:* The binary bits which represent the previous symbol ( $S_p$ ) and current symbols ( $S_c$ ) are used to perform XOR operation to get the next channel state (output) and it is shown in Table 1.

Table 1. XOR operation of  $S_p$  and  $S_c$

$S_p$	$S_c$	Output
0	0	0
0	1	1
1	0	1
1	1	0

*Step 2:* If the outputs are 0 (s), the state of the channel is believed to be either 'G' or 'B'. It also verifies the symbol  $S_p$  or  $S_c$  from the two inputs; if  $S_c=0$ , the channel state is in the 'B' state; if  $S_c=1$ , the channel state is in the 'G' state. When both  $S_p$  and  $S_c$  are the same value, the outcome of the XOR operation is 0.

*Step 3:* In this step, we assume one symbol, expected symbol ( $S_e$ ), in order to determine the next channel state, which is either 'G' or 'B,' as shown in Tables 2 and 3, by using majority voting among the input symbols  $S_p$ ,  $S_c$ , and  $S_e$ . The output from the Tables 2 and 3 obtained 0 (B) and 1(G) states. Thus, the Fig. 5 is obtained from Fig. 4.

Table 2.  $P(S_1) = P(S_p S_c) = P(01)$  whether  $S_e$  is 0 or 1

$S_p$	$S_c$	$S_e$	Output
0	1	0	0
0	1	1	1

Table 3.  $P(S_2) = P(S_p S_c) = P(10)$  whether  $S_e$  is 0 or 1

$S_p$	$S_c$	$S_e$	Output
1	0	0	0
1	0	1	1

We can find the complete transmission probability from Eq. (1), which is given by Eq. (5).

$$CT_{i=1} = [1 - (1 - CP(r_0, t))^n]^i \quad (5)$$

' $n$ ' is the number of molecules sending from sender (Tx) to receiver (Rx) and  $i$  denotes the number of retransmissions. Thus, if the preceding molecules received less than the threshold value, the complete transmission probability of a desired molecules for the retransmission of duplicate copies is given by Eq. (6).

$$CT_{i=2} = [(1 - (1 - CP(r_0, t))^n)^2] \quad (6)$$

If the multipath approach is used, the average successful complete transmission of desired or wanted molecules is provided by Eq. (7).

$$CT_{k=2} = [1 - (1 - CP(r_0, t))^n]^n + [1 - (1 - CP(r_0, t))^n]^n \quad (7)$$

Allow one unit of energy (E) to be utilized for one transmission cycle. Eq. (8) and eq. (9) can then be used to calculate the mean energy consumption for  $CT_i$  and  $CT_k$

$$E(CT_{i=1,2,3...r}) = \frac{1}{\prod_{i=1}^r [1 - (1 - CR(r_0, t))^n]} \quad (8)$$

$$E(CT_{k=1,2,3...m}) = \frac{1}{\sum_{k=1}^m [1 - (1 - CR(r_0, t))^n]} \quad (9)$$

Communication rate (CR)<sup>24, 25, 26</sup> can be given by Eq. (10).

$$CR = (1 - PE)\log_2 n \quad (10)$$

For molecules that are employed to transmit repeatedly in a single channel, Eq. (11) provides the CR.

$$CR^i = [(1 - PE)\log_2 n]^2 \quad (11)$$

If the molecules are used to send in multipath ( $k=1, 2, 3\dots m$ ), then CR is given by Eq. (12), where  $i$  signifies the number of retransmissions in the same path.

$$CR^m = \sum_{k=1}^{k=m} (1 - PE)\log_2 n \quad (12)$$

## 5. Results and Discussion

The simulation findings for the performance of diffusion-based MC under feedback channel are discussed in this part. The performance is measured in terms of molecule concentration at various time intervals as a function of distance. This section discusses the communication rate in a multipath feedback channel with various PE values. We also compare communication rates for single path and multipath communication for various PE values. The estimated completion time and average energy consumption of the proposed work are explained and addressed.

### 5.1. Communication Rate (CR)

PE=0.2, 0.4, 0.7, and 0.9 are used to determine the CR in Fig. 6. When variable amounts of molecules are carried from Transmitter to Receiver. The CR is higher when PE is between 0.5 and 1; when PE is between 0 and 0.4, the CR is lower. As a result, it can be deduced that the higher the PE values, the slower the CR.

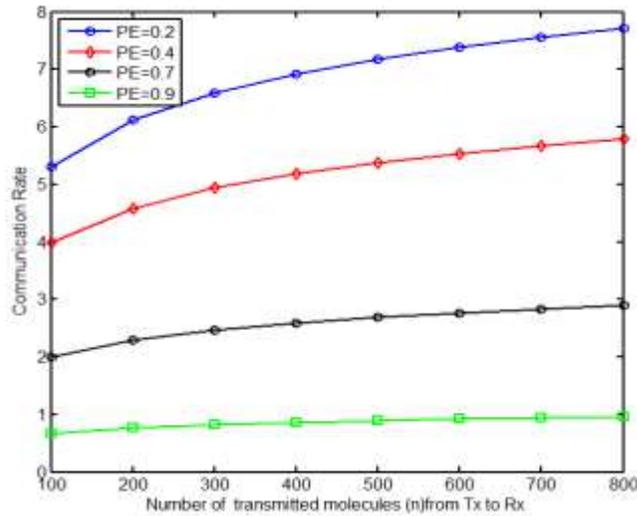


Fig. 6. Communication rate at PE=0.2, 0.4, 0.7 and 0.9

In the multipath technique, the CR is compared in Fig.7 and Fig.8 when the value of  $k = 1, 2, 3,$  and  $4$ ; and different numbers of molecules are communicated at PE=0.8 and PE=0.5. The CR has been shown to increase as the number of transferred molecules and the number of pathways between Tx and Rx both increase. The CR decreases as the number of paths decreases. As a result, the multipath technique for feedback channel in MC is more reliable for faster communication between bio-nanomachines.

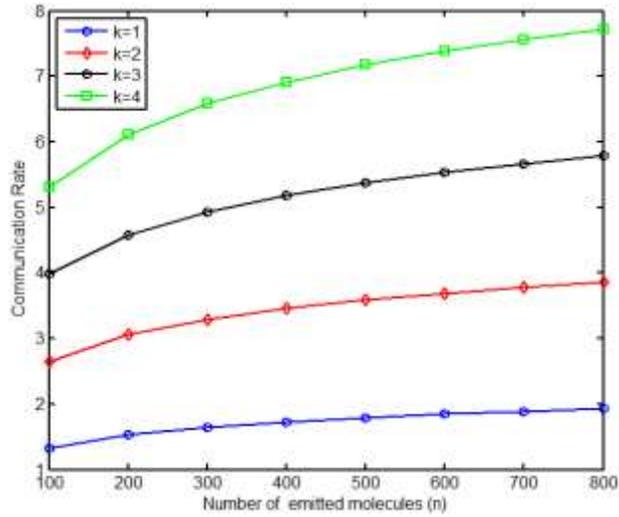


Fig.7. Communication rate when  $k=1,2,3$  and  $4$  with  $PE=0.8$

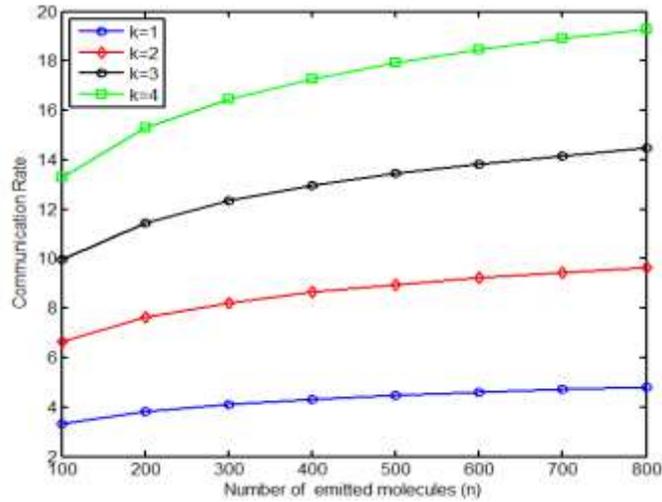


Fig. 8. Communication rate when  $k=1,2,3$  and  $4$  with  $PE=0.5$

To know the importance of multipath technique for feedback channel in MC, we portray Fig. 9 and Fig. 10. With different number of emitted molecules, the performance of multipath approach is displayed and elaborated with  $k=2$ , and  $3$  when  $PE=0.3$ ,  $0.5$  and  $0.8$ . From these figures, the value of  $k$  increases the communication rate also increases. Also, we can observe that lower the value of  $PE$  and higher the value of  $k$  then communicate rate is higher.

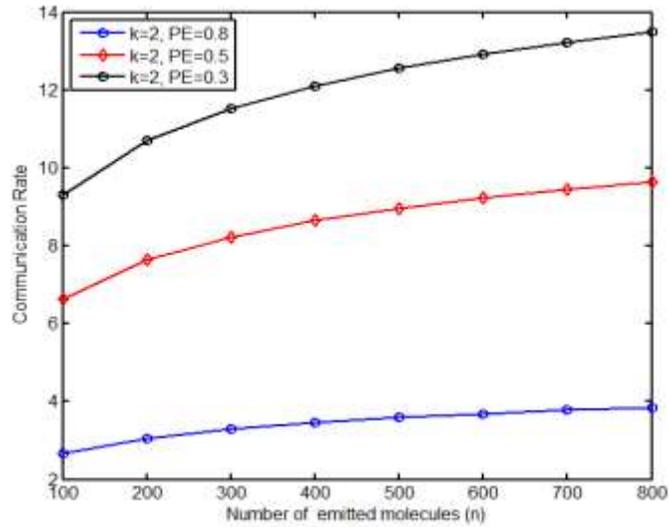


Fig.9. Communication rate when PE=0.3, 0.5, 0.8 with  $k=2$

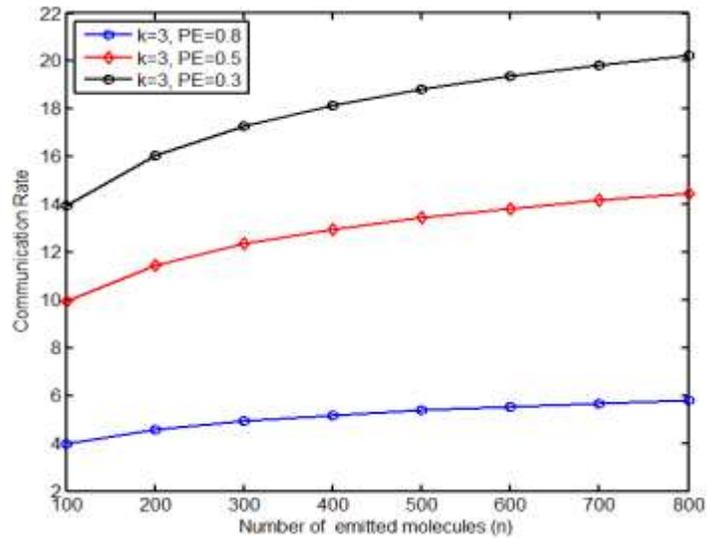


Fig.10. Communication rate when PE=0.3, 0.5, 0.8 with  $k=3$

The performance of single path retransmission technique is portrayed in Fig. 11 with  $i=1, 2$  when PE=0.5 & 0.8. It is observed that communication rate is more when  $i=2$  with PE=0.5 as compared to  $i=1$  with PE=0.8. Therefore, the communication rate is higher with higher value of retransmission and lower value of PE in single path retransmission technique.

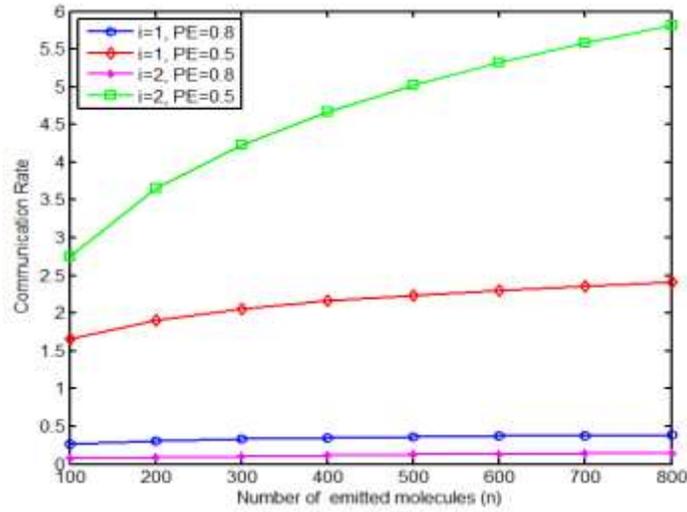


Fig.11. Communication rate when  $i=1, 2$  with  $PE=0.5, 0.8$

A comparison result in terms of communication rate for multipath and single path retransmission techniques is portrayed in Fig.12 with different number of emitted molecules. The figure shows higher communication rate when  $k=2$  with  $PE=0.5$  as compared to  $i=2$  with same probability value of  $PE$ . It is also showing that communication rate increases as the number of emitted molecules increases.

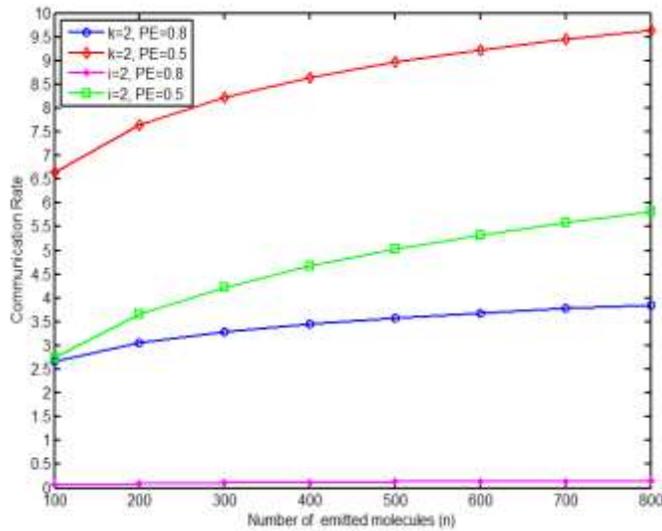


Fig. 12. Comparison of communication rate when  $k=2, i=2$  with  $PE=0.5, 0.8$

### 5.3. Expectation of complete transmission

By releasing varying numbers of molecules, the comparative performance of single path and multipath approaches is displayed and elaborated. In comparison to single path retransmission, the multipath approach gives a greater performance in terms of communication rate. However, when compared to single path retransmission, the multipath approach has a higher expectation of complete delivery of intended information molecules. Additionally, when the number of molecules transported grows, the expectation of complete transmission increases. The performance on expectation of complete transmission of desired molecules for multipath and single path retransmission technique is portrayed in Fig. 13 with different values of  $CP(r_0, t)$ . When value of  $k=2$  and the emitted molecules  $n=200$ , the expectation of complete transmission of desired molecules is higher as compared to single path technique. In MC, the concentration of molecules decreases as the distance increases. Therefore, the expectation of complete transmission of desired molecules for both multipath and single path decreases as the distance between Tx and Rx increases.

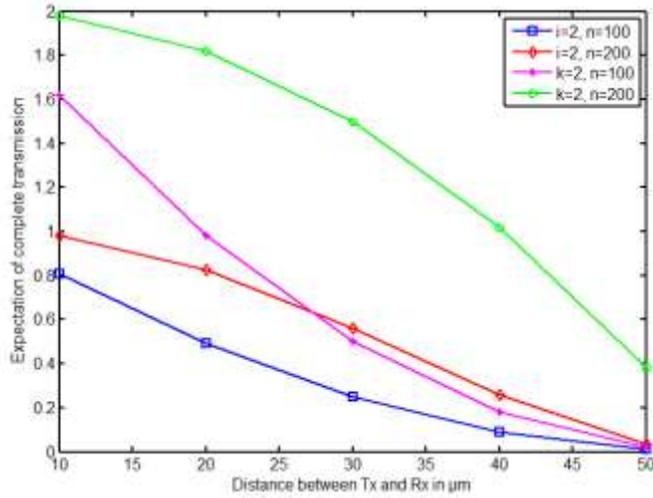


Fig. 13. The performance on expectation of complete transmission for proposed work

#### 5.4. Mean energy consumption

The energy consumption is an important parameter of MC. Here, we show the mean energy consumption in MC for single path and multipath retransmission. Fig. 14 demonstrates mean energy consumption by multipath retransmission technique and single path retransmission technique. We consider  $i=2$ ,  $k=2$  and  $n=100$  and  $200$  to illustrate the mean energy consumption by both techniques with different capture probabilities. We can observe that the multipath retransmission technique requires lower mean energy consumption with higher value of  $k$  and higher capture probability.

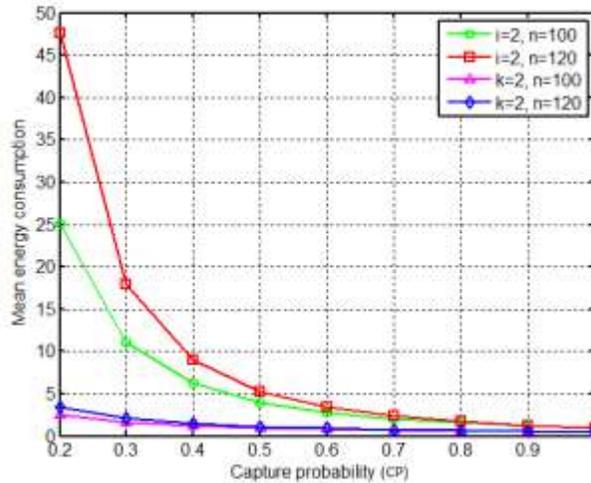


Fig. 14. Mean energy consumption for different values of  $i$  and  $k$

In the feedback channel, Fig.15 shows the mean energy consumption of the multipath and single path retransmission technique in terms of distance between Transmitter and Receiver. In single path retransmission,  $i=2$  and  $n=100$  and  $120$  are taken into account; the mean energy usage increases as the distance between Transmitter and Receiver grows. When  $k=2$  and the same values of  $n$  are used in a multipath retransmission method, the mean energy usage is lower than when a single retransmission technique is used. For different values of  $n=100$  and  $120$ , the multipath approach offers a better outcome by expending less energy.

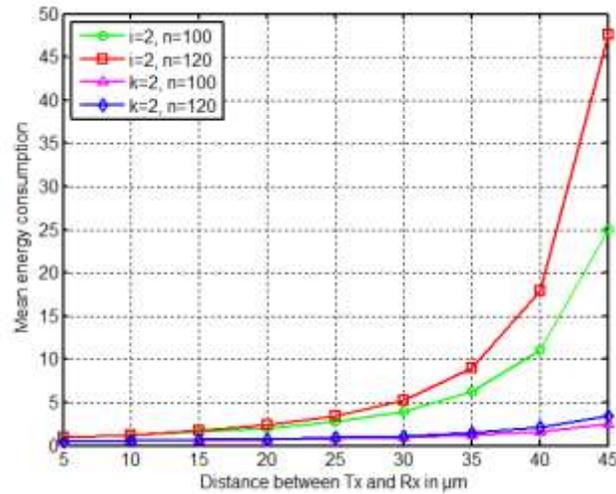


Fig. 15. Mean energy consumption versus distance

## 6. Conclusion

The major findings of proposed work from simulation results are summarized. In MC, molecule concentrations differ at different locations, but smaller the duration, higher will be the molecular concentration. It is also observed that lower the value of PE and higher the value of  $k$  then communication rate is higher. As the number of released molecules ( $n$ ) grows, so does the communication rate. The probability of complete transmission rises as the number of molecules ( $n$ ) transported rises. As the distance between the Tx and Rx bio-nanomachines grows, the probability of complete transmission of target molecules for both multipath and single path diminishes. However, with a greater value of  $k$  and a higher capture probability, the proposed work requires a lower mean energy consumption. Thus, from the simulation results we conclude that the communication rate is more in multipath technique. According to the findings, utilizing a multipath strategy saves energy while boosting the chances of delivering all essential molecules. Based on the simulation results, it is determined that, for reliable, efficient, and higher communication rates in the feedback channel in MC, multipath technique is better to single path technique if PE is larger. As a result, study in this field could be broadened to incorporate a new technique that can be utilized to increase dependability during various time periods of the "G" and "B" phases.

## DECLARATIONS

### - Human and Animal Ethics

Not Applicable

### - Authors' contributions

All the authors contributed to the design and implementation of the research, to the analysis of the results, and to the writing of the manuscript.

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## Ethical Approval

The manuscript is original and has not been published, accepted for publication or under editorial review for publication elsewhere.

## Consent to Participate

Not applicable

## Consent to Publish

Not applicable

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## Availability of data and materials

All data generated or analyzed as part of this study are included in this published article.

## Competing Interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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