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Performance Investigation of Molecular Nano Communication Over Channels Under Dynamic Scenarios

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Abstract

In this paper, Molecular Communication (MC) system, which is likely to be used in a variety of domains including targeted medicine delivery and health monitoring, is investigated over the channel under dynamic scenario. A diffusive mobile MC system with a pair of transmitter and receiver nano- machines suspended in a fluid medium with a uniform flow is considered. It is noteworthy to mention that the Channel Impulse Response (CIR) changing over time and irregular movements of the transmitter as well as receiver nano-machines make MC system most challenging. Establishing reliable communication between mobile nano-machines in such scenario is even more challenging as its statistics change with time. However, Signal to Noise Ratio (SNR) is most suitable parameter which is used to quantify the system reliability. Therefore, this research investigates the effect of mobility of transmitter and/or receiver nano machines on SNR. In particular, SNR under three dynamic scenarios is derived and analysed with the help numerical quantification. In the first scenario, both the transmitter and receiver are in motion. Whereas, in the second scenario, the transmitter is in motion and the receiver is fixed. Finally, in the third scenario, the transmitter is fixed and the receiver is in motion. For each scenarios, effect of different physical parameters such a diffusion coefficient, emission time, concentration of information molecules, radius of receiver and delay time are included in the analysis. The simulation results shows perfect agreement with the theoretical background. Simulation is performed in Maple-18.

Keywords Molecular communication · Signal to Noise ratio · Channel impulse response

1 Introduction

Molecular Communication is determined by the exchange of molecular information between Bio-nano devices and is inspired by molecular information transport in nature [1]. MC Basic building blocks or key element of MC system are similar to traditional wireless communication. The encoder is the first element, and it encodes chemical information based on the type or concentration of the molecule, or the time of arrival. The information

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can be transformed into a variety of molecule properties, including molecular concentration [2, 3], molecule type [4], and molecule releasing time [5].The encoded molecules are allowed to leave in the propagation medium through the second element transmitter. So far, several methods for propagating information molecules have been proposed [6], ranging from molecular motors [7] to bacteria [8] to free diffusion [9]. However, the focus of the present research lies in diffusion-based architecture as it is the most common and prominent MC design in nature. Diffusion allows molecules to propagate through the propagation medium and reach the receiver. These information molecules are captured by the receiver. The decoder uses the received molecules to decode the transmitted information. Many fascinating uses are made possible by molecular communication, including medical and healthcare, military applications, and environmental monitoring. It is noteworthy to mention that cost effective and efficient implantation of MC system makes it most viable communication paradigm.

MC can outperform regular wireless communication as a communication paradigm in some specific applications such as, in intracellular and intercellular communication calcium signalling [10]. Due to the antenna size constraint, it is challenging to develop effective electromagnetic wave communication systemsat a very small dimensions [11]. In general, MC approaches like calcium signalling have been viewed as promising techniques for implementing nano communication system [12]. Knowledge of channel statistics is required to establish a stable communication link between transmitter (Tx) and receiver (Rx) nanomachines [13]. However, focus of majority of research articles in the field of MC system rely on static transmitter (Tx) and receiver (Rx) nanomachines in which the relative distance between the transmitter and receiver nanomachines is kept as fixed with time. At the same time it is noteworthy to mention that mobile transmitter (Tx) and receiver (Rx) nanomachines most suitably represent a practical MC systems. Therefore, mobile transmitter (Tx) and receiver (Rx) nanomachines are envisioned for better understanding of the practical MC system [14]. Further, due to the random movements of the Tx and Rx nanomachines, the statistics of the channel impulse response (CIR) change over timewhich makes communication even more challenging. It's more difficult to establish dependable communication between mobile nano-machines.

Furthermore, typically molecular concentration or the number of molecules in the receiver's observation region represents the received signal in MC system [15]. Also, an artificial cell or bacteria with the ability to release molecules for information exchange with another nanomachine can be used as the nanomachine [16]. If nanomachines know how far apart they are, they may plan their functionality, such as the transmission rate and the number of molecules released etc. [17]. For instance, a loss of channel capacity might come from either an excess or inadequate transmission rate. Nano-machines can change the transmission rate to achieve an ideal trade-off between these two qualities when the distance is known [18, 19]. Tx nanomachine with known channel state information can perform better decisions on the relevant parameters to balance the transmission time and energy [20]. It is again, important to mention that Signal to Noise Ratio (SNR) determines the strength of a signal to the strength of noise. Higher SNR indicate a better specification since there is more valuable data (the signal) than undesired data (the noise). A diffusive MC system designer can use an estimate of SNR to alter various parameters to regulate the degree of residual noise, allowing the SNR to be raised to the level required for optimal system performance. Where, remaining molecules from previously transmitted symbols are available at the present symbol in diffusion-based propagation, resulting in residual noise at the receiver. As the propagation scenario, transmission data rate, and other factors such as information molecule(N), delay for a fixed time(τ), emission time (T_e), the radius of the receiver(a_{rx}), variance of residual noise (σ_{nr}^{2}), diffusion coefficient(D_1) and flow velocity(ν) influence both the signal and residual noise. Therefore, SNR analysis in terms of different physical parameters is utmost requirement of the technocrats and researchers in the field of MC system [21].

The remaining of manuscript is organised as follows. The system model is introduced in Sect. 2. The proposed stochastic channel model is developed in Sect. 3. In Sect. 4, the simulation results are shown. Finally, Sect. 5 brings the paper to a conclusion.

2 System Model

MC system in an unbound three-dimensional fluidic environment with constant temperature and viscosity with a pair mobile Tx and Rx nanomachine is depicted in Fig. 1 [22]. The transmitter and receiver nano machines could both be mobile. Initial locations of Tx and Rx nanomachine are (0, 0, 0) and (x_0, 0, 0), respectively.

Whereas, the initial relative distance between Tx and Rx nanomachine is r_0. Also, Tx and Rx nanomachine are represented by transparent spheres of radius a_{tx} and a_{rx}, respectively. D_{tx} and D_{rx} are the diffusion coefficients for the Tx and Rx nanomachine respectively. For transmitting information to the receiver, the transmitter uses type A molecules. The A molecules are thought to be released in the centre of the transmitter. Also, it is assumed that each A molecule diffuses with a constant diffusion coefficient D_a that is independent of A molecule concentration [23] and that individual A molecule diffusion processes are independent of one another. It is assumed that the environment has a uniform flow of $v=[V_x, V_y, V_z]$, where $V_x, V_y and V_z$ are the components of v in the x, y, and z directions respectively of a Cartesian plane. The positions of the transmitter and receiver fluctuate over time due to Brownian motion and flow. The time-varying positions of the respectively at time t are denoted by $r_{tx}(t) and r_{rx}(t)$, respectively. At time $t_0=0$, we suppose the transmitter is at the origin of the Cartesian space, $r_{tx}\ (t_0=0)=[0, 0, 0]$, while the receiver is at $r_{rx}\ (t_0=0)=[x_0, 0, 0]$. As a result, $r(t_0)=r_{rx}\ (t_0)$ and $r(t_0=0)=r_0$ at time $t_0=0$.

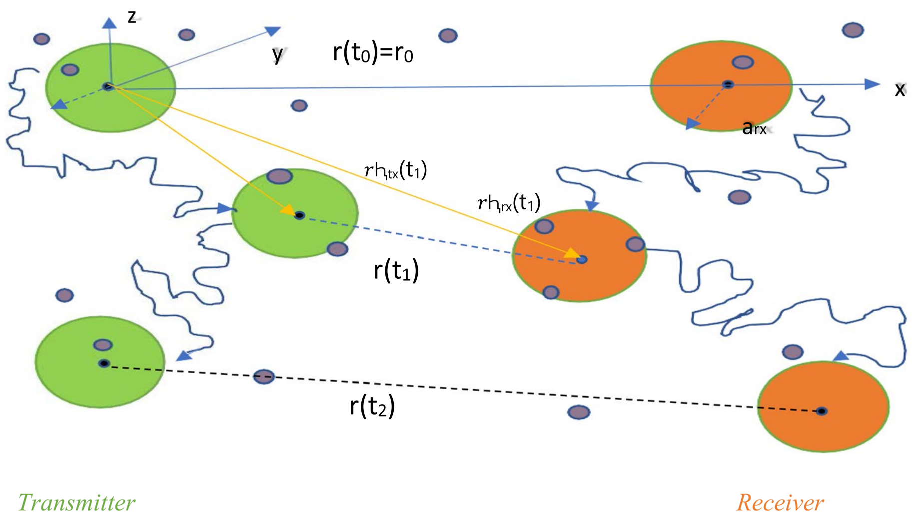

Fig. 1 System model

Application Specific application of the proposed system model includes, targeted drug delivery in which transmitted nanomachines carry the drug molecules and deliver them at Rx nanomachines. Molecular imaging is another area where mobile nanomachines plays a vital role. In this case, in a group namely mobile nano-machines such as, viruses carry certain proteins (GFPs) in order to collect the environmental information. Intracellular therapy is yet another application of proposed system model with movable Tx/Rx.

3 Proposed SNR under Different Scenarios

In this section analytical expressions for SNR under different scenarios has been derived. Further, $X_{tx}(t)$, $Y_{tx}(t)$, and $Z_{tx}(t)$, respectively represent 3-D location of Tx nanomachine. Whereas,$X_{rx}(t)$, $Y_{rx}(t)$, and $Z_{rx}(t)$ respectively represent 3-D location of Rx nanomachine. Also, $r_{tx}(t)$ and $r_{rx}(t)$ respectively represents position vector of Tx nanomachine and Rx nanomachines respectively.

3.1 Mobile Transmitter and Mobile Receiver

In this case, the transmitter and receiver, as well as the information molecules, travel with the bulk flow of the environment. In this situation. r(t) changes randomly due to the unpredictable movements of both the transmitter and the receiver.

The expression for SNR is given by [21]

$$\Upsilon = \frac{N^2}{\sigma_{nr}^2} \int_0^T h^2(t)dt \tag{1}$$

where, h(t) is the channel impulse response, N are the information molecules and σ_{nr}^2 is the residual noise variance.

The channel's impulse response, or the likelihood that a given signal will be received A molecule discharged at the transmitter's centre at $\tau = 0$ and observed inside the passive receiver's volume at $\tau > 0$ can be expressed as [22]

$$h(t) = \frac{V_{obs}}{\left(4\pi D_1 \tau\right)^{\frac{3}{2}}} \left(\exp \frac{-\left|\overrightarrow{r(t)}\right|^2}{4D_1 \tau} \right) \tag{2}$$

where, $V_{obs} = \frac{4\pi a_{rx}^2}{3}$ is the volume of the receiver, $D_1 = D_a + D_{rx}$ is effective diffusion coefficient, t is the time of release of molecules at transmitter and τ is the relative time of observation of the signalling molecules at the receiver for fixed value of t.

Furthermore, we introduce the following notations for clarity of presentation:

$$\alpha = \frac{1}{4D_1 \tau}, \Psi = \frac{V_{obs}}{\left(4\pi D_1 \tau\right)^{\frac{3}{2}}}$$

Therefore Eq. (2) becomes

$$h(t) = \Psi\left(\exp\frac{-\left|\overrightarrow{r(t)}\right|^2}{4D_1\tau}\alpha\right) \tag{3}$$

Putting the value of h(t) from Eq. (3) into Eq. (1) we get

$$\Upsilon = \left(\frac{N\Psi}{\sigma_{nr}}\right)^2 \int_0^T \left(\exp\left(-(r(t))^2\right)\right)^2 dt \tag{4}$$

The expression for r(t) is given as [17]

$$r(t) = \sqrt{\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right)\cdot\ln}\left(\frac{t}{t-T_e}\right) \tag{5}$$

where, T_e is emission duration.

Putting the value of r(t) from Eq. (5) into Eq. (4) we get

$$\Upsilon = \left(\frac{N\Psi}{\sigma_{nr}}\right)^2 \int_0^T \left(\exp\left(\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)\right)\alpha\right)^2 dt \tag{6}$$

Now, assuming $\left(\exp\left(\frac{6D_1 t}{T_e}.\left(t-T_e\right).ln\ln\left(\frac{t}{t-T_e}\right)\right)\alpha\right)^2$ part as S, and taking log on both sides we get

$$\log_e \mathrm{S} = \int_0^T \log_e\left(\exp\left(\frac{6D_1 t}{T_e}.\left(t-T_e\right).\ln\ln\left(\frac{t}{t-T_e}\right)\right)\alpha\right)^2 dt \tag{7}$$

Equation (7) can be rewritten as,

$$\log_e S = 2\int_0^T \left(\left(\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right)\cdot\ln\left(\frac{t}{t-T_e}\right)\right)\alpha\right)dt \tag{8}$$

Using integration by parts for solving the above Integration

$$\log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\int_0^T\left(\frac{6D_1T^2}{T_e}-6D_1T\right)dt - \int_0^T\left\{\left(\frac{d\ln\ln\left(\frac{t}{t-T_e}\right)}{dt}\right)\int_0^T\left(\frac{6D_1t^2}{T_e}-6D_1t\right)\right\}dt\right] \tag{9}$$

With various mathematical steps Eq. (9) can be given as (please refer Appendix).

$$\log_e \mathrm{S} = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e}-3D_1T^2\right)+D_1T^2-D_1T_eT+D_1T_e^2\left(\frac{T_e-T}{T_e}\right)\right] \tag{10}$$

Equation (10) can be rewritten as,

$$S = \exp\left\{2\alpha D_1\left[lnln\left(\frac{T}{T-T_e}\right)\left(\frac{2T^3}{T_e} - 3T^2\right) + T^2 - T_eT + T_e^2\left(\frac{T_e - T}{T_e}\right)\right]\right\} \tag{11}$$

From Eq. (11) and Eq. (6),

$$\Upsilon^o = \left(\frac{N}{\sigma_{nr}}\right)^2 \frac{a_{rx}^4}{36\pi(D_1\tau)^3}\left\{exp\left[\frac{1}{2\tau}\left(ln\left(\frac{T}{T-T_e}\right)\left(\frac{2T^3}{T_e} - 3T^2\right) + T^2 + T_eT + T_e^2\ln\left(\frac{T_e - T}{T_e}\right)\right)\right]\right\} \tag{12}$$

3.2 Fixed Transmitter and Mobile Receiver

In this case, the transmitter node is fixed while the receiver is mobile, and the effective diffusion coefficients is $D_1 = D_a + D_{rx}$.

For this condition the expression for channel impulse response is similar to the first condition. Therefore, the expression for SNR will also be the same.

$$\Upsilon^{tx} = \left(\frac{N}{\sigma_{nr}}\right)^2 \frac{a_{rx}^4}{36\pi(D_1\tau)^3}\left\{\exp\left[\frac{1}{2\tau}\left(\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2T^3}{T_e} - 3T^2\right) + T^2 + T_eT + T_e^2\ln\left(\frac{T_e - T}{T_e}\right)\right)\right]\right\} \tag{13}$$

3.3 Mobile Transmitter and Fixed Receiver

In this situation, since the receiver is fixed, D_1 is given by D_1=D_a.Similarly, the time-variant MC channel's impulse response can be represented as [22]

$$h(t) = \frac{V_{obs}}{\left(4\pi D_1\tau\right)^{\frac{3}{2}}}\exp\left(\frac{-\left|\overrightarrow{r(t)} - \tau\vec{v}\right|^2}{4D_1\tau}\right) \tag{14}$$

Which can be rewritten as

$$h(t) = \Psi\left(\exp\left(-\left|\overrightarrow{r(t)} - \tau\vec{v}\right|^2\alpha\right)\right) \tag{15}$$

Putting the value of r(t) from Eq. (5) into Eq. (15) gives,

$$h(t) = \Psi\left\{\exp\left(\left(-(r(t))^2 - \left(\vec{v}\tau\right)^2 + 2r(t)\vec{v}\tau\right)\alpha\right)\right\} \tag{16}$$

Putting the value of h(t) from Eq. (16) into Eq. (4),

$$\Upsilon^{rx} = \left(\frac{N\Psi}{\sigma_{nr}}\right)^2 \int_0^T\left\{\exp\left(\left(-\frac{6D_1t}{T_e}.(t-T_e)\cdot\ln\ln\left(\frac{t}{t-T_e}\right) - (\vec{v}\tau)^2 + 2\sqrt{(\frac{6D_1t}{T_e}\cdot(t-T_e)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)}(\vec{v}\tau)\right)\alpha\right)\right\}^2 dt \tag{17}$$

Now, assuming

$$A = \exp\left(\left(-\frac{6D_1t}{T_e}\cdot(t-T_e)\cdot\ln\ln\left(\frac{t}{t-T_e}\right) - (\vec{v}\tau)^2 + 2\sqrt{(\frac{6D_1t}{T_e}.(t-T_e)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)}(\vec{v}\tau)\right)\alpha\right) \tag{18}$$

Taking log both sides,

$$A = 2\alpha\left[\int_0^T -\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)dt - \int_0^T \left(\vec{v}\tau\right)^2 dt + \int_0^T 2\left(\vec{v}\tau\right)\sqrt{\left(\frac{6D_1 t}{T_e}.\cdot\left(t-T_e\right)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)dt\right.}\right] \quad (19)$$

With Eq. (17) and Eq. (17),

$$\Upsilon^{rx} = \frac{a_{rx}^4}{108\pi\left(D_a\tau\right)^3}\times\exp\left\{\frac{1}{2D_a\tau}\sqrt{\left[\begin{array}{c}\left(\frac{2D_aT^3}{T_e}-3D_aT^2)\right)\\ \left(T\cdot\ln\left(T_e\right)-\left(T-T_e\right)-\left(\left(T-T_e\right)\cdot\ln\left(T-T_e\right)-1\right)-T_e\cdot\left(\ln\left(-T_e\right)-1\right)\right)\\ -\left(\vec{v}\tau\right)^2T-D_a\left[\left(\ln\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2T^3}{T_e}-3T^2\right)\right)+T^2+T_eT+T_e^2\ln\ln\left(\frac{T_e-T}{T_e}\right)\right]\end{array}\right]}\right\} \quad (20)$$

4 Channel Impulse Response under Different Scenarios

This section Channel Impulse Response for three different scenarios discuss in subsequent sections have been presented.

4.1 Mobile Transmitter and Mobile Receiver

With Eq. (5) and Eq. (3) we get CIR for mobile Tx and Rx nanomachines as

$$h^{\circ}(t) = \Psi\left(\exp\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)\frac{1}{4D_1\tau}\alpha\right) \quad (21)$$

4.2 Fixed Transmitter and Mobile Receiver

For this condition the expression for channel impulse response is similar to the first condition. Therefore, the expression for CIR will also be the same.

$$h^{tx}(t) = \Psi\left(\exp\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right)\cdot\ln\ln\left(\frac{t}{t-T_e}\right)\frac{1}{4D_1\tau}\alpha\right) \quad (22)$$

4.3 Fixed Receiver and Mobile Transmitter

With Eq. (5) and Eq. (23) we get CIR for fixed Tx and moving Rx nanomachines as

$$h^{rx}(t) = \Psi\left(\exp\frac{\frac{6D_1 t}{T_e}\cdot\left(t-T_e\right).\ln\ln\left(\frac{t}{t-T_e}\right)-\left(\tau\vec{v}\right)^2}{4D_1\tau}\right) \quad (23)$$

5 Numerical Analysis

This section presents numerical simulation for the SNR of mobile molecular communication system. The set of simulation parameters are as follows, information molecule(N), delay for a fixed time(τ), emission time (T_e), the radius of the receiver(a_{rx}), residual noise of variance(σ_{nr}^2), diffusion coefficient(D_1) and flow velocity(ν).

In Fig. 2 we investigate the impact of time on SNR of the received signal when both transmitter and receiver are in motion for $D_1 = \{23,26,28,30,32,34,36,38\} * 10^{-2}$ m^2/s, N = {1000,1300,1500,2000,2200,2400, 2600}, $a_{rx} = \{0.033,0.035,0.037,0.039,0.042,0.044,0.046,0.048\}$ µm, $\tau = \{80,76,73,71,69,66,63,61\}$ µs. For simulation results, we kept the value of $\sigma_{nr}^2 = 1$, $T_e = 10^{-5}$ ms. From Fig. 2 is can be observed that as time of the release of molecules at the transmitter (T) increases, SNR also increases. This is because as time increases, the transmitter will emit molecules for a longer time. This will result in the increase of signal at the receiver. Thus, the SNR also increases.

In Fig. 3 we investigate the impact of concentration of information molecules on SNR of the received signal when both transmitter and receiver are in motion for $D_1 = \{50, 48, 46, 44, 42, 40, 38, 36\} * 10^{-5}$ m^2/s, T = {2,3,4,5,6,7,8,9} µs, $a_{rx} = \{0.0119, 0.0118, 0.0117, 0.0116, 0.0115, 0.0114, 0.0113, 0.0112\}$ µm, $\tau = \{85, 83, 81, 79, 77, 75, 73, 71\}$ µs.

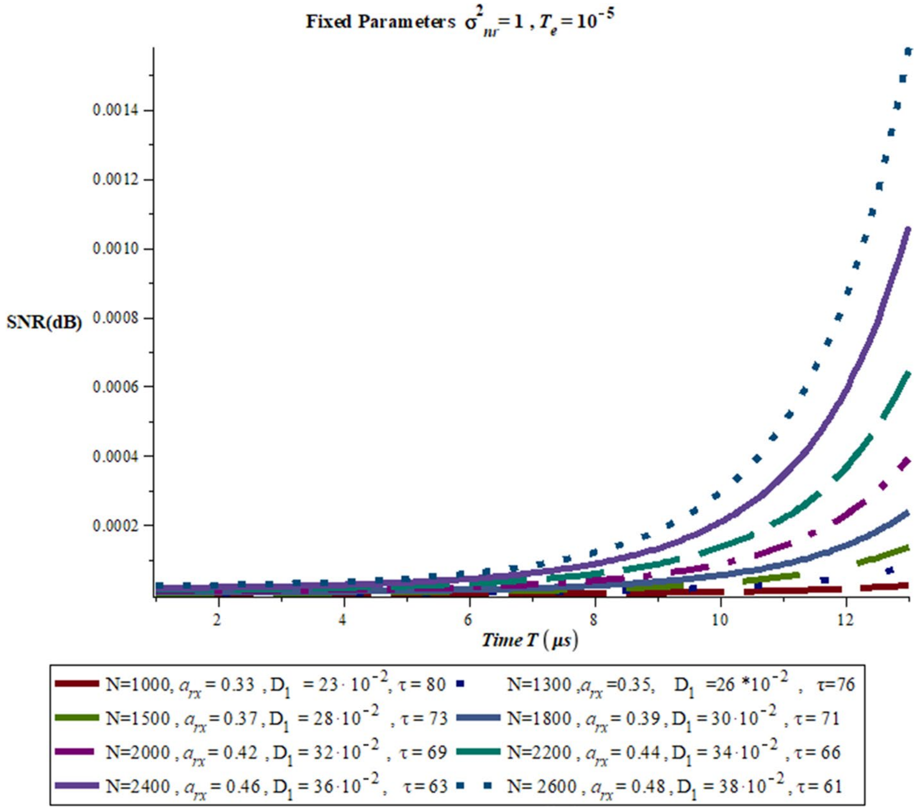

Fig. 2 Signal-to-noise-ratio v/s time for mobile transmitter and mobile receiver

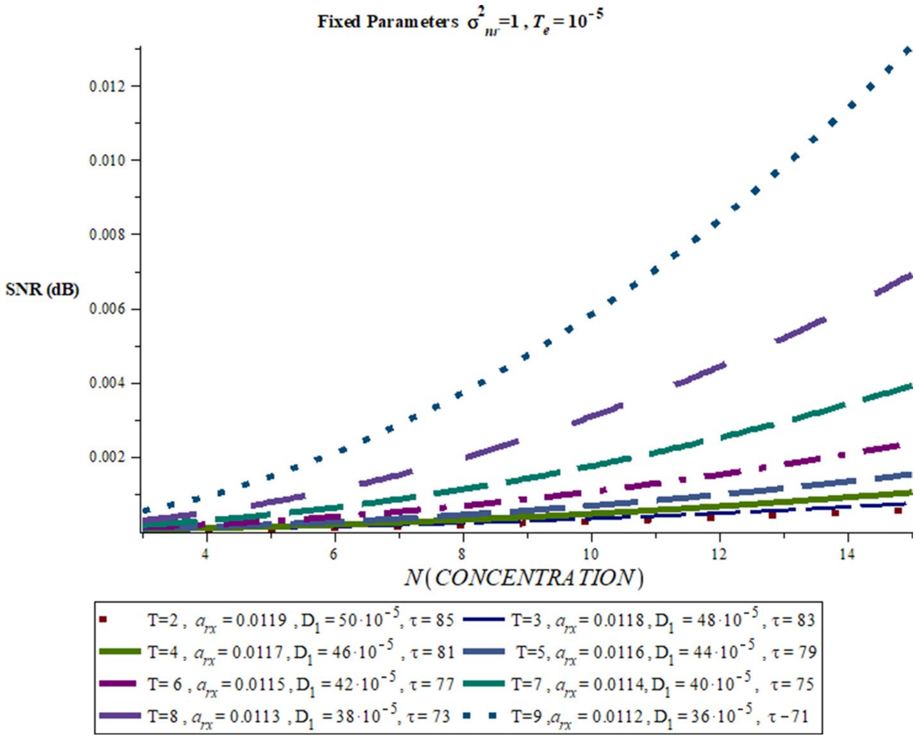

Fig. 3 Signal-to-noise-ratio v/s concentration for mobile transmitter and mobile receiver

For simulation results, we kept the value of $\sigma_{nr}^2 = 1$, $T_e = 10^{-5}$ ms. Figure 3 shows that as N (concentration of information molecules) increases, SNR also increases. This is because as N increases, the receiver will observe more molecules. This will result in the increase of signal at the receiver. Thus, the SNR also increases.

In Fig. 4 we investigate the impact of delay on SNR of the received signal when both transmitter and receiver are in motion for $D_1 = \{31, 30, 29, 28, 27, 26, 25, 24\} *10^{-5}$ m^2/s, T = {1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5} µs, a_{rx} = {0.00011, 0.00012, 0.00013, 0.00014, 0.00015, 0.00016, 0.00017, 0.00018} µm, N = {1000, 1010, 1020, 1030, 1040, 1050, 1060, 1070}. For simulation results, we kept the value of $\sigma_{nr}^2 = 1$, $T_e = 10^{-5}$ ms. Figure 4 shows that as τ increases, SNR decreases. This is because as τ increases, the receiver will take a longer time to capture molecules. This will result in a decrease in the signal at the receiver. Thus, the SNR also decreases.

In Fig. 5 we investigate the impact of time on the SNR of the received signal when both transmitter and receiver are in motion for $D_1 = \{46, 40.5, 40, 41, 42, 43, 44, 45\} *10^{-2}$ m^2/s, N = {0.0328, 0.0321, 0.0322, 0.0323, 0.0324, 0.0325, 0.0326, 0.0327}, T_e = {0.82, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8} µs, τ = {2.2, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1} µs. For simulation results, we kept the value of $\sigma_{nr}^2 = 1$, v = 1 m/s and a_{rx} = 0.5 µm. Figure 5 shows that as T (time of the release of molecules at the transmitter) increases, SNR also increases. This is because as time increases, the transmitter will emit molecules for a longer time. This will result in the increase of signal at the receiver. Thus, the SNR also increases.

In Fig. 6 we investigate the impact of the concentration of information molecules on the SNR of the received signal when both transmitter and receiver are in motion for D_1 = {5,

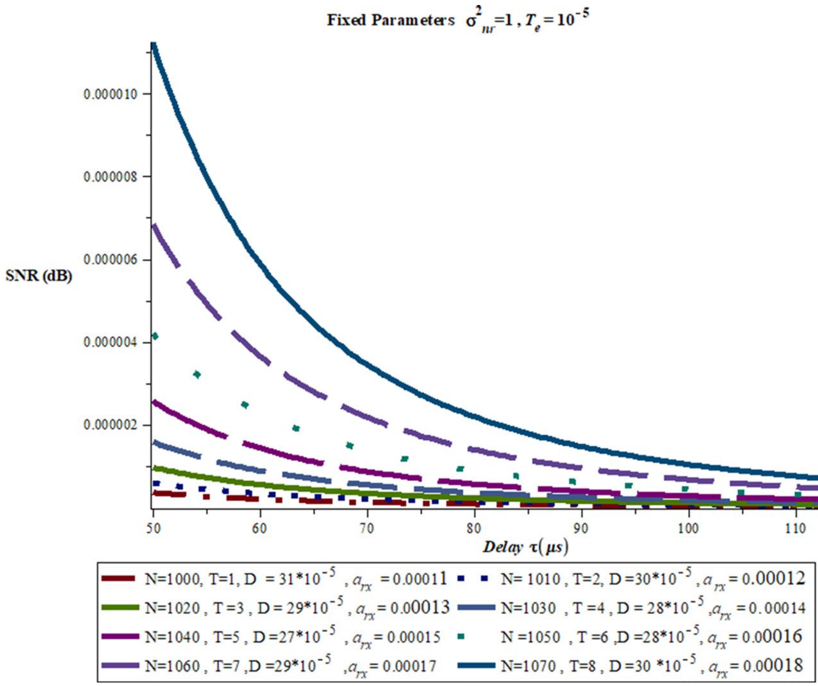

Fig. 4 Signal-to-noise-ratio v/s delay for mobile transmitter and mobile receiver

4, 3, 2, 0.8, 1} $*10^{-2}$ m^2/s, a_{rx} = {12.4, 12.6, 12.8, 13, 13.2} μm, τ = {2.5, 2.6, 2.7, 2.8, 3.0, 2.9} μs, T_e = {1.3, 1.2, 1.1, 1, 0.8, 0.9} ms. For simulation results, we kept the value of $\sigma_{nr}^2 = 1$, v = 1 m/s, T = 2 μs. Figure 6 shows that as N (concentration of information molecules) increases, SNR also increases. This is because as N increases, the receiver will observe more molecules. This will result in the increase of signal at the receiver. Thus, the SNR also increases.

In Fig. 7 we investigate the impact of delay on SNR of the received signal when both transmitter and receiver are in motion for D_1 = {2, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7} $*10^{-5}$ m^2/s, v = {1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7} m/s, a_{rx} = {2, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7} μm, N = {250, 249, 248, 247, 246, 245, 244, 243}. For simulation results, we kept the value of T = 2 μS $\sigma_{nr}^2 = 1$, T_e = 1 ms. Figure 7 shows that as τ increases, SNR decreases. This is because as τ increases, the receiver will take a longer time to capture molecules. This will result in a decrease in the signal at the receiver. Thus, the SNR also decreases.

In Fig. 8, we investigate the impact of τ (delay) on the channel impulse response of the molecular communication for mobile transmitter and mobile receiver for Ψ = {60, 62, 64, 66, 68, 70, 72, 74}, D_1 = {80, 82, 84, 86, 88, 90, 92, 94} $*10^{-1}$ m^2/s, r = {0.23, 0.24, 0.25, 0.26, 0.27, 0.28, 0.29, 0.30) μm, T = {110, 111, 112, 113, 114, 115, 116, 117} μs. For the simulation results, we kept the value of$T_e = 10^{-2}$ μs.

In Fig. 9, we investigate the impact of τ (delay) on the channel impulse response of the molecular communication for mobile transmitter and mobile receiver forΨ = {60, 62, 64, 66, 68, 70, 72, 74}, D_1 = {80, 82, 84, 86, 88, 90, 92, 94} $*10^{-1}$ m^2/s, r = {0.23, 0.24, 0.25, 0.26, 0.27, 0.28, 0.29, 0.30) μm, T = {110, 111, 112, 113, 114, 115, 116, 117} μs. For the simulation results, we kept the value of$T_e = 10^{-2}$ μs, v = 2 m/s.

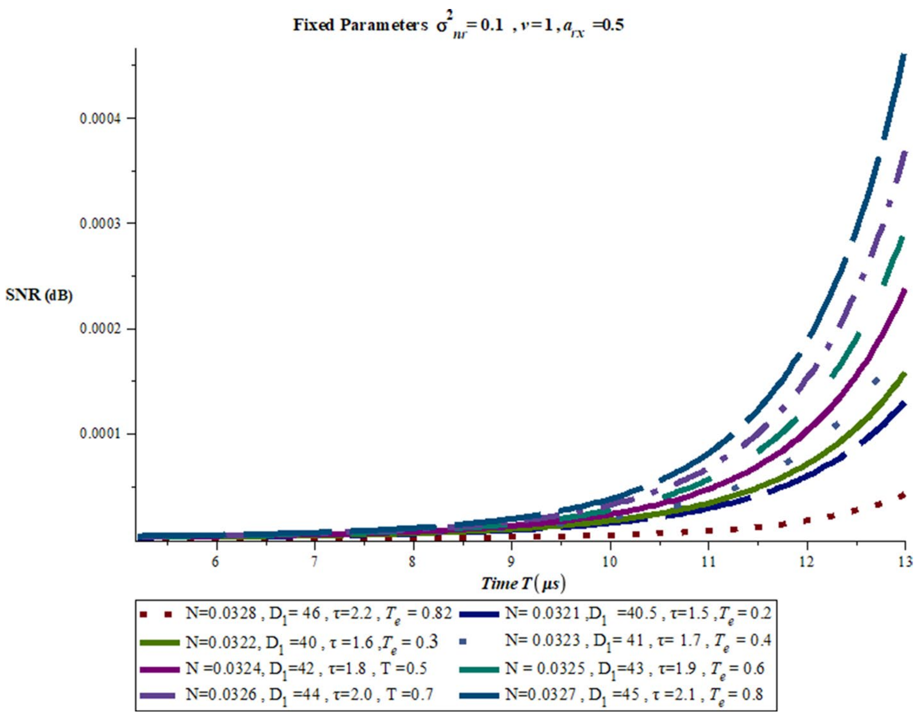

Fig. 5 Signal-to-noise-ratio v/s time for mobile transmitter and fixed receiver

6 Conclusion

Mobile molecular communication system is presented under different practical scenarios. The effects of mobility of transmitter and/or receiver nano-machines on SNR under different scenarios have been investigated. In particular, three scenarios namely, both the transmitter and receiver moving, only transmitter is moving and only receiver is moving have been considered. It has been observed that an increase in time of the release (T) of molecules from the transmitter (Tx) results in an increases in SNR. It shows perfect agreement with the theory. As longer transmission duration of the information molecules will certainly results in more information or signal which leads to increase in SNR. Also, an increase in the concentration of information molecules (N) results in an increase in SNR. This is because as N increases, the receiver will observe more molecules. This will result in the increase of signal at the receiver. Finally, it is observed that as transmission delay (τ) increases, SNR decreases. This is evident as τ increases, the receiver will take a longer time to capture molecules. This will result in a decrease in the signal at the receiver. Thus, the SNR also decreases. Mobile MC systems under a variety of scenarios presented in this manuscript provide better understanding and quantification of the received signal. Statistical measures such as, PDF, CDF along with different performance measures such as outage probability, throughput, Capacity of the communication system are various future aspect of the presented work.

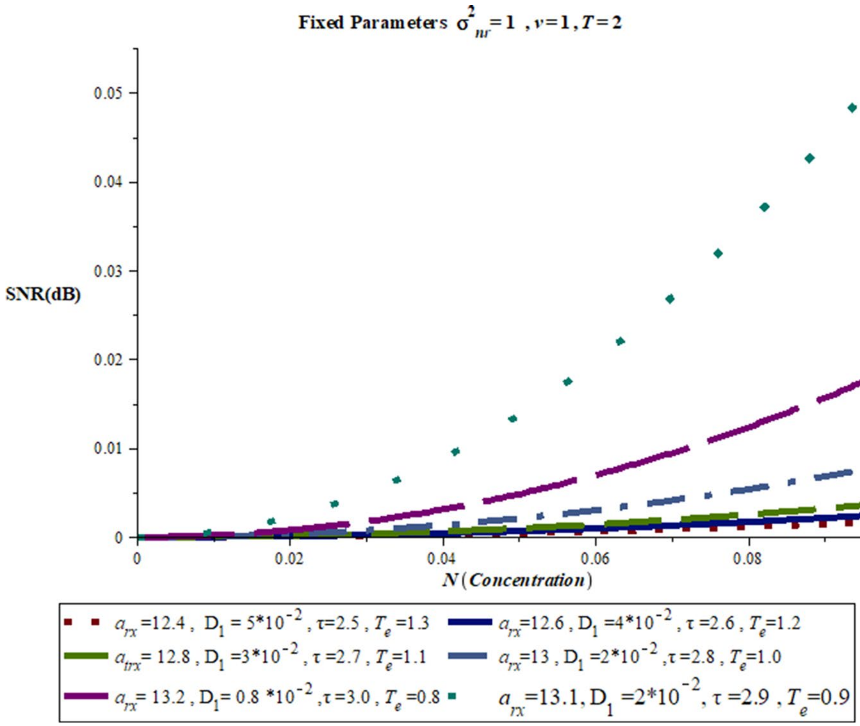

Fig. 6 Signal-to-noise-ratio v/s concentration for mobile transmitter and fixed receiver

Appendix A

We have,

$$\log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e}-3D_1T^2\right)-\int_0^T\left(\frac{t-T_e}{t}\right)\left(\frac{(t-T_e)-t}{(t-T_e)^2}\right)\left(\frac{2D_1t^3}{T_e}-3D_1t^2\right)dt\right] \tag{A1}$$

$$\Rightarrow \log_e S = 2\alpha\left[ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e}-3D_1T^2\right)-\int_0^T\left(\frac{t-T_e}{t}\right)\frac{(-T_e)}{(t-T_e)^2}\left(\frac{2D_1t^3}{T_e}-3D_1t^2\right)dt\right] \tag{A2}$$

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e}-3D_1T^2\right)+T_eD_1\int_0^T\left(\frac{t}{t-T_e}\right)\left(\frac{3T_e-2t}{T_e}\right)dt\right] \tag{A3}$$

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e}-3D_1T^2\right)+D_1\int_0^T\left(\frac{t}{t-T_e}\right)\left(\frac{T_e-t+T_e-t+T_e}{T_e}\right)dt\right] \tag{A4}$$

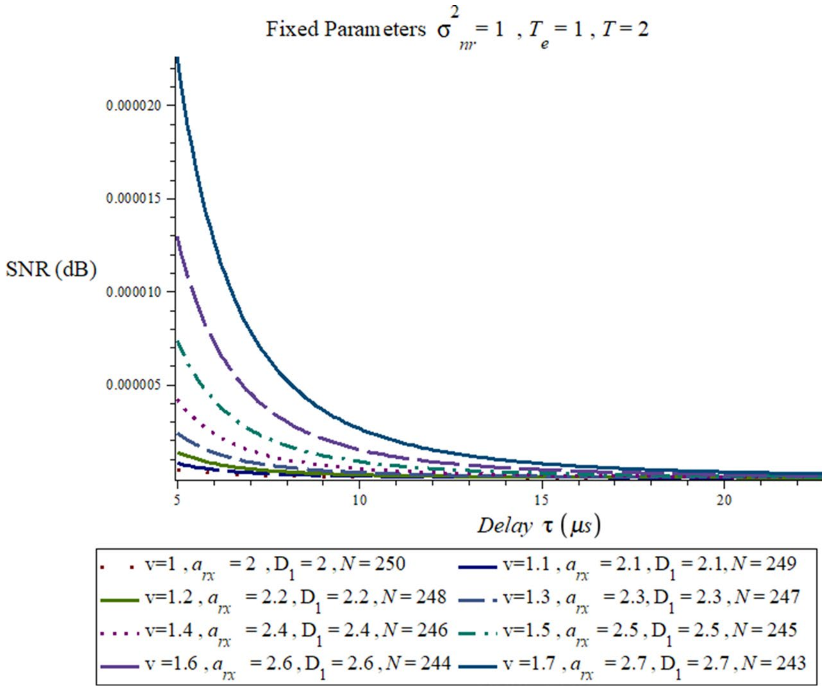

Fig. 7 Signal-to-noise-ratio v/s delay for mobile transmitter and fixed receiver

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e} - 3D_1T^2\right) + D_1\int_0^T 3t + \left(\frac{t^2}{T_e - t}\right)dt\right] \tag{A5}$$

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e} - 3D_1T^2\right) + \frac{3D_1T^2}{2} + D_1\int_0^T \frac{t^2 + T_e^2 - T_e^2}{T_e - t}dt\right] \tag{A6}$$

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e} - 3D_1T^2\right) + \frac{3D_1T^2}{2} - D_1\int_0^T (t+T_e)dt + D_1\int_0^T \frac{T_e^2}{T_e - t}dt\right] \tag{A7}$$

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e} - 3D_1T^2\right) + \frac{3D_1T^2}{2} - \frac{D_1T^2}{2} - D_1T_eT + D_1\int_0^T \frac{T_e^2}{T_e - t}dt\right] \tag{A8}$$

$$\Rightarrow \log_e S = 2\alpha\left[\ln\left(\frac{T}{T-T_e}\right)\left(\frac{2D_1T^3}{T_e} - 3D_1T^2\right) + D_1T^2 - D_1T_eT + D_1\int_0^T \frac{T_e^2}{T_e - t}dt\right] \tag{A9}$$

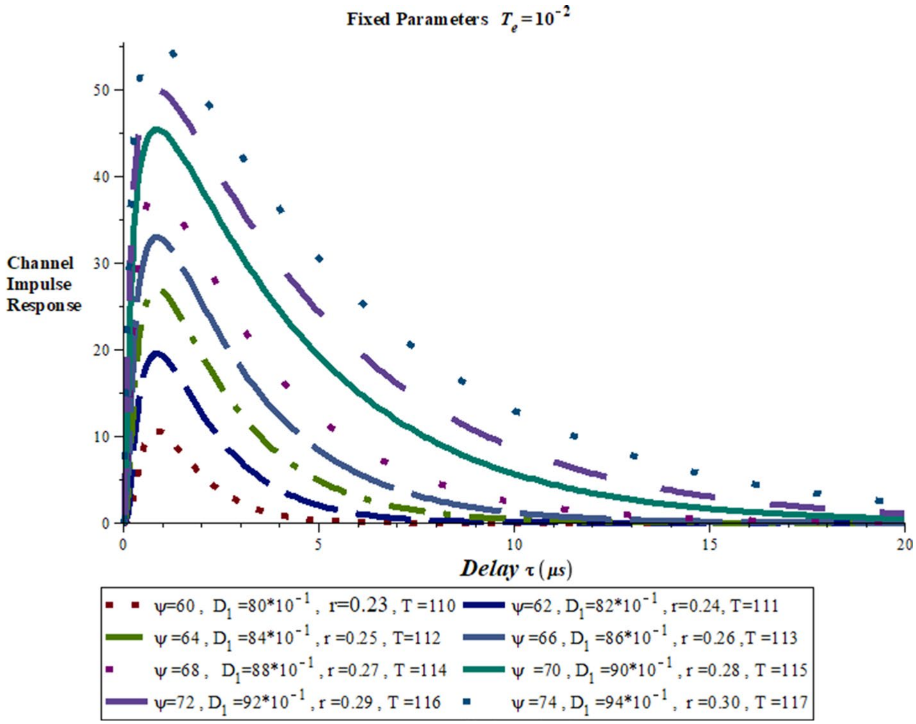

Fig. 8 Channel impulse response v/s delay for mobile transmitter and mobile receiver

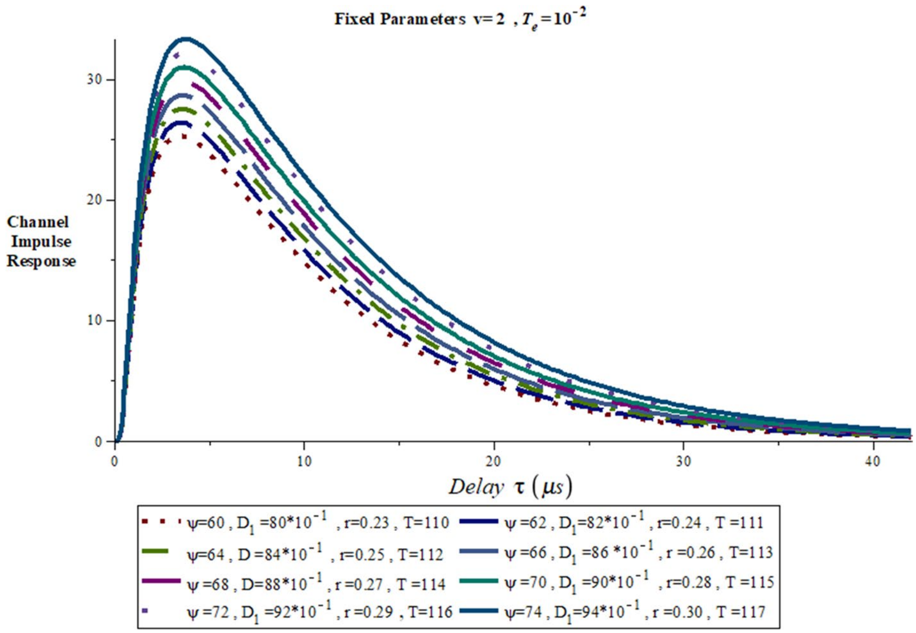

Fig. 9 Channel impulse response v/s delay for mobile transmitter and fixed receiver

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Declartions

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