**Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 11(4): 2695-2705, 2021**
**Journal of the Institute of Science and Technology, 11(4): 2695-2705, 2021**
**ISSN: 2146-0574, eISSN: 2536-4618**
**Elektrik Elektronik Mühendisliği / *Electrical Electronic Engineering*** **DOI: 10.21597/jist.918571**
**Araştırma Makalesi / *Research Article***
**Geliş tarihi / Received: 17.04.2021** **Kabul tarihi / Accepted: 12.08.2021**

**To Cite:** Isik I, Isik E, 2021. Comparison of the Mobile and Fixed Nano/Micro-Scale Systems by Using Monte Carlo Simulation for Different Viscosity Values. Journal of the Institute of Science and Technology, 11(4): 2695-2705.

# Comparison of the Mobile and Fixed Nano/Micro-Scale Systems by Using Monte Carlo Simulation for Different Viscosity Values

Ibrahim ISIK[1], Esme ISIK[2*]

**ABSTRACT:** Nano networks that are defined as a communication of nano-sized devices (Nano Machines) are a new nano/micro-scale system subject. In this study, on the contrary to the literature, a mobile nano network model has been used to analyze the proposed system in a different viscosity environment by using some Physics law. Because it is known that besides the molecules, which transport information between transmitter and receiver, the transmitter and receiver parts of the biological cells can be mobile in the blood or any other fluid media. In addition, the effect of viscosity which is an important part of the environment of the nano-device systems and distance between transmitter and receiver are analyzed detailed in Matlab with analytical and simulation results by comparing the fixed and mobile nano scale systems. It is concluded that when the receiver and transmitter are mobile, distance between them changes and finally this affects the probability of the received molecules at the receiver. As is expected, the fraction of received molecules is obtained the highest when the viscosity of the environment and distance are the lowest for both fixed and mobile system models. Also positions of receiver and transmitter show that when the distance of transmitter and receiver increases from the origin, fraction of received molecules decreases.

**Keywords:** Nano networks, viscosity, fraction of received molecules, Fick's law.

[1]Ibrahim ISIK (**Orcid ID:** 0000-0003-1355-9420), İnönü University, Engineering Faculty, Department of Electrical Electronics Engineering, Malatya, Turkey
[2] Esme ISIK (**Orcid ID:** 0000-0002-6179-5746), Malatya Turgut Özal University, Department of Optician, Malatya, Turkey

***Corresponding Author:** Esme ISIK, e-mail: esme.isik@inonu.edu.tr

## INTRODUCTION

A lot of studies have been carried out about the communication of nano-devices in recent years (Bi et al. 2021; Koca et al. 2021; Lin et al. 2019; Rusinque and Brenner 2019). The transmitter (Tx) and receiver (Rx) parts are investigated to analyze transmitted and received molecules in a fluid media. However, the Rx part and the received signal are generally considered to analyze Molecular Communication (MC) systems.

For instance, channel transfer function and the number of received molecules with a point transmitter and fully and half fully absorbing spherical receiver formulation for Molecular Communication via Diffusion (MCvD) are analyzed in (Yilmaz et al., 2014). Pulse peak time and pulse amplitude concerning for the distance between transmitter and receiver, and attenuation, propagation delay is analyzed for MCvD channel in a 3-dimensional (3-D) environment. Finally, it is obtained that when the distance between Tx and Rx increases pulse peak time also increases and pulse amplitude decreases for both analytical and simulation studies.

In addition to the receiver, some receptor models which are placed on the receiver randomly are considered as antenna using graphene and carbon nanotubes due to their prominent sensing capabilities in the literature. In (Felicetti et al. 2018; Singh and Singh 2016), a novel architecture of molecular antenna model which can be used for receiving part of MC system and some coding techniques are introduced. Different shapes of a shell such as a sphere and cylinder which is placed on the receiver is considered as antenna and number of absorbed molecules are increased with these shells.

In addition to fixed MC models, there are also mobile MC models in the literature. Because some projected applications of MC models such as human body monitoring and drug delivery need mobile nanomachines in the vessel (Okaie et al. 2018). In (Wu et al. 2017), the closed form expression of unbounded communication channel for expected hitting rate is derived using a mobile spherical receiver and fixed point transmitter. In (Lin et al. 2019), an adaptive threshold mechanism, signal to interference, and bit alignment scheme are investigated for a simple and effective demodulation scheme for a mobile receiver with a speed of drift $V = 7.9 \times 10^{-4}$ *m/s* and diffusion coefficient of $D = 2.42 \times 10^{-10}$ $m^2/s$. The parameters such as the ratio of flow and receiver velocity and symbol interval are analyzed in terms of Bit Error Rate (BER) using a fixed transmitter and mobile receiver. BER with or without Inter Symbol Interference (ISI) mitigation for different transmitting intervals is calculated and analyzed in this study (Lin et al. 2019).

In (Chang et al. 2018), correct signal detection systems with an ISI mobile MC mitigation approach are suggested. Due to the randomly varying Channel Impulse Response) (CIR) in mobile MC systems, current detection schemes for static MC systems are not suitable for the mobile MC.

In (Kumar 2020), an iterative maximum probability prediction of the position of the nanomachine is calculated. Particularly, for nanomachine localization, both signal-dependent noise and ISI effects are taken into account using Hammersley–Chapman–Robinson Lower Bound (HCRLB) to get insight into the performance of the suggested estimator. The receiver can predict CIR and set an effective detection threshold in advance with knowledge of distance. The distance calculation and developing a mechanism between nanomachines should therefore be a primary justification for the design of MC systems using a neural networks or deep neural networks (Niitsoo et al. 2018; Farsad and Goldsmith 2018.; Huang et al. 2020; Wu and Tseng 2021).

In (Okaie et al. 2019), a systematic study of the new field of mobile Molecular Communication science is being discussed. Finally, a mobile model of bionanomachines is introduced to discuss how groups of such bionanomachines working in an agreement can provide useful features. Furthermore, some features relating to mobile Molecular Communication to the principle of cooperative drug delivery are illustrated to outline and address unresolved research challenges in this field (Walsh, 2013).

In addition to theoretical and simulation studies there are also some industrial application of MC systems. MC systems are a perfect example of innovation from technology. From a technical point of view, MC is not a single technology, but a systematic approach in which devices, networks, computing infrastructure, and software used to extract information. Real-world objects and places are equipped with devices containing sensors and actuators to capture and control physical properties. Different types of networks are required, depending on the type of object of interest, to collect data from devices and enable remote control. In order to analyze and discuss data and automate processes involving various physical objects, special software is required to process the data, depending on the needs and goals of those interested (Chouhan and Sharma 2020; Koca et al. 2021; Schurwanz et al. 2021).

The use of MC in the medical field is generally made for the diagnosis and treatment of diseases that have no cure today. In this context, there are many studies in the literature in which nano-robots and cell models (Barros et al. 2018) and electronic circuits generally designed on a chip are proposed (Farsad et al. 2012). For example, in the study on nano-scale neuro-spike communication systems, a new model has been proposed for the development of diagnosis and treatment methods in nerve diseases, inspired by digital communication systems (Balevi et al. 2013). As a result, it was concluded that there is a potential to treat some incurable or difficult nervous diseases with biologically inspired artificial Molecular Communication systems, but this is not possible with current technology. It is thought that by creating artificial immune systems and injecting them into the body, a significant contribution can be made to the treatment of many diseases in the future. These injected systems can be trained in advance, some of them can be used to find a pathogen in the body, and some of them can be used to destroy a pathogen, just like in a real immune system (Balevi et al. 2013; Okaie et al. 2018).

In this present study, the effect of viscosity which is an important part of the environment of the nano-device systems and distance between transmitter and receiver are analyzed detailed in Matlab with analytical and simulation results for fixed and mobile nano-scale systems. In literature, generally hitting probability of the transmitted molecules is analyzed at the receiver part using fixed viscosity of environment and fixed system models (Akkaya et al. 2015; Isik et al. 2020). In addition to viscosity, position of transmitter and receiver is also given with respect to time step by comparing the fraction of received molecules.

The rest of the paper is as follows. In Section 2, the proposed system model is explained for simulation and analytic results. In Section 3, the proposed system model is analyzed and results are given for both mobile and fixed models. Finally, Section 4 concludes the paper.

## MATERIALS AND METHODS

In nano networks, chemical transceiver systems may be more favorable for implementation issues in transmitting information from transmitter to receiver or vice versa. In several fields, such as dentistry, bio-medical, environmental monitoring, industrial and defense purposes, these models can be used (Akkaya et al., 2015). Messenger molecules (MM) that transmit signals to mobile and fixed MCvD systems between Tx and Rx. At this size, Brownian motion is modeled on the spontaneous movement/diffusion of MM that is governed by the combined forces applied to the MM by the liquid molecules due to thermal energy within a fluid (Moore et al., 2009; Yilmaz and Chae, 2014). There are two current mechanisms which are drift and diffusion that cause the charges moving. Charge moves under the influence of an electric field since the applied field exerts a force,

$$F=qE, \tag{1}$$

on the charge carriers where $E$ and $F$ represent applied field and force respectively. This movement results a current which is known as drift current,

$$I_d = nqV_dA, \tag{2}$$

where $I_d$, $V_d$, $A$, $n$ and $q$ are drift current, drift velocity of charge carrier, area of the medium, number of charge carriers per unit volume, charge of electron respectively. The mobility carrier, $\mu$ can be measured how easily charge carriers move under the influence of an applied field or $\mu$ determines how mobile the charge carriers are (Walter and Vreeburg, 1989),

$$\mu = V_d/E. \tag{3}$$

If the medium is at thermodynamic equilibrium (there is no applied field) the carrier have thermal energy of $\frac{k_BT}{2}$ for 1-D (one dimensional) and the thermal energy and velocity of the electron for 3-D (three dimensional) environments are given below,

$$E = \frac{3k_BT}{2} \quad \text{and} \quad V_{th} = \sqrt{\frac{3k_BT}{m^*}}\ , \tag{4}$$

where $V_{th}$, $k_B$, $m^*$ and $T$ refer to thermal velocity of electron, Boltzman Constant ($1.38 * 10^{-23}$J/K), the effective mass and temperature of the medium (Kelvin), respectively. If there is no applied field, the movement of the molecules will be completely random and this randomness causes no net current flow. Molecules move in the system due to its thermal energy or applied field but they collide with each other. The average time taken between collisions is called relaxation time or mean free time, $\tau$. So we can define the mobility as,

$$\mu = \frac{q\tau}{m^*}. \tag{5}$$

A concentration gradient produces a pressure gradient that also generates the force on the molecules causing to move them (Walter and Vreeburg, 1989). According to the electrical mobility equation, the diffusion constant ($D$) for charged particles is defined as follow,

$$D = \frac{\mu k_BT}{q} \tag{6}$$

The diffusion process causes the substance concentrations in a system to equalize or occurs by the distribution of an equilibrium concentration resulting from the random movement of the system elements (Guidoni and Aldao, 2002; Peskir, 2003). Einstein showed that the diffusion coefficient $D$ in an infinitely dilute solution is given by the equation,

$$D = \frac{k_B\,T}{f} \tag{7}$$

where $f$ is the frictional coefficients of the particle. While the value of $f$, in general is unknown, G. Stokes (Charbonneau et al., 2018) showed that for the special case of a spherical particle of radius $R_B$ which is moving with an uniform velocity in a continuous fluid of viscosity $\eta$, the frictional coefficient $f$ is given by

$$f = 6\pi\eta R_B \tag{8}$$

It is known that the transfer of information generally takes place in the form of free diffusion movement of molecules in the environment. The feature of the transmission medium is determined with diffusion coefficient; $D$ for the diffusion of spherical uncharged particles through a liquid is given below (Walter and Vreeburg, 1989). Einstein (Breki and Nosonovsky, 2018) pointed out that if one can assume that this equation also applies to spherical molecules, then their diffusion coefficient and viscosity should be given by the equation,

$$D = \frac{k_BT}{6\pi\eta r} \text{ and } \eta = \frac{k_BT}{6D\pi r}\ . \tag{9}$$

The Molecular Communication channels are primarily divided into two groups, the first being pure diffusive channels where the molecules only pass between the two regions due to the concentration gradient it is known as the Brownian motion, the movement of information molecules within the pure diffusive medium (Iwasaki et al., 2017). Flow-based diffusion channels are the second type of channel, where the location of molecules depends on the fluid flow along with the diffusion. Communicating of NMs is required to pass information molecules into the channel during Molecular Communication and the mobility of NMs affects the hitting rate of information molecules at the receiver nanomachine. The mobility of NMs and their effect on the end-to-end efficiency of diffusive Molecular Communication is therefore worth investigating (Walsh, 2013; Wu et al., 2017). Hitting probability of a transmitted molecule in 1-D and 3-D environments is as follows:

$$Fhit_h^{1D}\,(d,t) = \frac{d}{\sqrt{4\pi D t^3}}\, e^{\frac{-d}{4Dt}} \tag{10}$$

and in a 3-D environment obtained as

$$Fhit_h^{3D}\,(d,t)=\left(\frac{r_r}{r_r+d}\right)\frac{d}{\sqrt{4\pi D t^3}}\, e^{\frac{-d}{4Dt}} \tag{11}$$

where $D$, $r_r$, and $d$ show the diffusion constant, the radius of the receiver, and distance from the transmitter to the receiver, respectively.

The proposed MC system model consists of point transmitter, receiver and carrying molecules. The shape of the receiver is chosen as a sphere in this study. The transmitter is assumed to be a single point in the space. MMs are used as the information carriers between transmitter and receiver. Firstly, the receiver is placed at the origin (0, 0, 0) and the transmitter is placed randomly at a distance $d$ from the receiver in 3-D environment as shown in Fig. 1. The position of the transmitter is chosen randomly at every time step to do a more realistic analysis. The transmitter and receiver both reside in a fluid propagation medium. The medium is believed to be unconfined, thereby expanding in all directions to infinity. They possibly arrive at the receiver after the molecules are released to the medium where they propagate according to Brownian motion. System parameters used in the proposed models are also given in Table 1.

**Table 1.** System parameters

| | |
|---|---|
| Radius of receiver, $r_r$ | 3.101 $\mu m$ |
| Distance between receiver and transmitter, d | 5, 10 $\mu m$ |
| Radius of receptor, $r_s$ | 0.01 $\mu m$ |
| Number of receptor | 7200 |
| Number of transmitted molecules | 20000 |
| Number of simulation | 100 |
| Viscosity, $\eta$ | 54, 34, 27, 13, 4 $\mu kg/ms$ |

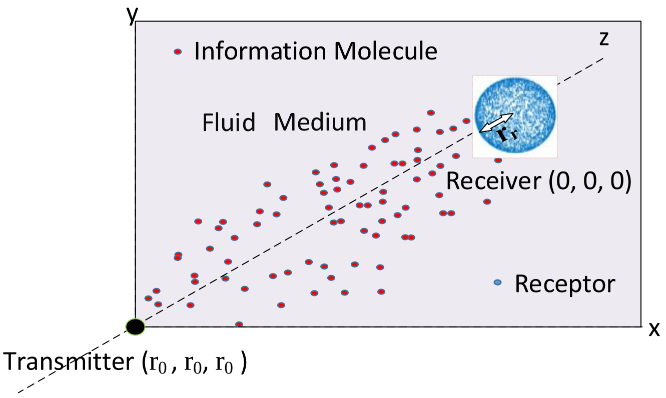


**Figure 1.** The proposed MC model

## RESULTS AND DISCUSSION

### Fixed System Model

Molecules are emitted from transmitter with Brownian motion principle and at each time step of the simulation, number of received molecules is calculated. Then fraction of received molecules is analysed for different system or environment parameters as given below. In this model firstly, the viscosity of the medium, position of the receiver and transmitter kept constant. Fixed MC model is analyzed for two different *d* values as shown in Fig. 2. When the distance between transmitter and surface of the receiver is chosen as 5 $\mu$m the fraction of received molecules is obtained as almost 1 however when this distance is chosen as 10 $\mu$m then the fraction of received molecules is obtained almost 0 for 1 second simulation time. Fraction of received molecules cannot seen fully for d=10 $\mu$m when simulation time is chosen 1 second because molecules reach to receiver very late. Analytical and simulation results of the proposed model are also obtained same as shown in Fig. 2. Secondly, the proposed fixed MC model is analyzed for different viscosity values of the environment as shown in Fig. 3. In this model, position of the receiver and transmitter kept constant. When the viscosity of environment decreased, the fraction of the received molecules also increased as expected. Because viscosity has a reverse relationship with Diffusion constant as given in Eq 9. When the viscosity decreased the force against to molecules in the fluid environment decreased and then molecules move faster and they reach to receiver with a higher probability.

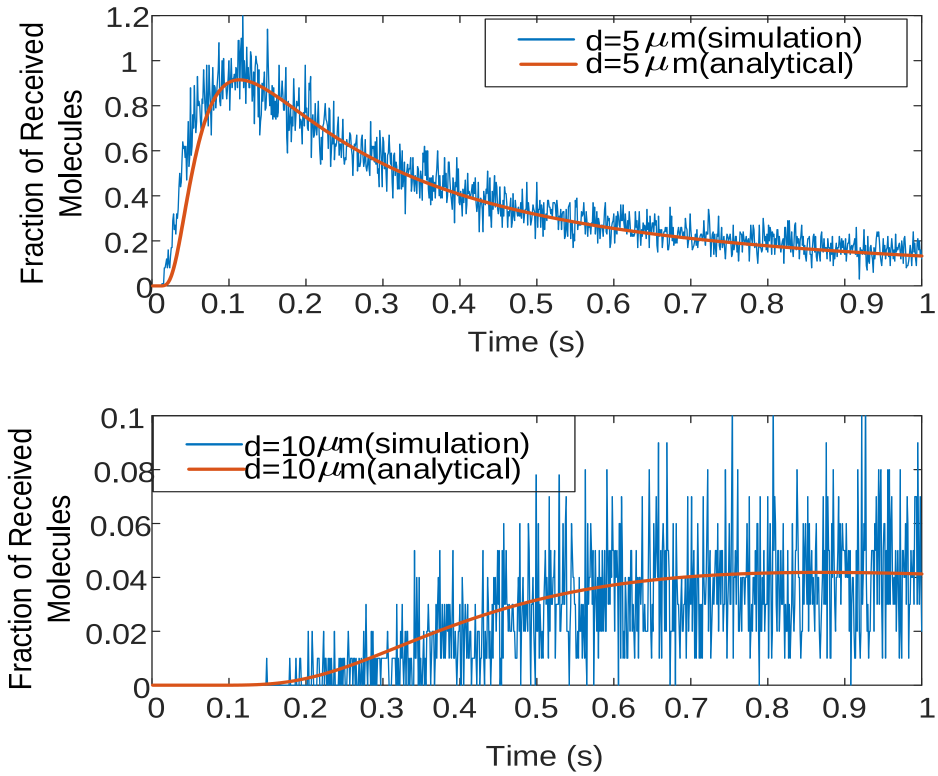


**Figure 2.** Analytical and simulation results of the fraction of received molecules for the fixed system model with different d values of 5 and 10 µm

### Mobile System Model

Secondly, the proposed model is analyzed for a mobile MC model for d=5 and 10 $\mu m$. These distances show first position of transmitter and receiver because the proposed model is mobile in this part so position of transmitter and receiver changes at each time step and also distance between them changes. In a mobile MC model, both transmitter and receiver are chosen as mobile for analytical and simulation analysis. As shown from the Fig. 4, when the distance increases number of the fraction decrease as expected. However, fraction of received molecules is obtained more for mobile system because of the mean distance between transmitter and receiver in the model. On the other hand, the general shape of fraction of received molecules are same for fixed and mobile system models. However number of fraction molecules are seen clearer for mobile system model because of mobility of transmitter and receiver.

In Fig. 5, $\eta_{Rx}$ and $\eta_{Tx}$ show viscosity values of transmitter and receiver in other words mobility of them. In this system model, viscosity of environment is chosen as fixed on the other hand viscosity of the transmitter and receiver are chosen as mobile. When the mobility of transmitter and receiver is analyzed for different viscosity values of 34 and 4 $\mu kg/m$s, the fraction of received molecules is obtained higher for the highest viscosity values of transmitter and receiver as expected as shown in Fig. 5.a. Because when the viscosity increases, both the transmitter and receiver move less and this will causes a less mean distance between transmitter and receiver. It is known that when the distance increases between transmitter and receiver the communication performance decreases. To show that, the position of the receiver is also shown in Fig. 5.b and c for the viscosity of 27 and 4 $\mu kg/m$s. The position values of transmitter and receiver is obtained between 1 and -1 for viscosity value of 4 and -0.2 and 0.2 for viscosity value of 34. Simulation run time is chosen as 1 second with 1000 time steps and 1000 different position values are used for this analysis.

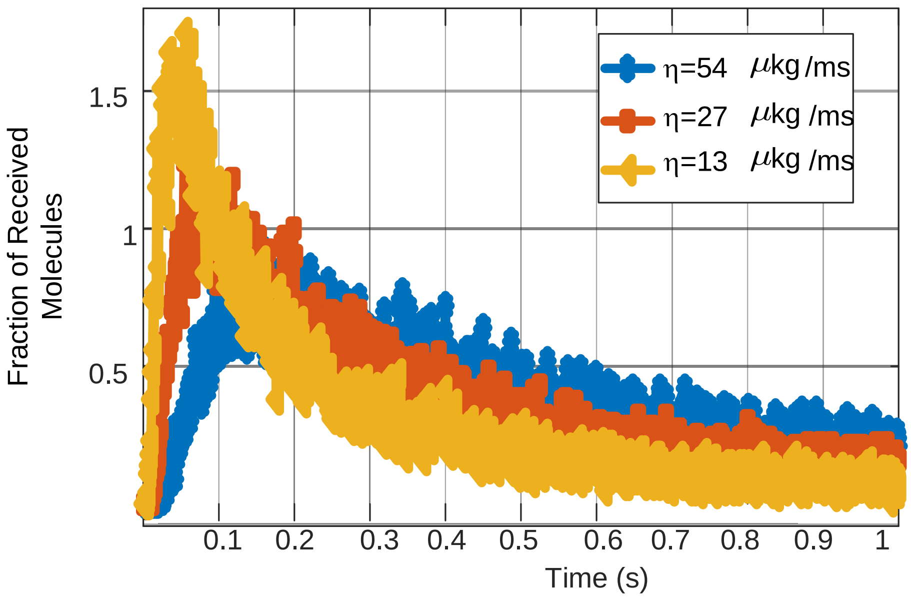


**Figure 3.** The fraction of received molecules with a different value of viscosity for simulation results of the fixed receiver model

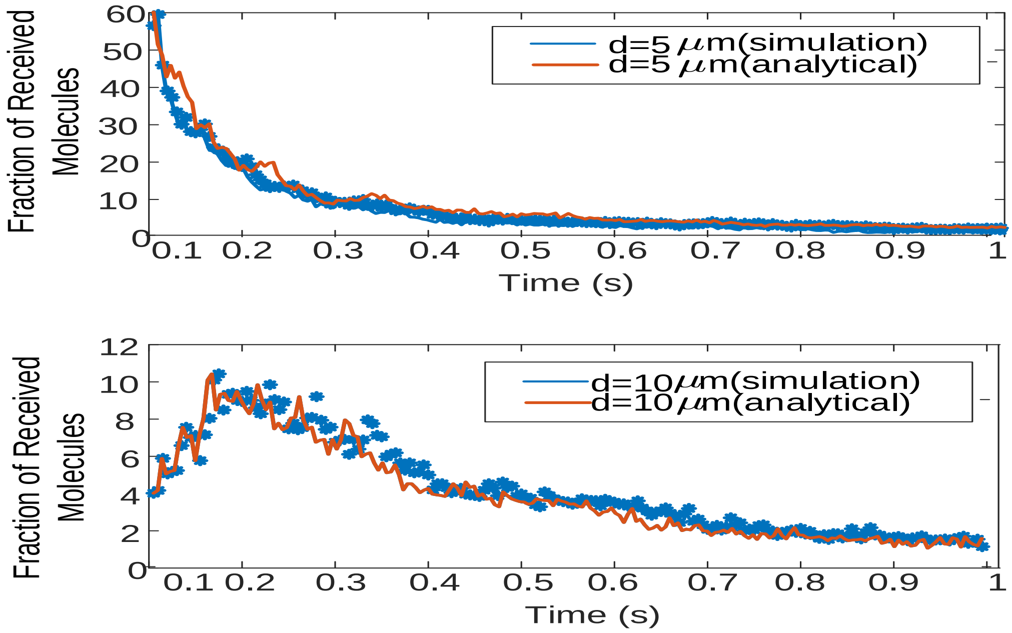


**Figure 4**. Analytical and simulation results of the fraction of received molecules for the mobile system model with different *d* values of 5 and 10 μm

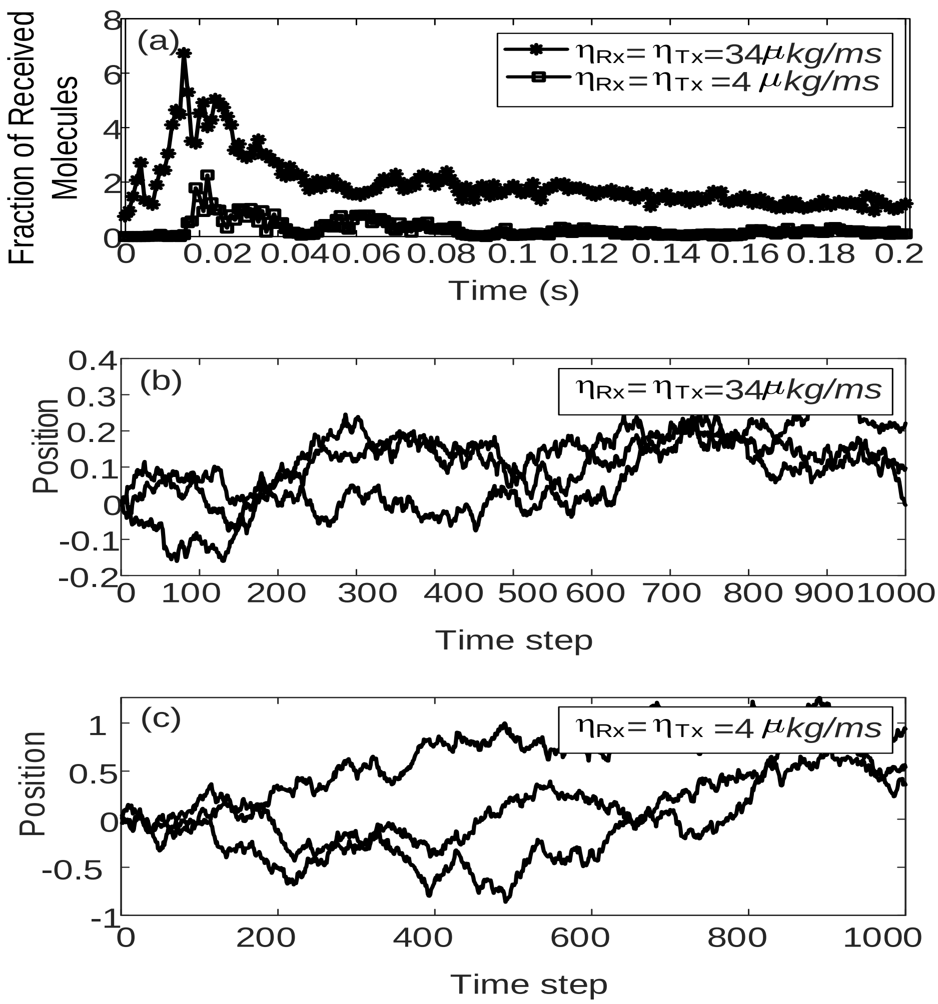


**Figure 5.** The fraction of received molecules with different values of viscosity for the mobile receiver

## CONCLUSION

In this paper, a new mobile MC model is proposed to increase the hitting probability of MMs. In contradistinction to literature, both the transmitter and receiver are chosen as mobile and the mobility of them can be adjusted for different values of viscosity separately by using some Physics lows. The position of the receiver and transmitter are changed for every time step of the simulation. The fraction of received molecules is obtained higher for the mobile MC model. In addition, the effect of viscosity and distance between transmitter and receiver are analyzed by comparing the fixed and mobile nano scale systems. It is concluded that when the receiver and transmitter are mobile, distance between them changes and finally this affects the fraction of received molecules at the receiver. As is expected, the fraction of received molecules is obtained the highest when the viscosity of the environment and distance are the lowest for both fixed and mobile system models. Also positions of receiver and transmitter show that when the distance of transmitter and receiver increase from the origin, fraction of received molecules decrease.

In the future, more dynamic and biological systems can be developed by taking more practical conditions such as accurate drift velocity, vascular branching, the influence of blood molecules by developing a proposed mobile MC model. Also, estimation of the position of Tx and Rx in the environment can be considered to design a more dynamic model that has less signal to interference rate and high reception probability at the receiver using deep neural network (Niitsoo et al., 2018; Er, 2020; Wu and Tseng, 2021).

### Conflict of Interest

The authors declare that they have contributed equally to the article.

### Author's Contributions

The article authors declare that there is no conflict of interest between them.

## REFERENCES

Arne NA. Niitsoo, T. Edelhäußer, E. Eberlein, N. Hadaschik, C. Mutschler. 2018. "A Deep Learning Approach to Position Estimation from Channel Impulse Responses." Sensors 1(D):1–23. doi: 10.3390/s19051064.

Akkaya, Ali, H. Birkan Yilmaz, Chan Byoung Chae, and Tuna Tugcu. 2015. "Effect of Receptor Density and Size on Signal Reception in Molecular Communication via Diffusion with an Absorbing Receiver." IEEE Communications Letters 19(2):155–58. doi: 10.1109/LCOMM.2014.2375214.

Balevi, Eren, Student Member, Ozgur B. Akan, and Senior Member. 2013. "A Physical Channel Model for Nanoscale Neuro-Spike Communications." 61(3):1178–87.

Barros, Michael Taynnan, Walisson Silva, and Carlos Danilo Miranda Regis. 2018. "The Multi-Scale Impact of the Alzheimer's Disease in the Topology Diversity of Astrocytes Molecular Communications Nanonetworks." (October):1–16.

Bi, Dadi, Apostolos Almpanis, Adam Noel, Yansha Deng, and Robert Schober. 2021. "A Survey of Molecular Communication in Cell Biology: Establishing a New Hierarchy for Interdisciplinary Applications." IEEE Communications Surveys and Tutorials 1–51. doi: 10.1109/COMST.2021.3066117.

Breki, Alexander, and Michael Nosonovsky. 2018. "Einstein's Viscosity Equation for Nanolubricated Friction." Langmuir 34(43):12968–73. doi: 10.1021/acs.langmuir.8b02861.

Chang, Ge, Lin Lin, and Hao Yan. 2018. "Adaptive Detection and ISI Mitigation for Mobile Molecular Communication." IEEE Transactions on Nanobioscience 17(1):21–35. doi: 10.1109/TNB.2017.2786229.

Charbonneau, Benoit, Patrick Charbonneau, and Grzegorz Szamel. 2018. "A Microscopic Model of the Stokes-Einstein Relation in Arbitrary Dimension." Journal of Chemical Physics 148(22). doi: 10.1063/1.5029464.

Chouhan, Lokendra, and Prabhat K. Sharma. 2020. “Molecular Communication in Three-Dimensional Diffusive Channel with Mobile Nanomachines.” Nano Communication Networks 24:100296. doi: 10.1016/j.nancom.2020.100296.

Er, M. B. 2020. “A Novel Approach for Classification of Speech Emotions Based on Deep and Acoustic Features.” IEEE Access 8.

Farsad, Nariman, Andrew W. Eckford, Satoshi Hiyama, and Yuki Moritani. 2012. “On-Chip Molecular Communication: Analysis and Design.” IEEE Transactions on Nanobioscience 11(3):304–14. doi: 10.1109/TNB.2012.2186460.

Farsad, Nariman, and Andrea Goldsmith 2018. “Neural Network Detectors for Sequence Detection in Communication Systems.” Electrical Engineering and Systems Science, 1–15.

Felicetti, L., M. Femminella, and G. Reali. 2018. “Directional Receivers for Diffusion-Based Molecular Communications.” IEEE Access PP(c):1. doi: 10.1109/ACCESS.2018.2889031.

Guidoni, S. E., and C. M. Aldao. 2002. “On Diffusion, Drift and the Einstein Relation.” European Journal of Physics 23(4):395–402. doi: 10.1088/0143-0807/23/4/302.

Huang, Shuai, Lin Lin, Weisi Guo, Hao Yan, Juan Xu, and Fuqiang Liu. 2020. “Initial Distance Estimation and Signal Detection for Diffusive Mobile Molecular Communication.” IEEE Transactions on Nanobioscience 19(3):422–33. doi: 10.1109/TNB.2020.2986314.

Isik, I., Yilmaz, H. B., Demirkol, I., & Tagluk, M. E. 2020. “Effect of Receiver Shape and Volume on the Alzheimer Disease for Molecular Communication via Diffusion.” IET Nanobiotechnology 14(7):602–8.

Isik, Ibrahim, Mehmet Bilal Er, and Mehmet Emin Tagluk. 2020. “Analysis of Half Sphere Receiver Model in Molecular Communication Through Diffusion.” Journal of Physical Chemistry and Functional Materials 3(2):63–67.

Iwasaki, Satoru, Jian Yang, and Tadashi Nakano. 2017. “A Mathematical Model of Non-Diffusion-Based Mobile Molecular Communication Networks.” IEEE Communications Letters 21(9):1969–72. doi: 10.1109/LCOMM.2017.2681061.

Koca, Caglar, Meltem Civas, Selin M. Sahin, Onder Ergonul, and Ozgur B. Akan. 2021. “Molecular Communication Theoretical Modeling and Analysis of SARS-CoV2 Transmission in Human Respiratory System.” IEEE Transactions on Molecular, Biological, and Multi-Scale Communications 1–11. doi: 10.1109/TMBMC.2021.3071748.

Kumar, Sudhir. 2020. “Nanomachine Localization in a Diffusive Molecular Communication System.” IEEE Systems Journal 14(2):3011–14. doi: 10.1109/JSYST.2019.2963790.

Lin, Lin, Qian Wu, Maode Ma, and Hao Yan. 2019. “Concentration-Based Demodulation Scheme for Mobile Receiver in Molecular Communication.” Nano Communication Networks 20:11–19. doi: 10.1016/j.nancom.2019.01.003.

Moore, Michael John, Tatsuya Suda, and Kazuhiro Oiwa. 2009. “Molecular Communication : Modeling Noise Effects on Information Rate.” 8(2):169–80.

Okaie, Yutaka, Shinya Ishiyama, and Takahiro Hara. 2018. “Leader-Follower-Amplifier Based Mobile Molecular Communication Systems for Cooperative Drug Delivery.” 2018 IEEE Global Communications Conference, GLOBECOM 2018 - Proceedings 1–6. doi: 10.1109/GLOCOM.2018.8647185.

Peskir, Goran. 2003. “On the Diffusion Coefficient: The Einstein Relation and Beyond.” Stochastic Models 19(3):383–405. doi: 10.1081/STM-120023566.

Rusinque, Hector, and Gunther Brenner. 2019. “Mass Transport in Porous Media at the Micro- and Nanoscale: A Novel Method to Model Hindered Diffusion.” Microporous and Mesoporous Materials 280(November 2018):157–65. doi: 10.1016/j.micromeso.2019.01.037.

Schurwanz, Max, Peter Adam Hoeher, Sunasheer Bhattacharjee, Martin Damrath, Lukas Stratmann, and Falko Dressler. 2021. “Duality between Coronavirus Transmission and Air-Based Macroscopic Molecular Communication.” IEEE Transactions on Molecular, Biological, and Multi-Scale Communications 1–9. doi: 10.1109/TMBMC.2021.3071747.

Singh, Satbir, and Hemant Rajveer Singh. 2016. "Molecular Receptor Antennas for Nano Communication : An Overview." 9028:13–16.

Walsh, Frank. 2013. "Protocols for Molecular Communication." Waterford Institute of Technology.

Walter, H., and J. Vreeburg. 1989. Fluid Sciences and Materials Science in Space - a European Perspective. 50.

Wu, Guan-sian, and Po-hsuan Tseng. 2021. "A Deep Neural Network-Based Indoor Positioning Method Using Channel State Information." 290–94.

Wu, Qian, Lin Lin, Zhan Luo, and Hao Yan. 2017. "Bit Alignment Scheme for Mobile Receiver in Molecular Communication." International Conference on Ubiquitous and Future Networks, ICUFN 750–52. doi: 10.1109/ICUFN.2017.7993892.

Yilmaz, H. Birkan, and Chan-byoung Chae. 2014. "Simulation Modelling Practice and Theory Simulation Study of Molecular Communication Systems with an Absorbing Receiver." Simulation Modelling Practice and Theory 49:136–50. doi: 10.1016/j.simpat.2014.09.002.

Yilmaz, H. Birkan, Akif Cem Heren, and Tuna Tugcu. 2014. "3-D Channel Characteristics for Molecular Communications with an Absorbing Receiver." IEEE COMMUNICATIONS LETTERS 3-D 1–4.

Yutaka O, Shouhei K, Tadashi N,, Yasushi H, Tokuko H, Takahiro H, 2019. "Methods and Applications of Mobile Molecular Communication." Proceedings of the IEEE 107(7).