Nano-Communication Propagation Channel Model Using Flow and Diffusion

Abstract

Inspired by biological communication systems, nano-communication in particular molecular communication has been proposed as a viable scheme to communicate between nano-sized devices separated by a very short distance. Here, molecules are released by the transmitter into the medium, which are then sensed by the receiver .Thus, this has necessitated the research on the potential applications of nanotechnology in a wide range of nano-networking areas. Nano-networking is a new type of networking which can also be applied to the communication theory. In this paper, a well justified channel propagation model for flow-based nano-characteristic communication channel is considered. The signal propagation model based on the advection and diffusion processes is analyzed. Furthermore, a sound mathematical justification for the linearity and time-variance properties of flow and diffusion based nano-communication channel model is investigated.

Keywords: Nano-communication; Propagation; Molecular; Diffusion; Flow

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A Azari, S Kamal S Sahbari* and A Fahim

Department of Electrical Engineering, Tabriz Branch Islamic Azad University, Iran

***Corresponding author:** S Kamal S Sahbari, Department of Electrical Engineering, Tabriz Branch Islamic Azad University, Tabriz, Iran, Email: kamalsahbar@ymail.com

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Introduction

Nano-technology is a science and technology of engineering operative systems at molecular scale. Figure 1 shows different approaches for nano-machines developments. As it can be seen in this figure, development of nano-machines can be accomplished using three approaches [1]:

a. A top-down approach in which nano-machines are developed using current micro-electronic devices [1,2].

b. A bottom- up approached in which nano-machines are developed using molecular components [2].

c. A bio-hybrid approach in which the development of nano-machines is based on studying existing biological models [2].

In general the concept of nano-technology and development largely remains in the research phase. However, only recently a manufacturing approach has been provided for nano-machines with 1.5-nanometere switch which can be used to detect and count specific type of molecule [3].

The most important application of nano-networks is in biology and biomedicine. Molecular communication (MC) is also a bio-inspired paradigm where the exchange of information is accomplished through the transmission, propagation, and reception of molecules. MC is considered a promising option for communications in nano -networks, which are defined as interconnection between nano-machines. The process of molecular propagation is based on radically different phenomenon with respect to the electromagnetic propagation in classical communication systems. While electromagnetic waves operate the propagation of the energy at the speed of light, the molecular diffusion process is caused by random motion of molecules in fluid. As a result, while electromagnetic propagation is mostly in the defined direction, molecular motion usually propagate in a random direction with high delay for almost all transmission ranges. In order to provide a biocompatible nano-communication scheme which in particular applicable to biomedical applications, we consider a molecular communication system model. So, to define a very reliable nano-communication system, in particular a molecular communication system, a well justified channel model is of great significance.

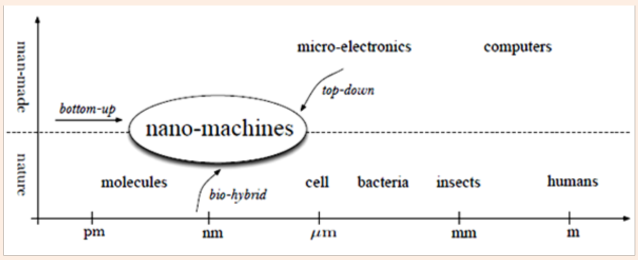

Figure 1: Different approaches for nano-machines development.

Molecular Communication System Model

Designing a realizable transmitter and receiver structure requires a well-justified model for channel propagation. In nano-communications in general, and molecular communication in particular, transportation of messenger molecules is mainly affected by the stationary and non-stationary nature of the propagation environment. Hence, based on the stationary aspect of the propagation environment, molecular communication channels are classified into two groups: diffusion-based and flow-based molecular channels. In diffusion-based communication channels, in contrast to the flow-based communication channels, the propagation medium is stationary. Thus the molecular communications can be the most practical means for realization of communications between nano-machines. In molecular communications paradigm, transmitters use molecules for encoding and transmitting information in contrast to the conventional electromagnetic communications in which the information is transmitted using electromagnetic waves. In general two molecular communication techniques are considered:

a) Molecular communication using molecular motors such as, kinesin, myosin or dynein for information transmission

b) Molecular communication using calcium signalling, in which calcium ions are used for information transmission. Also with respect to the communication range, molecular communications are classified as follows; short-range communications, in which communication range is from nm to mm as intra-cell and inte cell communications, medium-range molecular communications, in which in general communication range is from μm to mm, and long-rage molecular communications, in which the communication range is from mm to km.

Diffusion-based molecular communication System model

In Figure 2 a schematic of diffusion-based molecular communication system is illustrated. The Propagation of the desired signal is mainly governed by the transport mechanism of the emitted molecules. In the diffusion-based molecular communication channels (i.e.; where the propagation medium is stationary), the propagation process of emitted messenger molecules is accomplished by means of thermally activated diffusion mechanism. In this transport mechanism, molecular flux is achieved from regions of high density to low density via random collisions with underlying medium. As it can be seen similar to a conventional digital communication system; there must be three major stages for any molecular communication process, transmission, propagation, and the reception processes.

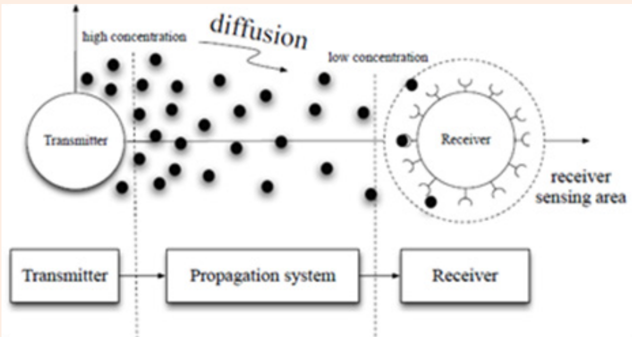

Figure 2: A schematic of a molecular communication system.

Flow-based Molecular Communication System Model

When the propagation medium is stationary (i.e.; diffusion based molecular channels), Viscose forces of the propagation medium dominates the propagation process and the emitted messenger molecules are propagated by thermally activated diffusion mechanism [4,6,8,10-12]. However, when the propagation medium is in motion (i.e.; flow-based molecular channels), the messenger molecule propagation are effected both by diffusion and advection mechanism. Figure 3 illustrates a flow-based molecular communication system.

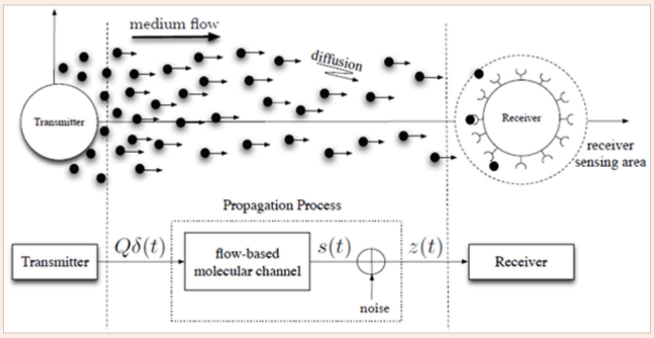

Figure 3: Flow-based molecular exchange system.

Flow-based Molecular Communication Channel propagation Model

When the propagation medium is stationary (i.e.; diffusion-based molecular channels), viscous forces of propagation medium dominate the propagation process and the emitted messenger molecules are propagated by means of thermally activated diffusion mechanism [4,6,8,10-12]. However, when the propagation medium is in motion (i.e.; flow-based molecular channels), the propagation of emitted messenger molecules are effected both by diffusion and advection process. Hence, there are two sources of flux for which the messenger molecules are propagated:

a. Diffusion flux which is calculated by the Fick's first law [13]:

$$J_{diff} = -D\nabla\overline{U}(X(t),t) \quad (1)$$

Where $\overline{U}(X(t),t)$ is the molecular concentration with X (x(t),y(t)) the two dimensional molecular position at time t, and D being the diffusion coefficient..

b. Advective flux which is due to the motion of the medium and is written in [13,15] as:

$$J_{adv} = V(t)\overline{U}(X(t),t) \quad (2)$$

Where $v(t) = \left(vx\ (t).vy\ (y)\right)$ is the two dimensional vector velocity of the propagation motion at time t.

Signal propagation model

Thus the convection-diffusion equation is used to model the effects of both advection and diffusion in the flow-based molecular communication. If $\overline{U}(X(t),t)$ is the mean molecular concentration at time t, then we may write [13-15]:

$$\frac{\partial\overline{U}(X(t),t)}{\partial t} = D\nabla^2\overline{U}(X(t),t) - V(t)\nabla\overline{U}(X(t),t) + S \quad (3)$$

where X(t) being the two dimensional molecular position at time t and S being any extra source in the medium in case exists. In our analysis we will assume that S =0. Let us simplify the notation X(t) by omitting time t ,and assume that the concentration of

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emitted molecules is much lower than the concentration of medium molecules [5-7,9,11]. We now show that the Eq. (3) is nothing more than the Fick's second law of propagation.

We now proceed by defining a new coordinate system that moves along with the medium flow (i.e.; with the same velocity vector). Hence,

$$X = X' + X_{tx} + \int_{t_0}^{t} v(\beta)d\beta \quad or \quad X' = X - X_{tx} - \int_{t_0}^{t} v(\beta)d\beta \quad (4)$$

Where Xtx= (xtx , ytx) is the two-dimensional position of the transmitter with t0 being the initial time of an impulse messenger molecule transmission.

Since

$$\nabla^2 \overline{U}(X,t) = \frac{\partial}{\partial X}\left(\frac{\partial U}{\partial X}\right) \quad (5)$$

Substituting Eq.(4) in Eq.(5) and noting that

$$\frac{\partial \overline{U}(X,t)}{\partial t} = \frac{\partial U(X,t)}{\partial X}\cdot\frac{\partial X}{\partial t} = \frac{\partial \overline{U}(X',t)}{\partial X'}\cdot\frac{\partial X'}{\partial t}$$

and

$$\nabla^2 U(X,t) = \frac{\partial}{\partial X}\left(\frac{\partial U(X,t)}{\partial X}\right) = \frac{\partial}{\partial X}\left(\frac{\partial U(X,t)}{\partial X'}\cdot\frac{\partial X'}{\partial X}\right) = \frac{\partial}{\partial X'}\left(\frac{\partial \overline{U}(X',t)}{\partial X'}\cdot\frac{\partial X'}{\partial X}\right)\cdot\frac{\partial X'}{\partial X}$$

We then get the following result:

$$\frac{\partial \overline{U}(X',t)}{\partial X'}\cdot\frac{\partial X'}{\partial t} + \frac{\partial \overline{U}(X',t)}{\partial t} = D\frac{\partial}{\partial X'}\left(\frac{\partial \overline{U}(X',t)}{\partial X'}\cdot\frac{\partial X'}{\partial X}\right)\left(\frac{\partial X'}{\partial X}\right) - v(t)\frac{\partial \overline{U}(X',t)}{\partial X'}\cdot\frac{\partial X'}{\partial X})$$

Hence Eq.(3) can be rewritten as :

$$\frac{\partial \overline{U}(X',t)}{\partial t} = D\nabla^2 \overline{U}(X',t) \quad (6)$$

Which is nothing more than the Fick's second low of molecular motion, the model of propagation process in a stationary medium [5,6,10-12]. Now if we assume that at time t0, Q number of messenger molecules are transmitted, then the mean molecular concentration at location X' and time t is given by [11]:

$$\overline{U}(\overline{X},t) = \frac{Q}{4\pi D(t-t_0)})\exp\left(\frac{|X'|^2}{4D(t-t_0)}\right) \quad (7)$$

Substituting Eq. (4) in Eq.(7), we get the following result as the mean molecular concentration in the reference coordinates :

$$\overline{U}(X,t) = \frac{Q}{4\pi D(t-t_0)})\exp\left(\frac{\left|X - X_{tx} - \int_{t_0}^{t} v(\alpha)d\alpha\right|^2}{4D(t-t_0)}\right) \quad (8)$$

Hence, from Eq. (8), we can compute the mean number of messenger molecules in the receiving sensing cross section area Arx as follows:

$$S(t) = \iint_{A_{rx}} \frac{Q}{4\pi D(t-t_0)}\exp\left(\frac{\left|X - X_{tx} - \int_{t_0}^{t} v(\alpha)d\alpha\right|^2}{4D(t-t_0)}\right)dxdy \quad (9)$$

Fig.4 shows the mean number of messenger molecules in the receiver sensing area in terms of time for five different scenarios. The diffusion coefficient D =1.7× 10-9 m^2/s. The distance between transmitter and receiver nano-machines is considered to be 500 µm [16] and it is assumed that the transmitter and receiver nano-machines are located at (0,0) µm and (500,0) µm, respectively. The number of the transmitted messenger molecules per information symbol is Q = 2 × 104.

Linearity of the channel

In this part, we assume that two transmitters are transmitting pulses simultaneously with different amplitudes as follows:

$gi\ (t) = Qi\ \delta\ (t)\ ,\ i = 1,2$ Then using Eq. (9), the mean number of received messenger molecules in the receiver cross section are:

$$S(t) = \iint_{A_{rx}} \frac{Q}{4\pi D(t-t_0)}\exp\left(\frac{\left|X - X_{tx} - \int_{t_0}^{t} v(\alpha)d\alpha\right|^2}{4D(t-t_0)}\right)dxdy \quad (10)$$

Since the Qi number of messenger molecules are transmitted at time to =0, then the lower limit of the velocity integral is taken to zero.

To show the linearity of the channel, we must show that for input signal ag1 (t)+bg2 (t) (where a and b are constants) , the output signal is equal to af1(t)+bf2(t) . For the transmitted signal:

$$g3(t) = af1(t) + bf2(t) = (aQ1 + b\ Q2\ )\ \delta(t) \quad (11)$$

The received signal is:

$$f_3(t) = \iint_{A_{rx}} \frac{aQ_1 + bQ_2}{4\pi Dt}\exp\left(\frac{\left|X - X_{tx} - \int_0^t v(\alpha)d\alpha\right|^2}{4Dt}\right)dxdy = af_1(t) + bf_2(t)$$

(12)

Thus, the molecular channel when the propagation medium being in motion confirms the linearity property.

Time-variance of the channel

To show the time –variance property, we consider two transmitters are sending their pulses at different time instants as follows:

$$g1(t) = Q\ \delta(t)\ , g2(t) = Q\ \delta(t - \alpha). \quad (13)$$

Then, the signals arriving in the receiver are:

$$f_1(t) = \iint_{A_{rx}} \frac{Q}{4\pi Dt}\exp\left(\frac{\left|X - X_{tx} - \int_0^t v(\alpha)d\alpha\right|^2}{4Dt}\right)dxdy$$

$$f_2(t) = \iint_{A_{rx}} \frac{Q}{4\pi D(t-\beta)}\exp\left(\frac{\left|X - X_{tx} - \int_0^t v(\alpha)d\alpha\right|^2}{4D(t-\beta)}\right)dxdy \neq f_1(t-\beta)$$

(14)

Which illustrates the time-variance of flow-based molecular communication channel?

Since, the channel response not only depends on the observation time but also on when the signal is applied. Therefore, the received signal, s(t), is simply the convolution of the input signal (i.e.; impulse of transmitted messenger molecules) with the channel response. This is due to the fact that in wireless channel models, input symbol chosen to be and to be an impulse of almost zero width. Hence, we may write s(t)= Q δ(t) * h (t, τ) with h(t, τ) being the time varying channel response at time t due to the impulse applied at time t- τ. Hence, using Eq.(10), we can conclude that the time-varying impulse response of a flow-based molecular channel is given by:

$$h(t,\tau)=\iint_{A_{rx}} \frac{Q}{4\pi D(\tau)}\exp\left(\frac{\left|X-X_{tx}-\int_{t-\tau}^{t} v(\alpha)\,d\alpha\right|^{2}}{4D(\tau)}\right)dxdy \quad (15)$$

Conclusion and Future work

An important challenge in nano-network research concerns the modelling of physical layer communications. When the propagation medium is stationary, the propagation of emitted messenger molecules is accomplished by a thermal diffusion mechanism, where Brownian motion statistical model may be considered. However, when nano-machines communicate in a moving propagation medium, the propagation of messenger molecules are accomplished by advection mechanism as well as diffusion mechanism.

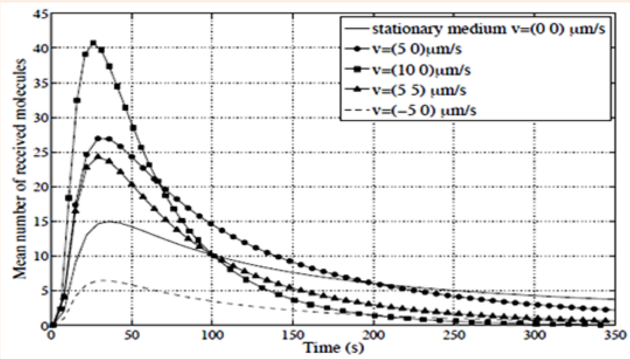

Figure 4: The mean number of messengermolecules in the receiver sensing area in five
Scenarios: 1) v = (0, 0) μm/s, 2) v = (5, 0) μm/s, 3) v = (10, 0) μm/s, 4) v = (5, 5) μm/s, and 5) v = (-5, 0) μm/s.

In this study, a physical layer channel model for nano-machines in a nano-network was analyzed. With huge potential applications to nano-networks in biomedicine and biology, the primary focus was on the molecular communications. The channel model based on flow-diffusion was addressed. The signal model also was provided where the linearity and time- variance properties were established. It is believed that one of the current unexplored challenges in nano-communication particularly, in the molecular communication systems is pulse shaping. As it can be seen from the Figure 4, the molecular channel response has a long tail which causes residual noise and intersymbol interference in communication. Also, the effects of electromagnetic and electrostatic fields on the transporting characteristics of the molecular communication should be investigated. Existence of such external field, applies forces on the emitted messenger molecules, which will ultimately have negative effect on their motions. Finally, studying channel capacity based on signal propagation and noise in the nano-communication systems especially, in molecular communications can be a very interesting and attracting field to be considered.

References

1. F Akyildiz, F Brunetti, C Blazquez (2008) Nanonetworks: A new communication paradigm. Computer Networks (Elsevier) Journal 52: 2260-2279.
2. F Akyildiz, J Jornet (2010) Electromagnetic wireless nanosensor networks. Nano Communication Networks 1: 3-19.
3. R Patel (2013) Nanorobotics ideas in nanomedicine. Asian Journal of Pharmaceutical Sciences and Research 3(3): 15-22.
4. B Atakan, OB Akan (2010) Deterministic capacity of information flow in molecular nanonetworks. Nano Communication Networks (Elsevier) Journal 1(1): 31- 42.
5. AW Eckford (2007) Achievable information rates for molecular communication with distinct molecules. Bio-Inspired Models of Network, Information and Computing Systems pp. 313- 315.
6. AW Eckford (2007) Nanoscale communication with brownian motion. 41st Annual Conference on Information Sciences and Systems pp. 160-165.
7. S Kadloor, R Adve, A Eckford (2011) Molecular communication using brownian motion with drift. IEEE Trans NanoBioscience 11(12): 89-99.
8. M Pierobon, IF Akyildiz (2010) A physical end-to-end model for molecular communication in nanonetworks. IEEE Journal on Selected Areas in Communications 28(4): 602-611.
9. Llatser, E Alarcon, M Pierobon (2011) Diffusion based channel characterization in molecular nanonetworks. 1st IEEE International Workshop on Molecular and Nano Scale Communication (MoNaCom), pp. 467-472.
10. N Garralda, I Llatser, A Aparicio, M Pierobon (2011) Simulation-based evaluation of the diffusion based physical channel in molecular nanonetworks. 1st IEEE International Workshop on Molecular and Nano Scale Communication (MoNaCom), pp. 443 - 448.
11. H Shah Mohammadian, GG Messier, S Magierowski (2012) Optimum receiver for molecule shift keying modulation in diffusion based molecular communication channels. Nano Communication Networks (Elsevier) Journal 3(3): 183-195.
12. M Pierobon, IF Akyildiz (2011) Noise analysis in ligand-binding reception for molecular communication in nanonetworks. IEEE Transactions on Signal Processing 59(9): 4168-4182.
13. SA Socolofsky, GH Jirka (2005) Mixing and Transport Processes in the Environment. (5th edn), Texas A&M University, USA.
14. PM Adler, JF Thovert (1999) Fractures and Fracture Networks. Kluwer Academic Publishers, USA.
15. D Scullen (1992) Finite difference methods for advection in variable-velocity fields. Master's thesis, The University of Adelaide, South Australia.
16. R Freitas (1999) Nanomedicine, Volume I: Basic Capabilities. TX: Landes Bioscience, Georgetown, USA.