CHARACTERIZATION OF MOLECULAR COMMUNICATION CHANNEL FOR NANOSCALE NETWORKS

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Abstract: Recently molecular communication is being considered as a new communication physical layer option for nanonetworks. Nanonetworks are based on nanoscale artificial or bio-inspired nanomachines. Traditional communication technologies cannot work on the nanoscale because of the size and power consumption of transceivers and other components. On the other hand, a detailed knowledge of the molecular communication channel is necessary for successful communication. Some recent studies analyzed propagation impairment and its effects on molecular propagation. However, a proper characterization of the molecular propagation channel in nanonetworks is missing in the open literature. This goes without saying that a molecular propagation channel has to be characterized first before any performance evaluation can be made. Due to the nanoscale dimension of the nanomachines involved in molecular communication a measurement based approach using in vitro experiments is extremely difficult. In addition, a proper tuning of the experimental parameters is mandatory. This is why the authors were motivated to characterize the 'channel quantum response (CQR)' or equivalently the 'throughput response' of bio-inspired nanonetworks with an alternative approach. This paper considers the molecular channel as particle propagation. The CQR i.e. the throughput response and its characteristics have been found in order to better-understand the molecular channel behavior of nanonetworks.

1 INTRODUCTION

Molecular Communication is a new interdisciplinary field of research that has emerged from the amalgamation of three independent research fields named nanotechnology, biotechnology and information and communication technology (ICT). Molecular communication is one sub-division of the large research area of nanoscale communication and networking. Although scaling down of the macro-devices leads to nanoscale components and technologies in general, due to several practical limitations of available technologies it has been proposed that bio-inspired communications can solve some key problems and thus nanoscale molecular communication has become a good candidate for the new molecular communication based nanonetworking (Akyildiz, 2008, Lacasa, 2009). Communication in the form of concentration encoding and molecular encoding as well as networking among several nanomachines give rise to nanonetworks. Nanomachines are artificial or biological machines on the nanoscale dimensions (1 nm to 100 nm) responsible for extremely limited tasks. Conventional artificial dry techniques have several difficulties especially in the fabrication phases, for which bio-inspired communication techniques started to have been investigated very recently (Atakan and Akan, 2007, Moritani et al., 2006, Parcerisa and Akyldiz, 2009, Moore et al., 2009). Bio-inspired communication systems are derived from molecular biology and biotechnology. In addition to this, their advantages are realized when nanotechnology and information and communication technologies are brought together to integrate into technologies based on molecular communications, giving rise to the new field of nano-bio-communication technology. Molecular communication is in fact quite common in the nature in living organisms as a means to communicate with each other by enabling one or more biological phenomena. Short-range molecular communication

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based on concentration encoding and long-range communications based on pheromones are some examples to mention (Akyildiz, 2008, Lacasa, 2009). Received molecular concentration or even the transmitted molecules bound with the chemical receptors on the cell boundary of nanomachines contain biologically meaningful information which triggers one or more biological phenomena to perform the required task. Biological systems found in nature perform both intra-cellular communication through vesicles transportation and inter-cellular communication through neurotransmitters, as well as inter-organ communication through hormones (Atakan, 2008). Molecular nanonetworks are in fact quite significant in the sense that communication and networking among a large number of nanomachines can create several new applications, for instance nanoscale distributed computation systems, nanoscale bio-inspired or hybrid sensing systems, improved health care systems, nanomedicine, chemical sensor networks for micro-nanoscale applications are just a few applications to mention.

There exists some related research in the area of molecular communication in the last few years. For instance, Atakan (2007) discussed an information theoretical approach for a molecular communication systems based on several infeasible assumptions (Lucasa, 2009). Akyldiz (2008) presented a survey of nanonetworks with an emphasis on bio-inspired molecular communications for short-range and long-range communications. To the best of our knowledge none of the papers in the open literature has considered the molecular propagation channel from particle propagation perspective and investigated the channel behavior of the same. This has given us the main impetus to write this paper. Section-2 explains the channel behavior in terms of channel quantum response (CQR). Some remarks are mentioned and comments are made on the findings. Finally, section-3 concludes the paper with several future research directions.

2 PERFORMANCE EVALUATION

2.1 Channel Quantum Response (CQR) Modeling

The idea of CQR for molecular propagation channel in nanonetworks came in fact from the well-known time-dependent solution to concentration of diffused substance as governed in macroscopic level by Fick's law and well documented in Bossert (1963) and Berg (1993). However, the same idea could be suitable for nanonetworks, too. Unlike RF propagation, molecular propagation should be treated with the quantum or particle theory of propagation. CQR is in fact to some extent analogous to channel impulse response (CIR) of traditional communication systems. For example, the number of molecules received from a point source per unit of volume can be calculated from the well-known Roberts equation (Bossert, 1963) as

$$U(r,t) = \frac{Q}{(4\pi D t)^{\frac{3}{2}}} \cdot e^{\frac{-r^2}{4Dt}} \quad (1)$$

where r is the distance of the receiver from the emitting source, Q is the amount of released molecules per second and D is the diffusion constant in cm^2/s unit. D depends on the medium through which the molecules propagate. To the best of our knowledge, there isn't any work in the open literature that has made an effort to extract and define the CQR or equivalently to the throughput. This has given us the main impetus for writing this paper. The CQR and its characteristics could be deduced from (1). The propagation of information molecules in a molecular channel in shown in Fig.1. In order to determine CQR, the molecular channel is excited by an instantaneous short duration quanta emission of molecules $Q(t)$ for a given time duration t_H as shown in Fig.2. Since molecule transmissions in biological nanomachines are in fact slow processes, to make it more practical we consider $Q(t)=Q$ for a duration of t_H where we also vary t_H as shown in Fig.2. Considering the generalized $Q(t)$ eqn. (1) can be written as (Bossert, 1963)

$$U(r,t) = \int_0^t \frac{Q(\tau)}{\{4\pi D(t-\tau)\}^{\frac{3}{2}}} \cdot e^{\frac{-r^2}{4D(t-\tau)}} d\tau \quad (2)$$

which for our purpose, can be re-written as

$$U(r,t) = \int_0^{t_H} \frac{Q(\tau)}{\{4\pi D(t-\tau)\}^{\frac{3}{2}}} \cdot e^{\frac{-r^2}{4D(t-\tau)}} d\tau = Q(t) \otimes g(t) \quad (3)$$

where $$g(t) = \frac{e^{\frac{-r^2}{4Dt}}}{(4\pi Dt)^{3/2}} \quad (4)$$

is defined as the CQR of the molecular channel and the symbol $\otimes$ indicates convolution operation. In this paper we have made a rigorous analysis of this CQR. Please note that propagation impairments are not considered for the time being, but indicated as future works. Fig.1. shows a generalized molecular communication channel, the blue circles representing the molecules transmitted by the

transmitter nanomachine (TN), propagated in the channel, and finally received by the receiver nanomachine (RN).

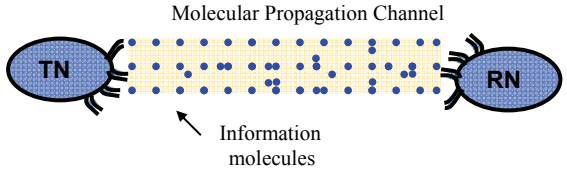

Figure 1: Propagation of information molecules: A generalized molecular propagation channel between a transmitter nanomachine (TN) and a receiving nanomachine (RN).

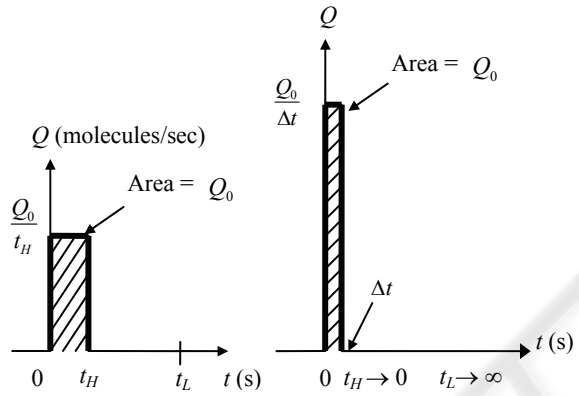

Figure 2: Input concentration excitation: practical case, when for $t_H \to 0$ ideal quantum excitation for concentration encoding is realized, the area (in shaded region) being constant.

The reasoning behind the idea that *g(t)* is considered as the channel quantum response is similar to what is found in the propagation of electromagnetic (EM) wave. However, *g(t)* must not be termed as channel impulse response (CIR), the reasoning being that unlike EM wave molecular propagation is based on particle (molecule) propagation. The modes of propagation can be concentration encoding where the concentration level is considered as the carrier signal, or molecular encoding where individual molecule is engineered such that its internal structure is altered and so it itself becomes a carrier and carries specific information. This is why the consideration of *g(t)* here as 'CQR' or 'throughput response' is justified. However, it is to be noted here that CQR *g(t)* is independent of the input molecular concentration *Q(t)*. This has made our reasoning to consider *g(t)* as channel quantum response (CQR) more solid. Please note that CQR can also be termed as 'throughput response' as an equivalent term.

2.2 Distance and Temporal Dependence

As shown in eqn. (4) the CQR is a function of both time, *t* and distance, *r* from the transmitting nanomachine (TN). Investigating into *g(t)* it is clear that unlike EM wave propagation modeling the molecular communication channel cannot be explained in terms of separate distance dependence and temporal dependence. The numerator in eqn. (4) is a function of both distance *r* and time *t*. In free space EM waves propagate at the speed of light (3×10^8 m/sec). In some cases wireless channels are realistically assumed to be stationary for short propagation times between sender and receiver. But unlike EM propagation molecular propagation is a very slow process and so the temporal variation of CQR cannot be ignored even for short distances on the nanoscale. The temporal variation rather plays a significant role in terms of pathloss and throughput analysis. In the next section an expression has been derived for the pathloss for a molecular channel. As mentioned, the concentration of molecules at a distance *r* and at time *t* i.e. *U(r,t)* is analogous to the energy of the molecular propagation. So the rate of change of concentration over time i.e. *dU/dt* would be analogous to power of EM signal. As a result it is important to have the *g(r,t)* energy normalized to the available total molecular energy. Figure 3 below shows the normalized CQR *g(r,t)* over a time of 250 seconds for a specific TN-RN distance of 2 cm.

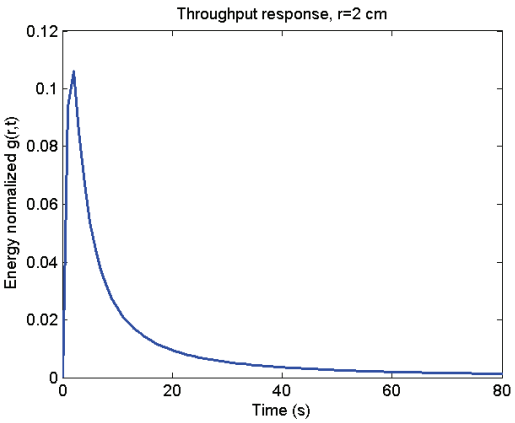

Figure 3: Normalized CQR i.e. throughput for molecular propagation channel.

It should be noted that in this paper we have been motivated to use the term 'throughput' rather than

'output' when referring to $U(r,t)$ because molecular propagation is not a wave propagation, it is rather the molecules themselves moving from TN to RN. Note that for ideal case when $Q(t)=\delta(t)$ the CQR $g(r,t)$ actually represents the throughput of the channel, i.e. $U(r,t)=g(r,t)$. In that sense Fig.3 also represents the throughput response of the molecular channel. The variation of the energy normalized CQR $g(r,t)$ for different distances in shown in Fig.4. Energy normalized CQR is of significant importance because of the fact that it indicates the amount of pathloss in the form of concentration loss in propagation for different TN-RN distances. This distance dependence of normalized CQR $g(r,t)$ can be used to derive the expression of pathloss as shown in section 2.4.

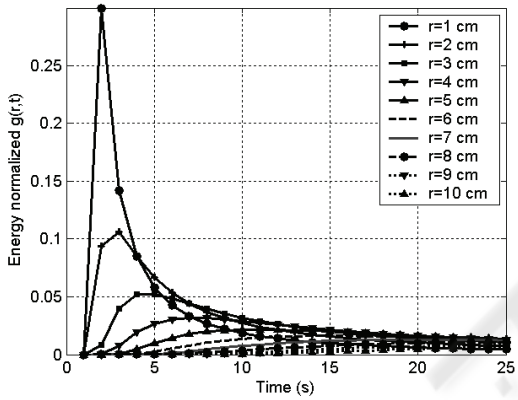

Figure 4: Comparison of energy normalized $g(r,t)$ i.e. throughput (i.e. concentration output) profile of the unicast molecular channel.

As expressed in eqn. (3) the throughput $U(r,t)$ of a molecular channel depends on $Q(t)$. For ideal case when $Q(t)=\delta(t)$ the throughput is $U(r,t)=g(r,t)$. However, for all practical purposes an impulsive $Q(t)$ is not possible. So, practical values of $Q(t)$ as shown in Fig.2 are considered where the average number of transmitted molecules $Q(t)$ occurs over the duration t_H seconds. The throughputs for different TN-RN distances from 1 cm to 10 cm are shown in Fig. 5. As shown in Fig.5 the molecules available for reception at the RN are significantly reduced as the distance increases. It should be noted that Fig. 5 shows the molecules available at receiver only, not the molecules received by the receiver. This is because reception by the receiver depends on several other factors including principally the affinity of information molecules to the receptor of the receiving nanomachine RN. This paper deals with the molecules available for receiving only, while the details of reception mechanism are beyond the scope of this paper.

Throughput depends also on the duration t_H of molecular transmission. As shown in Fig.2 the ideal situation occurs when $\Delta t=0$, which is impractical. For our purposes we have assumed a fixed amount molecules Q_0 which are transmitted at an average rate of Q_0/t_H molecules per second over the duration of t_H seconds. As a result the total number of transmitted molecules Q_0 is analogous to the strength of an impulse in traditional impulse response analyses. The normalized peak throughputs $U(r,t)$ for different TN-RN distances and different transmission duration t_H have been shown in Fig.6. The throughput gains have been shown in Table 1. Referring to Fig. 6 as shown in Table 1 increasing the value of t_H gives a gain in peak value of $U(r,t)$, i.e. increased number of molecules are received even if the distance is unchanged (r=3 cm for Table 1). However, it is also found that there is a decreasing relative gain (in dB/octave) when we double the transmission duration t_H while keeping the distance r unchanged.

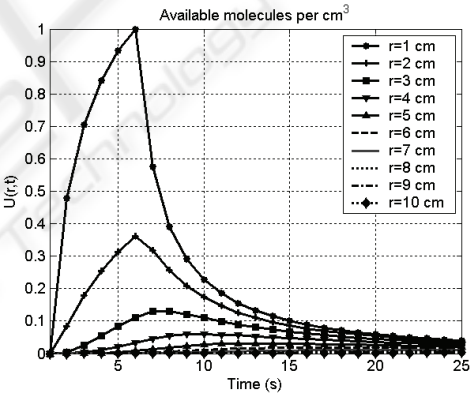

Figure 5: Available molecules per cm^3 at distance r with duration t_H=5 seconds.

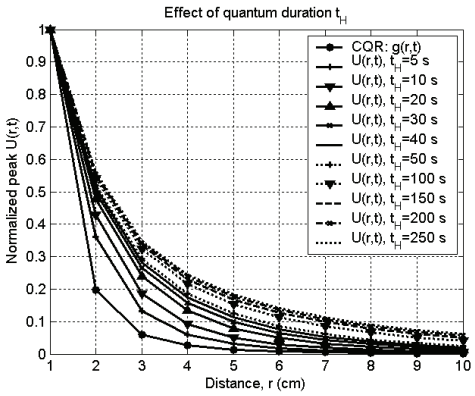

Figure 6: Peak variation of CQR $g(r,t)$ and throughput $U(r,t)$.

Table 1: Throughput $U(r,t)$ gain for different t_H at r=3 cm.

	t_H=0 sec	t_H=5 sec	t_H=10 sec	t_H=20 sec
$U(r,t)$	0.05	0.15	0.2	0.25
$\text{Gain}_{U(r,t)}$	-	4.7 dB	6.02 dB	6.98 dB
Gain (dB/octave)	-	-	1.32 dB	0.96 dB

2.3 Throughput Delay Profile

As shown in eqns. (3) and (4) the CQR can also be termed as the throughput since $U(r,t)$ actually shows the molecules per unit volume (cm^3) at a distance r at time t. In traditional wireless communications the term 'output' is analogous to the term 'throughput' here in molecular communication (i.e. molecular concentration in this case). That is why in the similar way what is known as the 'pathloss' in traditional wireless communication is analogous to 'concentration loss' in molecular communication. An expression of pathloss is derived in the next section. In order to characterize any communication channel the conventional approach finds channel gain and channel delay.

A way to characterize the delay profile of a molecular communication channel is to find out its mean excess delay and RMS delay spread using the channel quantum response (i.e. throughput response). In this research efforts are made to come up with mean excess delay and RMS delay spread values for a unicast molecular channel and the results are shown in Fig.7 and Fig.8 respectively. An observation time of 250 seconds has been considered because this is a reasonably sufficient observation time, provided that referring to Fig. 3 and Fig. 4, almost all the channel energy are located within 25 seconds of the observation (i.e. $1/10^{th}$ of 250 seconds). The time-step considered in our simulation was 1 second.

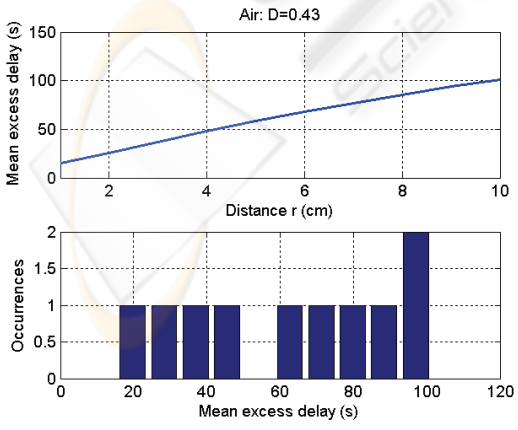

Figure 7: Excess delay characteristics for air medium.

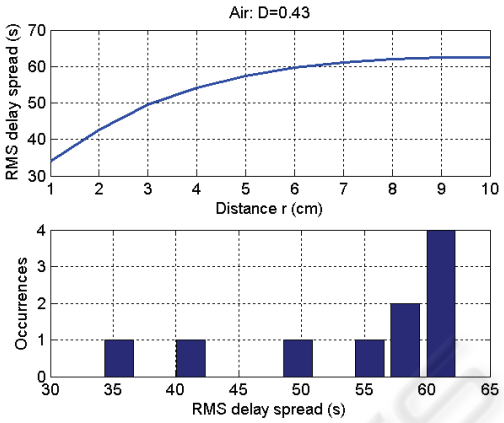

Figure 8: RMS delay spread characteristics for air medium.

2.4 Pathloss Modeling

In this section a pathloss expression has been computed using the distance and time dependent CRQ $g(r,t)$. It is already shown earlier that in the ideal case when the input is $Q(t)=\delta(t)$ the throughput of a molecular communication channel is given by $U(r,t)=g(r,t)$. So according to eqn. (4) the available molecular concentrations at distances r_1 and r_2 from the transmitting nanomachine TN where $r_2>r_1$ are given as

$$U(r_1,t)=\frac{e^{\frac{-r_1^2}{4Dt}}}{(4\pi Dt)^{\frac{3}{2}}}$$
$$U(r_2,t)=\frac{e^{\frac{-r_2^2}{4Dt}}}{(4\pi Dt)^{\frac{3}{2}}} \quad (5)$$

Pathloss in molecular communication can be defined as the loss of concentration (in the case of concentration encoding). The molecules are diffused from TN to RN through the channel. At any time instant t and distance r the molecular concentration $U(r,t)$ represents the bit information. Using eqn. (5) pathloss in molecular communication can be expressed as

$$PL(dB)=10\log_{10}\left(\frac{U(r_1,t)}{U(r_2,t)}\right)=10\log_{10}\left(e^{\frac{r^2}{4Dt}}\right) \quad (6)$$

where the TN is located at $r_1=0$ and the molecules are available at a distance $r_2=r$. In contrast to the conventional wireless communication systems the molecular communication is a very slow process, so there is a high probability that the channel suffers

from pathloss. This is how it is shown in the pathloss equation above that the pathloss is a function of both distance *r* and time *t* and both of these two variables have to be handled simultaneously. This makes the pathloss in molecular communication a bit complicated by not being able to express it as a function of distance only. The pathloss for different distances as a function of time are shown in Fig. 9. Initially there is a high pathloss because when the TN starts transmitting the molecules, there is no molecules available at the RN side as being a slow process it takes some time for the molecules to propagate from TN to RN. After a long time transmitted molecules reach the intended RN and so the pathloss decreases with time. This indicates the *t* in the denominator in the power of $exp(r^2/4Dt)$ in eqn. (6).

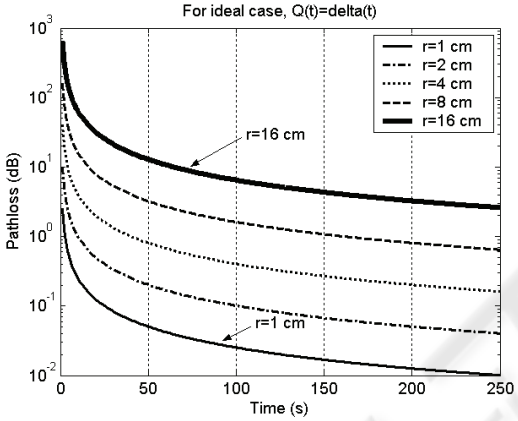

Figure 9: Pathloss as a function of time *t* for different distances *r* from TN.

3 CONCLUSIONS

In this paper we have developed an analytical approach for getting the channel quantum response (CQR) or equivalently the throughput response for molecular communication. This analysis contributes to the recent research of molecular propagation channel modeling and subsequent analyses. An analytical approach is useful in the sense that real propagation of molecular communication is very difficult due to extremely small (nano) scale of dimensions and experimental requirements. In such cases if a molecular propagation channel could be characterized analytically then the results would become very handy to analyze such a propagation channel without actually waiting for analyses with real molecular data and *in vitro* experiments. The approach presented in this paper is based on the spatial and temporal distribution of received concentration of the information molecules in a given propagation medium. Two things to be noted regarding the diffusion coefficient parameter *D,* firstly, it is assumed that the diffusion coefficient *D* remains constant during the period of analysis. This is validated by several open literature in this area. Also it is to be noted that propagation in air is considered (D=0.43) in this paper. However, similar results in aqueous medium e.g. water, blood plasma can also be obtained. Please note that different values of the diffusion coefficient *D* of the propagation media characterize differently the Brownian motion of information molecules in different media. As a second thought, the effects of the information molecules themselves on the propagation are not considered for now but are left as the on-going part of our current research. Statistical analyses of the results obtained in this paper are also one of our recent research works in this area.

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