Effects of Routing for Communication via Diffusion System in the Multi-node Environment

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Abstract—Molecular communication is a pioneering paradigm focusing on the communication between nano- and micro-scale machines, encompassing various novel communication systems. Currently, most of the studies in the literature regarding these systems focus on single transmitter single receiver topologies. However, in a more realistic environment there would be many nodes and the system should be able to handle additional and more complex mechanisms (e.g., routing, scheduling). In this paper, we describe a multi-node environment model for the Communication via Diffusion system and show the benefits of utilizing a routing mechanism in such an environment. The contribution of this paper is twofold: First, the performance of the multi-node environment is evaluated regarding the probability of hit and average propagation delay parameters. Second, we show and evaluate how the system benefits from a routing mechanism by selecting the optimal release point for emitting messenger molecules.

Index Terms—nanonetworks, communication via diffusion, molecular communication, routing, multi-node environment

I. INTRODUCTION

Nanomachines, machines that perform useful functions in the nanoscale, are expected to be one of the future approaches to machinery [1]. Due to their minute sizes, nanomachines will be able to perform tasks in very small scales where their higher scale counterparts cannot. However, these nanomachines are not expected to work individually since their capabilities are fairly limited. Instead, a collection or group of nanomachines are needed to accomplish complex tasks. This collaboration of nanomachines over a given set of tasks infers the need of communication between these nanomachines. In the literature, these communication systems are called nanonetworks [1].

While some nanonetworking solutions are based on well known communication systems (e.g., RF based-communication), others employ communication systems used by living organism cells. These systems are called Molecular Communication systems. In the literature, various molecular communication systems, such as Communication via Diffusion (CvD), Ion Signaling, Microtubules, Pheromone Signaling, and Bacterium based communication are proposed [2, 3, 4, 5, 6]. Among these systems, CvD aims intermachine communication in short-to-medium ranges (i.e., up to tens of micrometers). In this system, the data is encoded over various properties (e.g., concentration, type of molecule) of a wave of molecules that are released from the transmitter.

These so-called messenger molecules propagate through the environment via probabilistic motion (i.e., Brownian Motion/Diffusion). Based on the properties of the environment and the type of molecules, some of these molecules reach the receiver while the rest dissipates to the environment (Figure 1).

$$\Delta x, \Delta y, \Delta z \sim N(0, \sqrt{2 D \Delta t})$$

D : Diffusion coefficient
Δt : Step time
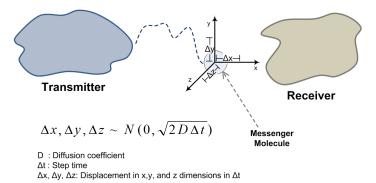Δx, Δy, Δz: Displacement in x,y, and z dimensions in Δt

Figure 1. Propagation in CvD system

Currently, most of the works on CvD system are based on the single transmitter single receiver (STSR) topology [7, 8]. Nonetheless, in a realistic nanomachine deployment topology, there are many nanomachines in close proximity. Thus, a more complex multi-node topology of nanomachines is required for a detailed analysis of the CvD system. A multi-node environment is considerably different from a STSR system in several aspects. Firstly, an addressing scheme is required since a transmission can target different receivers. Also, the nanomachines other than the receiver affect the propagation behavior of the messenger molecules. If the addressing structure is embedded to the molecule type, based on the addressing structure used in the system, they can act as impenetrable barriers, signal repeaters, or signal guiders.

In this paper, we describe a multi-node environment for the CvD system in nanonetworks and evaluate its performance regarding probability of hitting and average propagation delay. We also elaborate on the requirement and benefits of a routing mechanism in such an environment. The rest of the paper is organized as follows. In Section 2, we describe the 3D multi-node environment and evaluate the performance of the environment. In Section 3, we show the necessity of a routing

mechanism on such an environment and explain its benefits. Finally, Section 4 concludes the paper.

II. MULTINODE ENVIRONMENT

Nanomachines can be deployed in a wide variety of environments for a vast number of applications. They can be deployed inside living organisms to provide health monitoring, disease/threat detection, immune system enhancement, and cure administration. They can also be deployed inside or outside man-made constructs and machinery, for condition monitoring, capability enhancement via molecular structure manipulation, management of interaction between machinery and living organisms (e.g., bridging the gap between prosthetics and nervous system to provide highly sensitive control over prosthetic limbs) to enumerate a few.

Based on the application, the nanomachines will be placed in the target environment using different placement schemes. The selection of deployment inside or outside the living organisms implies significantly different environments. Similarly, deployments inside different tissues suggests different nanonetworking topologies and transmission media capabilities. For example, a health monitoring system deployed inside the capillaries of a mammal has to take the blood flow into consideration. Thus, the range between two adjacent nanomachines can be selected larger compared to a free diffusion environment. However, in such an environment energy-wise it would be extremely ineffective to try transmitting molecules in the reverse direction to the blood flow. Thus, the transmission must follow the direction of the blood flow.

In this paper, we consider a multi-node environment model in which nanomachines are deployed close to each other (i.e., a few to tens of micrometers) to form 3D meshes of nodes. This environment can be mainly applicable to outside living organism cases since the environment is only composed of nanomachines. By choosing some of the nanomachines as foreign objects to the network (i.e., cells of a living organism), this topology can also reflect a deployment of nanomachines inside living organism tissues. In the rest of the paper, we use the terms nanomachine and node interchangeably.

A. Model Description

In our multi-node environment model, the nodes are assumed to have a spherical size of equal radius (r_{cell}). The shortest distance between each adjacent node couple is also selected to be equal (d) for the sake of simplicity of the analysis. To attain the equidistant property while providing maximum area density, the spherical nodes should be deployed in a specific lattice. Among various lattices that conform this property, we choose the Hexagonal Close-Packed (HCP) lattice in this work (Figure 2). In this lattice, nodes are placed on a number of 2D planes and a given node has twelve neighboring nodes; six in the same plane, three in one higher plane, and the last three in one lower plane. The distance between each adjacent 2D plane is equal to $\frac{2\,r_{cell}}{3}\sqrt{6}$.

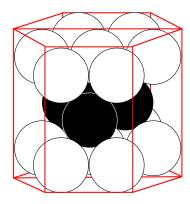Along the boundaries of each node, there are receptors that are specific to a single type of messenger molecule. We

Figure 2. HCP lattice example, $d = 0$ (image copyright in the public domain; Courtesy of Wikipedia)

use protein-based messenger molecules that are composed of several amino acids. Due to the chemical relationship between the messenger molecule and its receptors, nodes without the corresponding receptors cannot take in the molecule from the environment. Thus, the usage of different messenger molecules and their corresponding receptors imply an addressing structure in this communication system. The propagation dynamics are also affected from this structure since other nodes just act as an impenetrable barrier to the propagating messenger molecule. Different types of messenger molecules can be attained by changing the sequence, type, and number of amino acids of the molecule.

Receptors in CvD system are not passive receivers as antennas in wireless RF-based communication. The reception between the messenger molecule and its appropriate receptor is governed by specific chemical reactions. These reactions also attract stray molecules in the environment towards the receptor if the molecule is inside the affinity radius of the receptor ($r_{affinity}$). This relationship is called receptor affinity in biology literature [9]. Different receptor and molecule couples have different affinity capabilities and ranges. This leads to nodes having an effective radius, $r_{effective} = r_{cell} + r_{affinity}$, in addition to their actual physical radii. Considering this phenomenon, a messenger molecule is received by its target not only if it directly hits the receiver nanomachine, but also if it enters the effective radius of the receiver.

As stated above, during the communication between two nodes in multi-node environment, the remaining nodes act as obstacles. To avoid passing of molecules through these obstacles, the propagation model should be altered to reflect this limitation to the regular Brownian motion. There are several movement models in the literature that can be used for such an environment. Two of the most important movement models are Blind Ant and Myopic Ant models [10] (Figure 3). According to the Blind Ant model, at the end of each time step, if the new position of the molecule is illegal (i.e., inside an obstacle) the movement is rolled back. On the other hand, in the Myopic Ant model, when a molecule is close to an obstacle, its movement pattern (and therefore the normal

distributions) is altered so that it cannot move to the illegal direction. In [11], Avraham et al. show that both models converge to the same movement pattern in the long run. We choose the Blind Ant model for our simulations since it is computationally less intense than the second model.
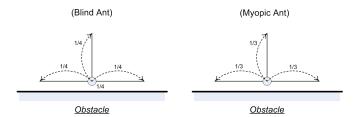

Figure 3. Next step probabilities in Blind and Myopic ant models in a step size 2D random walk

Figure 4. Effect of the environment on probability of hit

B. Evaluation of the Model

We evaluate the performance of the CvD system in a multi-node environment with nodes placed in the HCP lattice pattern as explained above. There is no boundaries in the environment. The messenger molecules are modeled after an amino acid based molecule, the insulin hormone in the human body. The sizes of the nodes are selected based on the average size of an eukaryotic cell and the fluid in the environment is selected as water. The environment consists of three planes, and in each plane there are 49 nanomachines, distributed evenly in 7 rows and 7 columns. We use Monte Carlo simulations and evaluated the results by averaging over 10,000 trials. Other simulation parameters are as given in Table I. As the random number generator algorithm, we use the widely used Mersenne Twister algorithm.

Parameter	Value
Stokes' radius of messenger molecule (r_s)	$2.86\,nm$ [12]
Radius of messenger molecule (r_{mm})	$2.5\,nm$ [13]
Viscosity of the fluid (η)	$0.001\,\frac{kg}{s.m}$
Temperature (T)	$310^\circ K$
Drag constant (b)	$5.391\,10^{-11}\frac{kg}{s}$
Diffusion coefficient (D)	$79.4\,\frac{\mu m^2}{s}$
Radius of the nanomachines (r_{cell})	$10\,\mu m$ [9]
Simulation time	$10.000\,s$
Plane count	3
Row/Column count	7

Table I
SIMULATION PARAMETERS

The results of the multi-node environment are compared to the free diffusion environment used in our previous work [14]. In this free diffusion environment, the only node in the environment is the receiver and there are no obstacles that affect the propagation of the messenger molecules. In both environments, the interaction between messenger molecules (i.e., collisions, attraction, repulsion) are assumed to be negligible.

As seen in Figure 4, the probability of hit at the receiver increases in the multi-node environment compared to the free
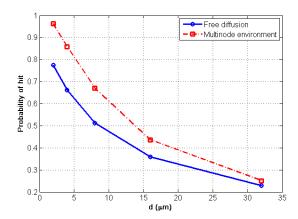
diffusion environment. This is a direct consequence of the fact that, in the multi-node environment, the molecules released from the transmitter cannot go back through the transmitter node since it acts as an obstacle for the messenger molecules. Neighboring nodes also limit the movement of the molecules and act as walls that compose a passage way. The sharp decrease in the hitting probabilities as d increases, is observed in both environments. So, even though there are obstacles that limit the movement of the molecules, communication at long distances (more than 10 μms) require the release of many molecules to be effective. Even then, the energy/bit value of the communication is too high for an effective transmission [14]. Also, such a transmission generates many stray molecules in the environment, which in turn increases the noise for all nearby CvD transmissions and inter-symbol interference.
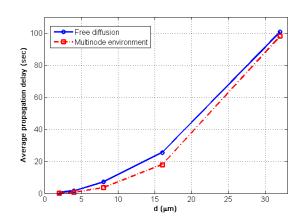

Figure 5. Effect of the environment on average propagation delay

In the multi-node environment, the average propagation delay of molecules is less than that in the free diffusion environment (Figure 5). This decrease is also based on the obstacles in the environment since they decrease the chance that a molecule wanders around and reaches at the receiver

over a long path. Also, in the multi-node environment if a molecule enters a path between several nodes it is very unlikely that it will reach back at the receiver. Thus, avoidance of the longer paths reduces the delay.

III. ROUTING IN MULTI-NODE ENVIRONMENT

In a multi-node environment, a transmitter communicates with other nodes by using different messenger molecules that interact only with specific receptors. This can be implemented via various methods such as using proteins with different amino-acid patterns and building molecular structures in which some parts refer to the addressing information while the rest represents the data and other header information of the message.

A node can emit the messenger molecules from any part of its boundaries (i.e., release points). The selection of the release point of the messenger molecules affects the performance of the communication since it determines the distance to be traversed by the messenger molecules to reach at the receiver, especially when r_{cell} is comparable to d. As seen in the previous section, with the increase in the distance that the messenger molecules traverse, the probability of hit decreases and the average propagation delay increases. Thus, in the CvD system, in order to maximize the efficiency of the transmission, a node should select the release point which is closest to the receiver.

A. Effect of the Release Points

In order to show the effect of selecting different release points on the communication performance, we conduct simulations in the multi-node environment. The simulation parameters are again selected as in Table I with two different d values. The results are averaged over $30,000$ trials. In addition to the previous parameters, we introduce a new parameter, α, that describes the angle between the two following lines; the line between the release point and the center of the transmitter and the line between the centers of the transmitter and the receiver (Figure 6).
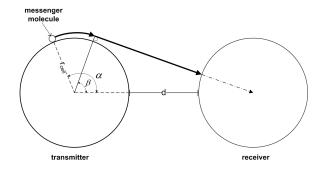

Figure 6. Selecting the angle between the release point and the center of the sphere

As seen in Figure 7, the probability of hit sharply decreases after $30°$ and becomes less than 0.2 after $130°$. As α increases, the shortest distance to the receiver also increases. After
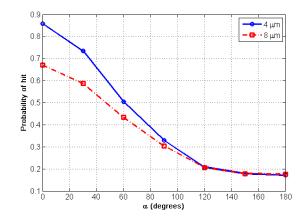

Figure 7. Effect of angle of the release point over probability of hit

$90°$, the molecules are forced to travel to the other side of the transmitter in order to reach the receiver, which further decreases the probability of hit values.
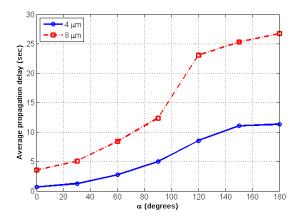

Figure 8. Effect of angle of the release point over average delay

The average delay of the molecules is also adversely affected by the angle of the release point (Figure 8). If α is chosen larger than $30°$, the average delay increases considerably as the angle increases.

The selection of r_{cell} also affects these two performance metrics. As r_{cell} increases, the performance degradation based on the selection of the release point becomes more severe since the shortest distance increases with r_{cell}. On the other hand, if the radius decreases, the effect over the performance is decreased. We select r_{cell} value as $10\,\mu m$, equal to the average size of an eukaryotic cell.

Based on these results, it is clear that selection of the appropriate release point has a significant effect over the probability of hit and the average propagation delay. Also, the stray molecules in the environment have adverse effects on other communicating pairs.

B. Benefits of Routing Mechanisms

For a given node, the appropriate release point would be different based on the target of the transmission in question. If the node does not have any routing capability, it can employ only very simple release point selection schemes. The simplest scheme is to choose one release point for all transmissions. While this method will be suitable for some of the adjacent nodes, transmission to other nodes would suffer from low hit probabilities and long average propagation delays. A more advanced scheme would be the selection of an arbitrary release point for each transmission. This scheme provides fairness among receivers to some extent, but on the average the performance of a given transmission would still be far from optimal.

In the arbitrary selection case, the distance a molecule has to traverse can be calculated based on the selection of the α value and denoted by $P(\alpha)$. Using trigonometric relations from Figure 6, this distance in a 2D circle can be found as

$$P(\alpha) = \begin{cases} \frac{\pi r_t (\alpha - \beta)}{180} + \sin(\beta)(2\,r_{cell} + d) - r_t \,, & \alpha > \beta \\ \sqrt{f^2 + e^2} - r_t \,, & \alpha \leq \beta \end{cases} \tag{1}$$

where

$$f = \sin(\alpha) \cdot r_t \,, \tag{2}$$

$$e = 2\,r_{cell} + d - \cos(\alpha) \cdot r_t \,, \tag{3}$$

$$r_t = r_{cell} + r_{molecule} \,, \tag{4}$$

and β is the release point angle at which the straight line between the centers of the molecule and the transmitter is perpendicular to the straight line between the centers of the molecule and the receiver (both the α and β values are in degrees). This angle is calculated as

$$\beta = \arccos(\frac{r_t}{2\,r_{cell} + d}). \tag{5}$$

By integrating these paths $P(\alpha)$ over α, the average path distance can be found by using symmetry as,

$$E[P] = \frac{1}{180} \cdot \left[\int_0^\beta (\sqrt{(f^2 + e^2)} - r_t)\,d\alpha \right. \tag{6}$$
$$\left. + \int_\beta^{180} (\frac{\pi r_t (\alpha - \beta)}{180} + \sin(\beta)(2\,r_{cell} + d) - r_t)\,d\alpha \right]$$

We evaluate the $E[P]$ for different d and r_{cell} values using this arbitrary scheme and compare them against the optimal distance that can be attained using a routing scheme. We also add another sub-optimal solution in which the routing scheme cannot select the optimal release point but chooses points close to the optimal one subject to a normal distribution (i.e. $\mathcal{N}(0, \sigma)$) where $0°$ refers to the α value of the optimal release point.

As seen in Table II, using the arbitrary scheme, a molecule has to traverse more than four times the d value. With the

d	Optimal	Sub-optimal ($\sigma = 20$)	Arbitrary Scheme
$4\,\mu m$	4	4.925	16.287
$8\,\mu m$	8	8.858	19.976
$12\,\mu m$	12	12.812	23.84
$16\,\mu m$	16	16.780	27.682

Table II
$E[P]$ VALUES (μm) USING DIFFERENT ROUTING SCHEMES
($r_{cell} = 10\,\mu m$)

r_{cell}	Optimal	Sub-optimal ($\sigma = 20$)	Arbitrary Scheme
$1\,\mu m$	4	4.064	5.103
$5\,\mu m$	4	4.427	9.986
$10\,\mu m$	4	4.925	16.287
$15\,\mu m$	4	5.435	22.680

Table III
$E[P]$ VALUES (μm) USING DIFFERENT ROUTING SCHEMES ($d = 4\,\mu m$)

increase of d, the difference between the optimal and the arbitrary scheme results decreases since d starts to become the prevalent factor in $E[P]$. The sub-optimal solution is used with a small σ value; therefore it gives results very close to the optimal solution. In Table III, it is shown that the effect of using a routing scheme varies based on the value of r_{cell}, as explained in section III-A. The increase in r_{cell} proportionally increases the efficiency of a good routing mechanism. Contrarily, as r_{cell} decreases, the selection of the optimal release point turns out to be insignificant.

IV. CONCLUSION

In this paper, we develop a 3D model for the multi-node environment for the CvD system consisting of many nanomachines. Using simulations, we compare the performance of this environment against a simpler free diffusion environment composed of a single receiver and a point based transmitter. Based on the results, we observe that the existence of the third party nodes, nodes other than the transmitter and receiver of a given transmission, and the transmitter in the environment improve the performance of a CvD transmission since these nodes behave like obstacles in the environment and prevent molecules from wandering away from their intended target.

Different from the free diffusion environment, in a multi-node environment additional capabilities are required from the communication system, such as routing and scheduling. We evaluate the performance effect of sending the molecules from different parts, release points, of the node. According to the results, this release point selection has a significant effect on the aforementioned performance metrics since selecting a random release point increases the total distance a molecule is required to traverse, which in turn degrades the transmission efficiency. Based upon this result, we compare the performance of three release point selection schemes, an arbitrary scheme, an optimal scheme, and a sub-optimal scheme. Our results show that the existence of a routing mechanism, even though it is sub-optimal, greatly increases the probability of hit of the molecules while reducing the average propagation delays.

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