Distance Effect of Molecular Harvesting over Signal Reception and Harvesting Performance in DIRECT

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***Abstract*—Since the introduction of the nanonetworks, molecular communication has become a popular research area in computer science. Although there are several methods proposed to implement molecular communication, none of them treats resources as discrete entities. We define resources as the discrete physical particles taking part in the communication tasks in a nanonetwork, such as information encoding. DIRECT is a novel networking scheme particularly aimed to model the re-use of resources in a confined operating environment. In DIRECT, resources do not disperse, they do not attenuate over time and they are considered 100% reusable, if properly harvested. In this paper, the impact of harvester location over the signal reception and the harvesting performance of the nodes are investigated. The main outcome of the paper is that, in terms of signal reception, the optimum location for the harvester is the midpoint between the sender and receiver nodes, whereas the harvesting performance increases as the harvester approaches the sender node.**

I. Introduction

Nanomachines are basic units which are capable of performing simple tasks at the nanoscale. Nanomachines equipped with communication capabilities allow the creation of nanonetworks, or networks of nanomachines [1]. With the introduction of nanonetworks, molecular communication came up as an alternative to electromagnetic communication to enable interaction among nanomachines [2]. Molecular communication relies on the usage of particles, known as *resources* in DIRECT [3], for information encoding.

In molecular communication, resources are physically transferred from sender to receiver nodes. The transmission process can be accomplished in several ways, including the usage of molecular motors [4], bacteria [5], through gap junction channels [6] or by means of diffusion [7]. For instance, in diffusion-based molecular communications, which is the most widely used molecular communication technique to date [7], resources propagate by means of diffusion in a fluid medium, according to Fick's laws of diffusion [8].

DIRECT is a recently introduced novel networking scheme [3], focused to the analysis of molecular communication techniques operating in a confined operating environment.

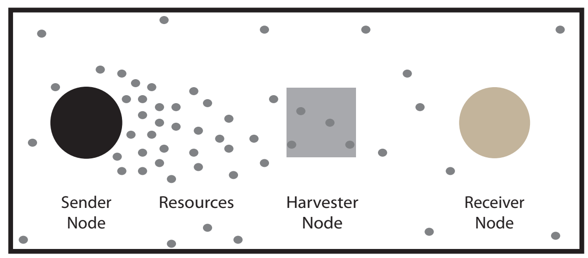

Fig. 1. Essential constituents of DIRECT

In such an environment, the total amount of resources remains constant over time; thus, if resources are properly harvested, they can be theoretically reused an infinite number of times. Therefore, harvesting nodes, or harvesters, play an important role in DIRECT. In this paper, we investigate the impact of the harvester location over its harvesting performance and the signal reception performance of the receiver.

II. DIRECT

A formal definition of DIRECT can be given as a set of techniques, models and protocols developed to efficiently operate a network within a confined environment, which utilises and relies on discrete entities. The essential constituents of DIRECT can be listed as nodes, a confined environment, and resources (Fig. 1).

Nodes are autonomous agents operating in the network, basically comprising processing, communication and harvesting capabilities. In DIRECT, every node is assumed to contain the necessary components to perform the sending, receiving and harvesting operations. In addition, every node has an internal reservoir to keep the harvested resources for future use. Any harvesting operation performed by a node fills the node's reservoir, whereas any sending operation empties it.

The confined operating environment is modeled as a closed space with reflecting boundaries. Any resource reaching the boundaries of the environment reflects back into it; thus, the total amount of resources remains constant over the network lifespan.

Any physical particle which is involved in a communication task, such as information encoding or transportation, is considered a *resource* in DIRECT. Resources do not disperse, nor do they attenuate over time. They can be reused if properly harvested from the operating environment. In a nanonetwork, in a confined environment, the reusability property of resources theoretically yields an infinite network lifespan.

Resources can be located either inside a node's reservoir, or in the operating environment. Resources in the operating environment can be used either to encode information, or they can be considered as *noise*. Formally, any resource in the operating environment which is not used to encode information is considered as noise in DIRECT.

Harvesting nodes can harvest resources from both information and noise. Although both information and noise are composed of resources, they can be reused after being harvested for future transmissions. This property of DIRECT is called *the duality of the resources*, and it allows 100% recycling of resources, both information and noise. This feature represents, to the best of our knowledge, a unique case which does not appear in any other communication paradigm.

Our intention in DIRECT is to define the capacity of a system such as that described above. The system capacity in DIRECT is defined, differently from other communication paradigms, as the maximum number of nodes which can be supported for a given amount of resources in an infinite lifespan. From another perspective, the capacity relates to the optimum amount of resources required to operate a given number of nodes in an infinite lifespan, inside a given confined operating environment.

III. Harvester Location

The recirculation of resources is sustained by the continuous harvesting and information-encoding processes. Thus, the harvesting operations have an important role on the persistence of the resource recirculation. As we will see next, the location of an harvesting node has a significant impact over its harvesting performance, as well as over the signal reception performance of a receiving node.

In this paper, we have investigated the role of the harvesting node location over the performance of DIRECT. We have performed a series of experiments, considering diffusion-based molecular communication using *pulse based modulation (PBM)* [10], [11] as the modulation technique.

To modulate a single bit of information in PBM, the sender node instantaneously emits a pulse consisting of Q resources. The emitted pulse propagates over the operating environment according to Eq. (1), eventually reaching the receiver node.

$$\rho(x,t) = \frac{Q}{4\pi D t} e^{-x^2/4Dt} \tag{1}$$

In Eq. (1), Q is the number of resources emitted by sender node, i.e., the *pulse amplitude*, x indicates the distance from the sender node and t is represents the time elapsed since emission of the pulse. ρ represents the concentration of

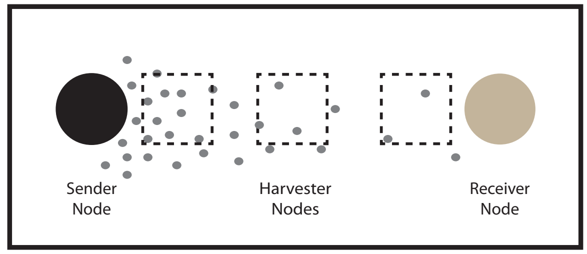

Fig. 2. Different locations of harvester nodes between sender and receiver nodes

resources at location x and time t, whereas D is the diffusion coefficient of the operating environment.

We have used N3Sim [9], a previously-developed simulation software for diffusion-based molecular communication, to visually observe the impact of the harvester location.

In the simulations, we have considered a confined operating environment with 3 nodes. The first operating node acts as an harvester, the second acts as a sender and the last acts as a receiver. We have fixed the locations of the sender and the receiver nodes, while different locations were considered for the harvesting node (dashed squares in Fig. 2). We assumed that our harvester has a reservoir with an infinite capacity and it can instantaneously harvest the desired amount of resources. We also considered the following assumptions:

- The sender node is located at $x = 0$ and it sends Q resources at time $t = 0$.
- The receiver node is located at $x = x_d$ and it receives R resources at time $t = t_d$.
- The harvester node can instantaneously harvest up to H resources
- $Q \gg R$

In this scenario, we can consider 4 cases with respect to the harvester location. As we describe next, each of them has a different effect on the signal reception and the harvesting performance of the system.

A. Harvesting node located at the receiver node

If we have an harvesting node at the same location with the receiver node, the harvesting node will absorb H resources instantaneously. If $H \geq R$, all resources reaching the receiver node would be absorbed by the harvester. For $H < R$, the receiver would receive $R - H$ resources:

$$\rho = \begin{cases} 0 & \text{if } H \geq R \\ R - H & \text{if } H < R \end{cases} \Bigg|_{x=x_d, t=t_d} \tag{2}$$

B. Harvesting node located at the sender node

If we have an harvesting node located at the location of the sender node, the harvester will absorb H resources at time $t = 0$. This scenario is similar to sending $Q - H$ resources at time $t = 0$. In this case, the concentration of resources reaching the receiver node is given by:

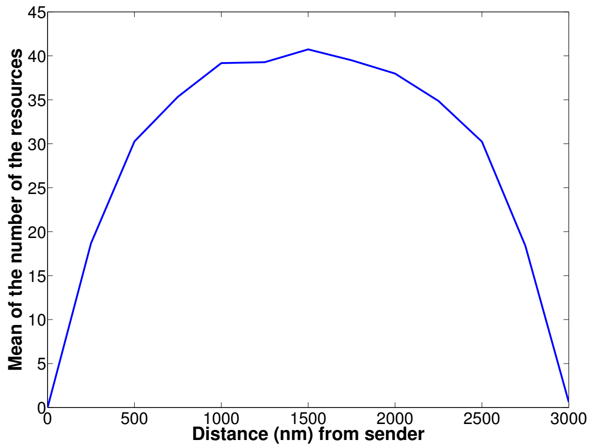

Fig. 3. Mean of the number of resources received for different locations of the harvester node

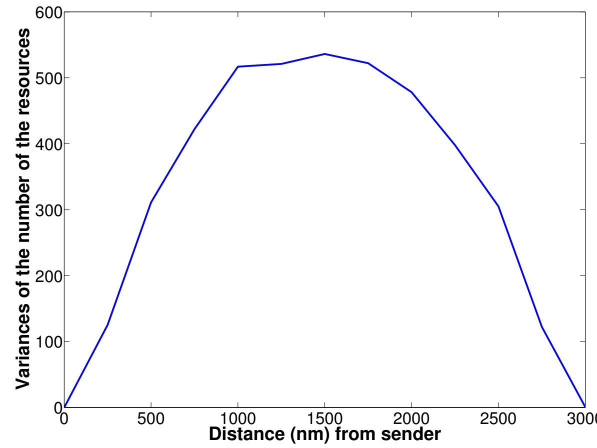

Fig. 4. Variance of the number of resources received for different locations of the harvester node

$$\rho(x,t) = \frac{Q-H}{4\pi Dt} e^{-x^2/4Dt} \tag{3}$$

C. Harvesting node at an irrelevant location

If the harvesting node is located behind the sender node, ahead of the receiver node or at any other location other than the direct diffusion path of the resources from sender to receiver, we can consider that it does not have an excessive influence over the signal measured by the receiving node.

D. Harvesting node between sender and receiver nodes

If the harvesting node is located between the sender and receiver nodes, as seen in Fig. 2, the impact of the harvesting operation may vary according to the harvester location. Please note that a pulse amplitude consisting of 300000 resources is used in the simulations, and the receiver node is placed 3000 nm away from the sender node.

The mean, i.e., the mean signal strength, and the variance of the received resources at receiver node for different locations of the harvesting node can be observed in Fig. 3 and Fig. 4, respectively. In both figures, the x axis represents the distance of the harvesting node from the sender node. During the simulations, the receiver node continuously monitored the concentration of resources at its location. As it represents the mean of the total number of received resources during the simulation, an increase in Fig. 3 directly indicates a stronger signal strength at the receiver side. On the other hand, the variance is an indicator which can used to monitor the variation of the resource concentration throughout the simulation. Furthermore, it acts as an indicator for the rate of resource recirculation. In this scenario, an increase in Fig. 4 also indicates an increase in signal reception at the receiver.

From both figures 3 and 4, we can visually conclude that the best location for the harvester, in terms of signal strength, is the midpoint between the sender and receiver nodes. As we approach the harvester towards the sender or the receiver nodes, the signal strength dramatically decreases, eventually reaching 0.

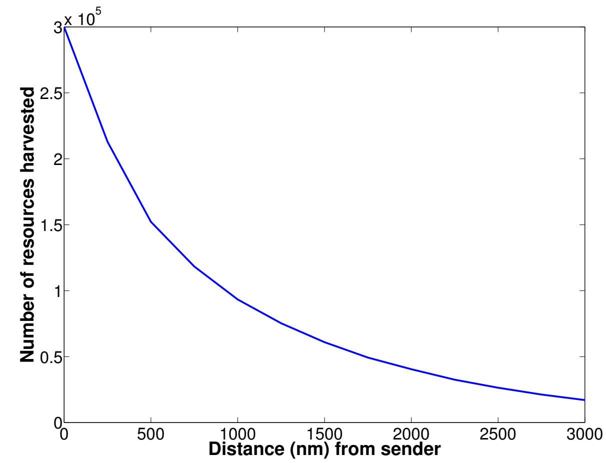

Fig. 5. Total number of resources harvested for different locations of the harvester node

In Fig. 5, we represent the total number of harvested resources by the harvesting node. We can visually observe that the best location for the harvester node, in terms of resource harvesting, is the sender node location, which acts as the main source of resources in this scenario. As we move the harvesting node away from the sender and bring it closer to the receiver, it harvests fewer resources.

From Fig. 3 and Fig. 5, we observe a trade-off in terms of the location of the harvesting node between harvesting performance and signal strength metrics. Therefore, the optimal value of the harvester location will depend on the requirements of the specific application considered.

IV. Conclusions

DIRECT is a novel networking paradigm, particularly aimed towards molecular communications. DIRECT introduces new concepts to the networking community, such as the *duality of the resources*, which allows 100% recyclable information and noise. With its particular properties, we believe that DIRECT suits well to nanonetworks using molecular communication techniques.

The location of the harvester nodes plays an important role over the performance of DIRECT. The harvesting performance and the signal strength are two essential metrics, and there is a clear trade-off between them over the location of the harvesting node. An harvesting node receives more resources as it is located closer to the sender node, whereas the midpoint between sender and receiver nodes is the optimum location in terms of signal strength at receiver node. We conclude that the best location of harvester depends on the design goals of the network according to essential metrics.

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REFERENCES

[1] I.F. Akyildiz, F. Brunetti, C. Blázquez, Nanonetworks: A new communication paradigm, Computer Networks, 52(12):2260-2279, August 2008

[2] I. F. Akyildiz, F. Fekri, R. Sivakumar, C. R. Forest, B. K. Hammer, Monaco: Fundamentals of Molecular Nano-communication Networks, IEEE Wireless Communications, 19(5):12-18, October 2012.

[3] D. Demiray, A. Cabellos-Aparicio, E. Alarcón, D. T. Altilar, I. Llatser, DIRECT: A Model for Molecular Communication Nanonetworks Based on Discrete Entities, submitted for publication to Nano Communication Networks, 2013.

[4] M. Moore, A. Enomoto, T. Nakano, R. Egashira, T. Suda, A. Kayasuga, H. Kojima, H. Sakakibara, K. Oiwa, A Design of a Molecular Communication System for Nanomachines Using Molecular Motors, Fourth Annual IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOMW'06), pp.:554-559, 2006.

[5] P. Lio, S. Balasubramaniam, Opportunistic routing through conjugation in bacteria communication nanonetwork, Nano Communication Networks, 3 (2012):36-45

[6] T. Nakano, T. Suda, T. Koujin, T. Haraguchi, Y. Hiraoka, Molecular Communication Through Gap Junction Channels. Transactions on Computational Systems Biology X, pp.:81-99, 2008.

[7] I. Llatser, A. Cabellos-Aparicio and E. Alarcón, Networking Challenges and Principles in Diffusion-based Molecular Communication, IEEE Wireless Communications, 19(5):36-41, 2012.

[8] J. Philibert, One and a Half Century of Diffusion: Fick, Einstein, Before and Beyond, Diffusion Fundamentals 4 (2006) 6.1 - 6.19

[9] N. Garralda, I. Llatser, A. Cabellos-Aparicio, M. Pierobon, Simulation-based Evaluation of the Diffusion-based Physical Channel in Molecular Nanonetworks, IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp.:443-448, 2011.

[10] N. Garralda, I. Llatser, A. Cabellos-Aparicio, E. Alarcón, M. Pierobon, Diffusion-based Physical Channel Identification in Molecular Nanonetworks, Nano Communication Networks, 2(4):196-204, July 2011.

[11] I. Llatser, E. Alarcón, M. Pierobon, Diffusion-based Channel Characterization in Molecular Nanonetworks, IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp.:467-472, 2011.