DIRECT: A Model For Networks That Are Based On Discrete Entities To Encode Messages

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Abstract

In this paper, a novel networking concept, DIRECT is presented and it's essential properties are introduced. DIRECT differs from conventional networking models by the way of treating resources as discrete entities. Resources can be involved in different tasks in a network such as encoding of the message. Resources do not attenuate in physical terms and they are considered 100% reusable. We explore essential properties and investigate key parameters throughout this paper.

1. Introduction

DIRECT can be defined as a set of techniques, models and protocols developed to efficiently operate a network which utilizes and relies on discrete entities, i.e. resources. These resources are both used to encode messages, and act as carriers over a medium within a confined environment.

With the introduction of nanoscale communications [1], molecular communication became an alternative approach to electromagnetic communication at nano scale. Although there are different communication protocols proposed for molecular communications [1], they rely on the use of small particles, which we call resources in DIRECT. These resources include small molecules, such as ions (for example Ca^{2+}) and hormones.

Most of the previous works miss the fact that the resources are discrete entities which do not attenuate and do not disperse over time. However the permanence of the resources constitutes the main idea behind DIRECT, whereas

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with to the best of our knowledge, none of the previous communication paradigm address this property.

If properly harvested, any resource in a confined system can be reused which yields a system with infinite recirculation. Infinite recirculation, i.e. continuous use and harvest cycle, naturally introduces the concept of resource conservation in a confined system. Our intention in DIRECT is to model such a resource recirculation; to investigate the properties of such a confined system and to define limits and capacity of the system.

Harvesting issue has been studied in electromagnetic communication nearly a decade. However the electromagnetic energy concept does not completely overlap with resource concept in DIRECT, since electromagnetic waves attenuate. We think that DIRECT is a good candidate to model molecular communication at nanoscale.

The rest of the document is organized as following: in Section 2 the state of the art and related works are briefly explained by stressing the differences from DIRECT. In Section 3, different operating environments are introduced and the importance of a confined environment is explained. In Section 4, formal definitions and explanations for resources, nodes, lifespan and capacity are given. In Section 5, a case study for DIRECT in which pulse based modulation is analyzed. A number of tests are performed in order to see interdependencies between essential parameters that define the environment and simulation results are discussed. We conclude the paper in Section 6, and a path for a future work is given.

2. State of the Art

Molecular communication has been an attractive topic for researchers after the introduction of the nanoscale communications. Numerous potential applications of nanonetworks makes molecular communication even more appealing. These potential applications are ranging from biomedical applications, such as intelligent drug delivery and health monitoring systems, to military and environmental applications such as air pollution monitoring [1].

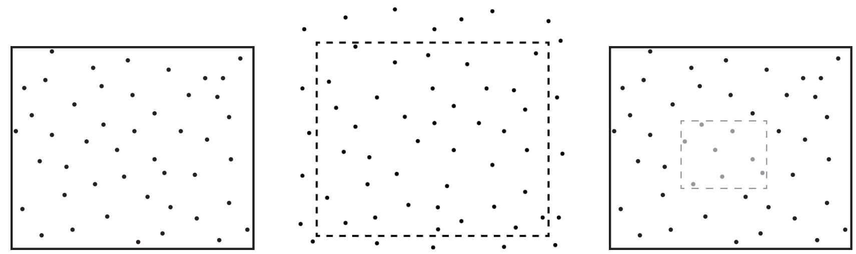
A number of different models have been proposed to describe molecular encoding, channel and transmission. Some of these models use gap junctions [11], some others use molecular motors [10], and ligand receptors [5].

Another group of researches focussed on proposing models and defining capacities from an information theoretical perspective [2, 3, 14, 13].

An energy model for molecular communications is introduced in [8], providing biological background of the energy consumption of different elements of the process.

A broad study for energy harvesting in electromagnetic communications is given in [16]. [15] refers to the information capacity of such networks.

Compared to the researches available in literature, DIRECT can be considered as an abstract model defining general rules for different models, with similar or common properties. Our intention in DIRECT is to state common



(a) Confined environment (b) Unconfined environment (c) Locally unconfined environment

Figure 1: Different operating environments

properties, like the use of discrete resources in a confined environment, and define and model a system through some related features such as communication capacity and its limits. In this paper we investigate a way of defining a system by stating relations between resource concentration, number of node and communication capacity in a confined environment.

3. Operating Environments

Considering the use of discrete resources in DIRECT, operating environments (or working spaces) can be classified into three categories according to the scope of the particle movement according to the existence of the boundaries: confined, unconfined and locally unconfined (fig.1).

A confined operating environment (fig.1a) is a closed working environment, bounded with reflective borders. Any resource reaching to the boundaries, reflects back into the environment. Thus, the number of total resources within the environment remains the same at any time.

An unconfined operating environment (fig.1b) has no boundaries and any resource can pass through the virtual borders of the monitored environment through time. Thus the total amount of discrete resources can vary in the environment.

A locally unconfined operating environment (fig.1c) is a special case of a confined operating environment, where the environment dimensions is extremely large such that we can consider a relatively small portion of the environment as unconfined.

In this paper, we consider a confined operating environment in which the total amount of resources remains constant over network lifespan. Constant number of resources in a confined operating environment, can theoretically make the network indefinitely operational in terms of resources, if proper harvesting and emitting mechanisms are applied. During operation, network may temporarily stop functioning due to the lack of local resources. However that could be overcome by harvesting over time, since resources naturally diffuse from higher density locations to the lower density ones. On the other hand, in an unconfined operating environment, network may become permanently not operational as a result of resource dispersal.

4. Resources and Nodes

It has been assumed that, resources are any kind of discrete entities which are required by a task, such as modulation of the signal, within the network. Resources are perpetual and reusable, they do not disperse or attenuate. If proper harvesting mechanisms applied, resources are 100% reusable.

Nodes are autonomous agents, and they constitute the basic functional unit, capable of processing/storing data, sensing and actuating. They are either organic or electromechanical nano machines [1], with communication capabilities. We assume that, every node operating in DIRECT includes proper harvesting mechanisms and an internal reservoir to keep resources within for future use. Any harvesting operation fills a node's reservoir, whereas a communication operation drains it.

The harvesting mechanisms in DIRECT differ from the ones in electromagnetic communication. Nodes in DIRECT harvest resources by absorbing discrete particle into the node's reservoir. However in electromagnetic communication, harvesting operation usually refers to the energy harvesting from different sources such as sunlight, body heat or vibration, all of which are produced as a result of external incidents that cannot be controlled within the system. The harvested energy is consumed by the nodes. However in DIRECT, resources are reusable.

Reusability property of the resources constitutes a recirculation in DIRECT. A resource can be found either inside a node's reservoir (in a pure resource form) or at large in operating environment (fig.2).

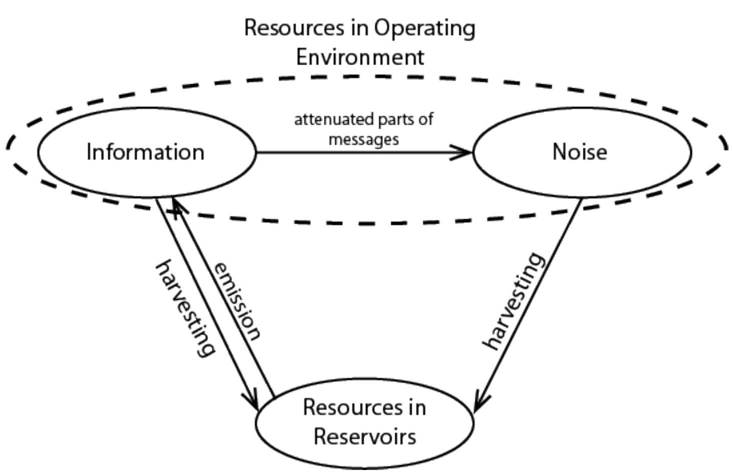


Figure 2: Resource recirculation

Resources in operating environment can have two different forms. They can be used to encode information, or they can be considered as noise. Information in DIRECT is represented by a group of discrete resources, whereas in electromagnetic communication, information is modulated using electromagnetic waves. During the propagation process, some of the resources, which belong to the attenuated parts of the propagating signal, may change their functionality and turn into noise. Note that no resource would be lost because of such a functionality change. Moreover, the emitted signal may attenuate during propagation.

Every resource in operating environment, which are not used for information encoding, are considered as *noise*. Noise can be generated from attenuated parts of the information, or can be initially given to the environment as *background noise*, to supply resources to the nodes. Whereas in electromagnetic communication, noise is a fluctuation or a random signal added to the original signal from an outside source.

As seen in fig(2), information is encoded using resources (emission), although a node can harvest resources from information. There is a complete overlap between information and resources, which we call *duality of the resources*. Duality of the resources also exists between resources and noise in a similar manner. Node can harvest resources from noise, however noise is made of resources.

Duality of the resources provides 100% recycling for resources in the form of both information and noise. Thus, DIRECT proposes reusable information and noise which, with the best of our knowledge, is a unique property that can not be found in any other communication paradigm.

Theoretically, infinite recirculation of resources can provide infinite lifespan to the DIRECT network, in terms of resources. Lifespan comes to an end when there is not a single node left that is capable of communicating in infinite time. During lifespan, there might be some intervals in which, network may not be operational due to the lack of resources. However nodes may continue harvesting until they collect sufficient resources from operating environment and resume with their operation.

Resource recirculation is broken if and when:

- Working environment is not confined.
- There is not sufficient resources to be harvested by the nodes which yields starvation.
- Deployment of excessive number of nodes which yields starvation.
- Nodes do not supplied with proper harvesting mechanisms.

Definition of *capacity* in DIRECT is different than any other communication paradigm. Considering previously introduced properties, capacity in DIRECT can be defined as the maximum number of nodes which can be supported for a given amount of resources in infinite lifespan. From a different perspective, capacity can be given as a function of the optimum amount of resources to obtain infinite lifespan for a given number of nodes.

5. Experiments

A set of experiments performed to observe the behavior of DIRECT in modeling molecular networks. Three essential parameters are investigated during experiments, and the relationship between them has been studied. These parameters are:

1. *Pulse amplitude (A)* is the number of resources that constitute an emitted pulse initially.
2. *Background concentration (b)* is the initial concentration of resources over operating environment.
3. *Number of nodes (n)* is the total number of nodes available in operating environment.

Pulse frequency (p), which is the ratio of the number of pulses emitted per unit time, is the essential metric which is monitored according to the variations of the given parameters.

Pulse based modulation (PBM) is recently applied to molecular communication as a modulation scheme by Llatser et al [6, 9]. In our experiments, we used PBM because it's properties and behavior are already studied.

In PBM, in order to represent 1 bit of information, sender must instantaneously emit a pulse which comprises of Q discrete resources. To emit a pulse, a sender node should have already harvested at least Q resources from the operating environment assuming that it possesses none initially. Emitted pulse will be propagated through the environment, like the ripples in water, eventually reaching at the receiver's location. The concentration of a pulse at time t at a distance x is given by (1) where D is the diffusion coefficient of the operating environment [4, 12].

An interested reader can find more information about PBM at [9] and [6].

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

Experiments are performed using N3Sim [7], a previously developed discrete event simulation software for molecular communication and PBM.

In the first set of experiments, we investigate the $pulse\ frequency$ as a function of *background concentration* and *pulse amplitude* (2), the results can be seen in fig.3. Please note that we used normalized values for parameters and metric, and we fixed *number of nodes* to 1. Lines in fig.3 represents different *pulse amplitude* values, and they are arranged from highest *pulse amplitude* value to lowest. Lines at the bottom, which represents a high *pulse amplitude* value, results a low *pulse frequency.* Whereas the upper lines which represents a low *pulse amplitude*, results a high *pulse frequency.*

$$p = f(b, A)\Big|_{n=1} \tag{2}$$

As we fixed *number of nodes* in fig.3, we observe the impact of *background concentration* over *pulse amplitude*, and vice versa. A higher *background concentration* value provides more resources to the environment, whereas a low *background concentration* value provides low resources. In order to emit pulses with higher amplitudes, a node requires more resources, thus it requires high *background concentration* values. On the other hand, pulses with low amplitudes requires less resources. To obtain a higher *pulse frequency*, environment must provide a high resource concentration, whereas pulses must contain low *pulse amplitude*. This claim is confirmed in fig.3, in which maximum value of *background concentration* parameter combined with lowest *pulse amplitude* value gives the best *pulse frequency*. Contrarily, we observe a minima at the point for maximum *pulse amplitude* and minimum *background concentration*.

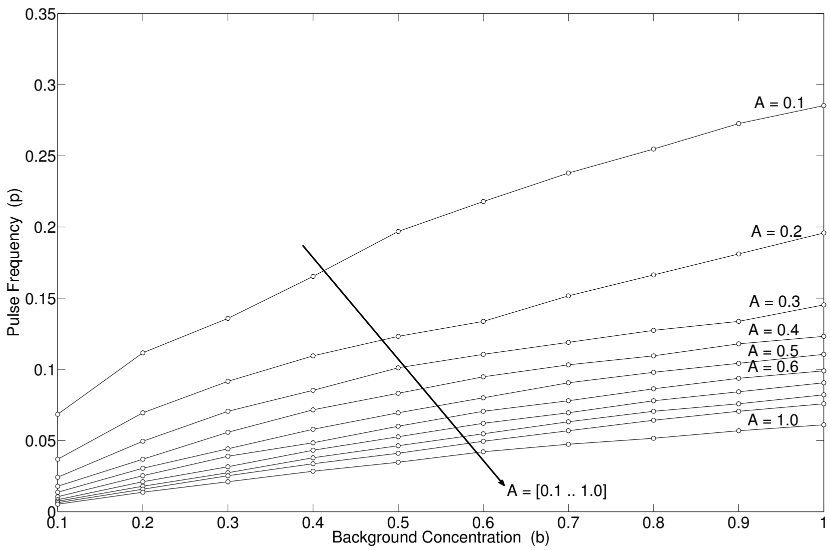


Figure 3: *Pulse frequency (p)* for different *background concentration (b)* and *pulse amplitude (A)* for $n = 1$

$$p = f(b, n)\,\Big|_{A=0.5} \tag{3}$$

In the second set of tests, we monitored *pulse frequency* against *number of nodes* and *background concentration* (3) (fig.4). Note that a fixed *pulse amplitude* value is used during this set of simulations. Each line in fig.4 represents a set of tests for a different *number of nodes* parameter. They are arranged in such a way that the one at the bottom stands for the lowest *number of nodes*, whereas upper lines designates higher *number of nodes* values.

Nodes in fig.4 are homogeneously spread over environment, forming a grid shape, and they concurrently harvest resources from different regions of environment. As we fixed *pulse amplitude*, we observe the relationship between *background concentration* and *number of nodes* values.

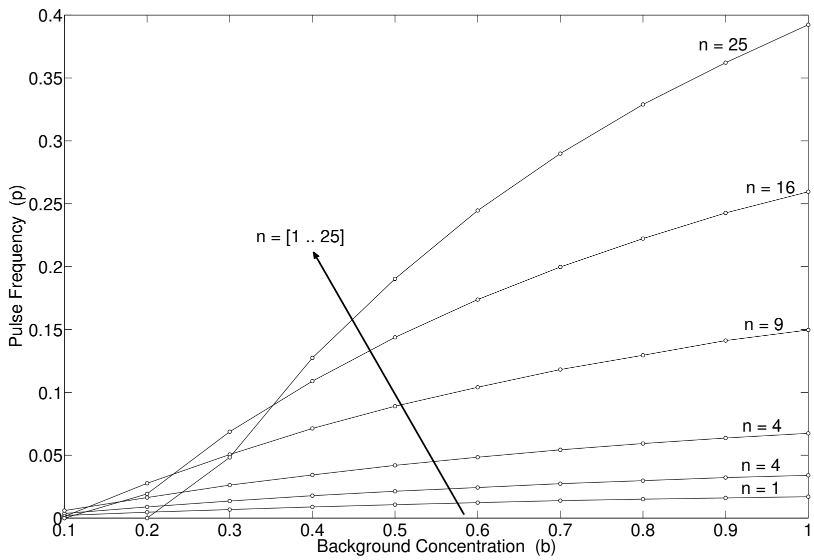


Figure 4: *Pulse frequency (p)* for different *background concentration (b)* and *number of nodes (n)* for $A = 0.5$

Higher *number of nodes* values represent more nodes, concurrently emitting pulses, and they inherently increase *pulse frequency*. More nodes emit more pulses, thus require more resources. If environment cannot feed nodes with necessary resources, they cannot harvest enough resources to emit pulses. We can observe this fact in fig.4 as a minima at the origin. Contrarily, we can observe a maxima at the highest values of *number of nodes* and *background concentration*. To operate more nodes, environment must provide more resources.

In the third set of tests, we monitored *pulse frequency* against *pulse amplitude* and *number of nodes* (4) (fig.5). Note that a fixed *background concentration* value is used during this set of simulations. Lines in fig.5 represents different *number of nodes* values, the one at the bottom represents lowest *number of nodes*, whereas upper lines represent higher *number of nodes* values.

$$p = f(A, n)\Big|_{b=0.5} \tag{4}$$

Pulses with higher *pulse amplitude* contains more resources than pulses with lower *pulse amplitude*. Similarly, need for resources increases if more nodes concurrently operates in the network. However, concurrently operating nodes involves higher pulse emissions per unit time. A high *pulse frequency* can be achieved if a high number of nodes operates concurrently, and each node releases pulses with low *pulse amplitude*. Please note that, operating environment cannot *feed* unlimited number of nodes, especially if they are emitting pulses with high

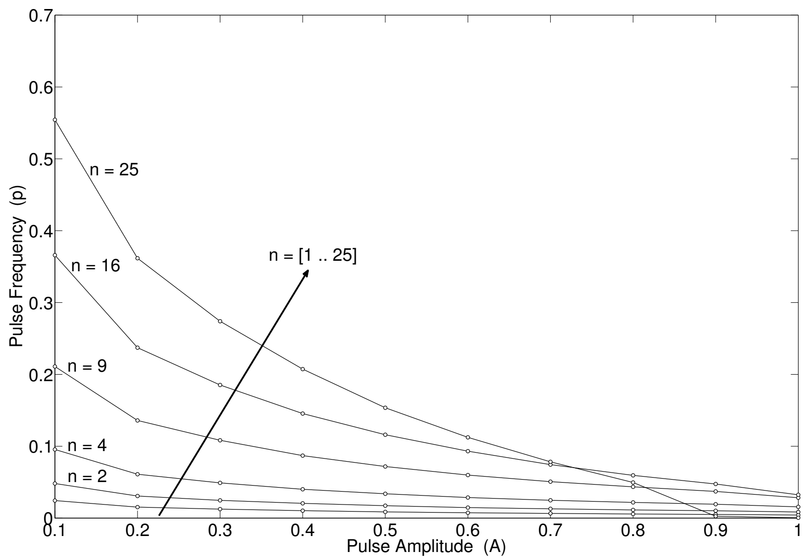


Figure 5: *Pulse frequency (p)* for different *pulse amplitude (A)* and *number of nodes (n)* for $b = 0.5$

pulse amplitude. This fact can be observed in fig.5 as a minima for highest value of *pulse amplitude*.

6. Conclusion and Future Work

As an abstract networking model, DIRECT can be used to understand general properties of the different networking paradigms, which uses discrete entities as resources, and which works in a confined environment. Theoretically, a DIRECT network can achieve infinite network lifespan in terms of resources, but network may be temporarily not operational during harvesting periods.

As a future work, the capacity of DIRECT, and the upper and lower bounds of the capacity for a given amount of resources will be investigated. Harvesting operations has a considerable effect over received signal at receiver node, we are working on the equations which establish a connection between harvesting and receiving operations.

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References

[1] Ian F. Akyildiz, Fernardo Brunetti, and Cristina Blazquez. Nanonetworks: A new communication paradigm. *Computer Networks*, 52(12):2260–2279, August 2008.

[2] Baris Atakan. On Molecular Multiple-Access, Broadcast, and Relay Channels in Nanonetworks. *Proceedings of the Third International Conference on Bio-Inspired Models of Network, Information, and Computing Systems (Bionetics 2008)*, 2008.

[3] Baris Atakan and Ozgur B. Akan. Deterministic capacity of information flow in molecular nanonetworks. *Nano Communication Networks*, 1(1):31–42, March 2010.

[4] W H Bossert and E O Wilson. The Analysis of Olfactory Communication Among Animals. *Journal of Theoretical Biology*, 5(3):443–469, November 1963.

[5] Arash Einolghozati, Mohsen Sardari, and Faramarz Fekri. Capacity of diffusion-based molecular communication with ligand receptors. *IEEE Information Theory Workshop*, pages 85–89, 2011.

[6] Nora Garralda, Ignacio Llatser, Albert Cabellos-Aparicio, Eduard Alarcón, and Massimiliano Pierobon. Diffusion-based physical channel identification in molecular nanonetworks. *Nano Communication Networks*, 2(4):196–204, July 2011.

[7] Nora Garralda, Ignacio Llatser, Albert Cabellos-Aparicio, and Massimiliano Pierobon. Simulation-based Evaluation of the Diffusion-based Physical Channel in Molecular Nanonetworks. *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, pages 443–448, 2011.

[8] Mehmet Sukru Kuran, H. Birkan Yilmaz, Tuna Tugcu, and Bilge Özerman. Energy model for communication via diffusion in nanonetworks. *Nano Communication Networks*, 1(2):86–95, June 2010.

[9] Ignacio Llatser, Eduard Alarcón, and Massimiliano Pierobon. Diffusion-based Channel Characterization in Molecular Nanonetworks. *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, pages 467–472, 2011.

[10] M. Moore, a. Enomoto, T. Nakano, R. Egashira, T. Suda, a. Kayasuga, H. Kojima, H. Sakakibara, and 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)*, pages 554–559, 2006.

[11] Tadashi Nakano, Tatsuya Suda, Takako Koujin, Tokuko Haraguchi, and Yasushi Hiraoka. Molecular Communication Through Gap Junction Channels. *Transactions on Computational Systems Biology X*, pages 81–99, 2008.

[12] Jean Philibert. One and a Half Century of Diffusion: Fick, Einstein, Before and Beyond. *Proceedings of Diffusion Fundamentals*, 4:1–19, 2005.

[13] Massimiliano Pierobon and Ian Akyildiz. A physical end-to-end model for molecular communication in nanonetworks. *IEEE Journal on Selected Areas in Communications*, 28(4):602–611, May 2010.

[14] Massimiliano Pierobon and Ian F. Akyildiz. Information Capacity of Diffusion-based Molecular Communication in Nanonetworks. *Proceedings IEEE INFOCOM*, 59(6):506–510, 2011.

[15] R Rajesh, Vinod Sharma, and Pramod Viswanath. Information capacity of energy harvesting sensor nodes. *2011 IEEE International Symposium on Information Theory Proceedings*, pages 2363–2367, July 2011.

[16] Sujesha Sudevalayam and Purushottam Kulkarni. Energy Harvesting Sensor Nodes: Survey and Implications. *IEEE Communications Surveys and Tutorials*, 13(3):443–461, 2011.