Universidade do Minho
Escola de Engenharia

Diogo Caldeira Ferreira

Design of a Molecular Nanocommunications System with Suitable Addressing and Routing Mechanisms

Tese de Mestrado
Mestrado Integrado em Engenharia de Comunicações

Trabalho efetuado sob a orientação de
Professor Doutor Nuno Vasco Lopes
Professor Doutor Luis Paulo Reis

Outubro de 2014

Acknowledgements

I would like to thank Professors Nuno Vasco Lopes and Luis Paulo Reis for the guidance and all the opportunities provided during the development of this thesis.

Abstract

Nanotechnology is a new and very promising area of research which will allow several new applications to be created in several fields, such as, biological, medical, environmental, military, agricultural, industrial and consumer goods. Although there are several sub-areas of research within the nanotechnology area, the main sub-areas in which the developed work was based were on target nanocommunications. The advances in this area will allow interconnected devices, at the nano-scale, to achieve collaborative tasks which will greatly change the paradigm in the fields described. In spite of this area of research being in its early stages and the various inherit challenges, there are several researches around the world that are contributing for the advances in different sub-areas, which translate in several small advances in the last years. This trend will enable nanocommunications applications to be a reality in a near future, which in turn motivates new researchers to embark on this area.

Determined to learn more about this fascinating area, help the research community design and implement new concepts that can influence the path of this new research area, and the knowledge that advances in this area provides a huge impact, changing the paradigm in different fields, were the main motivations that influenced the pursue of the area of research. During the research and study phase, several new concepts were learned, namely, a completely new paradigm which establish communication through molecules, i.e., molecular communication. This new communication paradigm will open a window for several applications to be possible, thus all work performed aimed at this area specifically.

After giving molecular communications a thorough research and studying all related concepts, the main challenges in this research area were targeted and solutions to solve them started to be planned. In this document a description of all the work done is presented, in which a molecular nanocommunications system is designed addressing several challenges mentioned in different research domains. Contrary to a traditional computer network, when designing a nanocommunication system there are several aspects that need to be addressed, and the answer for one obstacle is not always the best answer because these systems rely immensely on the synergy of

all components of the nanonetwork, specially in molecular communications. Hence, the different components of the system were designed having the synergy with each other in mind. The most promising information's encoding technique was chosen, and from there several concepts were analysed in order to select the appropriate communications techniques, a topology design was created in order to provide the nanonetwork the capability to solve some challenges, while using inherit features from the communications techniques selected.

Several challenges were addressed in the designed system, such as, the range scalability of a nanonetwork, the interaction with the micro and macro scales, reliability in the communication, error and flow control mechanisms, information encoding, and most importantly addressing and routing mechanisms. The whole system architecture is then analysed, and some information for the evaluation of the system designed is presented and discussed. Although several obstacles were met during the development, most of them were successfully overcome, but leaving a desire to continue work in the fascinating area. Since this research area is still on its infancy, it is very difficult to set a limit on the future work, but there are important aspects that could expand the concepts approached in this dissertation, such as, the creation of a simulation tool that would allow protocols to be tested, design and validate different protocols for different methods of communication and develop a simulation tool that would allow researchers to simulate a full molecular nanonetwork, with different communication techniques in simultaneous, different protocols, and the ability to connect them to traditional computer networks.

In the whole process of this dissertation a lot was learned about this new communication paradigm. This area of research definitely left the appetite to keep researching, designing and creating solutions that can impact several fields of our daily lives. Although this area of research is still on its early stages, a lot of interesting concepts were learned, and some new concepts were envisioned and described. The design of a molecular communication system showed me how different this communication paradigm is from traditional computer networks, as well as all the challenges there are still ahead. In spite of that, thanks to envisioned techniques and manipulations of features the designed system is able to function, increasing the efficiency of transmission. When advances in nanotechnology and nanomachines manufacturing permit it, a bridge between nano-scale and micro/macro-scale will be created.

Resumo

Nanotecnologia é uma nova e promissora área de investigação que irá permitir a criação de diversas novas aplicações em vários campos, tais como: biológico, médico, ambiental, militar, agrícula, industrial e bens de consumo. Apesar de haver diversas subáreas de investigação dentro da grande área de nanotecnologia, as principais subáreas em que o trabalho desenvolvido se foca, direcionam-se para nanocomunicações. Os avanços nesta área vão permitir dispositivos interconetados, à escala nano, alcançar a colaboração em tarefas que irão mudar o paradigma nos campos descritos. Apesar de esta área de investigação ainda estar nas etapas iniciais e de todos os obstáculos inerentes, existem diversos projetos de investigação pelo mundo fora que contribuem para os avanços nas diferentes subáreas, que directamente levam a que nos últimos anos se tenham feito vários pequenos avanços. Esta tendência vai permitir que aplicações que usem nanocomunicações sejam uma realidade num futuro próximo, que por sua vez motiva mais investigadores a embarcar nesta área.

Determinado a aprender mais sobre esta área fascinante, ajudar a comunidade científica a projetar e implementar novos conceitos que podem influenciar o caminho que esta nova área de investigação pode tomar, e saber que os avanços feitos nesta área podem ter um grande impacto, mudando o paradigma em diversos campos, foram as principais motivações que influenciaram a seguir esta área de investigação. Durante a fase de investigação e estudo, diversos novos conceitos foram aprendidos, nomeadamente, um paradigma de comunicação completamente novo, que estabelecia a comunicação através de moléculas, ou seja, comunicação molecular. Este novo paradigma de comunicação vai permitir que inúmeras aplicações sejam possíveis, sendo o principal objetivo do trabalho desenvolvido.

Depois de efetuar uma investigação cuidadosa sobre as comunicações moleculares, e estudar os conceitos relacionados, os principais desafios desta área de investigação foram definidos como objectivos e soluções para os resolver começaram a ser planeadas. Todo o trabalho desenvolvido é descrito neste documento, no qual um sistema de nanocomunicações moleculares é projetado abordando diversos desafios mencionados em diferentes trabalhos de investigação. Contrariamente às redes

tradicionais de computadores, quando se projeta um sistema de nanocomunicações há diversos aspetos que precisam de ser atendidos, e a resolução para um problema nem sempre é a melhor solução, pois estes sistemas dependem imenso na sinergia de todas as características da nanorede, especialmente em nanocomunicações moleculares. Portanto, os diferentes componentes do sistema foram projetados atendendo a sinergia entre eles. A técnica mais promissora para codificar a informação foi selecionada, e a partir daí diversos conceitos foram analisados de maneira a escolher o método mais apropriado de comunicação molecular, uma topologia foi projetada de maneira a fornecer à nanorede capacidades para resolver alguns obstáculos herdados das técnicas de comunicação escolhidas.

Diversos desafios foram atendidos no sistema projetado, tais como: a escalabilidade do alcance da nanorede, as interações com a escala micro e macro, a fiabilidade da comunicação, mecanismos de controlo de erro e fluxo, a codificação da informação, e de forma mais importante, mecanismos de endereçamento e encaminhamento. Em seguida, toda a arquitetura do sistema é analisada e informação para a avaliação do mesmo é apresentada e discutida. Apesar de terem sido encontrados alguns obstáculos durante o desenvolvimento, a maior parte foi ultrapassada, mas deixando uma vontade de continuar a trabalhar nesta área fascinante. Como esta área de investigação ainda está na sua infância, há imensas alternativas que podem ser alcançadas, então, é difícil de estabelecer um limite para o trabalho futuro. No entanto, há aspetos importantes que podem expandir os conceitos abordados nesta dissertação. Estes aspetos são a criação de uma ferramenta de simulação que permita testar protocolos de comunicação num ambiente de nanocomunicações, projetar e validar diferentes protocolos para diversos métodos de comunicação molecular e desenvolver uma ferramenta de simulação que permita investigadores simular uma nanorede molecular completa, que integre diferentes técnicas de comunicação molecular em simultâneo, diferentes protocolos, e ainda a habilidade de estabelecer uma ligação com redes tradicionais de computadores.

Em todo o processo desta dissertação, muito foi aprendido sobre este novo paradigma de comunicação. Esta área de investigação definitivamente deixou uma vontade de continuar a investigar, projetar e implementar soluções que podem ter impacto em diversos campos do nosso dia-a-dia. Apesar de esta área de investigação estar ainda nas suas etapas iniciais, muitos conceitos interessantes foram aprendidos, e novos conceitos foram imaginados e descritos. A conceção deste sistema de nanocomunicações moleculares mostrou-me o quanto diferente este novo paradigma é em relação às tradicionais redes de computadores, e ainda todos os obstáculos que ainda se encontram por ultrapassar. Mesmo assim, graças a todas a técnicas imaginadas e manipulação de características, o sistema projetado pode funcionar, aumentando a eficiência da transmissão, e quando os avanços em nanotecnologia e fabrico de nanomáquinas o permitir, vai ser possível estabelecer uma ligação entre a escala nano e a escala micro/macro.

Contents

List of Figures

Chapter 1

Introduction

This introductory chapter explains the context of this thesis subject, the motivation that led to its selection, the objectives and the structure of the document. Firstly, a brief context about the subject of this thesis is presented, followed by the motivating aspects that led to the selection of this field of research. Afterwards, the objectives of this thesis are explained in detail and finally, the structure of the document is presented.

1.1 Context

Nanotechnology is a recent field of research that will allow various advances in a high range of other fields. The study at a nano-scale will allow researchers to understand complex biological systems and materials, which will permit them to recreate them in other scenarios using man made nanomachines. Nanomachines are molecular scale robots, machines with a very simple specific task. A single nanomachine cannot accomplish a lot, but when they are interconnected, a larger goal can be reached. To be able to interconnect a large number of nanomachines, a new paradigm of communication was created, nanocommunication.

Nanocommunications has tremendous potential for applications in the biomedical, environmental, industrial and military fields. Molecular communication is a new communication paradigm which allows nanomachines to exchange information using molecules as carriers. This is the most promising communication method within nanonetworks, since using electromagnetic waves is not very feasible due to the size of the nanomachines. In molecular communication, information is encoded onto molecules at senders and the molecules propagate to receivers. The propagation method used by the molecules to travel in the channel and the way the traffic is routed between nodes are the most important challenges in this type of network and some solutions will be described in later chapters.

1.2 Motivation

As mentioned in the last section, nanotechnology is a recent field of research, which can have an impact in several other fields. This subject will be used in a high range of applications, like medical uses, military applications, industrial solutions and in materials researches. In spite of this subject being in its early stages of development, and the numerous inherit challenges due to its nature, it is a fascinating new research area, which completely changes all the preconceived notions of traditional networking systems. This subject allows the researcher to be part of the research community that will establish the technological future. The ability to discover, design and implement new features, concepts or protocols, can provide the scientific community a small innovation that will help in the creation of new applications. With the strong potential for applications in the medical field, a small contribution a research achieves, can, in the future, be part of an working application that will help people, and that knowledge gives an extra motivation to any author.

1.3 Objectives

As mentioned previously, this is a new area of research and there are many challenges that need to be addressed and resolved, in order to achieve complete working nanonetworking system and, later on, working applications. In this thesis the main focus is nanocommunications, more specifically, molecular nanocommunications, and due to the nature of this communication technique there are several inherit challenges.

The objectives of this thesis are research and study molecular communications in order to target and propose solutions for several of the challenges, design a system architecture for a molecular nanonetworking system capable of proving several networking requirements like information's encoding, error and flow control methods and addressing and routing mechanisms, evaluate the architecture and all the concepts created, and perform simulations in order to achieve results that support the evaluation and validation of the designed features. In order to achieve a complete nanonetworking system several aspects need to be designed, while taking in mind the synergy between them. In later chapters the importance of the synergy in molecular nanocommunications will be detailedly explained.

Although the objectives set for this dissertation are ambitious, due to the lack of knowledge about the subject, the limited sources of information available and the inherit nature of the subject, a latent objective of this thesis is to learn as much as possible, and specialize in this captivating subject, which is new, fresh and very likely the future of technology.

1.4 Structure

This dissertation is organized in six chapters. The first chapter is the introductory chapter where a brief context, motivation and objectives about the thesis are explained. In the second chapter a deeper look at the theory behind this area of research is presented. Starting with the general subject of nanotechnology, then nanocommunications, molecular communications and routing in nanocommunications. In chapter three, a state of the art of this area of research is presented, by firstly describing some related research works and then detailedly describing the state of the art of routing in molecular nanocommunications and simulation frameworks. These first three chapters create an introduction to nanocommunications and molecular nanocommunications, by explaining the basic theory and interesting concepts created in research papers.

Applying the knowledge these chapters provide, a system architecture for molecular nanonetworking is fully described in chapter four. The importance of the topology is explained as well as the impact the selection of communication techniques has on a molecular nanocommunications systems. Afterwards an approach for information's encoding is introduced, followed by the designed addressing and routing mechanisms. In chapter five this architecture is analysed by illustrating several mechanisms procedures, followed by an architecture evaluation and preliminary results obtained from simulation. Finally, in chapter six the conclusions of this thesis are presented, followed by the future work that would expand the work presented in this document.

Chapter 2

Related Concepts and Essential Theory

This chapter takes a deeper look at the context of this work, explains some concepts a bit further and complements with the theory that support it. Starts by generally talking about nanotechnology and then specifying by levels. Passing through nanocommunications, molecular communications and finally reaching routing in molecular communications. Since this subject is very recent, this chapter will help the reader understand and assimilate the theory and concepts behind nanotechnology and nanocommunications.

2.1 Nanotechnology

The European Comission defines nanotechnology as the study of phenomena and fine-tuning of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale [1]. The ideas and concepts of nanoscience and nanotechnology started in December 29, 1959 in the California Institute of Technology (CalTech), where the physicist Richard Feynman gave a talk entitled "There's Plenty of Room at the Bottom", in a meeting of the American Physical Society. In his talk, Feynman described a process in which scientists would be able to manipulate and control individual atoms and molecules to create more functional and powerful man-made devices [2].

Over a decade later, in his explorations of ultraprecision machining, Professor

Norio Taniguchi coined the term nanotechnology. It wasn't until 1981, with the development of the scanning tunnelling microscope that could "see" individual atoms, that modern nanotechnology began [3].

In Feynman's vision, he envisaged a billion tiny factories able to manufacture fully functional atomically precise nano-devices. During that same talk, he realized that several scaling issues would require the engineering community to totally rethink the way in which nano-devices and nano-components are created [2]. These predicted limitations are now being faced, more than half-century later, due to the fact that ongoing technological trends, are still mainly based on the miniaturization of existing manufacturing techniques. Therefore, there is a need to rethink and redesign the way in which components and devices are manufactured by taking into account the new characteristics of the nanoscale. A whole new range of applications can be enabled by the development of devices able to benefit from these nanoscale phenomena from the very beginning.

Nanotechnology has a broad range of research applications and can be classified in four main areas. *Industrial and Consumer Goods Applications* (for example, development of intelligent functionalized materials and fabrics, new manufacturing processes and distributed quality control procedures, food and water quality control systems) can be known as Nanomaterials, which are materials which often have specific properties due to their small particle size. At the moment, this field is the most prominent and has been the aim of various researches due the investment behind it. It is estimated a market value of 20 € billion according to the European Commission [1]. Other fields in which nanotechnology will have impact, although ongoing researches are still in their infancy, are *Biomedical Applications* (for example, intrabody health monitoring and drug delivery systems, immune system support mechanisms, and artificial bio-hybrid implants); *Environmental Applications* (biological and chemical nanosensor networks for pollution control, bio-degradation assistance, and animal and biodiversity control); and *Military Applications* (nuclear, biological and chemical defenses and nano-functionalized equipment).

Nanotechnology enables the miniaturization and fabrication of devices in a scale ranging from 1 to 100 nanometers. At this scale, a nano-machine can be considered as the most basic unit. Some nano-machines such as chemical sensors, nano-valves, nano-switches, or molecular elevators [4], cannot execute complex tasks by themselves. Nano-machines can be interconnected to execute collaborative task in a distributed manner. Exchanging information between them will allow a cooperative and synchronous manner to perform more complex operations such as in-body drug delivery or disease treatments. Resulting nanonetworks are envisaged to expand the capabilities and applications of single nano-machines in innumerous ways [5]. Nanonetworks will allow dense deployments of interconnected nano-machines enabling larger application scenarios.

2.2 Nanomachines

A nanomachine is described as "an artificial eutectic mechanical device that relies on nanometer-scale components" [6]. The nanomachine can be defined more generally as "a device, consisting of nano-scale components, able to perform a specific task at nano-level, such as communication, computing, data storing, sensing and/or actuation" [5]. Because of small size and low complexity of these machines, the tasks performed are very simple and limited to its close environment. Interconnecting several nanomachines will create a nanonetwork, the capabilities and application range of these nanomachines strongly depends on the way they are manufactured [2]. The development of nanomachines can be described in three different approaches,ranging from the use of man-made components to the reuse of biological entities found in nature, as shown in Figure 2.1.

In the top-down method, nanomachines are created by downscaling current mi-

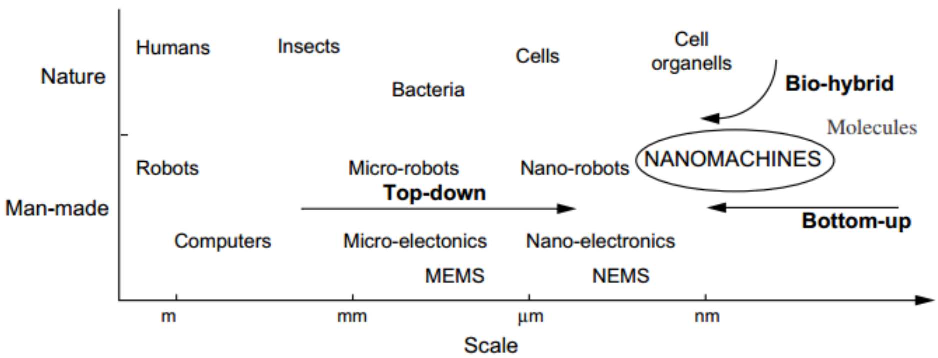


Figure 2.1: Approaches for the development of nanomachines [5].

croelectronic and micro-electro-mechanical technologies without atomic level control. In the bottom-up method, the design of nanomachines is performed from molecular components and synthesized nanomaterials, which assemble themselves chemically by principles of molecular recognition arranging molecule by molecule. Recently, a third approach called bio-hybrids has been proposed for the development of nanomachines [7]. This approach is based on the use of existing biological nanomachines, such as DNA strands, molecular motors, as components or models for the development of new nanomachines in combination with man-made nanostructures. In Figure 2.1, different systems are mapped according to their origin, biological or man-made systems, and to their size, ranging from nanometers to meters. In the future, nanomachines will be obtained following any of these three approaches. However, the existence of successful biological nanomachines, which are highly optimized in terms of architecture, power consumption and communication, motivate their use as models or building blocks for new developments.

Despite several technological and physical limitations, the advances in manufacturing procedures enabled the fabrication of components in a scale bellow 100nm. A new direction for the development of nano-components is being enabled with the researches in nanomaterials and manufacturing procedures. For instance, field-effect transistors can be created through the use of graphene nanoribbons and carbon nanotubes, and these transistors can be the building blocks that will allow the construction of new nano-computing machines. There are other important researches on fabrication of components like nanomaterials-based nanoactuators and chemical, physical, and biological nanosensors. The final goal of these researches is to be able to integrate several of these nano-components into a single functional unit, creating a device in the scale of 10-100 square micrometers [8], which is comparable to the size of an average human cell. Creating a single device by integrating several of these components is still one of the biggest challenges in the nanomachines manufacturing.

On the other hand, other philosophy is to adopt component coming from the nature, that is, biological components which can be adapted to create functional components. Most of the components of cells, molecules, proteins, DNA and organelles belong in the nanoscale domain. Some of these can be used as building blocks for integrated devices, for example an alternative energy source for bio-nano-

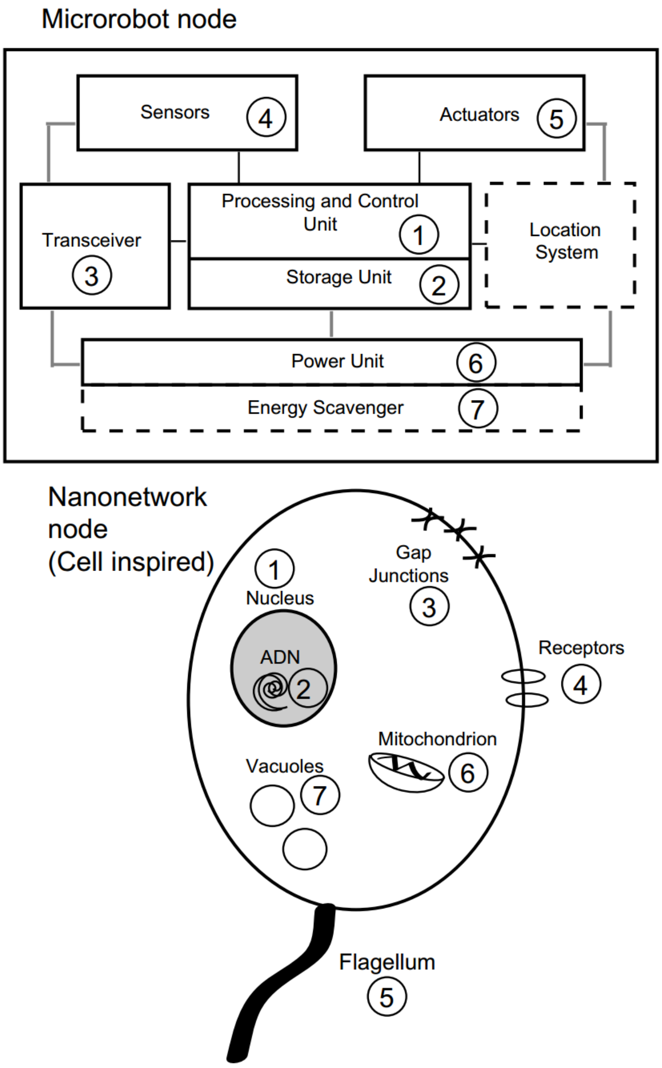


Figure 2.2: Architecture comparison between nanomachine of a nano-robot, and nanomachines found in cells [5].

devices can be achieved with AdenosineTriPhosphate, also known as ATP. Encoding information in DNA can be used in molecular computing machines and molecular memories, alternatively, DNA strands can also be used to build miniature circuit boards and stimulate the self-assembly of components such as carbon nanotubes, nanowires, nanoribbons and nanoparticles, by means of DNA scaffolding. In Figure 2.2, it is possible to see and compare the architecture mapping between the two approaches of nanomachine manufacturing. Although the researches on this philosophy of nano-components manufacture is still behind nanomaterial based components manufacture, being able to directly reuse biological structures found in living organisms or to engineer them will be especially useful in biomedical applications, as well as the enabling technology for bio-inspired communication.

2.3 Nanocommunications

Nanocommunication can be described as the exchange of information at the nanoscale and is at the basis of any wired or wireless interconnection of nanomachines in a nanonetwork. How that communication and interconnection between nanomachines is made, greatly depends on the way they are created. In addition, the specific application in which the nanonetwork will be deployed limits the selection on the particular type of nanocommunication.

With the idea of a nanonetwork, a new communication paradigm appeared. For a nanonetwork be able to operate, a communication between the nanomachines is needed. At this scale the communications concepts of regular computer networks, cannot be applied as easily. The way the information is exchanged at nano scale has not been defined yet, but different approaches have been presented, ranging from downscalling well-established communication means based on electromagnetic, optical, acoustic, or mechanical communication, to defining completely new paradigms based on biology, like molecular communication.

Nanotechnology is proposing new tools that are enabling the extension of well-known communication techniques to the nanoscale, such as the use of carbon nanotubes (capable of modulating and demodulating an electromagnetic wave by means of mechanical resonation), as the basis of an electromechanical nano-transceiver or nano-radio and the use of nano-antennas for electromagnetic communication, which have been projected using carbon nanotubes and graphene nanoribbons. A graphene-based nano-antenna is not just a simple reduction of a regular antenna, there are several quantum phenomena that affect the propagation of electromagnetic waves on graphene [9]. At this scale, the electromagnetic waves enters into Terahertz Band (0.1THz-10THz), a very high-frequency range, in between the microwaves and the far-infrared radiation, which has recently caught the attention of the scientific community because of its applications in security screening and nanoscale imaging systems. The Terahertz Band can support either a very wide transmission window that can allow the support for very high transmission rates in the short range, that is, a few Terabits per second for distances bellow one meter, or several transmission windows more than 10 gigahertz wide each. Although, it is unclear how nanomachines with limited capabilities will take full advantage of the properties of this huge band [10].

Electromagnetic communication has a lot of potential and provides features that no other method of communication can provide, due to the high frequency of the bands used. The nanonetworks based on molecular communication and electromagnetic waves seem to be the most suitable for creating a complex nanonetwork. Other known methods like nanomechanical and acoustic cannot achieve overall performance in the general applications. Nanomechanical is described as a communication process in which the information is exchanged through mechanical contact between the transmitter and the receiver. In acoustic communication the nanomachines use acoustic energy, that is, pressure variations, to encode the transmitted message.

Molecular communication can be described as the use of molecules as messages between the transmitter and the receiver. This mode of communication is the most promising for general applications. An example of this communication method is the communication between neighbouring cells in the human body, which is conducted by means of diffusion of different types of molecules that encode different types of messages [11]. Nowadays a lot of researches are being carried out to study how molecular messages are propagated by means of free diffusion. These studies try to analyse the behaviour of the diffusion channel in terms of attenuation, delay, capacity and more that will be described in further sections. Being the most promising and relevant method of communication for the general application of a nanonetwork, was an easy pick as the method to be studied for this thesis.

The several methods of communication at nano scale will allow for new system to be design and in some cases new paradigms to be unlocked, which can change present systems designs, specially for healthcare. These researches are the top priority for the development of nanosystems. Since a single nano machine cannot accomplish any task, or at the very least a task that can make a difference, nano machines need to be interconnected to perform complex tasks in a synchronous manner. For that reality there needs to be a communication between them at this scale, so these researches are imperative and top priority for the future development of system designs.

2.4 Molecular communications

Molecular communication is a new communication paradigm, which includes various areas of research, like nanotechnology, biotechnology, and communication technology [11]. This new area of research mimics a well-known biological function in nature in which information is encoded, transmitted and received through molecules. This method of communication allows cells and many other living organisms to exchange information. One of the most commonly known is the insect communication using pheromones, like bees and ants. In the Human body these communications also occur, biological systems achieve intra-cellular communication through vesicle transport, inter-cellular communication through neurotransmitters, and inter-organ communication through hormones [11]. One of the most important molecular communication mechanisms is based on the free diffusion of molecules in the space [2]. This mechanism is used in most biological systems, including cell communication in the Human body. For those reasons, current researches in this area focus on observation and understanding of present biological systems such as how communication is done within a cell or between cells.

Molecular communication allows biological and artificial-created nanomachines to communicate over a short distance using molecules. In molecular communication, senders encode information onto molecules (called information molecules). Information molecules are then loaded onto carrier molecules and propagate to a receiver. The receiver, upon receiving the information molecules, reacts biochemically to the incoming information molecules.

Senders and receivers possesses biologically and artificially created nanomachines that are capable of emitting and capturing molecules. Carrier molecules are neurotransmitters, hormones, molecular motors, viruses and more are being discovered and studied. The information molecules are proteins, ions, or even DNA strands. Studies show that this method of communication is a lot more suitable for communication from nano to nano scale than electromagnetic waves communication method.

	Traditional communication	Molecular communication
	Different communication paradigms	
Communication carrier	Electromagnetic wave	Molecule
Signal type	Electronic and optical signal	Chemical signal
Propagation speed	Light speed (3x10^5 Km/s)	Extremely slow speed
Data transfer rate	Very high	Low
Encoded information	Voice, text and multimedia	Phenomena and chemical states
Behaviour of receiver	A receiver interprets encoded information	Information molecules cause chemical reactions at the receiver
Synchronization complexity	Simple and low synchronization systems	Very high and complex synchronization systems
Communication precision	Accurate communication	Stochastic communication
Energy consumption	High energy consumption	Low energy consumption

Figure 2.3: Comparison of communication features

The latter is described with great potential for other applications, but due to the size of the nanomachines is not as feasible as molecular communication [11]. Molecular communication is being specially attractive for some different reasons:

- Molecular communications in a nano scale already occur in nature. Communication between cells and bacteria are a great natural phenomena which give studies a groundwork to model nanonetworks and to develop solutions;
- Molecular communications allows nanonetworks to be deployed into naturally occurring phenomena, consequently it provides fast engineering pathways to viable solutions;
- Diverse medical applications require biocompatibility furthermore properties that are already provided by nanonetworks using molecular communication.

Unlike existing communication systems that utilize electronic and optical signals as communication carriers, molecular communication utilizes chemical signals as communication carriers. Additionally, deviating from existing communication where encoded information such as text and multimedia is interpreted at the receiver, in molecular communication, information molecules create a reaction at the receiver and recreate a phenomenon and/or chemical status that sender transmits [11]. In the figure 2.3 the different features of molecular communication are compared against traditional communications.

In molecular communications there are several processes, which differ in the way molecules propagate through the communication channel from a network node to another. Since this method of communication is inspired by phenomena seen in nature, most of these processes mimic those phenomenons and there are active researches trying to master each new molecular communication process. Some relevant method being researched nowadays are:

- **Calcium signalling:** In this method the communication is done through a sensory cell, a neuron, or a cardiomyocyte which releases or absorbs calcium ions in reply to several stimuli that open/close particular channels on the cell membrane. The information in the variation of calcium ions concentration is propagated, as shown in Figure 2.4, causing a variation in the electrical charge of the cell membrane and, finally , the transduction of the information into an electrical signal. This method of communication can be used for short distances (*nm-mm* ranges).

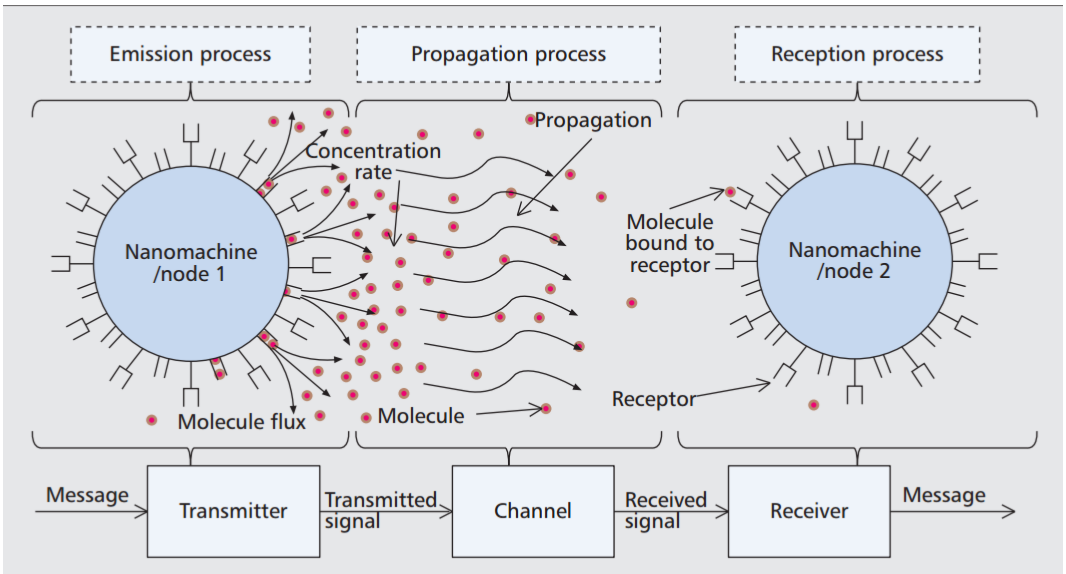


Figure 2.4: Calcium signalling communication between two nodes [12].

- **Molecular motors:** This method of communication allows a reliable point-to-point communication system because messages propagate in tracks, using mechanical energy, until they reach the destination.

  A molecular motor is a protein or protein complex that transforms chemical energy (e.g., ATP hydrolysis) into mechanical work at the molecular scale.

Since molecular motors walk internally along cytoskeletal tracks, molecules move in the direction corresponding to the orientation of the track rather than the random Brownian motion of diffusion. The cytoskeletal tracks are connections between two cells and are most often composed of microtubules or actin filaments, which are protein complexes found in cytoplasm. The direction the carrier molecular motor travels is decided by the protein complex that composes it, depending on the protein the reaction with the track will cause the molecular motor to travel to the corresponding direction of the track, as illustrated in Figure 2.5.

Some cells use molecular motors to transport large molecules that do not diffuse well and to transport other large cell structures such as organelles and vesicles. This method of communication is suited for short distances (*nm*-*mm* ranges).

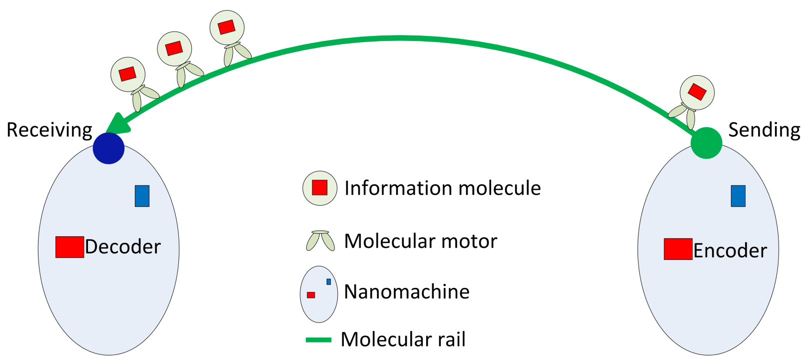


Figure 2.5: Communication between two nanomachines using molecular motors.

- **Bacteria communication:** Information is encoded in the concentration of molecules produced by the bacteria at the transmitter. The molecules produced propagate in the environment via a diffusion process. The bacteria at the receiver are actively sensing the environment, and the different concentrations of molecules sensed are decoded into information.

  In this type of communication method, communication inaccuracy can be caused by both the error in molecular production at the transmitter and the reception of molecules at the receiver. Due to high unpredictability in the individual behaviour of the bacteria, reliable communication between two bacteria is almost impossible. Therefore, a cluster of bacteria population should define a single node capable of molecular transmission and reception. This proposition allows this creation of a reliable node out of many unreliable bacteria, hence is being researched so future application can emerge. This method of communication is appropriate for short distances (*nm-mm* ranges) [13].

- **Flagellated bacteria communication:** Although this method of communication uses bacteria as well, it differentiates from the method described earlier in the way information is encoded and carried. This method has been increasing in popularity, but its research is still on its early stages.

  This method exploits the nature of some type of bacteria and the existence of flagellum. Flagellum is an appendage those bacteria have and one of its functions is to be a mechanism of propulsion, i.e., it allows bacteria to move converting chemical energy into motion. Bacteria have a great number of chemical receptors around its membrane which allows them to sense the environment. Bacteria of the same type release chemical attractants particles in the environment, the travelling bacteria upon sensing those attractants, will move towards the direction of those attractants. This process is called *chemotaxis*. When the travelling bacteria reaches the destination, it will follow its natural instincts and will try to initiate a process called Bacterial Conjugation, as shown in Figure 2.6. This process is a direct contact process in which there is exchange of genetic material accomplished by means of the bacterial appendage called *pilus*.

  So exploiting these processes researches have envisaged a system where DNA packets are encoded into the bacteria cytoplasm, and then they are released. Upon reaching the destination, that DNA packet will be transferred through the bacterial conjugation process. One feature of this communication is the self-reproduction of bacteria, which allows a natural and autonomous way of generating redundancy in the communication. The redundancy in this type of communication can be achieved by transmitting several bacteria containing the same information, or by relying on the self-reproduction of the carrier bacteria during its propagation. On one hand, this inherited feature offers a reduction of the probability of losing a packet, and a reduction of the propagation time because it is determined by the fastest bacteria to arrive at the destination.

On the other hand, self-reproduction also has inconveniences due to the over-population of bacteria in the environment it can cause. This problem can be solved by deploying an antibiotic, periodically, to cleanse the environment. This type of communication, contrary to the other bacteria communication described, is suited medium distances (μm-mm ranges).

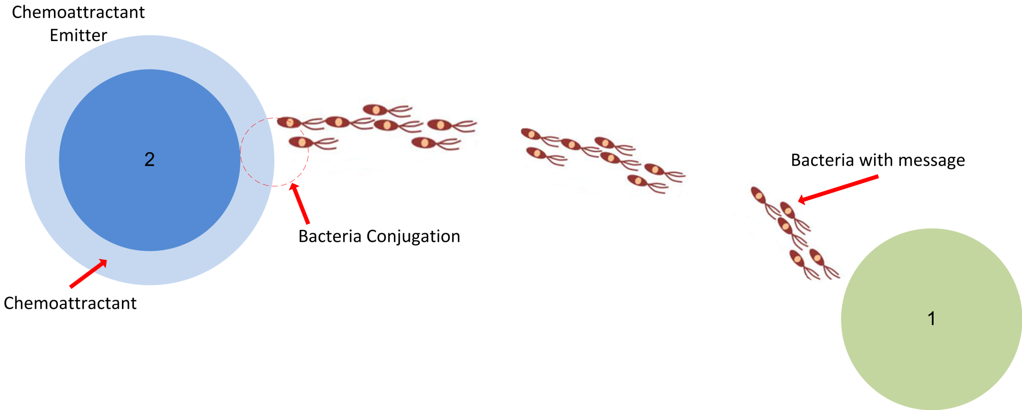


Figure 2.6: Communication between two nanomachines using flagellated bacteria.

- **Catalytic nanomotors:** This method of communication is still on its infancy stages but it uses artificially created nanomotors to carry messages. Contrary to all the other methods described, this one does not manipulate a nature phenomena. Catalytic nanomotors are defined as particles that are able to propel themselves and small objects, by means of self-generated gradients that are produced by catalyzing the free chemical energy present in the environment [14]. Some studies refer one of the most common catalytic nanomotor to be composed of platinum and gold nanorods. These rods when deployed in a aqueous hydrogen peroxide (H_2O_2) solution, propel themselves, roughly in a unidirectional way. The application window of this method is considerably slimmer than the other methods described but there are various researches on this subject and they show great promise for communications for medium distances (μm-mm ranges).

- **Pheromone communication:** This method mimic a well know communication system in nature used by several living organisms. Pheromones are a distinct type of molecules released by plants, insects, and other animals that trigger specific behaviours among the receptor members of the same species.

The pheromones released into the environment propagate in the air until they are captured by the receptors of their same type. This type of communication is suitable for long distances [15] (*mm*-*m* ranges).

The methods described above are the main methods of communication being researched in the molecular communications field. These methods can be categorized, by the ranged in which the communication is feasible, in three different classes, as it is shown in the Figure 2.7. The class of these methods is defined by the distance each one can provide a reliable communication. For instance, on concentration diffusion based methods, due to the randomness in the motion of molecules, the communication is no longer reliable when a certain distance between node is reached because the molecules are too dispersed in the environment. The molecular motors tend to detach from the molecular rail and diffuse away when they have moved distances in the order of 1 μm. Although a single method of communication excels in a certain distance range, more complex systems can be created merging different communication methods in the same system. The resulting systems would open a new window of applications, and can allow for routing between nodes to be implemented.

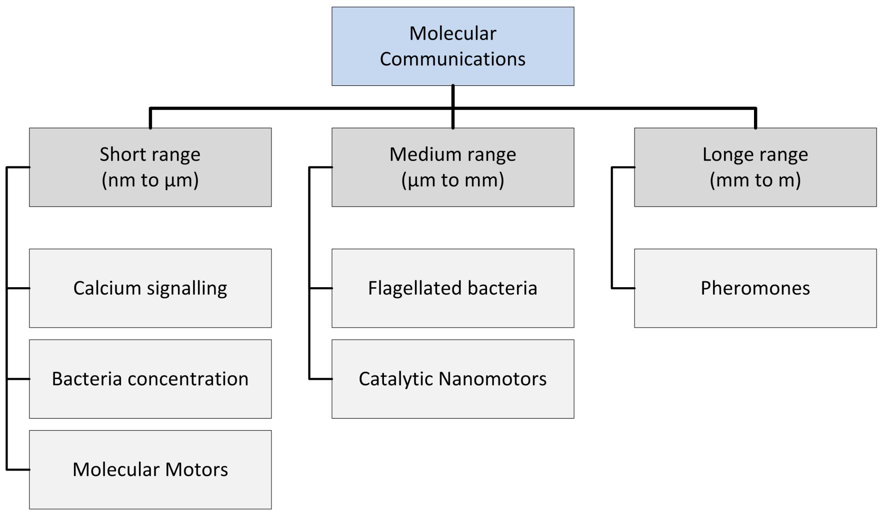


Figure 2.7: Distance classes for different methods of molecular communication

2.5 Routing in Nanocommunications

In any computer network routing is one of the most important aspects. Routing allows the information to be addressed, creating pathways that enable an organized flow of information. Being able to permit routing in nanocommunications is one of the biggest challenges in this new communication paradigm, but because it is so important, there are various researches trying to find the best way to do it.

In nanocommunications being able to route information, messages, has a deeper impact than traditional computer networks. At this scale routing will allow for new applications to be envisaged and concept ideas to be born, due to the low performance of a single nanomachine. A single nanomachine cannot accomplish complicated tasks, or even a couple of them with one-to-one communication, however a full complete network of nanomachines can create complex systems capable of performing incredible tasks. As discussed in the previous section, there are different techniques of communication with different effective ranges, so systems using a single technique will be locked to that range for operating. Routing allows the merge several communication techniques in a single nanonetwork, opening a window for new applications, for instance communication from the nano scale to meter scale. For routing to be possible there are sill many challenges to be beaten, for instance, how the addressing scheme will enable the transmission to target different receivers.

Although there are many communication techniques for nanocommunications, this section will focus on molecular communications techniques since it is the focus of this research duo to promising high potential for new applications. There are some techniques of communication that have features which can allow for a simple routing protocol to be deployed, like communication based on calcium signalling. Since this technique uses a diffusion method to establish intercellular communication, it is possible to create a recursive broadcast process which can allow the information to go through the network until it reaches the destination, mimicking the phenomena show in Figure 2.8. In a real scenario, this feature could be used in a monitoring scenario to initiate a state of alert if a certain event happened, the alert would then

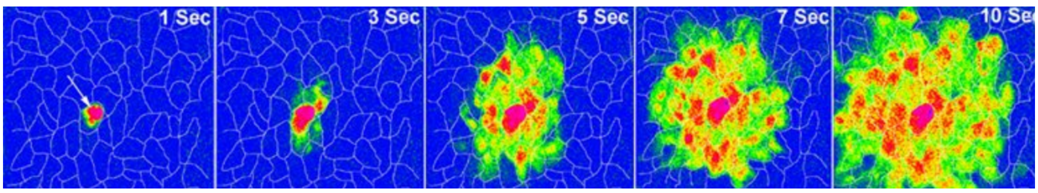


Figure 2.8: Calcium signalling propagation among biological cells [16].

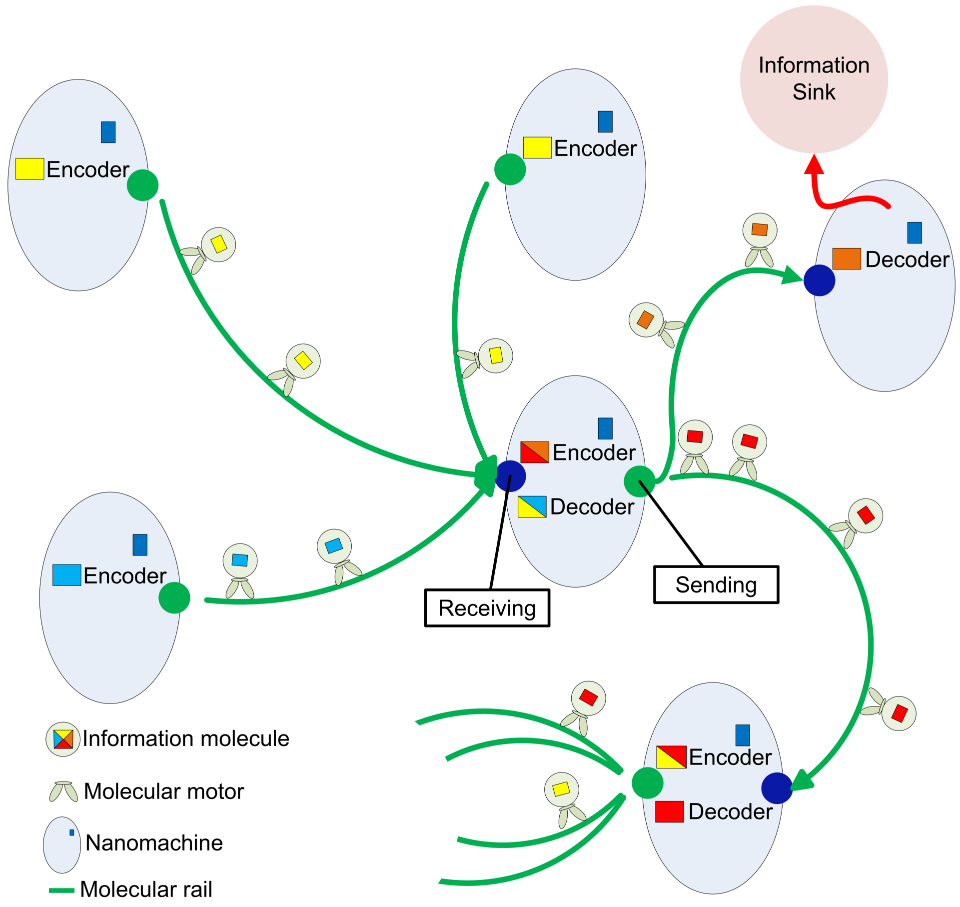


Figure 2.9: Illustration of information routing using molecular motors.

reach the destination node, for instance a nano-interface that connects to other layers of the system. There are some drawbacks with this concept, such as the low efficiency of the process and the stress it causes in the nanonetwork, but those cannot invalidate the concept since, depending on the type of application, it might be a feasible process.

When using molecular motors it is also possible to establish a simple routing protocol by taking advantage of how the technique forms a connection between nodes. Since the message travels in a molecular motor through a pre-determined molecular track, it is possible to create a network of N interconnected nodes in a star topology, i.e., there is a center node that serves as a bridge between nodes. Taking in mind that these molecular tracks can only have one-direction communication at a time, this can allow for an application such as a parameter sensing, and the information is routed to a information sink node. Other application can be explored using two tracks to connect each couple of nodes, achieving bi-directional communication.

In the Figure 2.9 an example is shown where some simple nodes send information to a higher complexity node, which can route the message it receives to different rails. This information can either go to an information sink or follow the network until it reaches the destination, depending on the application. In this example only one-way molecular rails were used, but it is possible for nodes to have a full-duplex communication between them.

Using flagellated bacteria can allow for a simple routing protocol to be created by manipulating the chemical phenomena happening in this process. Since bacteria travel through the environment in the direction of the corresponding chemoattractants, by working with different bacteria and attractants it is possible to achieve a system with routing. In these type of systems the nodes would have to follow the concept in which a node is constructed as a cluster of nanomachines to attain a certain level of computing power. The nodes would be required to have knowledge of the topology, then they would have to make a decision on which type of bacteria to use, encode the information and release the bacteria into the environment. The bacteria would then follow their natural instincts and travel to their destination which is actively releasing their type of chemoattractant. In the Figure 2.10 a simple communication process using this concept to route the information is presented.

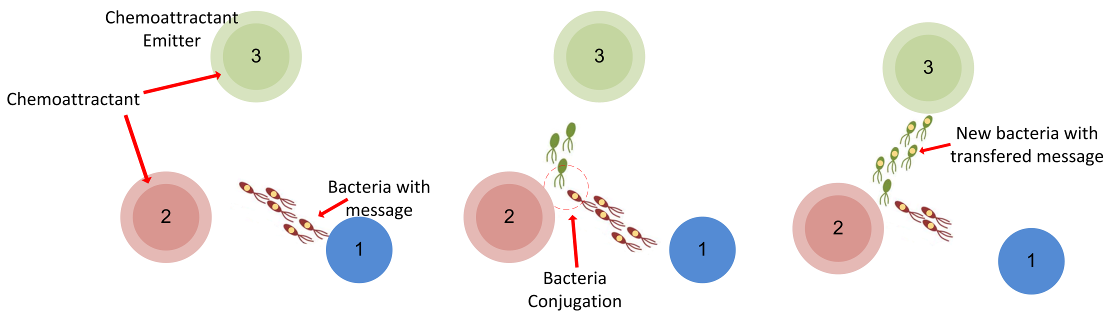


Figure 2.10: Illustration of information routing using flagellated bacteria.

In this section was described how important routing is in a nanonetwork and how the research on this subject is imperative. Some concepts for routing solution at this scale were introduced as well as their challenges and drawbacks. The concepts presented are based on native features of some molecular communication techniques and are the focus of researches due to promising expected results. Any of the concepts described can be used within a node (nanomachine cluster) which is part of a larger nanonetwork, or used in the network itself. As a result of their nature the applications window is very wide, allowing biomedic applications to be conceived.

2.6 Conclusions

In this chapter several theoretical concepts were introduced in the extent of the focus of this work. The information described in the chapter is very important to better understand the next sections and comprehend the architecture designed. The basic notions of nanotechnology and nanomachines manufacturing were mentioned, in which it is possible to realise that although there are still a great deal of research and development ahead, these important fields are following the right path to enable applications to be a closer reality.

This chapter then follows the path of nanocommunications which is the focus of this work, more specifically molecular communications. An overall overview of nanocommunications is given, focusing on molecular communication, in which several communications techniques are described. Applying features and concepts described, a section was created in which some routing concepts are explained, and how inherit features from specific molecular communication techniques can be manipulated in order to achieve routing and addressing capabilities in a nanonetwork.

After reading this chapter, it is important to understand the relevancy of the communication techniques in a nanonetwork. The selected techniques will define several aspects of the nanonetwork, like the range, the information's encoding, the capability to address nodes and route information. In the next sections this notion will be further described, and its importance will be further demonstrated.

Chapter 3

State of the Art

In this chapter current researches on this field are carefully described and separated in different sections. Firstly a brief introduction to nanotechnology and nanocommunications is presented, showcasing some researches and adding a brief description regarding their studies. Some nanocommunications applications are presented using the concepts described in the previous chapter. An extensive and detailed approach on routing in nanonetworks is displayed and the concepts and results taken from the researches described are examined. This section is important since it was on these researches that most concepts used were based on. Lastly, various researches in nanocommunications simulation are presented and their work is explained. This chapter provides an overall look at the state of the art in nanocommunications and other subjects directly related.

3.1 Related work

In this section an introductory approach to nanonetworks will be provided referring to important papers that summarize nanonetworks, how they work and their features. In [2], the authors make a complete description of the basics of nanocommunications starting providing a brief history on nanotechnology, where it stands in the present and the direction it is heading. Next it is explained the nanomachines manufacturing approaches and how they work, then a detailed analysis and explanation of the main methods of nanocommunication is structurally supplied. The paper is concluded with a breakdown of protocols for nanonetworking, referring some of the challenges for different methods of nanocommunication.

Some key points referred in [2] are explored deeper, and carefully explained in [5], which is a very complete paper that also covers nanocommunications from top to bottom. This paper gives a complete overview of nanomachines, providing a detailed explanation of their manufacturing processes, their features and most importantly an architecture concept for nanomachines to be used in nanorobots and bio-applications. Then the authors describe how wide the application window for nanonetworks is, giving several examples for biomedical, industrial, military and environmental applications. Nanonetworks importance and different methods of nanocommunications, with different effective ranges, are thoroughly explained, focusing on molecular based methods of communication. The last analysis given on the paper is the research challenges there are on this field, going from the simple nanomachine manufacturing process to the difficulties on the creation of nanonetworks. In [11] a clean description of molecular communications is given, making some intelligent arguments when comparing molecular communications to regular ones, and providing valuable information for Drug/DNA delivery systems (DDS).

On [15] a complete analysis of molecular nanocommunications for long range is provided. The authors give a great insight on different methods of communication for long range dividing them into groups of wireless and wired communications. Additionally of describing the most commonly known wireless method, i.e., pheromone communication, they explain how other methods can be studied further, such as pollen and spores, and using light transduction. In the paper its introduced the concept of long range nanocommunication using a wired method. The authors explain how axons, which are nerve fibres, or capillaries, which are the smallest body's blood vessels, can be used to establish a nanonetwork.

Although many papers give an excellent informational theory about molecular communications, some emerge and stand out with stellar information about imperative small topics connected to this method of communications. In [12] a great insight on molecular communication is provided by presenting notable information on communication with several nodes, the information capacity on the channel is explained and some processes for analysis are shown, a detailed study on protocols for molecular communication is given by describing architectures and techniques for protocols design and abstractions needed on this type of protocols. The authors go even further and explain their vision for a experimental platform based on communication among bacteria using *quorum sensing*.

On [17] it is presented a very detailed study on the information capacity on the channel using a diffusion process. The paper makes a thorough mathematical approach demonstrating that selecting appropriate molecular communication parameters such as temperature of environment, concentration of emitted molecules, distance between nanomachines and duration of molecule emission, it can be possible to achieve high capacity for the molecular communication between two nanomachines. The authors also establish that the molecular communication capacity between two nanomachines is heavily affected from the environmental factors such that appropriate coding and error control mechanisms for molecular communication must consider the environmental factors.

One common subject that several research papers talk about is the challenges for designing architectures and protocols for working nanonetworks. Although these challenges are real and their resolution is imperative for the development of the technology, there are challenges to overcome. In [18], the authors approach problems on nano and bio nanonetworks such as the reliability and pattern formation in distributed synthetic bio-circuits and unstructured nanowire NOCS. In the area of (distributed) bionetworks, insufficient understanding stochastic behavior of circuits within cells, susceptibility to environmental conditions, etc., represent major challenges. In the area of self-assembled nanowire interconnect, the lack of control over the fabrication process makes it hard to obtain both reliable and structured networks. However, there are two challenges in common of all the approaches: the difficulty to program the unreliable and potentially unstructured devices and the general issue of robustness.

Some molecular diffusion methods of nanocommunication were described so far and in the previous chapter it was explained how these methods can operate by encoding the information onto the concentration of molecules. On [19] the authors revise this approach creating a new technique to encode the information, that accordingly to the paper can increase the transfer rate and doesn't require a synchronous communication. In this new concept the information is encoded into an array of different types of molecules. Alternating the molecules in the array, the information is encoded, as shown in Figure 3.1, this also resembles the natural encoding of genetic information, i.e., DNA arrays consisting of different base pairs. The authors after theoretically introducing their concept thoroughly demonstrate mathematically that this approach can indeed improve the transfer rate, opening a window for future proof of concept with other frameworks.

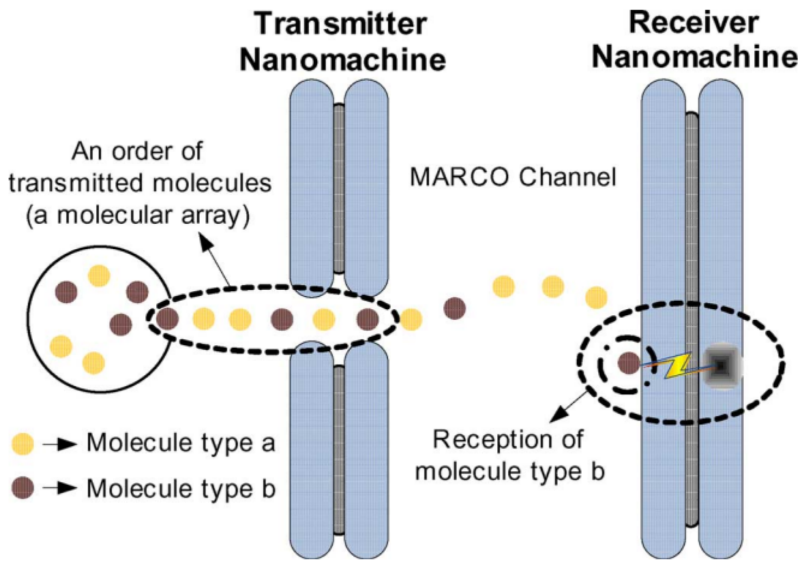


Figure 3.1: Two different molecules, a and b, encode information with their order. They are transmitted into the MARCO channel (Molecular ARray COmmunication). [19]

Another important aspect when talking about a communication system is the security. In [20] a limited study about security in nanonetworks is presented. The authors question themselves how security would work in these systems and create an observation about the subject, making some information clearer. Security will be as important on nanonetworks as it is on regular computer networks, if not even more important duo to implications it can have on medical/industrial application. Security will be, theoretically, easier to implement on nanomachines manufactured with the *top-down* approach that will be communication using electromagnetic waves. Implement security on bio-nanomachines that will be using molecular communication will be a significantly arduous obstacle to overcome. The authors state that using the vesicles from molecular motors communication technique, it is possible to create vesicles that only interact with a specific recipient, thus creating a *key-lock* security system.

3.2 Nanocommunications applications

In the previous chapter it is mentioned the importance of nanotechnology in today's world and in the future. Nanotechnology will open a window for several different applications and promising solutions in various fields, such as, biomedical, industrial, military and consumer and industrial goods. Nowadays researchers envisage several applications for nanonetworks, but most of the concepts or solutions published are in the biomedical field, which seems to be the most suitable field at this stage of research, since many molecular phenomena can be mimicked by nanomachines. Although there are several applications one can imagine, the tendency nowadays, not only for nanonetworks but for technology in general, is for systems connected to the Internet. In [21], the term *Internet of Nano-Things*(IoNT) was introduced and the authors outlined a general architecture for electromagnetic nanomachine communication, including challenges in channel modeling, information's encoding, and protocols creation for channel sharing, nanomachine's addressing and information routing. The authors present the architecture for the IoNT in two different applications, one being a intrabody nanonetwork for healthcare, which is a common concept, and the other being a future interconnected office work area, as shown in Figure 3.2.

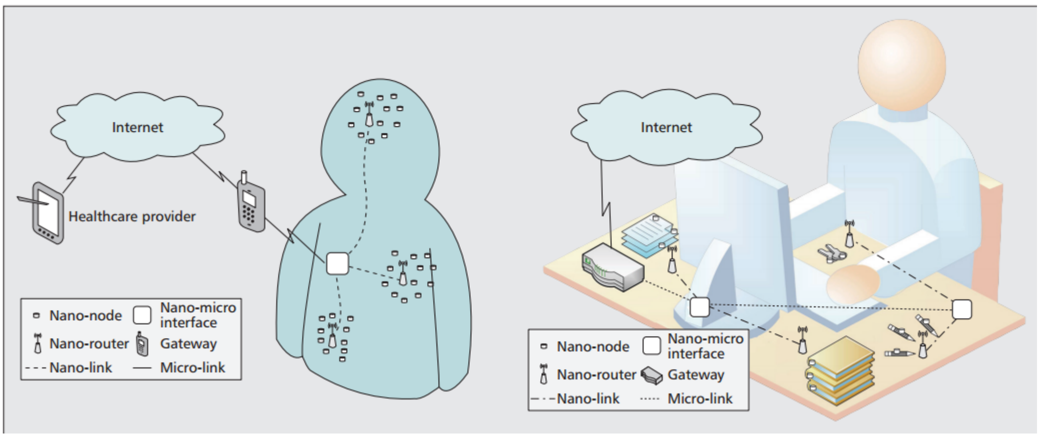


Figure 3.2: Architecture for IoNT systems. (Left) Intrabody nanonetwork for healthcare application; (Right) The future interconnected office work area. [21]

In intrabody nanonetwork architecture, several nanomachines are deployed inside the human body, such as nanosensors and nanoactuators, and they can be controlled, managed, over the internet by a external user. Healthcare applications seem to be the focus of several researches due to the existence of natural biologic nanosensors and nanoactuators, which enables researches to directly use them with electronic nanomachines. In the other concept idea, everyday objects found at a office desk are provided with a nanotransceiver which enables them to connect to the Internet, allowing the user to track the location and status of his belongings in a convenient way.

As mention above, [21] is a reference paper for pioneering in the IoNT concept, for envision the general architecture these application will follow, and correctly identify and describe the challenges this applications will encounter. However, in [22] a very complete description of IoNT systems is presented, discussing the challenges of these applications will encounter with data collection. This paper is relevant because the authors present several intelligent solutions for common problems this nanonetworks will come across. Additionally, the authors describe the concept of *middleware* for these systems, and importance of the of the role it will play in IoNT. An architecture for a IoNT *middleware* system is presented, and the value layered hierarchy consisting of nanomachines and gateways explained. To conclude this research paper, the authors describe some possible applications and state that the IoNT applications that will be created in the immediate future are going to focus on healthcare, environmental and agricultural monitoring. It was already described here how obvious it is an healthcare application when using nanonetworks, however there are other simple conceivable concepts, such as: the placement of nanosensors in public locations, like hospitals, airports, and urban public transports, to track the propagation of viral diseases; Nanosensors can also be used to monitor the environment, like city pollution levels, green house gasses, and radiation; In agricultural sector, these applications can allow for simple alerts to be sent if a plantation or livestock is infected with harmful bacteria, viruses, and other infectious agents, moreover a cross-domain application can be achieved by, for example, linking dairy products and healthcare to eliminate or minimize conditions that impact people with certain types of allergies.

As mentioned, healthcare applications are the most obvious and is the subject gaining more attention from the community. Most researches envisage a sensing nanonetwork, capable of monitoring the health of the recipient, such as endocrine diseases. One of the most important research paper on this matter is [23], which creates a full assessment of nanocommunication techniques and designs example architectures for a sensing nanonetwork for both molecular communication and electromagnetic communication. The authors created a silicon sensing component of the nanomachine, i.e., a nanosensor, and performed capability tests and presented the results. This paper offers a great in depth look at sensing nanonetwork systems for healthcare, and achieve the conclusion that molecular communication seems to be the most promising technique to use in healthcare applications, although there is still much work needed to achieve an implementation of these systems in the real world. Another important aspect that several researchers focus in the healthcare field is the drug delivery, i.e., *Drug Delivery Systems*(DDS). The objective of the DDS is to dispatch a drug where the medication is needed, whilst preventing the drug from affecting other healthy parts of the body. In [24] a thorough description of DDS is explained. The authors created and designed a DDS by developing a molecular communication channel model of the drug particle propagation though the cardiovascular system, i.e., the bloodstream. The authors were able to create several mathematical models, which in turn allowed them to run performance tests and results are shown to asses the flexibility and accuracy of an example application. The authors propose a thorough investigation into the safety of DDS for the human being, since care should be taken to ensure that the drug concentration does not reach toxic levels in the body, the interaction with naturally occurring molecular communications phenomena in the body such as the cell signalling through the endocrine system should be considered, and finally, the molecular communication system should be resilient against possible malicious attacks. These malicious attacks do not only mean external attacks, but by the immune system which considers the foreign therapeutic agent as a intruder to the body and tries to fight it. The results presented on this paper allow optimization techniques for DDS to be studied, which could permit an accurate selection of the location of injection with the objective of achieving a desired drug delivery at a targeted site, whilst minimizing the drug presence in the rest of the cardiovascular system. Mixing these two concepts, sensing and drug delivery, an advanced medical tool is created, and that is what the authors of [25] envisioned. They described a route towards an effective methodology to control nanorobots, which they envision to be nanocomputers capable of doing several tasks, in order to create a valuable medical tool. Medical target identification, improving diagnosis and providing new therapeutic procedures are some of the tasks a nanorobot is expected to accomplish in a healthcare application. The authors described an architecture for a nanorobot, explaining how manufacturing technology will allow these devices to be created and defining the components of the nanorobot, such as the chemical sensor, temperature sensor, the actuator, the energy supply and data transmission. A system was created and implemented for simulation, specifying drug delivery and diagnosis and other parameters of system behaviour, presenting the results from a 3D visualization of the system. Although the authors describe a device like a nanorobot to be achievable in the future, that future is still far way, but the envisaged concept is something to keep in mind of what future can hold for mankind, with the growth of this research field.

Although healthcare applications are the most popular research field, nanonetworks can be applied in several other fields as mentioned. With the advances in nanotechnology and nanocommunications it will be possible to build high-resolution ultra-sensitive nanocameras and ultrasonic nanophones, which can be used in defense and security applications, by combining imperceptible nanocameras for remote imaging and ultrasonic nanophones for concealed objects detection. These nanocameras can also provide ultra-high resolution imaging of crime scenes and assist forensics, and distant objects, which can help in space exploration. These devices can also aid multimedia applications, and in [26] the authors describe how these devices can generate a tremendous amount of visual and acoustic content with very high accuracy and resolution. With this high-performance video and audio capture, new processes of compression will have to be designed, in order to manage the large amounts of data.

In [5] a concise description of several applications for nanonetworks is presented and categorized by application areas. Starting in biomedical applications, the paper gives several examples of applications most of which already mentioned above. In applications for industrial and consumer goods, the authors describe an application in which nanonetworks monitor food and water quality, detecting small bacteria and toxic components that cannot be detected by traditional sensing technologies. In the same field, they describe an application in which nanonetworks are included in fabrics and materials to add new and improved functionalities, such as antimicrobial and stain-repeller textiles. In military applications, nanonetworks can be deployed over the battlefield or targeted areas to detect aggresive chemical or biological agents, additionally, similarly to consumer good, nanonetworks can be implemented in military equipment, enabling advanced camouflage, self-regulating temperature mechanisms underneath soldiers clothes, or even detect where a soldier has been injured. In the environmental field, the authors express an application that address an existing problem with garbage disposal, in this application a nanonetwork can help the biodegradation process in garbage dumps by sensing and tagging different materials that can be later located and processed by smart nanoactuators. Another application described for this field uses nanonetworks to control animals and biodiversity by using pheromones to trigger behaviours on animals. This process can allow interaction with those animals and also control their presence in particular areas.

In this section a description of current researches on applications and applications that are envisaged to be possible, demonstrate the importance and the impact nanotechnology and nanocommunication evolution will have in the world. These recent research disciplines will change the paradigm in several fields, and open a window for new applications that will allow to achieve features that weren't possible. Although most of these applications implementation in the real world is still in a far future, the theoretical possibility of creating such systems motivate researchers all over the world to continue working until an implementation is possible. One of the most important challenges to overcome is the ability to have a nanonetwork with routing capabilities, which will enable a wide variety of features for nanonetworks.

3.3 Routing in molecular communications

Current studies regarding these communication systems focus on single transmitter single receiver topologies to achieve results for their concepts. However, in a realistic environment there would be many nodes and the system should be able to handle additional and more complex mechanisms, such as routing. To achieve realistic applications, full nanonetworks need to be deployed and work in a distributed manner. These multi-node topologies require an addressing scheme since one transmission can involve several receivers. These multi-node systems enable a new degree of concept's complexity and open room for a new and vast application pool. However, routing methods need to be created and implemented on these nanonetworks in order for them to work.

Published researches on routing for molecular communication systems are very limited but there are a few theoretical approaches on some communication techniques that take advantage of features to create a routing mechanism. Several techniques and respective researches will be presented on this section that influenced the work performed on this thesis.

3.3.1 Diffusion communication

Communication via Diffusion (CvD) is one of the most researched methods of molecular communication due to the process's simplicity, therefore it is important to understand in what way routing can be implemented using this method. On [27] a very interesting study is presented, pin pointing CvD features that can be used to establish a routing mechanism and to what degree it affects the nanonetwork.

As it was described in Section 2.4, in these systems the information can be encoded on various properties, such as concentration or type of molecules and can achieve communication in short-to-medium distances (nm *to* μm ranges). Waves of molecules leave the transmitter and propagate through the environment via a probabilistic motion, i.e., Brownian Motion/Diffusion. Several information molecules reach the destination while the rest dissipates into the environment due to the properties of the environment and their type, as shown in Figure 3.3.

If the information can be encoded on the type of molecules sent from the trans-

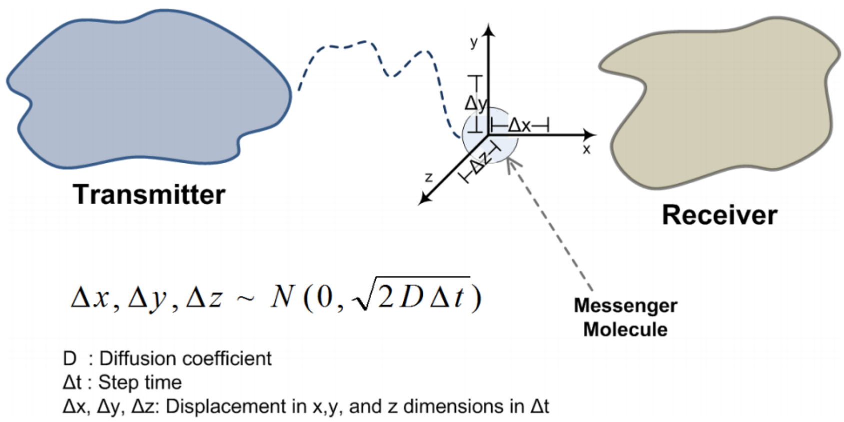


Figure 3.3: Propagation of information molecules when using diffusion. [27]

mitter, one can imagine a simple routing technique in which different types of molecules are used to target different destinations. However, when using CvD one aspect to have in mind is that nanomachines other than the receiver affect the propagation behaviour of the information molecules, hence when using an addressing structure embedded to the molecule type, nanomachines outside from the communication act as impenetrable barriers. However, these intermediary nanomachines can be designed to serve as signal repeaters or as signal guiders as shown with the performance tests performed on [27].

To perform these tests the scenarios would have to be as close to the real world as possible so some key features had to be modulated as well. The reception in CvD systems between the messenger molecule and its fitting receptor is conducted by specific chemical reactions, which attract stray molecules from the environment towards the receptor. This phenomena is called receptor affinity in biology literature [28]. Different receptor and molecules couples have different affinity capabilities and ranges. This leads to nodes having and effective radius, which is the total between the radius of the node and the radius of the affinity for that node, as stated in [27]. So having the phenomena in mind a messenger molecule is received if it enter the effective radius of the receiver, and not only if it directly hits the receiver. Another feature that was modulated on this research was the propagation model, which supposedly would be the Brownian motion but because this model is meant for a free space diffusion it would not have in mind the obstacles caused by neutral nanomachines in the environment. Two of the most important movement models are Blind Ant where 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, and the Myopic Ant that when a molecule is close to an obstacle, its movement pattern is altered so that it cannot move to the illegal direction [29, 30]. The authors of [27] decided to modulate Blind Ant model since it is computationally less intense than the second model.

After the initial considerations, defining their topology and environment parameters, the authors proceed with the first performance test where they make a comparison between a free diffusion environment with one transmitter and one receiver and the multi-node topology they created. This performance test shows that the probability of hit at the receiver increases in the multi-node environment. This result is a consequence of the existence of neighboring nodes that limit the movement of molecules in space and act as walls that compose a passage way. Information molecules instead of wandering off in space and disperse completely, are guided back into a good propagation trajectory when they encounter an neighboring nanomachine that doesn't react with that specific type of molecule. Another test performed in this research was the impact on hit probability of distance between nodes, and expected as distance increases the probability decreases and this apply for both free diffusion and multi-node topologies. This could be bypassed by releasing more molecules, but it is not feasible in terms of effort from resources needed and the overhead that would cause in the environment, which would increase the noise for nearby CvD transmissions and inter-symbol interference. This research also shows that in the multi-node topology the propagation delay of information molecules is less than in free diffusion due to the same reason as before. The existence of neutral nanomachines create pathways that guide the molecules, not allowing them to wander around in free space and taking longer paths to reach destination.

Considering that a node can emit information molecules from any point of its boundaries, the election of release point of the molecules influence the performance of the communication since it establish the distance that information molecules need to travel until they reach the receiver. This detail about the communication can have a considerable impact since as described previously the distance between transmitter node and receiver node can decrease the probability of information molecules hit the receiver and increases the delay of molecule propagation. Hence, the selection of the release point on CvD must consider that choosing the closest releasing point to the receiver will increase the communication efficiency. On [27] the authors performed tests to see the impact the release point has on communication by establishing a scenario of communication between two nodes and the transmitter node would swap releasing point in a 30 degree angle intervals, as shown in Figure 3.4, where α describe the angle between the releasing point and the line that connects the nanomachines, so when α is zero degrees it means the molecules have to travel the shortest distance. The results authors provided show that the probability of hit clearly decrease when the angle is greater than 30 degrees, after 60 degrees the probability is less than half and passing the 90 degrees mark the probability has decrease by almost 70%. The results also show that the average delay of information molecules is influenced by the angle of the releasing point, when the angle is larger than 30 degrees, the average delay increases considerably as the angle increases.

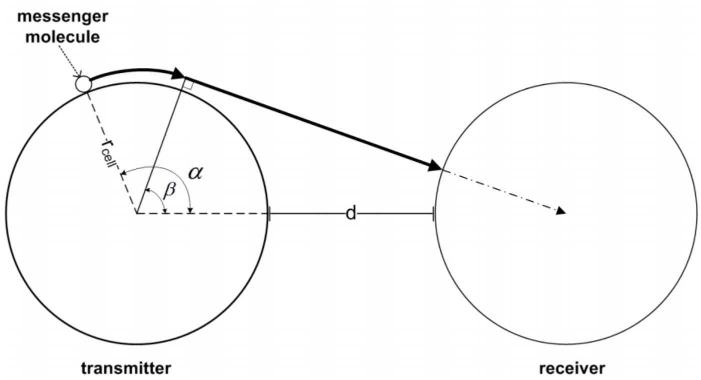


Figure 3.4: Release point's selection impact. [27]

So, in a routing mechanism perspective, the selection of the releasing point would be different based on the target of the transmission, for a given node. Although, the nodes may not have routing capabilities and so other schemes must be implemented. On [27] the authors approach three different methods, one being a pre-defined static releasing point which would be beneficial to adjacent nodes but other nodes would suffer from increased propagation delay and low probability of hit. Other method described uses an arbitrary selection of releasing point for each transmission, which grants fairness to all receivers, but on average the performance of transmissions would still be far from optimal. After modulating the arbitrary routing scheme, the authors show that the communication between adjacent nodes, i.e., short range, this scheme greatly decreases performance, but when the target receiver is at a longer distance the arbitrary scheme decreased performance is not so noticeable. Therefore, using this technique cause the standard deviation for the distance information molecules have to travel to decrease, but the average increases, i.e., the overall performance is decreased but the overall fairness increases by making all network work at the same rate. In the third scheme envisaged by the authors it is admitted that a node cannot select the optimal release point for a transmission, but he can pick a releasing point close to the optimal with a slight deviation, a sub-optimal scheme. As expected the results provided show that this method is clearly better than the arbitrary scheme, but comparing this scheme with the Optimal scheme shows that the difference between them is almost insignificant, making this a routing mechanism to have in mind.

The next research that creates a simple routing system it is based on Calcium signalling communication [16]. Calcium ions (Ca^{2+}) regularly act as a messenger to adjust several cellular activities, such as chemical secretion, contraction, proliferation, and death [31], in multi-cellular organisms. Information is precisely encoded on a frequency of concentration, which influence Enzymatic activity of Calcium and amplitude of concentration, which can cause differential gene activation, and are generally referred to as Calcium ions spikes and oscillation. Intercellular Ca^{2+} wave propagation is mediated by gap junctions, as shown in Figure 3.5, that directly connect the interior of one cell to another. Gap junction are not always open, the channel can close depending on several internal and external factors. In future systems using this communication technique, these factors will be manipulated so that the communication between nodes can be controlled.

When using a calcium signalling communication method the receiver nanomachine receives the message through a chain-reaction started at the transmitter, i.e., the transmitter nanomachine triggers signalling by stimulating neighboring cells producing the generation of propagating Ca^{2+} waves. The type, duration and strength of the stimulation influences the generated waves, and has an affect on whether Ca^{2+} waves reach destination or not, and if receiver nanomachine reacts to them. Sender nanomachines and cells forming gap junctions can directly reach the neighboring

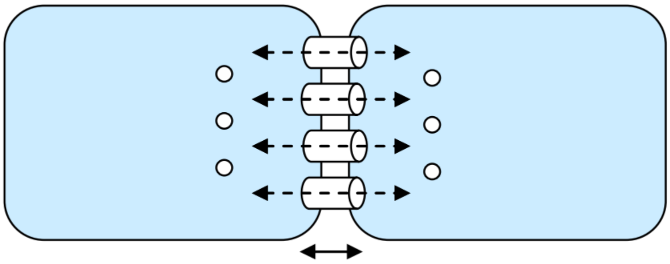


Figure 3.5: Gap junction between cells. [16]

cells cytosol, which allows them to broadcast Inositol trisphosphate, i.e., IP_3. Cytosol is the liquid found inside cells and one of the functions is signal transduction. IP_3 makes stimulated cells release their endoplasmic reticulum (ER), which are Ca^{2+} storages. The produced IP_3 diffuses through gap junctions to neighboring cells that triggers Ca^{2+} release from ER, the diffusion of IP_3 continues, thus propagating more Ca^{2+} waves over a number of cells. So basically, having access to the neighboring cells cytosol, allows the sender nanomachine to send IP_3, which in turn transforms into a Ca^{2+} propagation chain reaction. The detection or reaction of neighboring cells may be performed directly, where receiver nanomachines are allowed to form gap junctions with the neighboring cells, allowing receiver nanomachine to directly react to Ca^{2+} of neighboring cells. On the other hand, in indirect detection, receiver nanomachines may sense cellular activities, such as chemical secretion or morphological changes, which are caused from the Ca^{2+} variation on neighboring cells, and consequently the receiver nanomachine reacts.

The propagation of the signal can be broadcasted or directed depending on the type of network. When gap junctions have the same type and equal permeability, i.e., probability that the channel is open, the Ca^{2+} waves are equally broadcasted to neighboring cells, as seen on the previous chapter in Figure 2.8. Instead, the signals can be directed if the gap junctions are manipulated with different permeabilities in the cells that form the network. Using this technique, Ca^{2+} waves can be directed towards a specific direction because signals travel easier through gap junctions that are more permeable to signals. Consequently, a signalling pathway can be created by changing the permeability of the gap junctions.

The authors of [16] describe a process in which it is possible to design a cell switch that allows controlled signalling by dynamically changing the permeability of gap junctions. Their design shows that it is theoretically possible to route the Ca^{2+} waves through a N number of cells, by manipulating the gap junctions that create the path. The Figure 3.6 can illustrate an example where there are three types of connexins, Cx-X, Cx-Y and Cx-Z, which are connected to three cells, X,Y and Z, respectively. A given external signal is applied to the cell switch, changing the permeability of a gap junction from the switch to cell X, hence signals propagating from cell Z diffuse only to cell Y. These switches can be envisaged in such a way that an external signal can target specific types of connexins, in this case Cx-X, decreasing the permeability of the gap junctions from that connexin.

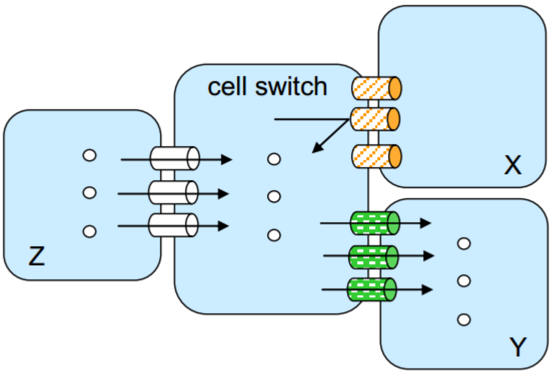


Figure 3.6: Ca^{2+} waves signalling switching. [16]

Using the same principal it is possible to achieve other schemes, such as signal aggregation. These systems can allow for the propagation of Ca^{2+} waves to reach receiver nanomachines at longer distances. In Figure 3.7, it is possible to see an example of such a system. The amount of IP_3 generated individually by S1 and S2 is not enough to reach the destination R, but when they are deployed in an aggregation topology the combined IP_3 generated from S1 and S2 is enough to reach the destination.

Although this research paper makes a theoretical approach to the routing problem, it provides a fresh insight on routing using calcium signalling. The next step for this technique its to identify cell types, materials to manufacture the envisaged system and mechanisms. A plausible choice to be researched is the transfected HeLa cells [32] since they are adherent cells that grow and form a network in a self-assembled manner.

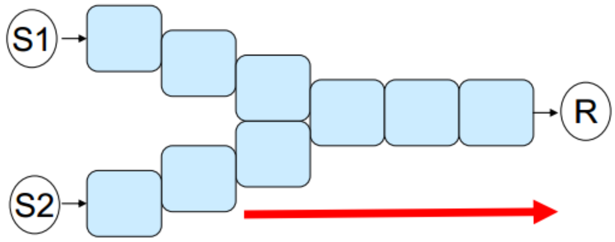


Figure 3.7: Signal aggregation scheme. [16]

3.3.2 Molecular motors communication

To this point researches mentioned are based on diffusion of molecules but other methods of communication, such as molecular motors, are also being researched. On this method rail molecules, or microtubules, are deployed creating a connection between nanomachines. The information is encoded into vesicles which travel along the rail molecules through molecular motors, such as kinesin. The vesicle travels on the molecular motors until it reaches the destination, which can be specified by protein tag that only binds to a certain receptor. When the topology of the microtubules is formed it determines in what direction molecular motors will move. In natural biologic systems, these topologies are generated within a single cell and generally create star-like topologies or random mesh forms. Star shaped topologies are great for either distributing molecules away from a single point or aggregate them in a location. Both of these functions have application like broadcasting molecules from a single source or collect molecules for analysis by a nanomachine, respectively. On the other hand, the random mesh topology formed can be used on an application which needs to evenly distribute molecules through the network.

The authors of [33] describe molecular communication through molecular rails with some detail, and acknowledge that they focus primarily on single hop communication, however they describe a few mechanisms that will allow implementation of multiple hop communication and more complex nanomachines systems. The first mechanism mentioned is the ability to do an amplification of information molecules which will be helpful to convert the signals from nano to macro scale, sending molecules over a long-distance or even multicast to target nanomachines. To be able to perform this task, the nanomachines would need to be coordinated to simultaneously perform the same function, in order to prevent the generation of information molecules in excess and the environment cleanse after the process is complete.

A mechanism is needed in molecular communication to provide the means for the receiver nanomachine to respond to the transmitter of a specific transmission. The authors describe a method they call *Feedback*, which can be applied in applications for querying a specific nanomachine for information or for requesting specific molecules. Other important mechanism is addressing, which allows the sender nanomachine to target a specific receiver nanomachine for a transmission. As explained previously, a simple addressing scheme can be applied by selecting a type of molecule that only the receiver can react to, another solution would be to address the destination according to spatial and temporal information, i.e., make a transmission along a specific link from the sender, so that only receivers on that direction receive the communication.

When talking about a multiple hop systems there are two functionalities that must be present, relay nodes and routing. Although routing is related to addressing, for a system to have a routing scheme implemented it is implicit that the network has the power to decide where to send, route the information molecules and not the transmitter itself. So the network must be responsible to choose a path between the transmitter and the receiver nanomachines, in the case where the transmitter can't reach the destination directly. The addition of intermediate nanomachines between the sender and the receiver, that participate in the communication, can extend single hop communication through relay communication. These intermediary nodes blindly transfer molecules extending the distance over which communication is sent.

After doing this theoretical approach on molecular motors communication, the authors on other research [34] envisage a new technique for molecular communication, which mixes features from molecular diffusion and molecular motors and present promising simulation results. In [34] the authors assess the probability of receiving information molecules for three different propagation techniques, diffusion-only, molecular motors and a hybrid design using both diffusion and motors. They measure signal, noise and information rate by modelling bit transmission, different scenarios were created modifying signal and noise by modelling the events of noise dissipation, sending multiple information molecules and receiving multiple information molecules.

As shown in Figure 3.8, the authors consider three cases (D), (M) and (H). In (D), there are none microtubules, i.e., molecular rails on the environment and the information molecules are propagated only through diffusion in random motion. In the (M) case, a molecular rail directly connects the transmitter and the receiver and the molecules travel the environment through molecular motors. In the last case, i.e., (H), several star-shaped molecular rails converge into the receiver, having their direction lead to the receiver. In (H), the transmitter is not directly connected to the receiver, hence information molecules diffuse from the transmitter, propagating in the environment, until they hit one of the molecular rails that belong to the receiver. The information molecules upon being bound onto the molecular rails, they will travel along the rail until they reach the receiver.

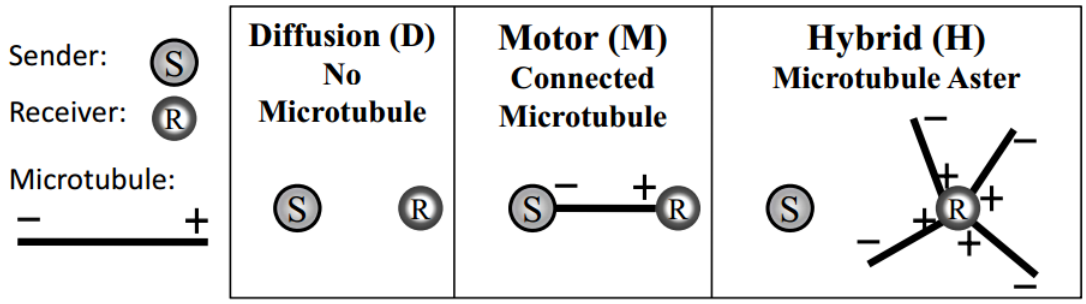


Figure 3.8: Uni-cast example of three propagation techniques (D, M, H). [34]

After modelling some environment parameters and propagation parameters the authors made a simulation to compare the probability of hit of the three different techniques. For instance, a messenger molecule diffuses until it hits a molecular rail, continuing to walk along the molecular rail at a fixed velocity of 800 nm/s, as observed in [35]. Another important aspect, which has already been mentioned, is that molecular motors disassociate from the molecular rail after losing their strength, and typically the average distance they travel is one μm. However, when several motors are attached at the same cargo, the probability that they will all disassociate at the same time is low, so the run length is increased up to 100's of μm, as described in [36]. Thus, the authors in [34] assumed several molecular motors are attached to the vesicles, so the average travel length on a rail is 100μm.

Figure 3.9 shows the cumulative probability that a certain messenger molecule hits the receiver by a given simulated time, for each propagation technique mentioned (D), (M) and (H). The authors refer that although the Figure 3.9 does not show the entire simulated time, the change in cumulative probability is insignificant after the time range presented. Another relevant information in Figure 3.9 is the different values of the cumulative probability for different distances between nodes (1, 8 and 64 μ), for each propagation technique used.

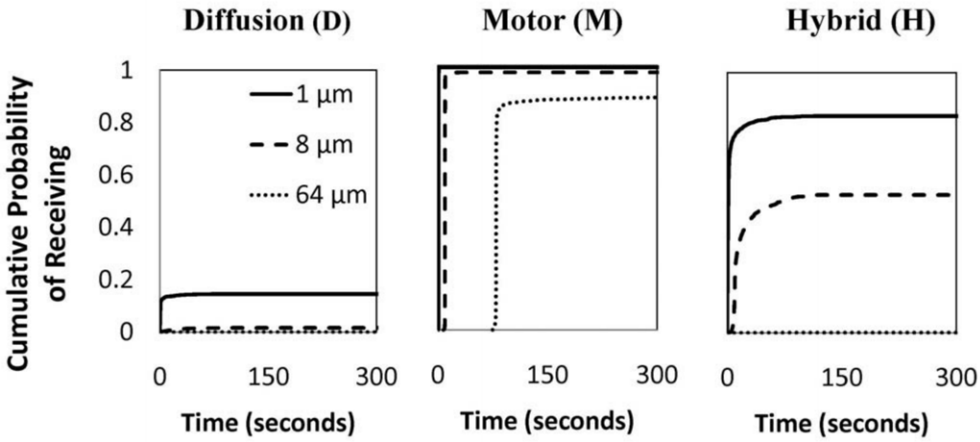


Figure 3.9: Cumulative probability of information molecules reach the receiver for each propagation method (D), (M) and (H). [34]

As expected, the technique (D) has the lowest cumulative probability, hence if a sender is releasing a limited number of information molecules it is unlikely to successfully perform diffusion-based communication to a single, distant receiver. However, directly connecting the sender to the receiver with a molecular rail (M) greatly increases the probability of the information molecules reach the destination, as Figure 3.9 shows. Although using directly connecting the sender and the receiver can theoretically create a reliable channel, as distances between them increases the probability that the messenger molecule will disassociate from the rail and wander off also increases. Adding more molecular motors to a single vesicle can increase the total distance the vesicle travels, but a limit to that distance will always affect this technique for longer distances. Alternatively, the third technique described (H), greatly increases the probability of receiving when comparing with the (D) technique. When an messenger molecule bounds to any of the molecular rails that converge to the receiver, it is presumably reaching the destination. As mentioned in

[27] when using a diffusion method, the receivers have an effective radius, which is the radius around the receiver in which molecules can be gather. In Figure 3.10 it is possible to see how the (H) technique can greatly increase the gather capability of molecules by increasing the effective receiving volume of the receiver nanomachine.

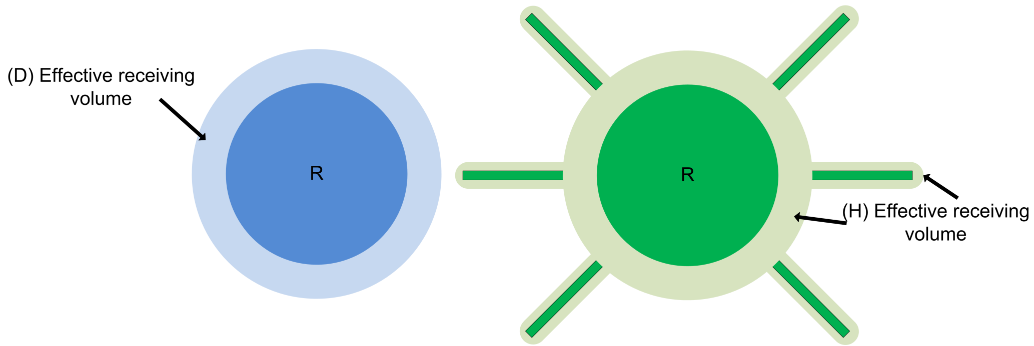


Figure 3.10: Difference between regular effective receiving volume in (D) and the increased volume when using technique (H).

The information rate measures how much information is transmitted per unit time. In [34] the authors created a scenario to where the sender transmits a binary sequence to the receiver, the receiver reacts to the information molecules and generates an output binary sequence. The transmitter nanomachine wants to transmit the bit "1", it emits a molecule(s), if the bit is "0" then it does not emit molecules. In this scenario the sender and receiver are clock synchronized, so if the receiver reacts to a molecule in that time interval a "1" will be appended to the output sequence, if the time interval passes and no reactions occur, the receiver appends a "0" to the sequence. This theoretical synchronization removes error control bits out of the transmission, easing the process of simulation on these infancy stages. However, a synchronization scheme can be implement through external signals that oscillate at regular intervals, such as molecular oscillations in molecular computing systems and electromagnetic waves.

The authors also state that in this scenario it is assumed that the sender emits information molecules with molecular motors already attached, the receiver acts to a single information molecule, similar to [37], and not by decoding the concentration of many information molecules. The sender does not begin to send the next bit before the previous transmission is complete, which can be very beneficial for diffusion based transmissions due to the variance in arrival time. When the receiver starts decoding an information molecule, all other duplicate molecules that arrive in the same interval are discarded, which can only be accomplished if the receiver nanomachine would enter a "off" state, in which it receives the duplicate molecules but does not decode the information, a process similar to neuron signalling.

The information rate results described by the authors show that, as expected, the distance has a huge impact on the performance of the communication for all three techniques, (D), (M) and (H). Two cases were created, one with noise from a previous transmission and the other with no noise. The information rate on the first case was clearly lower on techniques using diffusion into the environment, i.e., (D) and (H). When using the technique (D), some information can be transmitted at short distances (1 μm), however, as distance between nodes increases the efficiency of this technique decreases, and after reaching a distance threshold this technique is no longer feasible. On the other hand, the (M) technique didn't suffer as much with the existence of noise in the environment, which shows that using molecular motors for short range communication is the most reliable technique. As distance between nodes increases this technique still shows great promise, but the information molecules that disassociate from the rail increase, making the communication not as reliable as for short ranges. Moreover, the propagation time of information molecules in molecular rails increases directly with the distance between nodes, consequently there is a longer delay and the information rate decreases. Similarly to (M), the technique (H) can establish a communication to either short ranges and medium ranges, but although the information rate is only a few times lower than (M) for short ranges, it is decreases a lot for longer distances. On longer distances the features from diffusion overcome the performance of this technique, however the features from the molecular rail that converge to the receiver make this technique usable for longer distances that otherwise would not be possible. So the technique (H) is in fact enhancing the range which is possible to achieve when using a diffusion based communication. Although this technique may be appropriate for mid-range communication, it has significantly higher noise than (M) due to several information molecules bounding to different rails, causing the same information to arrive repeatedly at the receiver.

Although this paper gives some results from mathematical simulations for uni-cast communication systems, the information given can be important on the infancy stages of this research area. Routing in molecular communications is still a very tricky subject, and there are still many challenges ahead, but there is one concept that different researches are converging to. This concept is based on the idea that for the ideal routing scheme, different techniques of communication will have to merge together and create a standard, in order to establish a communication and route information in different ranges. In [34] the diffusion and molecular motors techniques we merged creating a hybrid method of communication that takes some features from each technique, creating a new one that will certainly have its use in specific applications, since it can increase the effective range and probability of receiving when comparing to a plain diffusion technique. In the previous chapter a description of molecular communication techniques is given, in which these are classified by effective range, and this technique can fill the gap there currently is in mid-range molecular communication, which in turn could open a window for routing scheme that bridge several techniques creating a communication system from short-range to long-range.

3.3.3 Bacteria communication

One method of molecular communication which has been proposed and presents itself as a very promising approach is the use of bacteria to establish communication. This method offers several attractive properties found in bacteria, such as the biased motility, i.e., the random walk towards the destination through chemotaxis process and the ability to transfer information, in this case genetic information, between each other using bacterial conjugation, which is a important mechanism of Lateral Gene Transfer (LGT). Through chemoattractants the motility of a bacteria can be directed, additionally most bacteria commonly produce easy to grow organism which can perform thousands of operations per second. Bacteria swim when molecular motors embedded in the bacterial membrane make thin helical flagella rotate, these motors can sporadically stop and start, change the arrangements of the flagella, hence their direction of rotation which steers the bacteria according to the surrounding environment.

In [38] the authors propose an opportunistic routing process for a bacteria communication network by using the properties described above. The bacterial conjugation is the process of transferring DNA from a donor to a recipient cell, and this process can be exploited for routing in a bacteria communication nanonetwork. Although this feature seems very attractive, the conjugation process has the disadvantage of being a very slow process because of the complexity of protein machinery and occasionally the security and trust procedures that reside inside the recipient bacteria [39]. Moreover, the time that takes to complete the process depends on the amount of information on the gene that is being transferred, additionally, the transfer process takes several minutes to start due to the structural bounding required. In order to implement a routing scheme with bacteria communication, the authors applied both bacterial conjugation process and bacteria chemoattractants enabling them to implement a Delay Tolerant Network (DTN) routing scheme on a bacteria communication nanonetwork. In the scenario created by the authors, each bacteria behaves like a mobile user, and the message is transferred through bacterial conjugation when the carrier bacteria encounters a different bacteria travelling towards a different chemoattractant. The authors performed simulation determining the success in message delivery, the average delay, as well as the reliability of message transfer.

To perform these performance tests the authors defined some assumptions, like each nanomachine has a single chemoattractant, similarly to computer networks where on terminal has a single IP address which allows the network to target him. Additionally, each nanomachine only has bacteria that will be attracted to the neighbor, i.e., bacteria chemoreceptors of a nanomachine must match the chemoattractant of the neighbor node. In this scenario a nanomachine cannot target two different receivers, so the message will hop from node to node until it arrives at the destination, i.e., a multi-hop network. Although the authors made this assumption, it is very likely that nanomachine will be able to target different nanomachines by selecting which bacteria to use, hence creating a routing scheme based on chemoattractants addressing.

The process of multi-hop envisaged by the authors relies on bacterial conjugation of different streams of bacteria. For example, node 1 wants to transmit a message to node 3, but its neighbor is node 2 so the bacteria carrying the message will propagate towards node 2. Meanwhile node 2 transmits bacteria that will swim towards node 3, when the two types of bacteria cross at a specific point, a bacterial conjugation process will begin between them transferring the message from bacteria that is travelling towards node 2 to bacteria travelling towards node 3. The second type of bacteria will resume its natural instincts after completing the conjugation, and travel towards node 3 with the message inside. The drawback of this process is that the message will be transferred to several bacteria creating a large number of duplicates, however this feature can be good to ensure reliability in the communication, creating a guarantee that at least one bacteria will arrive at the destination. In these type of communication nanonetworks, where there are so many probabilistic factors in the environment, reliability in the communication is imperative.

To simulate this multi-hop mechanism through chemotaxis and bacterial conjugation the authors design three simple topologies, as shown in Figure 3.11, and verify the impact that each topology shape will have on the bacterial conjugation process and how this in turn will affect the message delivery performance.

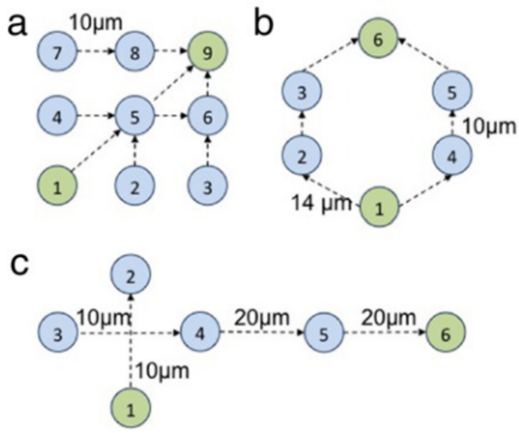


Figure 3.11: Topologies used in [38]. (a)Grid-topology 1, (b)hexagon-topology 2 and (c)T-shape-topology 3.

In the Figure 3.11, the sender and receiver are the green nodes, and shows the directionality of the chemotaxis through the dotted arrows. In the grid topology the chemotaxis is converging into the destination node, and in this topology the authors want to verify how converging several bacteria in a specific direction could accumulate the bacteria, forcing the conjugation process to occur and how it would enhance the reliability. In the hexagon topology the aim was to determine how the existence of two possible paths to destination can influence the motility of the bacteria, and in turn how would the number of conjugations be affected. The T-shape topology was designed to have the chemotaxis of the source node to flow in a different direction to the destination node, allowing for a several conjugation processes to happen where the chemotaxis flows from node 1 to 2 and node 3 to 4 cross, which will establish how many bacteria carrying the message will move towards the destination node.

Figure 3.12(a) presents the number of messages that have successfully arrived at the destination node. It is possible to see that increasing the number of bacteria emitted per node causes more bacteria with the message to reach destination, not only because of probabilistic factors, i.e., more bacteria sent therefore more bacteria received, but also due to more bacterial conjugation processes. Comparing the three different lines, which correspond to the topologies showed above, the number of successfully received messages in the destination node is higher in hexagon topology (topology 2), outperforming the other two topologies, specially when the number of bacteria per node is high. This increased performance is a result of the shape of the topology, although the most bacteria emitted from the node 1 follow a chemotaxis to node 2 and 4, as shown in Figure 3.11(b), the authors discovered that a large number of bacteria propagated from the void center of the topology, directly to the destination node 6. This phenomena can also been observed when comparing the number of conjugations between topology 1 (grid) and 2 in Figure 3.12(b), which shows that the grid topology generated a larger number of conjugations than the hexagon topology, although the latter has a larger number of successfully received messages.

Although the authors didn't describe this detail, it is possible to see in the results observed that the topology 3 (T-shape) has a solid standard deviation for the different cases of number of bacteria emitted. Additionally, in case of ten bacteria emitted per node, it is possible to see, in Figure 3.12(a), that the average number of successfully received messages of the T-shape topology it is really close to the average number of the grid topology, although the grid topology has almost the double of conjugation processes performed, as seen in 3.12(b). As described above, the conjugation process is a slow process that takes time, several minutes to give

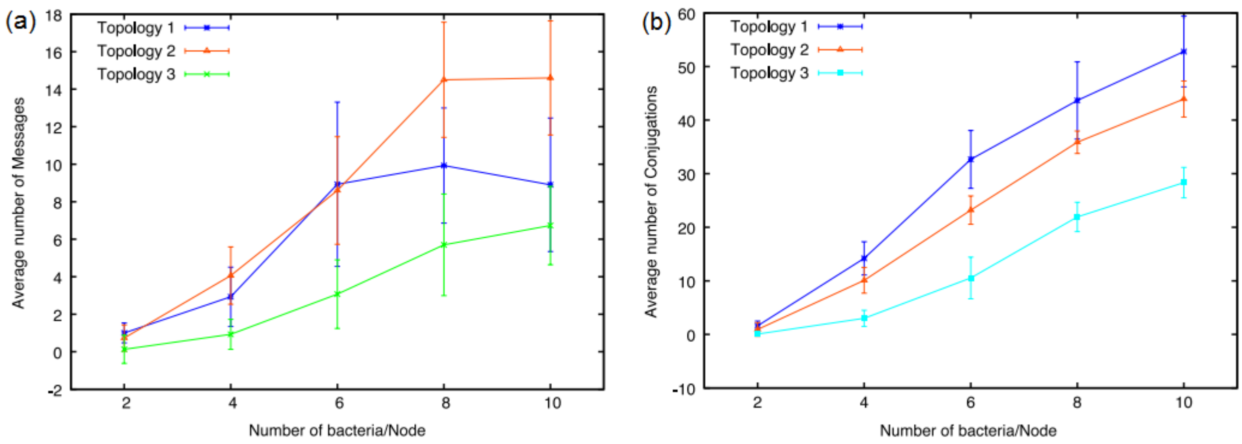


Figure 3.12: Simulation results of [38]. (a) Number of successful messages vs. number of bacteria emitted per node; (b) Number of conjugations performed vs. number of bacteria emitted per node.

a time scale. Which means that the grid topology concept, i.e., converging several chemotaxis to one direction, will cause a higher delay and additionally, the noise from previous transmissions would increase in the environment. In Figure 3.13 it is possible to see that for ten bacteria emitted per node the grid topology is already with a higher average delay than the T-shape topology, if the bacteria per node would increase this delay would increase accordingly, and one should have in mind that this is the delay for the first message to arrive. This analysis should not be studied from the point of view of the greatness of the T-shape topology, but contrarily from the unfeasibility of the grid topology, which can cause a serious overhead problem in the network, consequently increased noise in the environment and delay. The T-shape topology was chosen to do this comparison because even though its design is far from the optimal topology design, the simulation results show better promise than the grid topology.

Figure 3.13 also shows that the hexagon topology had the lowest delay for the first message to arrive, however, the authors state that the gap between the hexagon topology and the other two topologies could be attribute to the conjugation process, since the bacteria stay stationary while the process is in progress, simultaneously with the fault of the hexagon topology where bacteria swim right through the middle of the topology in direction to the destination, not executing a single bacterial conjugation. With this in mind comparisons with the hexagon topology are not

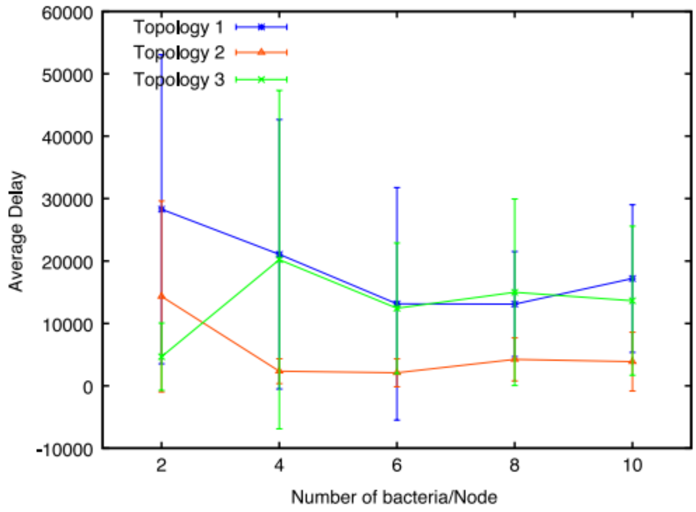


Figure 3.13: Simulation results of [38]. Average delay before first message arrived at destination.

very relevant, on the other hand comparisons between the grid topology and the T-shape topology can be made.

The delay between these two topologies was already discussed, but one detail which is relevant is the average distance from the source to the destination. In the grid topology these two nodes are vertices of square, and in the topology design provided in the paper states that the distance between two adjacent nodes, not diagonally, is 10μm, which means that the distance between two adjacent nodes diagonally is approximately 14μm, so the average distance from source to destination would be 28μm. On the other hand, applying the same principle, it's possible to calculate an average distance from source to destination in the T-shape topology, which is approximately 50μm. So the effective distance travelled by a bacteria might be less or more of the values described, but it possible to see that for a bacteria in the grid topology to travel a distance close to the average distance of the T-shape topology, it would have to drift away a lot. Therefore, it is established that bacteria need to travel a longer distance in the T-shape topology and it was already discussed the impact distance has on molecular communication. Even tough the distance is longer, the T-shape topology achieves a lower delay than the grid topology, which supports the previous discussion where the concept of converging all chemotaxis to the same location is questioned.

The performance tests on the three topologies show that the conjugation process greatly improves the T-shape topology by decreasing the average delay of receiving the message and increasing the reliability of information reaching the destination, while the hexagon topology doesn't benefit much from this process, due to his design fault. On a separate level, the grid topology starts to benefit from the conjugation process while the bacteria per node are still at a lower number by decreasing the average delay and increasing the message reliability, as the bacteria emitted per node starts to increase, it is possible to see that this topology will start to suffer and a degradation of performance will occur, although the scheme still guarantees the message delivery.

Since the T-shape topology showed great improvements from the conjugation process, the authors created different scenarios for this topology, in which the time of the conjugation process varies. Three cases were created by increasing the conjugation time, 600, 1200 and 1800 seconds. Simulations were ran to verify the impact that the conjugation process period has on the success of message delivery to destination. In Figure 3.14, it is possible to observe the average number of messages successfully delivered to the destination, as well as the average number of conjugation processes that occurred. The obtained results show that the number of messages that arrive at destination decreases as the conjugation time increases, moreover, the number of conjugations observed follow the same trend, occurring less processes as the conjugation time increases. So as the time of conjugation increases, the impact on the timely delivery of the messages will increase. This is mainly due to the fact that while the conjugation process occurs, the bacteria are stationary until the process completes.

The authors of [38] propose this opportunistic routing process of a multi-hop bacteria communication nanonetwork, and the results they present help to support this concept. Since molecular communication cannot be analyzed like traditional computer networks, these type of routing scheme are very important due to the fact that creating a real-time nanonetwork its very unrealistic in this stage. Molecular communications are slow, very dependent of the environment, which means unreliability, and at this stage, these type of routing mechanism are the best bet to create and test a real nanonetwork with routing capability in the near future. The authors take two inherent characteristics of bacteria, and apply them in an intelligent way

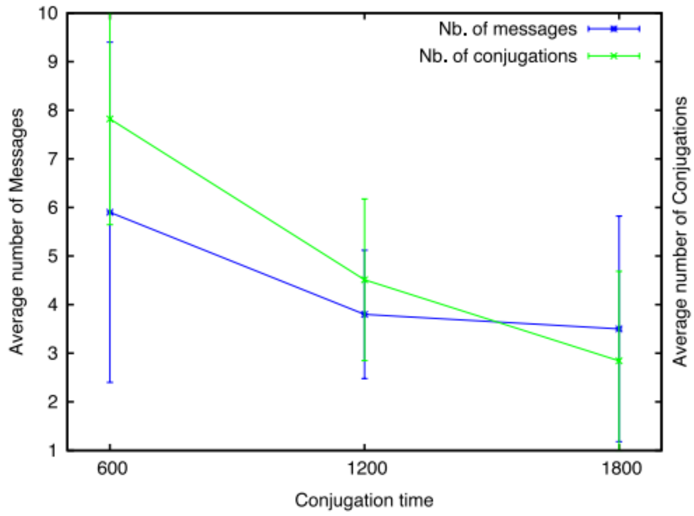


Figure 3.14: Simulation results of [38]. Impact of conjugation time in the average number of arrival message and conjugations.

in order to create a routing concept, opening a window for other researches teams, with access to more resources, to implement and expand its capabilities. Allowing for nanomachines to target different destinations by selecting a type of bacteria that will only interact with that destination, would be a huge step on molecular communications field.

This section detailedly reports the most important researches that influenced the work the next chapter describes. Several concepts are introduced in this section, from routing mechanisms to new communication techniques that can allow a routing scheme to be implemented. The methods of communication this section covers are considered the most relevant, and the ones that will most likely support a routing scheme due to the features this section illustrate. All the researches this section presents show promising results or concepts, which are obtained from the clever use of the inherit characteristics of certain molecular communication methods. The authors clearly describe their concepts, with all the information that makes them theoretically possible, and in some cases simulation results that validate the concepts. Although, there is a need for a more complete simulation framework that will allow the easy validation of these concepts.

3.4 Simulation of Nanocommunications

As mentioned in last section this research field is still in its early stages, and it is a specially difficult field to get performance tests conducted in real world scenarios, being only reachable by selected professional research teams. So most of the researches published on this field that manage to get some kind of proof of concept, are able to do it through simulation. From this group of researchers most of them use software that enables them to run mathematical simulations, since it is possible to describe most of the behaviours mentioned previously with mathematical expressions. These kind of simulations are very important to test the performance of a new concept and obtain an early proof of their concept, which is important to expand the concept, correct flaws and improve the performance with the analysis of the results. Although the mathematical simulations can provide helpful support to verify a performance of these systems, there is a need for a simulation framework, which allows researches to quickly perform simulations to validate their concepts. Simulation frameworks like this exists for regular computer networks, which help small researches validate small projects or new concepts. Being a new paradigm in communications, there are only some simulation frameworks focused for nanonetworks developed to date, targeting different types of nanocommunications.

In [40], the authors present a framework based on electromagnetic communication in the Terahertz band, designed for simulate wireless nanosensor networks (WNSN), the *Nano-sim*. This framework is a module of the well known Network Simulator 3, in which the authors implement the main types of nodes that are used in WNSN, MAC and PHY protocols, network layers, as well as channel access procedures. In this paper the authors also create a case study where they evaluate the performance of their framework, achieving promising results.

On the other hand, simulation frameworks like *N3Sim*[41], *NanoNS*[42], and the one proposed in [43] have been designed for molecular communications, which is the most promising communication method. The *N3Sim* was design in order to simulate a set of nanomachines that communicate through molecular diffusion, in which information is encoded into the variation of the concentration. This framework tool uses a configuration file based architecture, in which the user define a set of parameters, such as number and location of transmitters and receivers, the size of the emitted particles and the diffusion coefficient of the medium, amongst others. After completing the simulation, the framework outputs one file per receiver nanomachine simulated, which contains the concentration measured as a function of time. This framework is a very simple tool which implements a set of mathematical equations, but creates a level of transparency for the user, since the only requirement is to define the topology and the parameters, and a simple graphic output is generated. This tool was developed using a Java language, which can be good, since its a new language which many people are familiar with and can easily be expanded by new researchers, on the other hand is not a module for Network Simulator, which can take advantage of the existing network modules that would allow researches to modify the tool to support communication protocols. The authors used this framework on other paper where they explore the physical channel when using a molecular concentration diffusion-based communication [44]. The results they obtained show that this communication technique can be used, similar to early analogue electronics, with a train of pulses which encodes a binary message. In this type of communication the sender and receiver would have to be synchronized, so the receiver correctly detects when a pulse passes a certain threshold .

Although this framework is similar to the one in [43], since both are a Java implementation, the latter offers a overall solider solution by including important features that distinguish itself from other solutions. While in *N3Sim* the simulations are done in a 2D environment, this tool calculate simulation in a 3D environment, which produce simulation results closer to the real-world. Additionally, while other framework tools use a Brownian motion model to describe the diffusion process, this tool uses a lattice position scheme, i.e., the authors use a multiparticle lattice gas automata algorithm, which divides the medium into latices sides. Hence, the exact position of a molecule is not necessary, since only its lattice position is required. Moreover, while in *N3Sim* the receiving process is accomplished by counting the number of molecules in a given area close to the receiver node every time step, this tool implements a dedicated model for the receiver nanomachine, in which there are thousands of receptors distributed over the surface of the receiver nanomachine, and the reception process happens when any propagating molecule hits any of the receptors of the designated receiver nanomachine. This tool also enables the possibility of mobile nanomahines, i.e., they can change position during the simulation period, on the other hand other frameworks do not allow this feature.

One of the most important simulation framework for nanocommunication, specifically molecular communication, is the *NanoNS*[42]. This tool was developed as an expansion to the commonly used Network Simulator 2 (NS-2), which benefits this tool in several ways. Since it was created as group of modules that use the NS-2 functionalities, the modules were developed in C++ and object-Tcl (OTcl), contrary to the previous frameworks for molecular communication mentioned. Taking advantage of the NS-2 native modules, the authors of this framework developed modified versions of those modules, in order to create network modules for molecular communication. For instance, the NS-2 class *Node* was modified for molecular communications, but keeping several of its native characteristics, which means that a new module was create with room for future nanonetwork implementations, i.e., while other frameworks simply execute a set of equations with certain input parameters, the *NanoNS* is a tool that can allow nanonetwork concepts, like protocols, to be validated. The authors implemented a feature that allows the user to select different types of reactions between the propagated molecules and the receiver nanomachines, although the implementation described in the paper has three possibilities, it is possible for other researchers to implement their own reaction modules and use them in simulations, since the implementations supports it and it is a open-source framework. When the framework was envisaged and designed it, the authors implemented a network stack into the modules, including the physical, MAC and link layers. Although they implemented a very simple time-division multiple access as a MAC protocol, the framework architecture allows for future complex MAC, routing and transport layer protocols to be implemented. Moreover, the authors included a module capable of injecting errors into the simulation, which can occur in a outgoing or incoming link, i.e., the user can select the link where errors are going to occur, and even the error rate, allowing them to simulate a specific scenario to validate a theoretical concept. This is a very complete framework and the architecture creates room for easy expansions to be developed, such as: communication protocols, like previously described; new methods of communication, like molecular motors, gap junction, bacteria and pheromones based communications; allowing mobile nanomachines, i.e., change position during the simulation.

In [45] a simulation framework for neuron-based molecular communications, which utilizes electrochemical signals through neuronal networks, is proposed. Neurons are electrically excitable cells that process and transmit information via electrical and chemical signaling, and are connected with each other to form a network. This communication is achieved through variations of Na^+, which generates an electrical pulse called an action potential, that triggers cascading neuron-to-neuron communication. The authors of [45] propose a framework that will aid researchers in communication protocols design for neuron-based nanonetworks. The framework developed is not a *standalone* application, instead the authors implemented a tool in Java that integrates other frameworks for neuron-based communication. It integrates various simulation components such as visualizers and editors for neuronal networks, neuronal topology generators, media access controllers to neuronal networks and communication schedulers for neuronal signal transmissions. In the paper [45], the authors describe the components of the proposed framework, a topology visualizer (*Neuronal Topology Visualizer*), which allows the user to edit and view the structure of a neuronal network, and a media access controller, communication scheduler, (*Neuronal TDMA optimizer*), which seeks the optimal schedules for nanomachines to fire neuronal signaling in a given neuronal network. The authors created a mechanism that allows these two tools to work cooperatively through a XML file that encodes the topology of a neuronal network and the location of nanomachines. In the paper, the authors describe a case study in which they evaluate the performance of the topology through the cooperation of the two components.

This section describes some of the most relevant simulation frameworks developed for nanocommunications. Frameworks are being created according to the importance and relevancy of a given communication technique, and the ones that exist are being expanded. Overall the development of simulation tools is still on early stages, leaving several gaps to be filled, like the ability to merge several communication in the same simulation and implementation of protocols for different network layers. The simulation tools developed so far offer a good framework for researches make simple performance tests to validate small concepts, but they are a basic tool which is part of the evolution of this field. In the future tools like the ones presented will be absolute, but they are a necessary step in the growth of new research paradigm.

3.5 Conclusions

This chapter presented an overview of several aspects of the state of the art in nanocommunications by describing general researches about nanocommunications and its methods of communications, various nanocommunications applications concepts and actual ongoing application researches, several researches on routing mechanisms or techniques that can allow a routing mechanism to be envisaged, and finally, simulation frameworks for different methods of nanocommunication, which can help validate concepts. The routing mechanisms are of large importance for the work developed, since the designed system greatly focus on this main networking component. The simulation and applications section also influenced some decisions, and were used to assist in the process of development of the concepts that the next section describes.

Chapter 4

System Architecture

In this chapter a system architecture for molecular nanonetworks is designed and carefully described. This system concept was envisaged according to current researches presented in the previous chapter, however, it is a new and unique approach for a nanonetwork system. Since this field of research is still very recent, and researches are still trying to find the optimal way of composing a nanonetwork, the system concept in this chapter tries to answer several challenges mentioned by other researches, and aggregate positive features from several aspects, to create an optimum system. In the first section of this chapter, the information's encoding of this system is addressed, explaining the process and why it was selected. Then the importance and impact of topology in this system is discussed, followed by the communication techniques selected to operate in this system. In the next section the challenges of routing and addressing in nanonetworks are addressed, and a complete description of the envisioned concept to give the system these capabilities is presented. In the last section, all points mentioned along the chapter are briefly summarized, and some closing statements are given.

4.1 Topology and communication techniques

The first thing to understand in this concept is the importance and the impact the topology has on the system's performance. The envisioned concept wants to meet some challenges and features addressed in the previous chapter and in the researches studied, creating a system that would try to resolve known issues using established features from molecular communication. The molecular communication techniques individual features have an important role in the envisioned topology, since those features are manipulated in order to take advantage from them and thus, increasing the performance of the system.

The motivation behind this concept was to create a nanocommunications system that would resolve popular problems and challenges, by manipulating existing and known features. The challenges that were targeted focused in the transmission performance, the ability to address individual nodes in the nanonetwork and give the nanonetwork some routing capability scheme. Due to lack of resources and the early stages of research in this field, the most favorable approach is to cleverly use the inherited features from molecular communications, in order to address the challenges described.

4.1.1 Communication techniques

Most researches focus on one individual nanocommunication technique and in a single environment, i.e., communication at the same range-level. In the interest of expanding nanonetworks effective range and create building blocks for future communication from nano-scale to micro-scale, allowing IoNT systems to be a reality, a communication mechanism that would provide those capabilities was envisioned. With that in mind, the specified mechanism utilizes different molecular communication techniques, which co-operate to achieve communication between different range levels.

The communication techniques selected would be required to allow a unified communication from the short-range level to medium-range, i.e., from the nano-scale to micro-scale. The use of bacteria to establish a communication in the medium-range was almost immediate, since the features it offers makes it one of the most promising molecular communication techniques, as seen in the previous chapters. Since the bacteria communication uses a DNA encoding, which also offers very promising features, described in the next section, the objective was to select a short-range communication technique that would also use and benefit from DNA encoding. The choices are limited for a technique that answers the requirements, the molecular motors approach is the most popular, while other methods don't have as much information published, since so far they don't seem as relevant. In the initial concept the molecular motor technique was considered, but then the paper [34] analysed in the previous chapter, envisaged a clever approach in which a hybrid system between molecular motors and molecular diffusion is created.

Although the results presented on [34] don't seem to show great support for the concept, it is possible to see that the concept really takes features from both the molecular motors and the diffusion. The main advantage of using molecular motors is the reliability the technique provides to the transmission. On the other hand, the transmission process is very slow. The hybrid technique presented is faster than using a full molecular motors bases approach, and it offer and increased reliability than a diffusion technique, due to the molecular motor part of the system.

Using these two approaches, the communication techniques used in this system are established. A hybrid approach between molecular motors and diffusion is used for communications at a short-range level, while a bacteria communication approach is used to establish communication at a medium-range level. An unification between the different range levels is met by using the same DNA encoding process, which is described in the next section. A message created in the short-range level, i.e., small nanomachines and nanosensors, can be directed though the network until it reaches a nanogateway, a nanointerface, that possibly connects to, for instance, a personal area network, which is connected to the internet.

One of the most important challenges when using both of these communication techniques is the transmission flow control. In bacteria communication, as described in last chapter, researchers believe that advances in nanotechnology will allow nanomachines to produce different chemoattractants, so in this system is considered that the nanogateways in the medium-range level can be individually targeted using different chemoattractants. On the other hand, to efficiently control the reliability of the transmission in the short-range, additional efforts have to be made. In the previous chapter it was described how important is the release point when using a diffusion-based communication, so, in order to maximize the efficiency, a static release point was defined but the proposed approach allows a prediction of where that release point will be pointing to, so the topology would have to be built accordingly.

In this concept the proposed solution forces the simple nanomachines, nanosensors, to assume a position. The manufacturing process of these devices would have to include a gömböc proportional to their size, which will force the nanomachine to assume a specific position. A gömböc is a mono-monostatic body, which is a convex three-dimensional homogeneous body, which when resting in a surface has one stable and unstable point of equilibrium, which is a similar behaviour to the commonly known balancing toys called "comeback kid", as seen in Figure 4.1. The gömböc was proven in 2006 by the mathematicians Gábor Domokos and Péter Várkonyi [46, 47], and they discovered that there is no specific shape for a gömböc, but after ten years of research they found the equations that defines one, so it it feasible to manufacture a nano-gömböc.

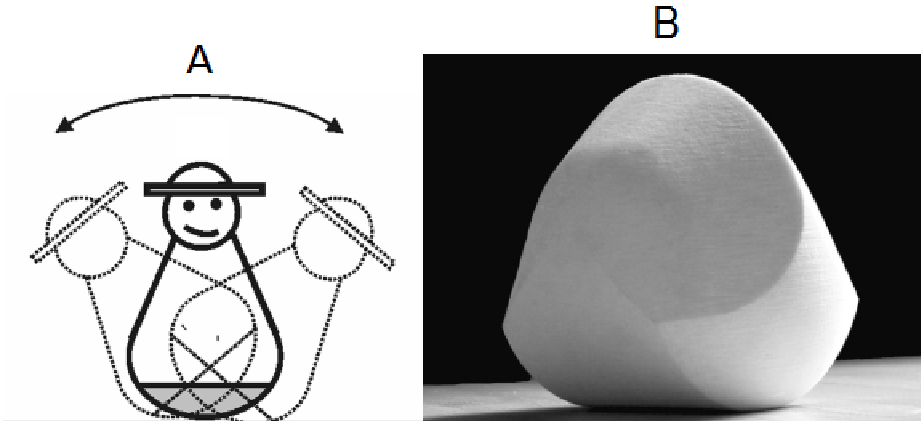


Figure 4.1: (A)Balancing toy with one stable and one unstable equilibrium inhomogeneous, mono-monostatic body. (B)A Gömböc with convex and homogeneous solid body with one stable equilibrium (mono-monostatic body). Adapted from [47].

Mono-monostatic body nanomachines or nanomachines with a gömböc integrated would force them to always stand in the same position, so if the releasing point is placed in the apex of the nanomachine, the transmission will always be upwards. It is possible to manipulate the density of the nanomachines in order to make some "heavier" to sink in the environment, and some that "float in the middle" of the environment. Hence, the simple nanomachines, nanosensors, would sink and only transmit upwards, where the gateways nanomachines would hover around, receive the information, and communicate with each other by means of bacteria.

In Figure 4.2 it is possible to see everything described in this subsection, there are

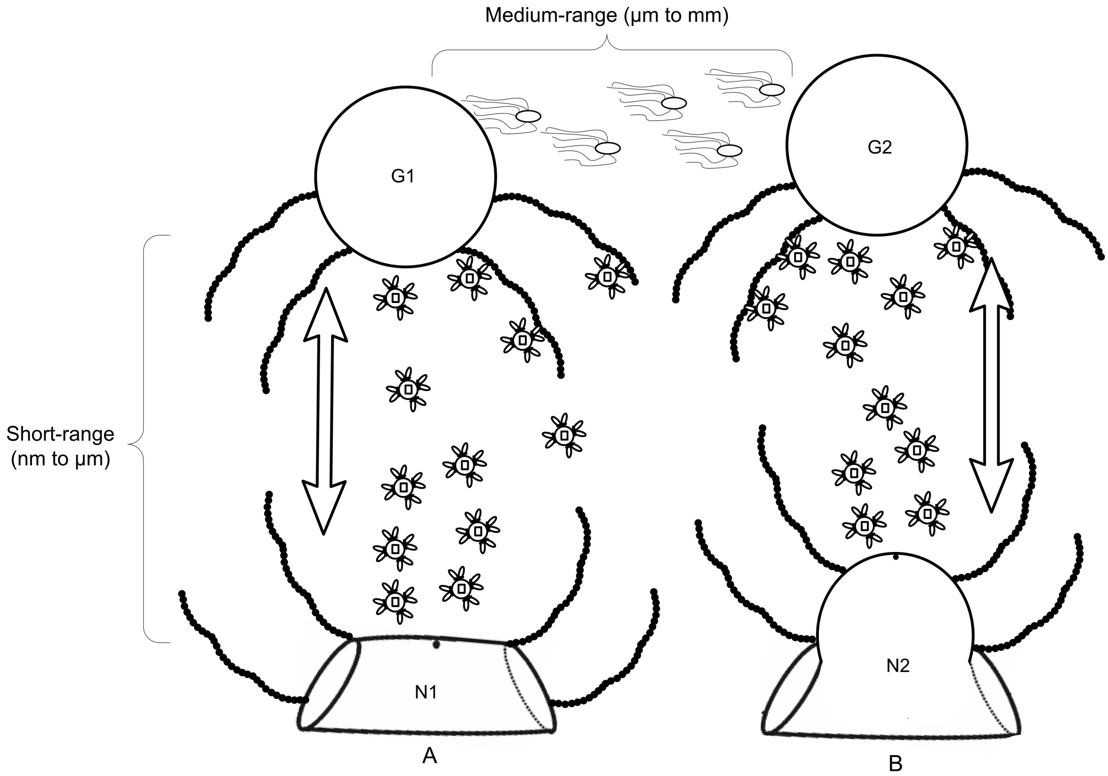


Figure 4.2: Illustration of the communication techniques used in this concept. (A)Mono-monostatic body manufacture approach [47]. (B)Modified mono-monostatic body manufacture approach. Adapted from [47].

two levels of communication illustrated, the bacteria communication in the medium-range to support communication between nanogateways and the hybrid method described in [34], which utilizes both features of molecular motors and diffusion based communications. The hybrid method diffuses vesicle molecules with several molecular motors attached, the nodes that take part in this communication contain several molecular rails, that have the direction configured to converge to the node. The diffused vesicles will travel the channel until they reach either the destination receptors or one of the molecular rails that will guide it to the receiver. This short-range communication can be design to support bi-directional or uni-directional communication, the only requirement is that the nanogateway must be able to diffuse downwards.

Also illustrated in the Figure 4.2 are some example approaches to the nanomachine body manufacture. In Figure 4.2(A) approach, the nanomachine entire body is a gömböc ,i.e., a mono-monostatic body, while in 4.2(B) the body is modified in order to have a gömböc in the bottom and the nanomachine itself is appended. With the method (B) some characteristic of the mono-monostatic body could be lost, depending on the manufacturing process, but with accurate construction most properties could remain unaltered.

4.1.2 Topology

With the notions described previously it is possible to see some characteristics that will define the final topology of the system. Of course there isn't only one topology setting which can benefit from the concepts described, but one approach was selected as example and is described in this section. One important aspect to mention is that in molecular communication the communications channel is also the environment where nodes are placed, where the three dimensional aspect as most impact. So when designing a topology, a three dimensional environment needs to be considered.

The concept topology selected as targeted at a sensoring network, for a biological or medical application. Since most efforts in molecular communications are for biomedical nanoapplications, the motivation was to design a system that could be used in these applications, using the concept ideas described during this chapter. The topology is based on a hierarchy topology, common to sensor networks, but it needed to be adapted for a three dimensional environment. When trying to find an analogy with real world system, the closest, in terms of operation, is the cell-phone communication system. Although the three dimensional aspect does not have the same impact, since the base station do not know the altitude of the terminal, there are some features that can be helpful, such as, the ability to target a terminal due to their geographical location, i.e., reaching a terminal through the base station it is connected to, and the hierarchy aspect of the network, which suits perfectly in the nanosystem.

As mentioned in the previous section the main communication levels focused on this concept are the short-range and medium-range. The advances in nanotechnology and manufacturing will allow the communication from the micro-scale to macro-scale to be done with ease, through nanointerfaces. The first level to be described is the bottom level of the topology, which is composed by simple nanomachine with nanosensors and/or nanoactuators, etc. When the system is deployed these will sink, as mention in the previous section, creating the first layer of the topology, as seen in Figure 4.3.

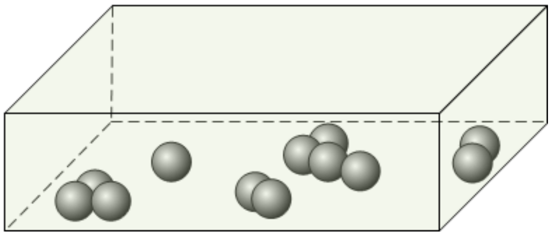


Figure 4.3: Illustration of short-range layer, with simple nanomachines with nanosensors and/or nanoactuators.

Using the approach described in the previous section, these nanomachines will communicate upwards to the closest nanogateway they encounter. These nanogateways are above the nanomachines, and communicate with one another using bacteria, establishing the medium-range level. In figure 4.4 is possible to see an illustration of the two levels stacked, in which the hybrid communication between levels is represented by the blue cones and blue bacteria are representative of the communication within the medium-range.

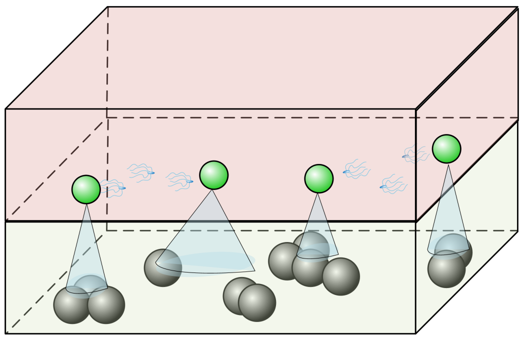


Figure 4.4: Illustration of the two stacked levels, and the communication technique used.

These two layers of communication create the foundation for nanonetwork based applications. It is possible for several applications to place more layers of communication on top of the medium-range layer, thus creating a more complex nanonetwork system or IoNT systems. At the micro-scale the nanointerfaces are a closer reality, so a transduction from molecular signals to electromagnetic signals become possible, additionally, a nanointerface is able to, theoretically, transform the DNA information into a pheromone signal, hence extending the range of the nanonetwork to the meter-scale. Some of the possible applications are illustrated in Figure 4.5. In case A.1, the nanonetwork uses a molecular-to-electromagnetic nanointerface to communicate with a user device (bracelet, smart-phone, etc..), which in turn transfer the information to a web server. This type of application could be used in a fitness or mobile monitoring medical application. In the case A.2, the nanonetwork directly connects to a small local server, possibly being a local information sink, or a relay server that transmits the information to a web server, which can be used in medical devices, like advanced imaging machines, medical condition monitoring for people that are bedridden at hospitals or their homes. In the cases B.1 and B.2 the nanonetwork uses a nanointerface that transform the DNA information of bacteria into pheromone signalling, expanding the range of communication to the long-range. In theses scenarios, the best applications could be used in environmental situations, like water and air quality control, agricultural situations like livestock and pest control, military application, like offensive/defensive measures, and several more applications which are still to be envisioned. On the other hand, the use of pheromones in medical applications is not very common, and most certainly will not have a great impact in the medical field.

In this section it was described the reasons for selecting two different types of communication techniques as well as the reasons for selecting a hybrid technique between molecular motors and diffusion to establish communication at short-range, and the bacteria technique for a medium-range communication. Important challenges with these methods were addressed, and concept solutions were proposed to resolve those challenges or increase the efficiency of the nanonetwork overall. A design for a base topology that takes advantage of the concepts described is presented, as well as several alternatives that can be placed on top of the base topology for different ranges of applications. However, for these applications to operate as intended the information gathered from the nanomachines needs to have an encoding process in order to reach the destination safely.

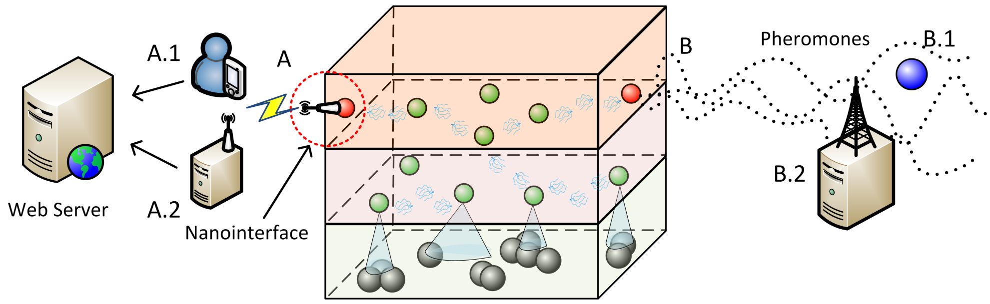


Figure 4.5: Illustration of example applications using the two-layered concept as base. (A) Applications through a molecular-to-electromagnetic nanointerface. (A.1) Nanonetwork communicates with user device (bracelet, cell-phone), which can transfer information to a web server. (A.2) Nanonetwork communicates with local small server, which can be a information sink or a relay node to transfer information to a web server. (B) Application though a nanointerface that transforms DNA encoded information into pheromone signals. (B.1) Nanonetwork communicates with another nanonode of the same or different nanonetwork, which is meters away, through pheromone signalling, thus increasing the range of the nanonetwork. (B.2) Nanonetwork communicates with a small server, through pheromone signalling, which in turn can gather information, or react to the information received.

4.2 Information's encoding

In a communication system it is important for transmitted information within that system to use an appropriate encoding, known to the networks node that use it, in order for them to communicate with each other. In previous chapters several encoding techniques for encoding information in nanocommunications were described, and although each one have its features that can be appropriate for specific systems, the technique selected for this system was DNA encoding. This technique was selected due to promising results in researches studied, and it can offer high flexibility, allow a larger quantity of data to be encoded, and with these features the performance of the designed concept greatly benefits, as it will be described in next sections. This type of encoding can be used by some communication techniques, allowing the system to diversify in terms of the techniques it uses and the effective range of communication. Additionally, with this encoding technique the system can easily decode information into *ASCII* characters, allowing a external user to directly interact with it. This encoding process is possible by using the four bases used in DNA: *adenine*(A); *cytosine*(C); *guanine*(G) and *thymine*(T). These four DNA bases can form a base-4 encoding, which can be used in long sequences in DNA strands. There are different methods of DNA encoding, but researches shows promising results using a DNA hybridization [48], in which a DNA encoded molecule is double-stranded and it is composed of two polymers of nucleotides, with each nucleotide from one polymer bonded to one in the other forming a base pair (bp). Each nucleotide contains one of the four possible bases mentioned, and the base in one nucleotide determines the base in the paired nucleotide, in which the pairs are either AT or CG, as shown in Figure 4.6, where an example sequence is loaded into a carrier molecule. According to [49], each base pair can encode 2 bits, since each nucleotide has four possibilities and the paired nucleotide is determined by the first, and in [50] states that is possible to encode up to 1.6 mbp (mega base pairs), which, by doing the math, brings an approximate of 3.2 megabits per DNA molecule.

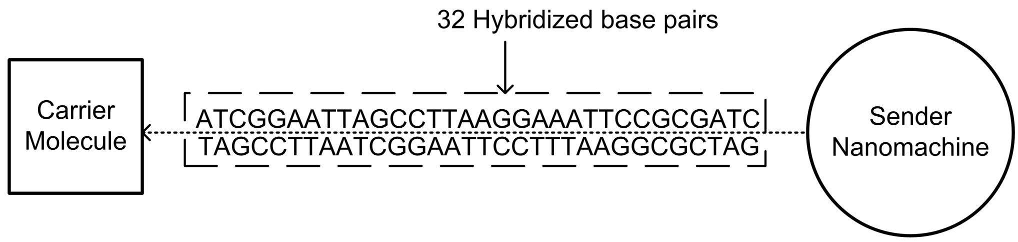


Figure 4.6: Example DNA sequence loaded into a carrier molecule. Each nucleotide has his base mirrored with the corresponding pair nucleotide.

This type of encoding can be used either with a bacteria based communication or using molecular motors, as described in the previous section. When using molecular motors the information is loaded into a carrier molecule, i.e., a vesicle, that will glide along the molecular rail until it reaches the destination. On the the other hand, when using bacteria based communication there are some features worth to mention, like the ability to load several plasmids, i.e., DNA encoded messages, into a single bacteria, which makes bacteria communication ideal to aggregate information from several sources, and transmit a larger quantity of data at a time. As mention in previous chapters, when using a bacteria communication, the information can be transferred from bacteria to bacteria or bacteria to receiver though a bacterial conjugation process. However, this process can be interrupted and the information in the new bacteria would be corrupted. To ensure only complete messages arrive at destination, the authors of [51] envisage a technique to remove this problem in the communication, in which targeted antibiotics are released into the environment removing bacteria. In order to only remove corrupted bacteria, the authors appended a antibiotic resistant gene to the encoded message. So if a complete bacterial conjugation takes places, the cloned bacteria will also inherit the resistant gene, so only defective bacteria will be removed with the antibiotics. In Figure 4.7 an example of a plasmid construction using this technique is illustrated, the other genes are common genes found in plasmids. Hence, with this technique an error detection mechanism is implemented into the system, and the number of defective bacteria arriving to the destination is reduced.

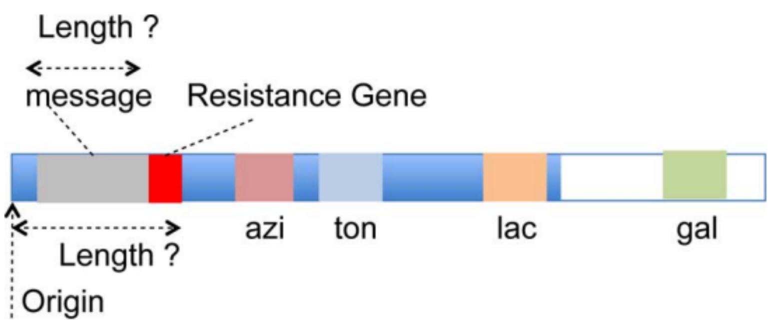


Figure 4.7: Example illustration of appending antibiotic resistant gene to the message in the construction of the plasmid that will be loaded into the bacteria. The genes present in this illustration are common genes that are present in plasmids. [51]

The packet envisioned for this system is very simple, containing three information blocks regarding destination and source, and one block for the information itself. There are three blocks for destination and source because it is required one block for the source and two for the destination, since one targets the destination nanogateway, and the other the destination nanomachine. The length, in base pairs, of each block is not rigid, since the total length for the message also depends on the type of molecules and plasmids the system uses, but a reasonable number would be 4 to 8 base pairs each to define the source and the destinations. The rest of the available length would be for the message, although this directly depends on the size of the network, as the number of nodes increases, the number of base pairs needed to identify source and destination would have to increase as well.

Considering that the message is encoded in a sequence of base pairs, and there are different blocks of information, it is important to differentiate them from other information in the plasmid. In order to achieve this communication requirement, a technique must be implemented in the system which manipulates different restriction enzymes. A restriction enzyme is an enzyme that recognizes a specific base pair sequence, and cuts the DNA in that specific site, the restriction site. These enzyme are commonly found in different bacteria, and they were created as a defense mechanism against invading viruses. There are several restriction enzymes discovered, and the sequences they react to, so when the sender nanomachine encodes the information, the sequences can be inserted between the information blocks in order to differentiate them. The only drawback is that the sequences and the enzymes to use must be integrated within the system, and cannot be changed on demand.

In this system concept two different restriction enzymes are used in order to wrap all blocks of information, as seen in Figure 4.8, in order to differentiate them from other information in the plasmid. The length of the sequence each enzyme reacts to, depends on the enzyme itself, so the selection of the enzymes had in mind the length they would require, choosing enzymes with short sequences. The picked enzymes are the *SmaI*, isolated from the *Serratia marcescens* bacteria, and the *HaeIII*, isolated from *Haemophilus aegyptius* bacteria. Both of these enzyme create a "blunt" cleave, i.e., the cut performed leaves the same amount of nucleotides in each side. In Figure 4.8 it is possible to see the base pairs sequences which these enzymes react to, and the "blunt" cleave they create. Although the use of two enzymes and length for addresses were defined in this example design, they are not a constraint in the design, so this architecture is open for other enzymes and address lengths to be used.

A gateway nanomachine after cleaving the message from the plasmid, can read the headers blocks in order to decide where to guide the message. Similarly with a multiplexing telecommunication system, the control sequences, in this case the sequences detected from the enzymes, can sometimes exist within the message, so the devices handling the messages need have well designed message processing procedures, in order to successfully transmit the messages. In this design the scope was

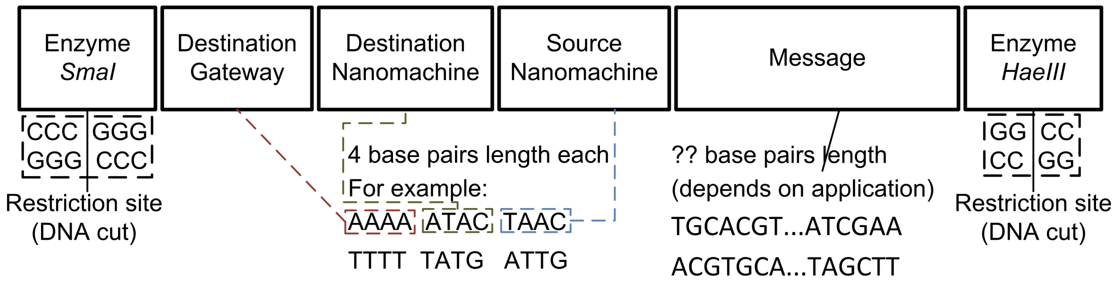


Figure 4.8: Example DNA packet encoded into the carrier plasmid.

not how gateway nanomachines will handle enzymes, but researchers studied the behaviour of these enzymes, and have used them in experimental scenarios, and the progress in DNA computing and nanotechnology will allow for complex nanogateways to be created, with capability for automated enzyme actuation, which will allow systems similar to the one presented to be a closer reality.

In this section a DNA encoding technique was described as well as the main incentives for selecting this approach. The process of how DNA encoding works was explained and some techniques for error and flow control were presented and discussed. A packet structure was presented and the reason for the information blocks that composed it was explained. After describing the communication techniques, the topology, and the information's encoding techniques that researches shows to be more promising and have the best synergy between them, it is important to specify how the information within the system can be routed to addresses locations.

4.3 Routing and addressing mechanisms

In a computer network the ability to address individual terminals and route the information in the network enables a more reliable and fast communications system. Several nodes can easily share information and participate in distributed tasks, achieving complex applications which would not be possible by a single terminal. These features are even more important to a nanonetwork than traditional computer networks. Although lot of the paradigms change from one to another, these features would allow nanonachines which, due to their small size and low complexity, cannot even achieve the performance of a single computer, to form a real nanonetwork which would place the research of nanocommunications a huge step forward.

Several researchers are focused on creating routing and addressing schemes and concepts, while others try to achieve implementation of basic mechanisms in simple nanonetworks. However, due to inherit challenges of this field, it is extremely difficult to obtain results. In the previous chapter various concepts for routing were described, which inspired the designing of the routing scheme applied in the system concept. Although molecular communication has several behaviors that pose as obstacles, when trying to establish a nanonetwortk, it also have features that can benefit the nanonetwork. An example of an inherit behavior that benefits a nanonetwork, in this case by proving a routing and addressing mechanism, is the use and manipulation of different bacteria and chemoattractants.

4.3.1 Addressing mechanisms

As described along this chapter, the envisioned concept uses a bacteria based communication to establish communication in the medium-range. So in order to address different nanogateways and route the information accordingly, the system controls different chemoattractants, while each nanogateway has the properties to create bacteria that will only react to a specific chemoattractant. These chemoattractants can be translated to a value address, for example if a nanogateway has the address AATC, the nanogateways that want to reach it will use bacteria that will react to the AATC chemoattractant. A translation table or a procedure which determines what type of bacteria to use in order to react to a specific address is needed. How nanogateways will achieve these functionalities is not the scope of this work, being the target of big research teams which focus in advancing nanotechnology and the manufacturing process. In Figure 4.9 it is possible to see a scenario where several nanogateways share information through bacteria and target different destinations using bacteria that will only react to the chemoattractants released by the targeted destination.

As mentioned in previous sections, the system design foresees two basic levels of communication, and while in the medium-range the information is routed and addressed through bacteria an their features, the short-range cannot use the same mechanism, so it was imperative to adopt another solution. As mention in previous sections the topology design has a big impact on this system, and while

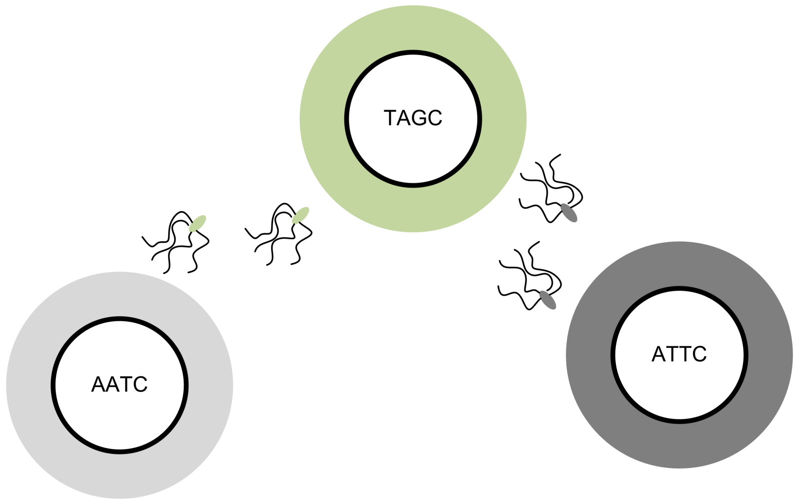


Figure 4.9: Illustration of communication between nanogateways using different chemoattractants.

describing a simple analogy to a real world system, it was mentioned the importance of geographical targeting. In this system concept the nanogateways can be compared with the base stations in a telecommunication system, while the simple nanomachines nodes can be compared with the cell-phones terminals. When the nanonetwork is deployed the nanomachines will proceed to look for a nanogateway, associating themselves with the first nanogateway they find. The nanogateway upon receiving a request from a nanomachine, will start a procedure in which it will designate an address for that nanomachine based on its own address, and answers the nanomachine with a message saying that acknowledged his request and containing the nanomachine address. The nanomachine will associate to the nanogateway which answer arrived first, which can mean that it is the closest nanogateway or the closest nanogateway which was able to attend his request, as illustrated in Figure 4.4. Several nanomachines can be associated with a single nanogateway, and when the nanogateway later on transmits information by diffusing molecules downwards, there will be molecules arriving at the wrong destination. When using this hybrid method of communication it is not possible to target a specific nanomachine, however the diffusion technique used will only affect a few nanomachines, which most likely are associated with that nanogateway. Nevertheless, the nanomachines will need to have a mechanism to discard packets which do not contain their address.

So far, two addressing schemes were mentioned, a chemoattractant based addressing in the medium-range that would enable to identify different nanogateways, and a short-range addressing scheme that enables nanomachines to have an unique address based on the address of the nanogateway they are associated with. Herewith, the destination address is composed of two blocks illustrated in the previous section, destination nanogateway plus the destination nanomachine. For example, a nanomachine with address TCTC can exist in several points of the network, as Figure 4.10(A,B) shows, but the nanomachine TCTC that is associated with the nanogateway AATC is unique, as seen in Figure 4.10(A). So messages that want to target that nanomachine are composed of the nanogateway address plus the nanomachine address, and these two block together can be objectively called the destination address, or destination nanomachine address.

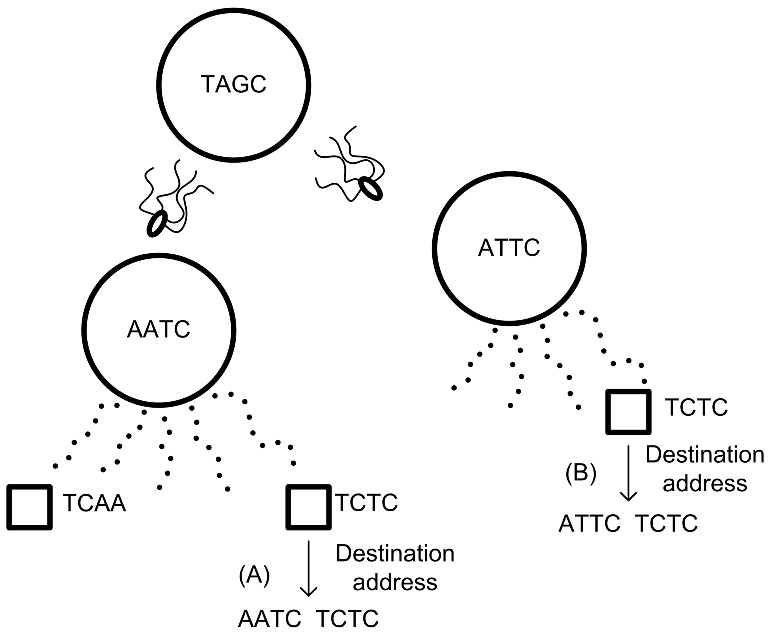


Figure 4.10: Illustration of destination addresses. (A) Correct destination nanomachine. (B) Example of a nanomachine with same address, but different destination address.

With these mechanisms it is possible to uniquely identify individual members of the nanonetwork, and this features provide the system the capability to route information within the network from a source to a destination. However, routing mechanism must be designed and implemented in the nanonetwork in order for it to actually be able to route messages in the nanonetwork.

4.3.2 Routing mechanisms

In this concept it is considered that nanogateways have capabilities to store information, like a translation table mentioned in the previous section, or a routing table that will be generated. The envisioned mechanism that would allow a routing table to be formed considers that all nanogateways have the same specific neutral chemoattractant, besides the individual chemoattractant, which can allow them to broadcast in the environment, similar to a broadcast address in computer networks.

When the nanonetwork is deployed the nanogateways will broadcast to the environment, using the neutral chemoattractant sensitive bacteria, their address, which is a value that translates to a specific chemoattractant. The neighboring nanogateways upon receiving that information will update their routing tables, and broadcast their routing table information. Consequently, the neighboring nanogateways will receive the routing table, and update their own, and proceed to re-broadcast their routing table. This process will go on, until a nanogateway receives a routing table from a neighbor and it realizes that no new information was given, so an update of its routing table is not needed, and he will not broadcast his routing table. This process is similar to a process used in ad-hoc networks, because the network nanogateways will form is objectively an ad-hoc network. This process is illustrated in Figure 4.11, in which the routing tables are shared with neighboring nodes, and those nodes updates their tables. After step (2.) the routing tables would remain unaltered since all possible targets were in all routing tables, although the nodes would still share their routing tables on that iteration.

After this process is completed the nanogateways will know how to reach any other nanogateway in the nanonetwork by using other nanogetways as bridges. When a nanogateway receives a message and processes it, it will read the destination nanogateway, if the address is his own, the message its diffused downwards to his associated nanomachines, otherwise it will check its routing table, look for that destination address and determine to which gateway it has to transfer the message. Once it knows where the message needs to be transferred next, it will determine what type of bacteria i needs to use, by querying the translation table, encode the message in the bacteria, and transmit the bacteria (Figure 4.12 (A)). This process continues until the message reaches the destination gateway, which

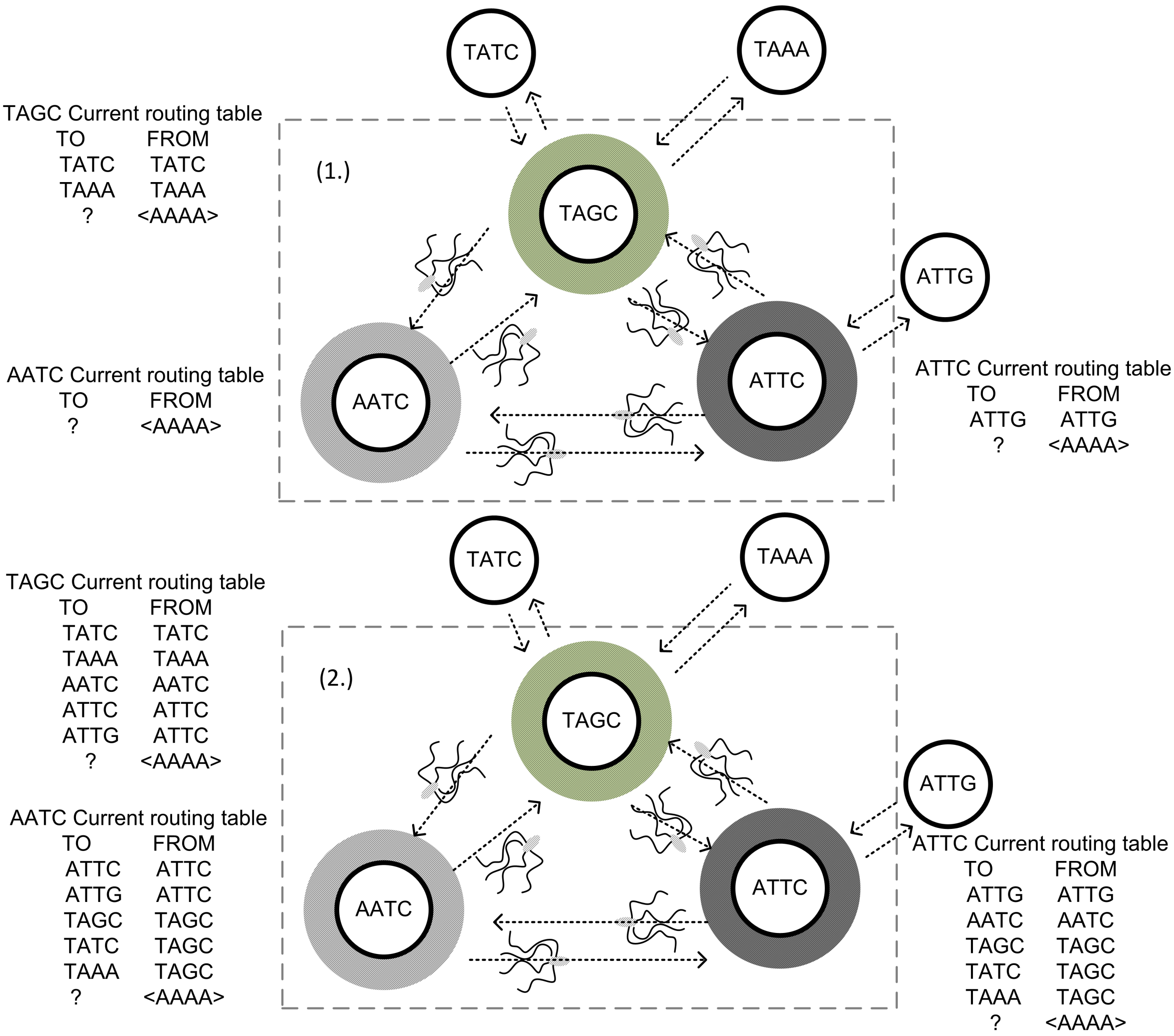


Figure 4.11: Routing tables generation mechanism in two steps. The black lines in the chemoattractant fields represent the neutral chemoattractant common to every node. In (2.) the updated routing tables are presented after (1.) is completed.

transfer the message to the associated nanomachines (Figure 4.12 (B)), however the message will reach all nanomachines he can reach, and when using a diffusion process is not possible to exactly target a specific nanomachine. So the nanomachines, upon receiving a message, will read the nanomachine address, if it does not belong to it, the message is immediately discarded (Figure 4.12 (C)), otherwise it continues to read the message (Figure 4.12 (D)). These procedures that enable the routing of information are illustrated in the Figure 4.12, where an example scenario is presented.

In this chapter the techniques designed to enable addressing and routing in the nanosystem created are described. Firstly, the addressing mechanism in the medium-

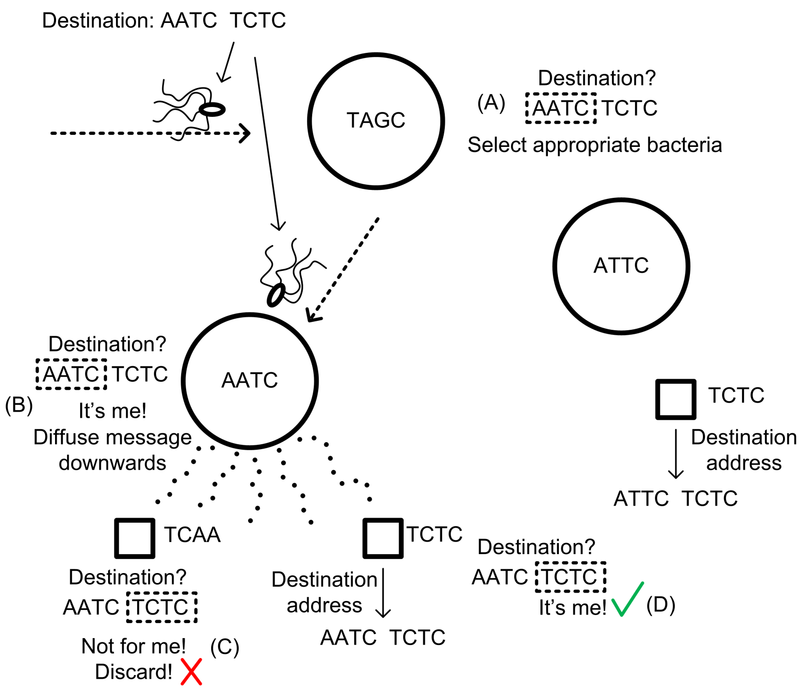


Figure 4.12: Example illustration of a message reaching a destination. The procedures presented are the main components that enable the routing of messages. (A) Nanogateways route the information until it reaches destination nanogateway. (B) Message arrives at destination nanogateway, it reacts to it and diffuses the message downwards to his associated nanomachines. (C) Message reaches a nanomachine which is not the destination, so the message is discarded. (D) Message reaches the final and correct destination nanomachine.

range layer is described, and how it uses the inherit functionalities from bacteria to establish an addressing scheme based on chemoattractants. An original twist to a known feature of other system is described and how it can provide the capability for the existence of an addressing mechanism for the short-range. This technique is fully described and shown how it would work in an illustrated scenario.

After explaining how the system would create unique addresses for all components of the network, some routing mechanisms were introduced which would enable a nanonode to reach any other nanonode within the nanonetwork. A technique for the generation of routing tables was described, and how mechanisms from other systems can be used, by being adapted first, in a nanocommunications scenario. Finally, an illustration of one example scenario, in which a message is routed though the nanonetwork until it reaches the destination nanomachine, is presented and explained.

4.4 Conclusions

In this chapter a solution for a molecular nanonetwork system, which provides the capabilities necessary for a working application, is designed and explained. Firstly, the communications techniques selected for this system are described, and the reasons for their selection. The ideal topology which would benefit the most this system is designed, and a few mechanisms are described which will improve the overall efficiency of the designed system.

The DNA information's encoding functionalities, which is used in this system, are described and mechanisms for this encoding method are introduced, like error and flow control. A mechanism designed in a different research and a new concept in the nanonetwork scenario are integrated in this system in order to increase the stability and reliability of the system. In this section, a packet of information is designed and each block of information is described, explaining the objective of each information block.

Finally, the key features that make this system function, addressing and routing mechanisms, are presented. In this section several concepts are introduced to nanonetworking and some techniques are modified in order to achieve the required capabilities to allow the information routing. This section is very important to understand the synergy between all elements of the designed system, since they all come together and individually provide features that allow the envisioned mechanisms to function.

The solutions presented to resolve the challenges on addressing and routing in nanonetworks, originally modify and integrate several mechanisms from other systems in a nanonetworking scenario, which also transmits an important message. Even though this is a new field of research, and researches from all over the world are trying to conceive new techniques which can allow nanonetworks to be closer to the reality, there are several mechanisms already implemented on other fields which, when modified correctly can be integrated in a nanonetworking scenario.

Although the presented concept might not be the most optimal approach, it provides the capability to reliably transmit information from the nano-scale to, possibly, the macro-scale, provide error and flow control mechanisms and address and route information in a nanonetwork. In the early stages of research of a recent field, achieving stable functionality is the first step. Later on, the research will focus on optimizing and increasing the efficiency of existing systems. However, systems or concepts like this are the most important, since they are the foundation for experimental work to begin, allowing validation of new concepts and techniques, which in turn will advance all other aspects of nanonetworking.

Chapter 5

Architecture Analysis

In the previous chapter the system architecture was fully described, explaining all the features and new envisioned concepts used in the system. However, the architecture needs to be objectively analysed in order to better understand how does it operate, and provide validation of the concepts applied, thus, a further look into the functionality of those mechanisms will be presented on this chapter. Firstly, the message exchange and some of the nanonetwork components behaviours will be described and illustrated, and then some insights will be displayed regarding the validation of the described architecture.

The first section will present different flowcharts and sequence diagrams which represent the different operation performed within the network, such as configuring and message transferring. This section provides the means to better understand how the system can achieve several features mentioned in the last chapter. Additionally, in the second section of this chapter some demonstration are shown regarding the validation of the system. Although initially, a system validation through simulation was intended, several obstacles didn't allowed that validation to occur, however by recurring to other processes the system's validation is described and discussed.

5.1 System's mechanisms procedures

When analysing a system architecture is important to fully understand its features, so this section presents different diagrams that help to explain how messages are transferred and the mechanisms that allow the nanonetwork to configure addresses.

Having a better knowledge of how these mechanisms work improves the perception of the autonomous characteristics this system architecture can provide. In a system of this nature, being able to automatically perform several tasks, not requiring external interactions is really important due to integrability tendency of future applications.

The previous chapter presents a brief description of how the nanomachines would obtain their address. Although the process was explained, there were some details in this mechanism that needed to be displayed. The process itself is an autonomous process, since it is initiated by the nanomachine itself after the deployment procedure. After the nodes are deployed the nanomachines will look for a nanogateway which they can associated with, in order to obtain an address and enter the nanonetwork.

In the diagram illustrated in Figure 5.1, the messages traded between nanomachines and nanogateways in order to associate them are displayed. Observing the diagram it is possible to see that is not a very complicated mechanism. When a nanogateway receives a association request it will process the request, by determining an address that it is able to attribute to that nanomachine, and will reply with the result. Upon receiving the reply, the nanomachine will set his address according to the reply it receives.

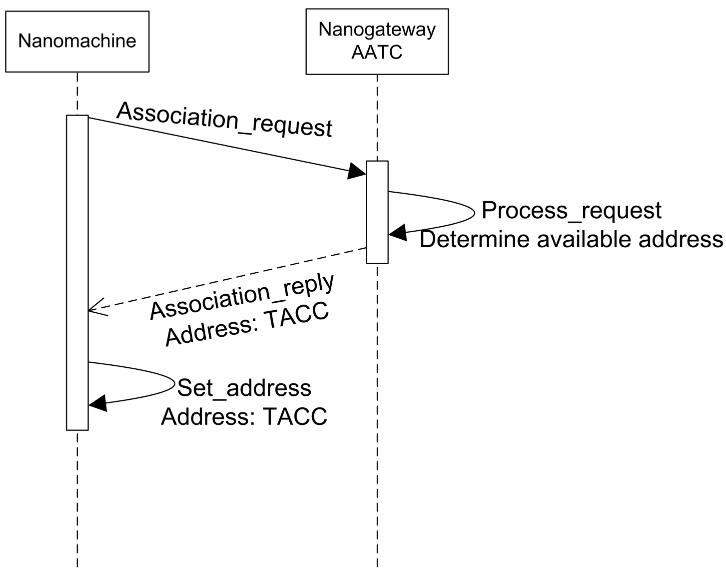


Figure 5.1: Attribution mechanism of Nanomachine's address sequence diagram.

However, it is possible that the nanomachine reaches several nanogateways when diffusing a request in the environment. In order to allow a nanomachine to only be associated with one nanogateway, some control mechanisms have also to be integrated. Assuming the first reply, the nanomachine received is the best offer, for various reasons, like proximity and availability, it is the address that will be set. Meanwhile, if the nanomachine receives another reply, it will discard the message and reply that nanogateway, with a request withdraw. This mechanism and the other mentioned above can be seen in the flowchart diagram illustrated in Figure 5.2.

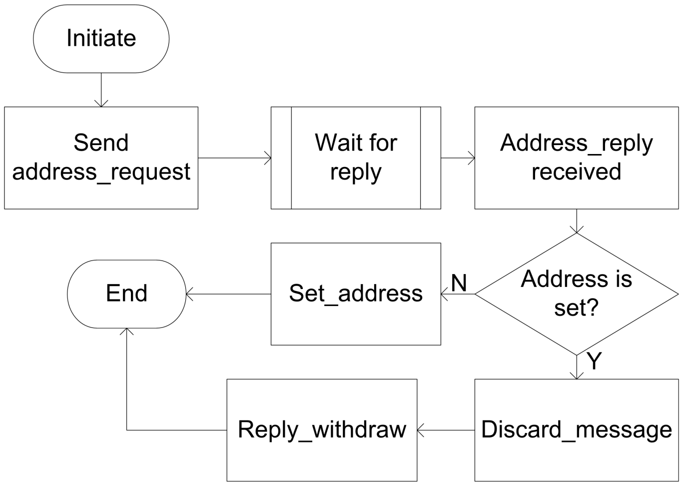


Figure 5.2: Nanomachine's behaviour when looking for an address flowchart diagram.

Another aspect mentioned in the previous chapter with some detail, was how the nanogateways discover the nanonetwork and generate routing tables. However, it is important to represent that mechanism in a standardized way in order for easy understanding. In Figure 5.3 it is illustrated a sequence diagram between a nanogateway and two neighbor nanogateways. The nanogateway reaches its neighbor nanogateways with its routing table, upon reception these nanogateways will verify if there are new nanogateways addresses being advertised and, if there is, they will update their routing tables. Every time a nanogateway updates its routing table, it has to advertise the new routing table to his neighbors, so in this scenario the two neighbors update their tables and advertise them to the initial nanogateway. This nanogateway will update its routing table, and advertises its routing table again, but this time the neighbors see that there are no new entries, so they do not reply. This internal procedure nanogateways execute when receiving a routing table advertisement can be better understood by observing the flowchart in Figure 5.4.

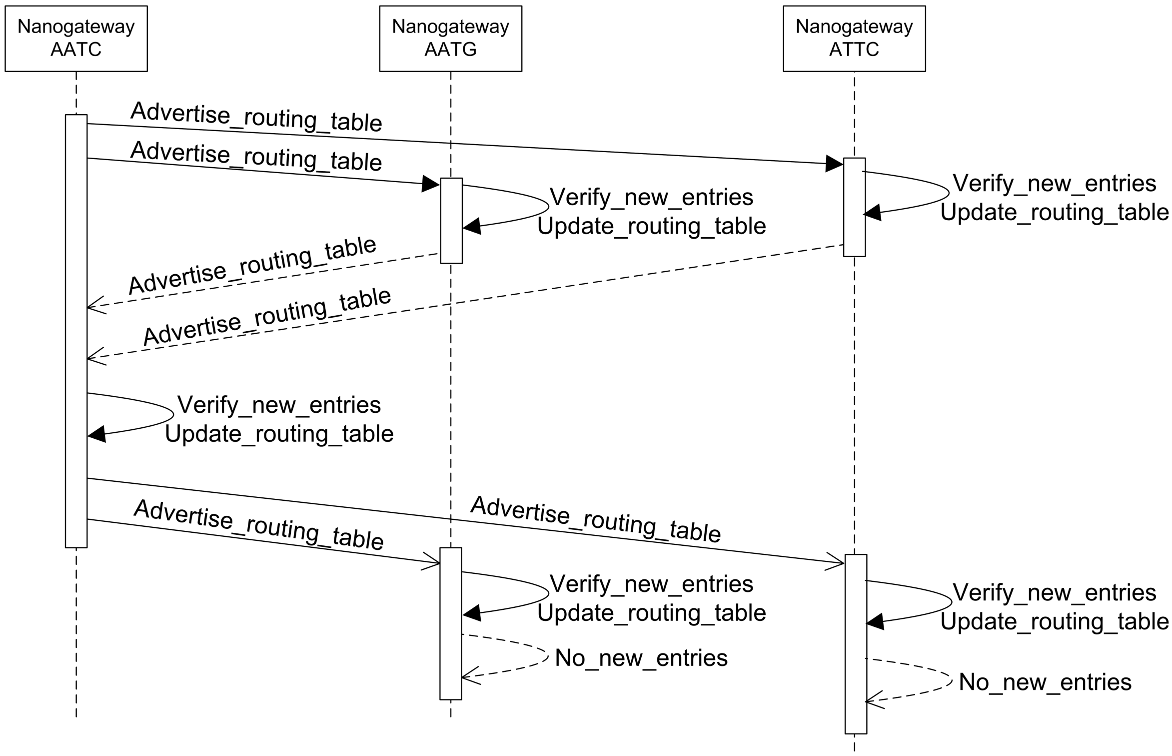


Figure 5.3: Routing table generation between three nanogateways sequence diagram.

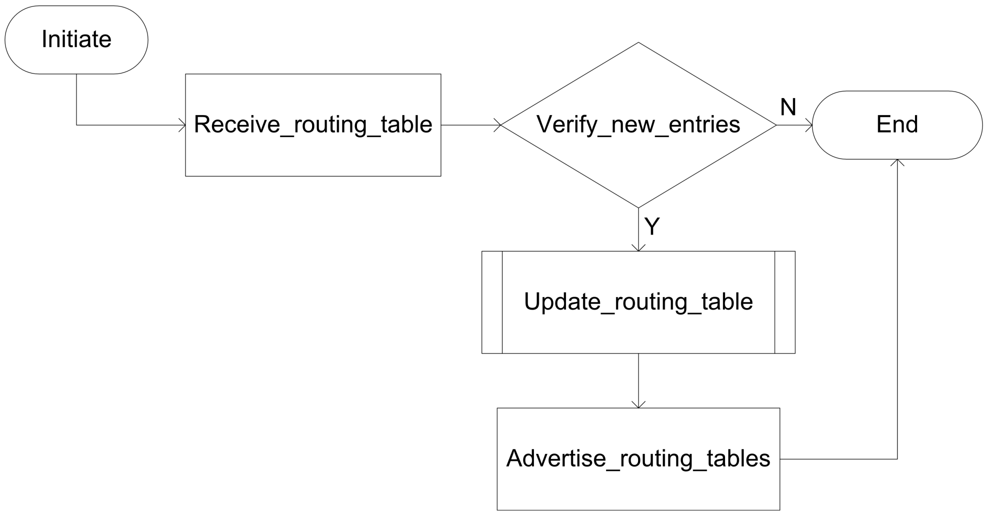


Figure 5.4: Nanogateway's procedure when receiving routing table advertisements flowchart diagram.

In any network it is important to understand how a message can leave the source and arrive at the destination in every step of the way. In order to better understand how the envisioned system routes a message safely to the final destination by using the created features integrated in the nanonetwork, an example scenario was created. In the sequence diagram illustrated in Figure 5.5, it is possible to see the routing steps performed for a message to be transmitted from the source nanomachine to the destination nanomachine, which can be a nanointerface, for instance.

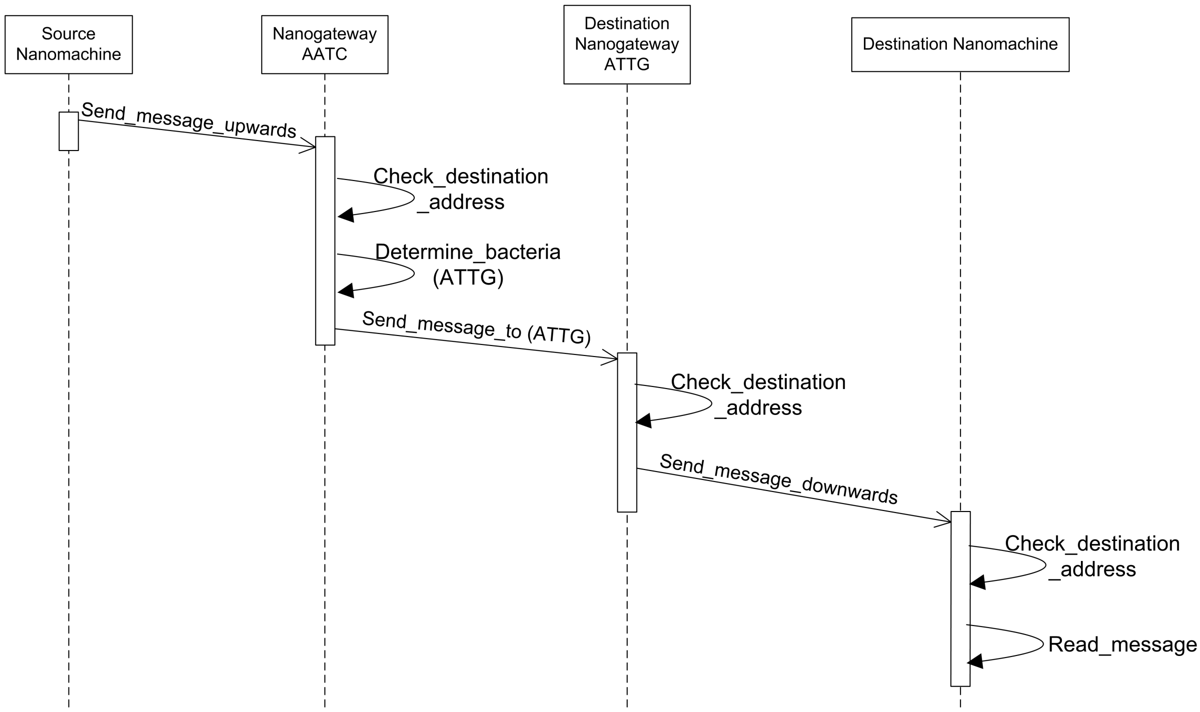


Figure 5.5: Routing mechanism for a message to reach the destination sequence diagram.

One aspect that can be easily seen is that the nanogateways always check the destination address not only to determine to which nanogateway they need to pass the message but to verify if the message is for them. In the sequence diagram both options are illustrated, and it is possible to see that if the message is not for them, they will execute a set of processes in order to route the message to an appropriate nanogateway that will eventually be able to reach the final destination. When the final nanogateway is reached and it determines the address and acknowledges the message belongs to it, by default it will diffuse the message downwards in order to reach the destination nanomachine. These processes executed in the nanogateways can be seen in the illustrated flowchart in Figure 5.6.

In this section the envisioned mechanisms for this system were explained with more detail than in the previous chapter, resorting to sequence and flowchart diagrams. These mechanisms provide the nanonetwork with addressing and routing capabilities, which are imperative features to achieve in this systems. In the next section a few insights regarding the system validation will be displayed, in order to

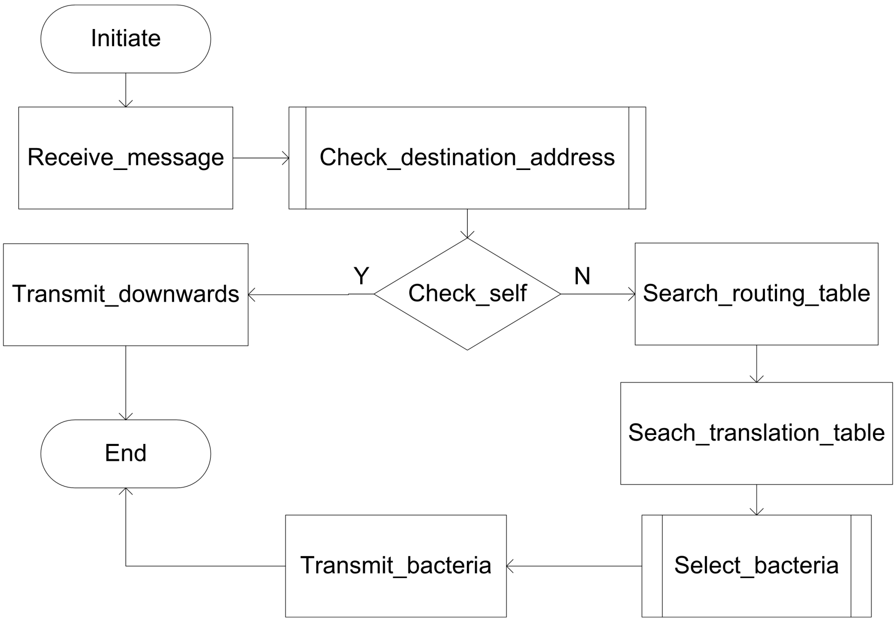


Figure 5.6: Processes executed by nanogateways to route messages within the nanonetwork flowchart diagram.

support other mechanisms conceived in this system.

5.2 Architecture evaluation

After envisioning and designing a system, a validation process must occur afterwards in order to gather data that can move the project to a implementation state. As mention in the previous chapters, this is a new field of research and the simulation framework tools developed by the community are still very limited. In order to obtain experimental results of an original system, these tools need to support several features, which they don't. Thus, the existing tools need to be developed further and modified to achieve the required features that allow these envisioned systems to quickly be tested and validated.

Having that in mind, one of the most promising framework tool, was selected to be expanded in order to create a simulation tool which could evaluate routing mechanisms. As it is described in the next chapter, this framework was studied and modified, and several simulation scenarios were ran in order to better evaluate the tool, and validate some concepts. However, due to resources limitation a full development of the expansion for this tool was not achieved. Hence, to validate part of the mechanisms integrated in this concept system, another approach had to be followed.

In the analysis of some researches, it was noted that some simulation results the authors present can actually be applied in the envisioned system. These researches are conducted in larger teams which perform analytical simulations with complex calculations, which could not be achieved with the resources available for this project. Although there are some features that cannot be evaluated as easily, like routing and addressing mechanisms, since they require specific framework tools to be developed, other envisioned concepts of this system can be evaluated and validated.

In previous chapters it was mentioned the importance of directional diffusing, or the influence of the releasing point in a communication through diffusion. To address this challenge in molecular communication, a new concept was envisioned that uses a mono-monostatic body in the nanomachines, as described in the previous chapter. With this concept idea, the nanomachines are forced to assume a position, and with that knowledge is possible to pre-determine the releasing point on the nanomachines. With this feature is possible to achieve a smaller angle between the destination and the releasing point of the source, which in turn increases the efficiency of the transmission. This can be seen in the simulation results of [27], where the authors test the impact this angle has on the transmission. In Figure 5.7, it is possible to see the influence the angle has on the accuracy of the diffusion process, which translates into the probability of the diffused molecules to reach the destination.

When observing the Figure 5.7, it can easily be seen that the decay of accuracy is very small until the angle reaches thirty degrees, which is the maximum angle expected in the system envisioned. Additionally, in Figure 5.8, where it is illustrated the impact the angle has on delay, it is possible to see that delay assumes its minimum values until the angle reaches thirty degrees.

In both Figures (5.7 and 5.8), two different lines are illustrated that represent different distances between the source and the destination. With no surprise, the shortest distance obtains the best results for the optimal angles, but as the angle gets bigger the differences between the lines become undistinguishable. With these re-

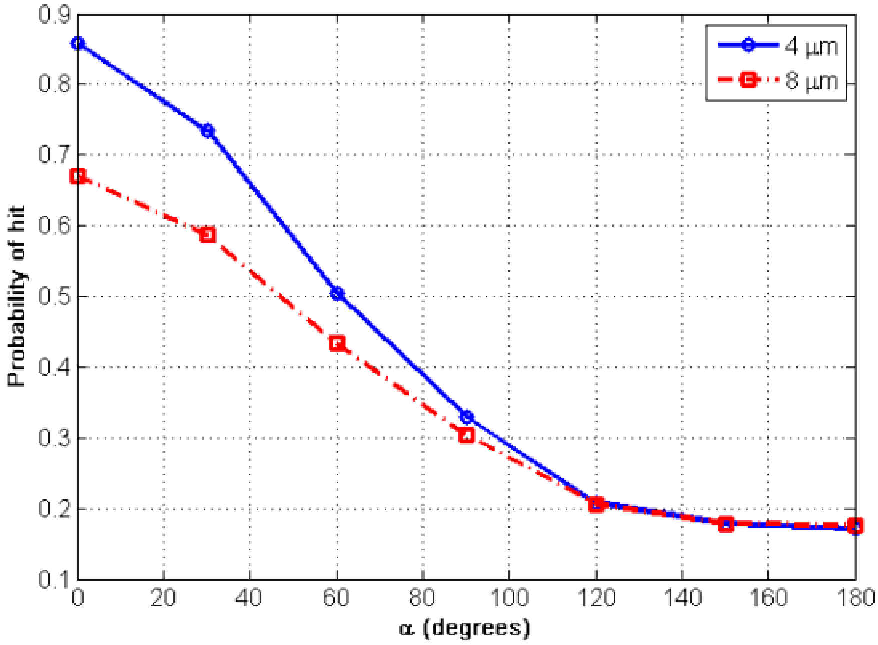


Figure 5.7: Influence of the angle on the probability of hit. [27]

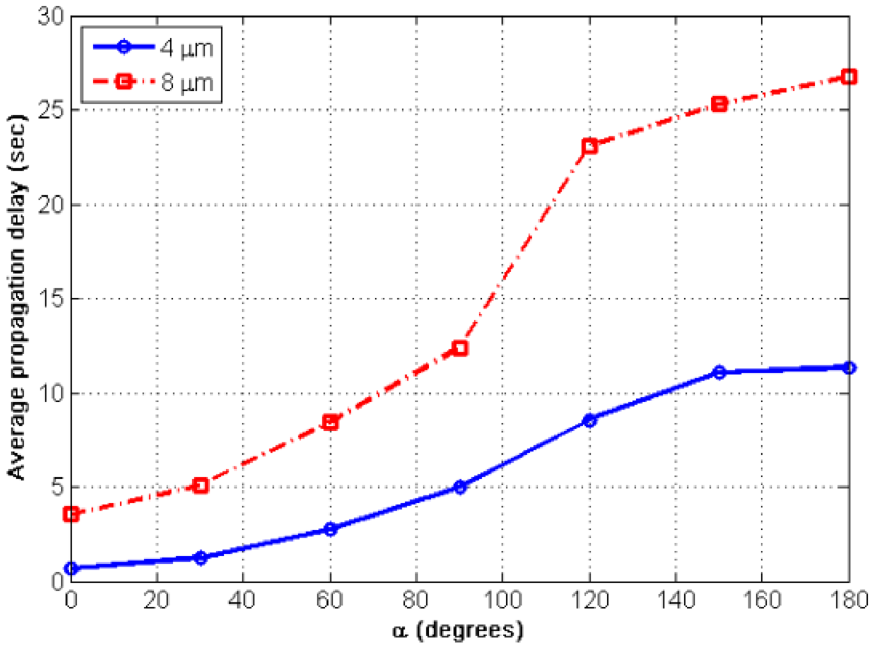


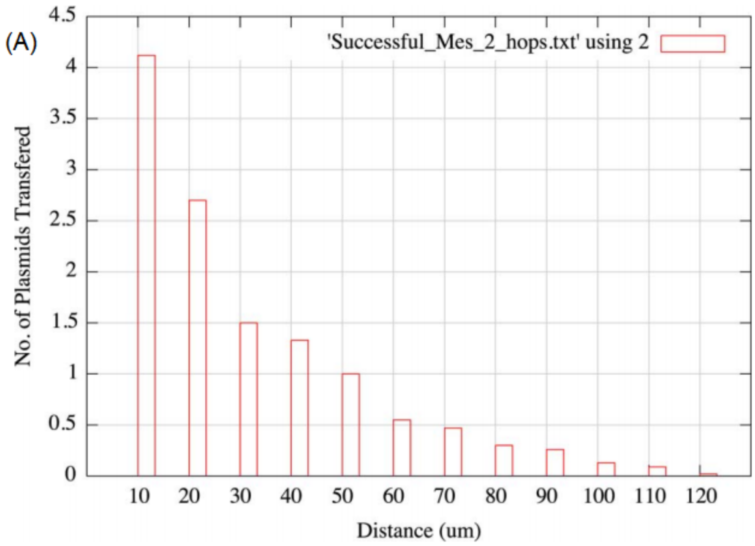
Figure 5.8: Impact of the angle on the delay. [27]

sults it is possible to see the importance of the angle between source and destination when using diffusion, and it is clear that the selection of an appropriate releasing point has a significant effect on the transmission performance. The mechanism envisioned to address this challenge can help nanomachines achieve optimal angles for the transmission, since the communication is always done through a pre-determined release point, and the ideal topology for this system has that feature in mind.

Having evaluated one of the short-range communication mechanisms implemented in the system it is important to also evaluate the medium-range communication, in order to achieve an overall assessment of the system. As described in the previous chapter, the communication in the medium-range, i.e., the communication between the nanogateways, is established through bacteria. The bacteria will be routed from nanogateway to nanogateway, until it reaches the destination, thus creating a multi-hop system. In [51] an in depth study of multi-hop systems using bacteria is presented, supported with several simulation results. In order to evaluate some mechanisms used in the medium-range of this system, a comparison was established with the simulation results obtained by the author of [51].

The author presents a very interesting result, which is important to mention since it shows behaviours that happen on the conceived system. In Figure 5.9(A) it is possible to see the number of plasmid, i.e., DNA encoded messages, that reach the destination in a single-hop communication, as the distance between the nodes varies. As expected, the observed behaviour represents a negative exponential curve as distance increases, however, when observing the Figure 5.9(B), it is possible to compare single-hop and multi-hop communication results. One important aspect that can be noticed, is that the average number of successful messages reaching the destination is increased when using a multi-hop communication. On the other hand, the delay of receiving the first message is increased, due to the slow conjugation processes.

Although there is a delay on message delivery when using a multi-hop bacteria communication technique, and the delay increases exponentially with the number of hops the message has to do to reach the destination, it is important to understand that the reliability of the transmission is being increased. In most molecular communication techniques, the unreliability of the transmission opposes a great challenge when developing nanonetworks for future applications, so a compromise must be made in this stage of the development. It is preferable to achieve a slower but functionable system than not even achieving functionability. Even though the slower characteristic of these systems can be seen as an obstruction for some applications, there are still several applications that can operate on a *Delay-tolerant Network*



(B)

Type	Mean No. of Messages	STD	Mean Time of 1st Message Arrival (s)	STD
Single	0.02	0.14	299.96	2557.91
Multi	0.21	0.41	34621.5	86246.8

Figure 5.9: (A)Distribution of successful messages arriving at destination with respect to varying the distance for single-hop. (B)Comparison of single-hop and multi-hop. Adapted from [51].

(DTN), or in this case a *Delay-tolerant Nanonetwork*.

In the architecture described, the nanogateways deployed in the medium-range will be scattered around the environment forming a random topology. Although the efficiency of this topology can be questionable, and is conceivable that a random deployment could not be the best approach, simulation results show otherwise. The author of [51] provides simulation results comparing different topologies, in which it is possible to discuss the message delivery success rate through the combined process of chemotaxis and conjugation for bacteria nanonetworks with multiple source-destination nodes. The topologies analyzed by the author that are relevant in the analysis of this architecture are the grid and random topologies, and the comparisons between them. As the name suggest, in the grid topology the nodes are positioned in a grid equally distanced from each other, while on a random topology the node position does not follow any rule. The Figure 5.10 presents the plasmid, i.e., DNA encoded message, arrival time for each topology, additionally, the blue stars indicate that a conjugation process occurred and the pink stars represent the bacteria killed by antibiotics, which is an error control measure.

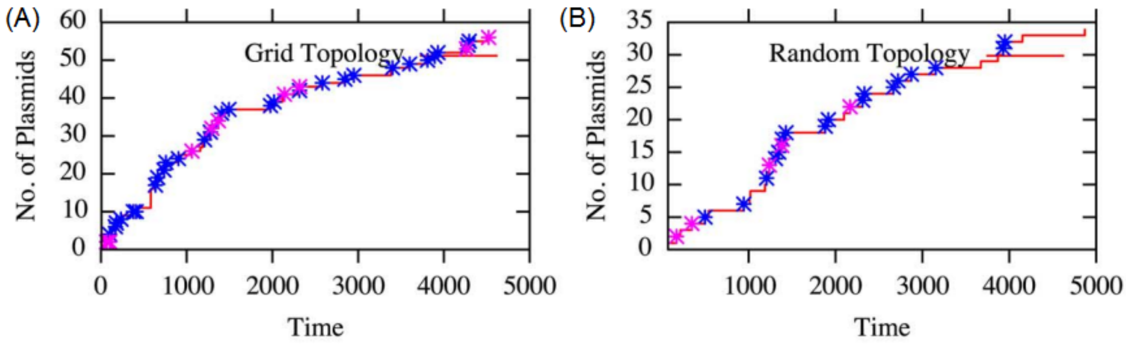


Figure 5.10: (A)Number of messages with respect to time for the grid topology. (B)Number of messages with respect to time for the random topology. Adapted from [51].

Observing these results, it is possible to see that the grid topology shows a higher number of conjugation processes, reflection from the high connectivity of the topology. Although the random topology shows a lower number of received messages by the end of the simulation, it is important to see that in the first 1500s the number of received message was very close, in spite of the lower number of backup paths when comparing with the grid topology. Even though the random topology is limited in pathway options, it can offer a feasible solution, without additional implementation challenges.

In the paper the author presents two more simulation results in which it is possible to compare the two topologies. In Figure 5.11 it is displayed the results on the successful messages reaching the destination with the variation of bacteria/chemoattractant links. It is possible to see that the number linearly increases and the number of bacteria/chemoattractant link is increased, for both cases. However, the grid topology can achieve the best results, and in the last scenario, i.e., 10 bacteria per link, the grid topology can achieve the double when comparing with the random topology. Although the results seem to favour the grid topology, it is important to remember that these results are a direct reflection of the number of connections of the topology, and does not directly translate into a better efficiency.

This connectivity of the topologies also affects the rate of conjugation that occurs, and it is possible to see in Figure 5.12 that the grid topology has a numerical lead over the random topology. Numerically analysing these figure it is possible to achieve a conclusion that the grid topology is better, as it should be. The obser-

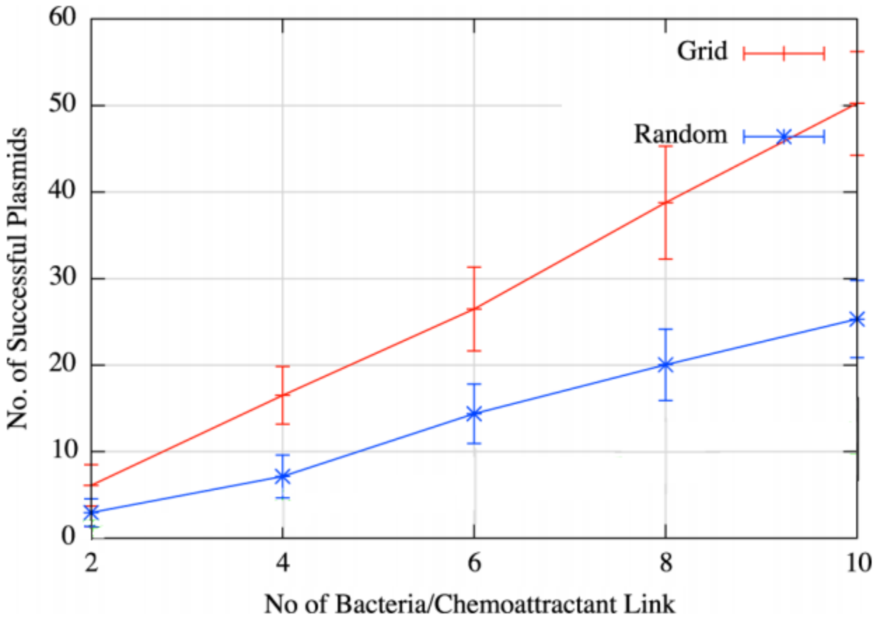


Figure 5.11: Number of successful messages with variation of the number of bacteria/chemoattractant link. Adapted from [51].

vation must be made from a point of view where the objective is to analyse how much worst is a random topology when comparing to a grid topology. Surprisingly, the random topology can perform with reasonable performance, and although it is mathematically worst than the grid topology, the question that remains is if these differences will actually be relevant in an application.

So even though, at first sight, the random topology seems less effective, the actual losses do not seem relevant when comparing with the challenges provided by organized deployment of nanonetworks. A random topology can provide the required means for a nanonetwork to operate, and the additional computational complexity required to produce self-organized nanonetworks might not be justifiable. In other words, the concept topology designed and described in the previous chapter not only can be easily achievable without requiring additional deployment challenges to be resolved, but the simulation results show that it can perform adequately, providing the requirements for a nanonetwork to fully operate.

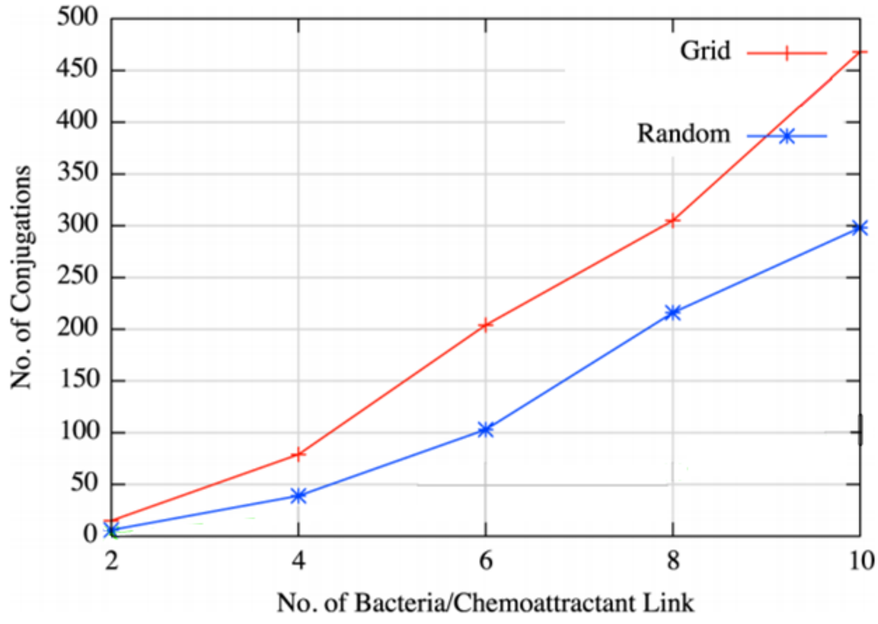


Figure 5.12: Number of conjugations with variation of the number of bacteria/chemoattractant link. Adapted from [51].

5.3 Preliminary results

In the development of this dissertation some preliminary simulations were performed, as a preparatory step, in order to better understand molecular nanocommunications and also research developed simulation solutions. In chapter 3 of this document a state of the art on simulation tools is given in which several tools are described, and one of those tools stood out, seeming a promising tool. In order to evaluate this simulation framework and, at the same time, create specific scenarios that would help to better understand and validate some concepts, several simulations were performed.

In previous chapters the molecular diffusion technique is often described as unreliable, unpredictable and not very efficient. This technique is influenced by environment parameters, like temperature and viscosity and suffers immensely from the randomness of the diffusion motion, the Brownian motion. Although several researches mention these aspects, few were the ones that showed simulation results validating the statements and there weren't any studies on molecule loss rate.

In order to investigate this technique, achieve conclusions on what parameters really affect the transmission, and what aspects of the nanonetwork could be improved, that would allow the efficiency of the transmission to increase, a simulation framework that suited the needs had to be found. The simulation tool described in chapter 3 by the name of *NanoNS* was the tool that better fitted the requirements, and Özgür Barış Akan, one of the authors, was kind enough to share the tool so these simulation could be performed. This tool was developed as an expansion to the commonly used Network Simulator 2 (NS-2), which benefits this tool in several ways. Since it was created as group of modules that use the NS-2 functionalities, the modules were developed in C++ and object-Tcl (OTcl), in contrast with other similar solution which do not interact with NS-2. Another important aspect of this tool is that it follows a diffusion model based on molecular reactions instead of concentration. This his helpful to achieve the goal of evaluating the loss rate in molecular diffusion because in a concentration based encoding the molecule loss rate is not as important.

In the next section several simulation scenarios will be presented and described, as well as the simulation results obtained from each one. On all simulation scenarios created the environment parameters were maintained in order to achieve fair and comparable results. In [52] a study was conducted which explored the optimal environmental parameters for a diffusion communication, so in the scenarios simulated the environmental parameters were set to be as close to the values mentioned in [52] as possible.

5.3.1 Simulation results

Besides the environmental variables being fixed through out all simulations, other parameter that needed to be fixed in order for molecule loss rate between scenarios be comparable, was the amount of molecules diffused by the sender. On all simulations this amount was set at one thousand molecules sent from the transmitter.

The first simulation scenario presented in this section is the baseline scenario created, in which all other scenarios can be compared. In this simple scenario a transmission between two nanomachines was configured, in which the distance between them is 100nm and they are located in a three dimensional environment. The Figure 5.13 shows the results obtained from this simulation and it is possible to see that the molecules that reach the receiver quickly scale up, but after 0.1 seconds the number of molecules received stabilizes and keeps more or less constant until the simulation time is depleted. However, it is possible to see that the number of molecules received doesn't even reach 120, having in mind that 1000 molecules were transmitted, a surprising result of a loss rate 88% is achieved. The expected results weren't very promising, but the results obtained suprisingely demonstrate how this communication technique is unreliable.

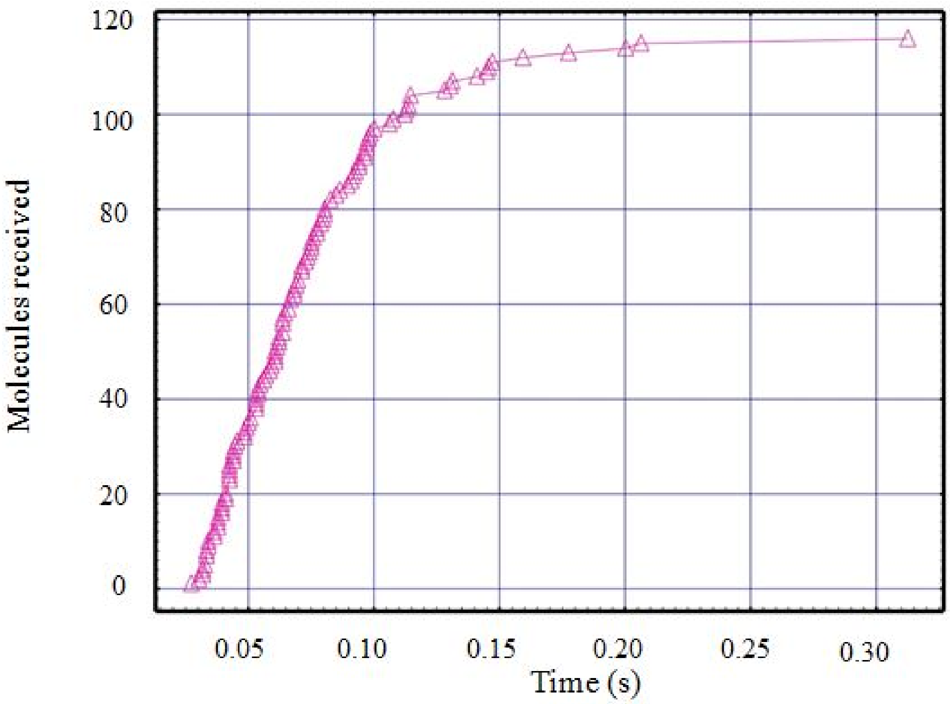


Figure 5.13: Baseline simulation result, molecules received measured as a function of time.

In the first scenario the molecular reaction were represented by direct hit on the receiver nanomachine, so by applying a stochastic equation to calculate a statistical reaction of molecules, like the Gillespie algorithm, another simulation scenario was created. In this simulation scenario is possible to see the impact receptor affinity, described in chapter 3, has in molecule reception. In Figure 5.14 it is possible to see that more molecules were received when comparing with the baseline scenario. Although there is only a slight increase, that is explained by the distance between nanomachines, since the distance from the baseline scenario was kept, the randomness factor of diffusion still is the most prominent element in the transmission. Comparing this scenario with the baseline, the differences in overall behaviour are very slim, however it can be observed an increase in molecules received and thus a decrease in loss rate, being around 86%.

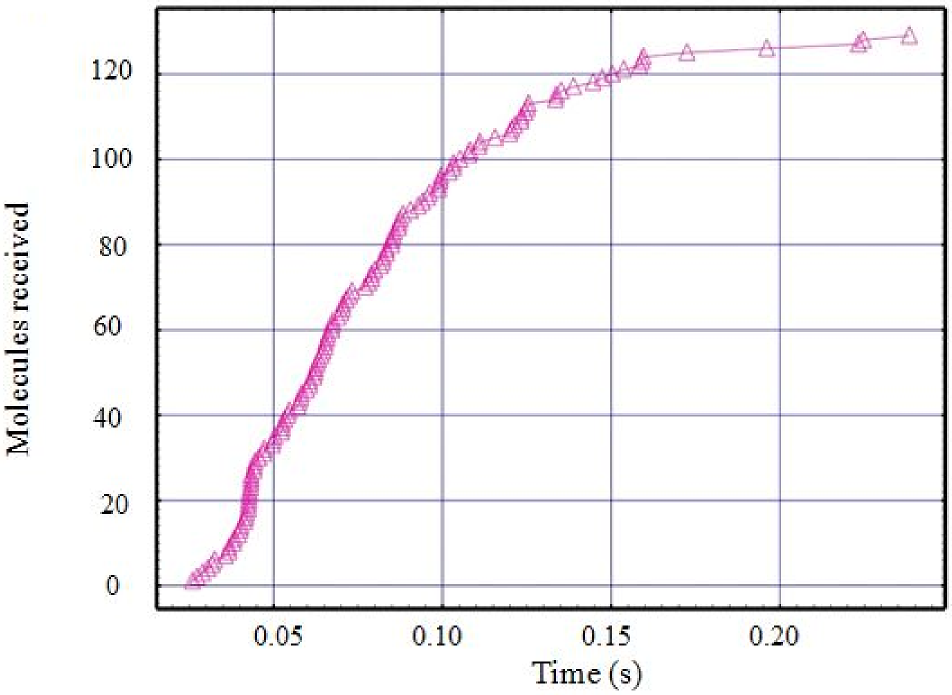


Figure 5.14: Gillespie algorithm simulation result, impact of receptor affinity, molecules received measured as a function of time.

It was already described in previous chapters the influence distance between nodes has in a diffusion based transmission. In this next scenario the distance between the two nanomachines was reduced by 70%, in order to evaluate the impact this parameter has in the transmission loss rate. Since the distance was reduced by 70% it was expected a dramatically decrease of loss rate, however the simulation results show that although the loss rate decreased, it wasn't a substantial decrease as expected, as shown in Figure 5.15. It is possible to see in the Figure 5.15 that the loss rate reached around 74%, although when comparing with previous scenarios it is possible to see that about one hundred more molecules were received.

The simulation scenarios described so far use equally sized nanomachines, and as described in previous chapters, the increased surface perimeter of nanomachines can increase the receiving efficiency of the nanomachines. In order to evaluate this feature a simulation scenario was created in which the radius of the receiving nanomachine was increased by 50%, in order to maximize the gathering capabilities of the receiver. The Figure 5.16 shows the simulation results of this scenario, and

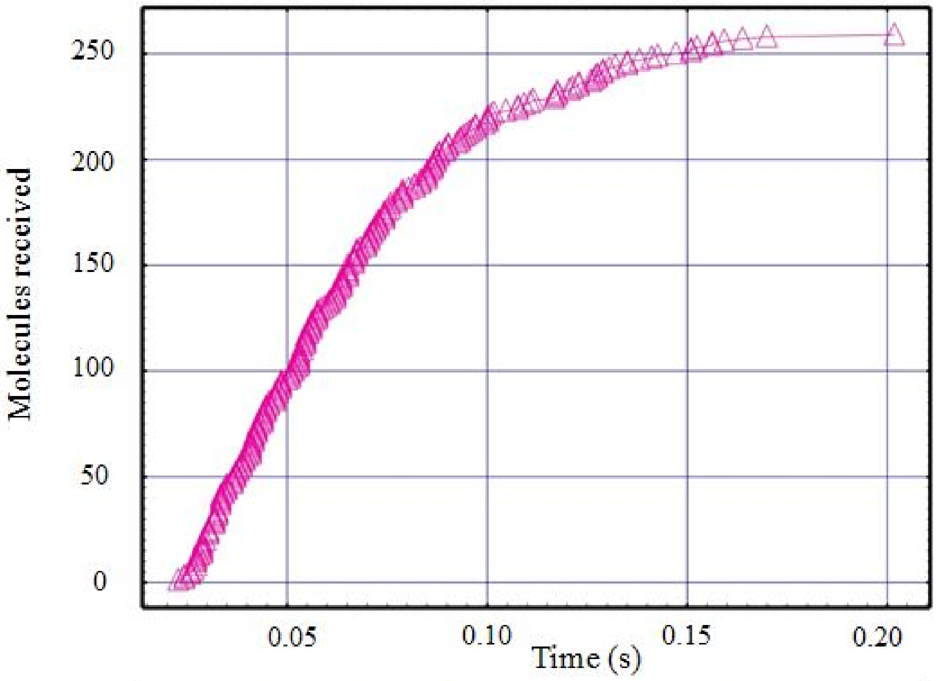


Figure 5.15: Impact of distance between nanomachines simulation result, 70% reduced distance when comparing with baseline, molecules received measured as a function of time.

it is possible to observe that the loss rate decrease to 15%. A closer look shows that in this scenario, there are over seven hundred molecules gathered, which is more than 70% of molecules sent, in 0.04s. From this result it is easy to see that in a molecular nanonetwork based on diffusion, it would benefit the transmission if receiving nanomachines would be slightly larger than other nodes.

Finally, to evaluate a simple concept, which consists on the idea that if a transmitter diffuses molecules in the environment, the transmission can always be one-to-many, i.e., broadcasting. Hence, a receiving node can be composed by a cluster of receiving nanomachines which are strategically positioned, in order to increase the efficiency of molecule reception. A simulation scenario was created in which two receiver nanomachines are strategically deployed, in order to simulate a receiving node composed of several receiving nanomachines. In Figure 5.17 its shown that with two receiving nanomachines the loss rate is around 70%, which means that the decrease in loss rate is a little better than a direct proportion to the number of receiving nanomachines. It is also possible to observe that in the first 0.1s the number of molecules captured is almost the double, when comparing with the baseline simulation result.

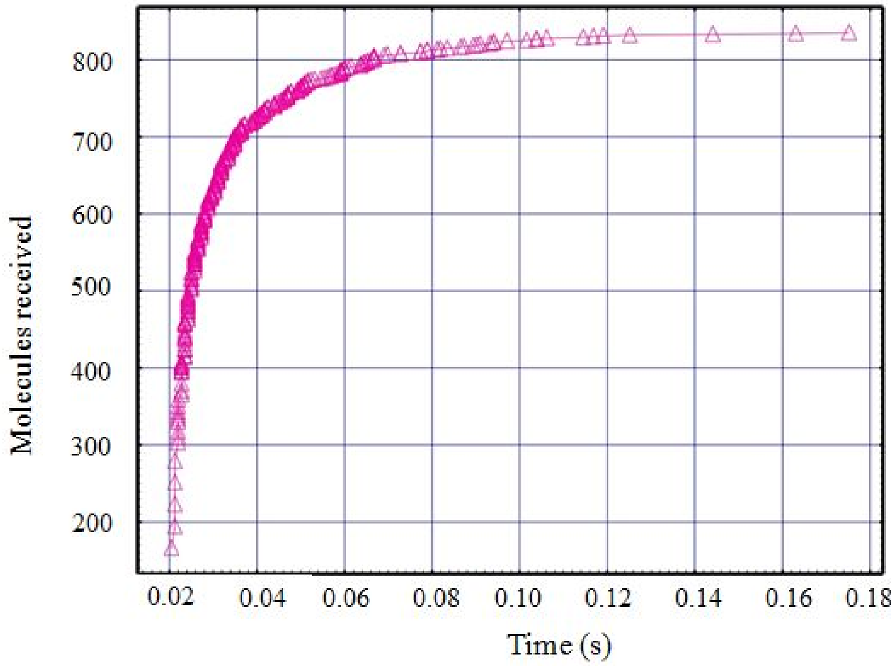


Figure 5.16: Increased radius in receiving nanomachine simulation result, molecules received measured as a function of time.

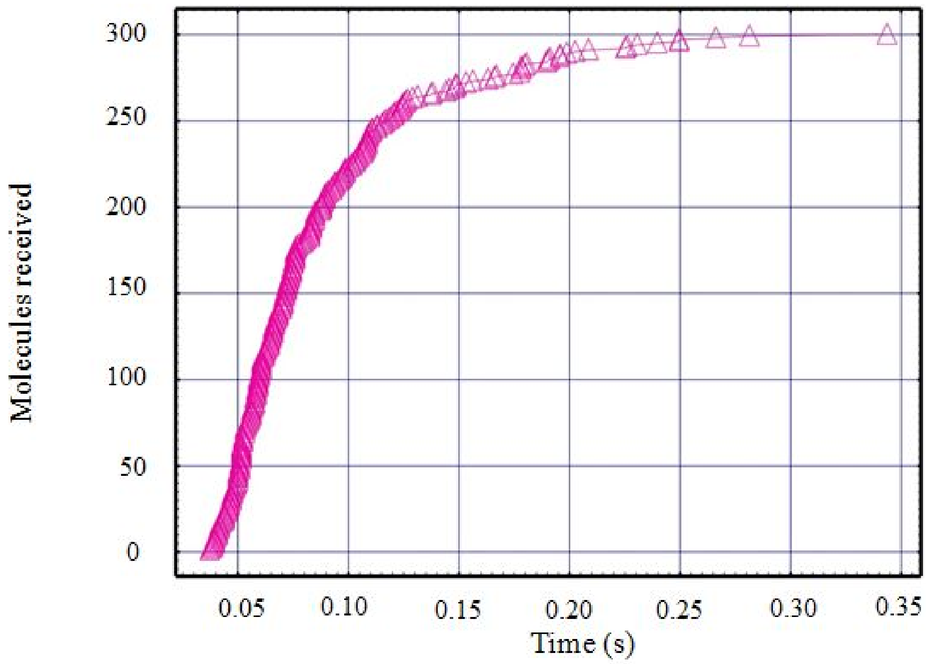


Figure 5.17: Two receiver nanomachines simulation result, molecules received measured as a function of time.

5.4 Conclusions

This chapter is important to analyze and evaluate the designed system, which was described in the previous chapter. Although this field of research is still on its infancy, new concepts and mechanisms can be designed according to theoretical concepts. The evaluation of these mechanisms is difficult to achieve with small resources, however some features can be evaluated by performing complex mathematical simulations. Although several approaches were attempted in order to perform an evaluation of the routing mechanisms designed for this system, several obstacles and lack of resources didn't allow for these to be achievable.

However, these mechanisms are detailed in this chapter, supported by sequence and flowchart diagrams, which can help to better understand how the mechanisms would work. The addressing and routing mechanisms described and specified are an original approach into a nanonetworking scenario, so past researches evaluation results could not be compared and discussed. In the next section of this chapter, the communication techniques chosen in this system are analysed and simulation results from other researches are presented. The simulations outcome presented show promising results, and help to support some system's features which are based on those techniques. As explained before, although the lack of resources didn't enable a simulation tool to be fully developed, which would be able to evaluate and validate all the features and mechanisms designed and integrated into the architecture, another approach was followed in order to provide a system analysis and evaluation. In the next chapter a future work section will better explain the path the project is heading, however, finishing the development of a simulation framework that would enable a system like this to be validated is imperative.

Several simulation results were presented evaluating concepts and features of molecular diffusion. The simulation scenarios created focused on classifying the loss rate in different scenarios in a diffusion based transmission, and the results obtained were unexpected. Although the expectations for the results were low, i.e., loss rates around 50%, the simulations showed that the loss rate is even larger. In order to establish comparisons between different simulation results, a baseline simulation was created.

In Figure 5.18 all simulation scenarios described in the previous section are presented. By observing the Figure 5.18, it is possible to compare all simulation results, and better identify the features that allow the loss rate to be minimized. The result for increasing the receiver nanomachine radius clearly stands out, and it possible to see the impact this feature can have on diffusion based transmissions. Although this type of transmission is very susceptible to environmental factors, if the nanonetwork is configured correctly and some features are implemented on that system, it is possible to achieved working applications. These features can be simple solution like decreasing the distance between nanomachines, creation of cluster nodes composed of several nanomachines in order to increase the reception potential, although in 5.18 a slight decrease in loss rate is seen, the results show promising results that motivate these features to be further investigated.

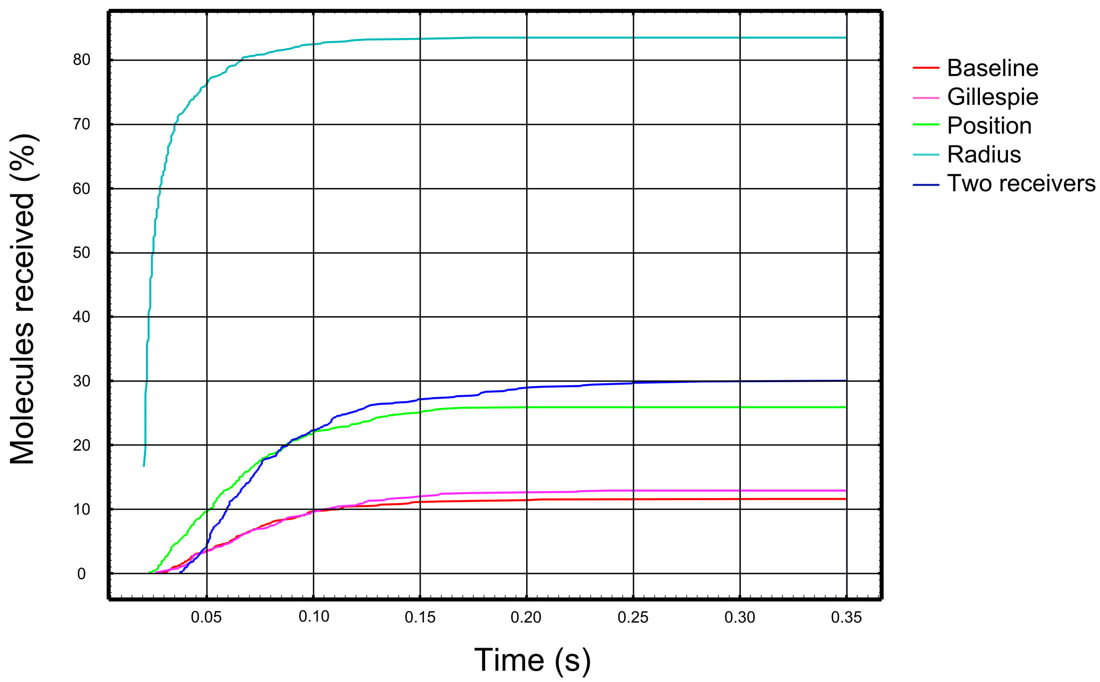


Figure 5.18: Comparison between all simulation results obtained, % molecules received measured as a function of time.

Chapter 6

Conclusions and Future Work

In this final chapter all the work performed during this dissertation will be discussed and what conclusions are possible to obtain from it. This chapter is very important to understand what was really achieved during the whole process, and what results and concepts the community can take from the work presented. Additionally, a section describing the future work that can expand this dissertation and advance this field of research in general is presented, focusing mainly on the aspects mentioned in this document, since this area of research still has a great deal of advances to be achieved.

6.1 Conclusions

The advances in nanotechnology and other research areas directly connected to it will continue and will have a great impact in almost every field of our lives, mainly increasing the quality of life of mankind around the world. The developments in this field will allow applications to be born that can help save lives by early disease detection and disease monitoring, the quality control of the environment will increase, the consumer goods will get better quality and agricultural applications will allow a better control of livestock and plantations fields. These new applications will completely change the paradigm in these fields, consequently changing the lives of every human being. Every year the technologic trends tend for devices more integrated with the user. Nowadays the trend are wearable devices like watches and glasses, and these advances will certainly help this trend to continue for several years, creating completely integrated devices within the user.

However, this trend will not continue if challenges in nanocommunication are not solved, and communication standards are not designed. If the simple, low complexity nanomachine is not able to communicate and to cooperate in order to achieve distributed complex tasks, nanonetworks cannot function. For that reason there is a need to create nanonetworks which can offer several features that enables the system to work. So the main objective of this dissertation was to create a solution for a nanonetwork system that would provide means to scale the network to reach current devices, reliable communication, error and flow control mechanisms, addressing and routing mechanisms and most importantly a system in which all components would synergyse.

Although innumerous obstacles and challenges were found along the way, most of them were successfully overcame and the main objective was achieved. A solution for a nanonetwork system that offers the required capabilities that allow new applications to be created was conceived. In spite of not accomplishing a full system validation through simulation scenarios, a conceptual validation is given by comparing to other simulation results. Since this research area is still on its infancy, the simulation solutions are very limited, which would require a complex implementation to be done in order to fully simulate the solution presented. However, some of the simulation tools were used and modified in order to obtain results to better evaluate the designed system.

All the work performed and presented in this document shows that the designed nanonetwork system is achievable when the nanotechnology and nanomachine manufacturing allows it. The initial validation of the system demonstrates that it would allow a nanonetwork to achieve communication with current devices, increase the efficiency of directed diffusion communication in a short-range scenario, nanomachines to be uniquely addressed and route information within the nano-scale, even with limited validation resources.

This document describes new techniques that are able to support the research community designing and developing new systems, increasing the efficiency of transmissions and design new routing mechanisms. Additionally, this document passes a message on the mentality that is needed while working on this field. The paradigm changes so much from what networking specialists are used to, which is not possible to apply the same methods. This document offers a great foundation in which future projects can be based on, and, personally, there is a desire to continue working on this field, and with all that I've learnt with all the work done, I feel more secure to design, develop and implement new concepts, systems and solutions, as the next section will describe.

6.2 Future work

This section is important to specify the features that weren't able to be achieved in the work developed, and to describe how the work presented on this document can be expanded in the future. Several mechanisms were envisaged and designed, they were integrated in a system, and when cooperating together, new features were provided to nanonetworks, however it is important to run extensive and detailed simulation to fully validate the entirety of the system, and to better evaluate the synergy between all components of the system.

Having a framework tool that provides researchers the means to simulate entire nanonetworks, in which it would be possible to integrate different communication techniques, select different encoding methods, specify deployment options and developing and testing nanonetwork protocols, would be fascinating. Although the development of such a framework requires a great deal of resources, it would be feasible to start developing it by steps, enabling a few features at a time. In the work developed, an existing tool, *NanoNS*, was explored and some development was made in order to extend the tool, however the achieved progress was not enough to be worth mentioning in the document. In the future, this project could continue the development of new modules, expanding that promising framework tool. Firstly new nanocommunication techniques must be implemented, like molecular motors and bacteria communication. This step would already provide the scientific community with an innovative framework, since by the time this document was written, there were no frameworks published that support those communication techniques.

Afterwards, it is imperative that protocol support in a simulation framework for nanocommunication is implemented. These modules would enable the researchers to envisage new addressing mechanisms, routing protocols or MAC protocols, and quickly evaluate their performance. Although these are very difficult tasks to achieve, specially for small researchers with very limited resources, it is conceivable that in a multi-year research and development project significant results would be made.

The difficulty of R&D projects in this area is not only due to the complexity of the new paradigm, or the fact that it is on its early stages and not a great deal of information is available, but the nature of the area itself. While on traditional computer communication systems, researchers can easily achieve performance tests, and behaviour studies by performing real-world scenarios, in nanocommunications is not possible to do that. Only a few selected researches have the resources to do real experimentation in laboratories, and better understand the behaviours of systems in specific scenarios. This makes the development of simulation frameworks for nanocommunication a even bigger and important aspect.

Although, in this research field, the future work for the scientific community has still many decades of researching and developing ahead, a small and important step would be the creation of stable simulation tools, and that is why it makes perfect sense to expand the work performed so far, and continue the development of new modules that step by step makes a complete simulation framework a reality. When this barrier is defeated, this research field is going to leap forward, and certainly enter a new phase of research, where new advances will be even more frequent and real applications will be in our grasp.

Even though not many features were mentioned in this section, the features are really important in this phase. In this document a system architecture was described in great detail, in which several mechanism and features were introduced and existing features were integrated to achieve new tasks. A full system validation is required, however, a simulation framework needs to be developed in order to perform the required tests. As described in this section, the development of the modules required to test a full nanonetwork system is still years away due to the complexity involved, and that is why it is counterproductive to mention any further work in the scope of this document.

References

[1] European Commission, "Research in Nanosciences & technologies", 2011. Available at: http://ec.europa.eu/research/industrial_technologies/policy_en.html. (Accessed 23 April 14).

[2] Akyildiz, I.F.; "Nanonetworks - A new frontier in communications". Proceedings of the 2010 International Conference on Signal Processing and Multimedia Applications (SIGMAP), vol., no., pp.IS-5,IS-5, 26-28 July 2010.

[3] National Nanotechnology Initiative, "What is Nanotechnology?", 2012. Available at: http://www.nano.gov/nanotech-101/what/definition. (Accessed 23 April 14).

[4] J.D. Badjic, V. Balzani, A. Credi, S. Silvi, J.F. Stoddar, "A molecular elevator", Science 303 (March) (2004).

[5] Ian F. Akyildiz, Fernando Brunetti, Cristina Blázquez, "Nanonetworks: A new communication paradigm", Computer Networks, Volume 52, Issue 12, 22 August 2008.

[6] E. Drexler, "Nanosystems: Molecular Machinery, Manufacturing, and Computation", John Wiley and Sons Inc., 1992.

[7] G.M. Whitesides, "The once and future nanomachine", Scientific American (September) (2001) 78-83.

[8] Akyildiz, I.F.; Jornet, J.m.; "Electromagnetic wireless nanosensor networks", Nano Communication Networks Journal 1, 1 (mar. 2010), elsevier, 3-19.

[9] Jornet, J.m.; Akyildiz, I.F.; "Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band". In Proceedings of 4th Eu-

ropean Conference on Antennas and Propagation (barcelona, spain, 2010), 1-5.

[10] Jornet, J.m.; Akyildiz, I.F.; "Channel modeling and capacity for electromagnetic wireless nanonetworks in the terahertz band". IEEE Transactions on Wireless Communications, 2011.

[11] S. Hiyama, Y. Moritani, T. Suda, R. Egashira, A. Enomoto, M. Moore and T. Nakano, "Molecular Communication". In Proceedings of NSTI Nanotech 2005, Anaheim, California, USA.

[12] Akyildiz, I.F.; Fekri, F.; Sivakumar, R.; Forest, C.R.; Hammer, B.K., "Monaco: fundamentals of molecular nano-communication networks", Wireless Communications, IEEE , vol.19, no.5, pp.12,18, Oct. 2012.

[13] A. Einolghozati, M. Sardari, and F. Fekri, "Molecular communication between two populations of bacteria". In Proceedings of IEEE Information Theory Workshop, Lausanne, Switzerland, Sept. 2012.

[14] Gregori, M.; Akyildiz, I.F.; "A new nanonetwork architecture using flagellated bacteria and catalytic nanomotors", IEEE Journal on Selected Areas in Communications, vol.28, no.4, pp.612,619, May 2010.

[15] Lluís Parcerisa Giné, Ian F. Akyildiz, "Molecular communication options for long range nanonetworks", Computer Networks, Volume 53, Issue 16, 10 November 2009.

[16] Nakano, T.; Suda, T.; Moore, M.; Egashira, R.; Enomoto, A; Arima, K., "Molecular communication for nanomachines using intercellular calcium signaling", 5th IEEE Conference on Nanotechnology, 2005 , pp.478,481 vol. 2, 11-15 July 2005.

[17] Atakan, B.; Akan, O.B., "An information theoretical approach for molecular communication", Bio-Inspired Models of Network, Information and Computing Systems, 2007. Bionetics 2007. 2nd , vol., no., pp.33,40, 10-12 Dec. 2007.

[18] Teuscher, C.; Grecu, C.; Ting Lu; Weiss, R., "Challenges and promises of nano and bio communication networks", 2011 Fifth IEEE/ACM International Symposium on Networks on Chip (NoCS), vol., no., pp.247,254, 1-4 May 2011.

[19] Atakan, B.; Galmes, S.; Akan, O.B., "Nanoscale Communication With Molecular Arrays in Nanonetworks", IEEE Transactions on NanoBioscience, vol.11, no.2, pp.149,160, June 2012.

[20] Dressler, F.; Kargl, F., "Security in nano communication: Challenges and open research issues", 2012 IEEE International Conference on Communications (ICC), vol., no., pp.6183,6187, 10-15 June 2012.

[21] Akyildiz, I.F.; Jornet, J.M., "The Internet of nano-things", Wireless Communications, IEEE , vol.17, no.6, pp.58,63, December 2010.

[22] Balasubramaniam, S.; Kangasharju, J., "Realizing the Internet of Nano Things: Challenges, Solutions, and Applications", Computer , vol.46, no.2, pp.62,68, Feb. 2013.

[23] Agoulmine, N.; Kim, K.; Kim, S.; Rim, T.; Lee, J.-S.; Meyyappan, M., "Enabling communication and cooperation in bio-nanosensor networks: toward innovative healthcare solutions", Wireless Communications, IEEE , vol.19, no.5, pp.42,51, Oct. 2012.

[24] Chahibi, Y., Pierobon, M., Song, S. O., and Akyildiz, I. F., "A Molecular Communication System Model for Particulate Drug Delivery Systems", IEEE Transactions on Biomedical Engineering, 2013.

[25] Cavalcanti, A.; Shirinzadeh, B.; Freitas, R.A.; Hogg, T., "Nanorobot architecture for medical target identification", Nanotechnology, 2008.

[26] Jornet, Josep Miquel; Akyildiz, Ian F., "The internet of multimedia nanothings in the Terahertz band", 18th European Wireless Conference, European Wireless, 2012 , vol., no., pp.1,8, 18-20 April 2012.

[27] Kuran, M.S.; Yilmaz, H.B.; Tugcu, T., "Effects of routing for communication via diffusion system in the multi-node environment", 2011 IEEE Conference on

Computer Communications Workshops (INFOCOM WKSHPS), pp.461,466, 10-15 April 2011.

[28] B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts, and P. Walter, "Molecular Biology of the Cell", Garland Science, fifth ed., November 2007.

[29] S. Havlin; D. Ben-Avraham, "Diffusion in disordered media", Advances in Physics, vol. 36, no. 6, pp. 695-798, 1987.

[30] D. ben Avraham; S. Havlin, "Diffusion and Reactions in Fractals and Disordered Systems", (Cambridge Nonlinear Science Series). Cambridge University Press, 1 ed., November 2000.

[31] Sanderson, M.J., A.C. Charles, S. Boitano, E.R. Dirksen, "Mechanisms and function of intercellular calcium signaling", Mol. Cell Endocrinol, 1994.

[32] Niessen, H.; H. Harz; P. Bedner; K. Kramer; K. Willecke, "Selective permeability of different conneixin channels to the second messenger inositol 1,4,5-triphosphate", Journal of Cell Science, 2000.

[33] 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". In Proceedings of the Fourth Annual IEEE International Conference on Pervasive Computing and Communications (PerCom'06), March, 2006.

[34] Moore, M.J.; Enomoto, A; Watanabe, S.; Oiwa, K.; Suda, T., "Simulating molecular motor uni-cast information rate for molecular communication", 43rd Annual Conference on Information Sciences and Systems, 2009. CISS 2009. pp.859,864, 18-20 March 2009.

[35] Hill, D. B., Plaza, M. J., Bonin, K., Holzwarth, G., "Fast vesicle transport in PC12 neurites: velocities and forces", Eur. Biophys. J., 33, 623-632, 2004.

[36] Beeg, J., Klumpp, S., Dimova, R., Gracia, R. S., Unger, E., Lipowsky, R., "Transport of Beads by Several Kinesin Motors", Biophysical Journal, vol. 94, pp. 532-541, 2008.

[37] Eckford, A. W., ”Nanoscale Communication with Brownian Motion”, Computer Science Information Theory, 2007.

[38] Pietro Lio’, Sasitharan Balasubramaniam, ”Opportunistic routing through conjugation in bacteria communication nanonetwork”, Nano Communication Networks, Volume 3, Issue 1, March 2012.

[39] L.S. Frost, G. Koraimann, ”Regulation of bacterial conjugation: balancing opportunity with adversity”, Future Microbiology 5 (7)(2010).

[40] Giuseppe Piro, Luigi Alfredo Grieco, Gennaro Boggia, and Pietro Camarda, ”Nano-Sim: simulating electromagnetic-based nanonetworks in the network simulator 3”. In Proceedings of the 6th International ICST Conference on Simulation Tools and Techniques (SimuTools ’13), 2013.

[41] I. Llatser, I. Pascual, N. Garralda, A. Cabellos-Aparicio, and E. Alarcon, ”N3sim: a simulation framework for diffusion-based molecular communication”, IEEE Technical Committee on Simulation, 2011.

[42] Ertan Gul, Baris Atakan, Ozgur B. Akan, ”NanoNS: A nanoscale network simulator framework for molecular communications”, Nano Communication Networks, Volume 1, Issue 2, June 2010, Pages 138-156.

[43] Luca Felicetti, Mauro Femminella, and Gianluca Reali. ”A simulation tool for biological nano-communication systems”. In Proceedings of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL ’11), ACM, New York, NY, USA, , Article 23 , 5 pages, 2011.

[44] Garralda, N.; Llatser, I.; Cabellos-Aparicio, A.; Pierobon, M., ”Simulation-based evaluation of the diffusion-based physical channel in molecular nanonetworks”, 2011 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp.443,448, 10-15 April 2011.

[45] Junichi Suzuki, Harry Budiman, Timothy A. Carr, Jane H. DeBlois, ”A Simulation Framework for Neuron-based Molecular Communication”, Procedia Computer Science, Volume 24, 2013, Pages 103-113.

[46] P.L. Várkonyi, G. Domokos, "Static equilibria of rigid bodies: dice, pebbles and the Poincare-Hopf Theorem", J. Nonlinear Sci, Vol 16, pp 255-281, 2006.

[47] P.L. Várkonyi, G. Domokos, "Mono-monostatic bodies: the answer to Arnold's question", Mathematical Intelligencer, 28, (4), pp34-38, (2006).

[48] Hiyama, S., Isogawa, Y., Suda, T., Moritani, Y., Sutoh, K., "A Design of an Autonomous Molecule Loading/Transporting/Unloading System Using DNA Hybridization and Biomolecular Linear Motors". In European Nano Systems, Paris, France, pp. 75-80 (2005).

[49] L. C. Cobo-Rus and I. F. Akyildiz, "Bacteria-based communication in nanonetworks", Nano Commun. Netw., vol. 1, no. 4, pp. 244-256, Dec. 2010.

[50] T.M. Finan, S. Weidner, K. Wong, J. Buhrmester, P. Chain, F.J. Vorhölter, I. Hernandez-Lucas, A. Becker, A. Cowie, J. Gouzy, B. Golding, A. Pühler, "The complete sequence of the 1,683-kb pSymB megaplasmid from the N2-fixing endosymbiont Sinorhizobium meliloti", Proceedings of the National Academy of Sciences of the United States of America 98 (17)(2001).

[51] Balasubramaniam, S.; Lio', P., "Multi-Hop Conjugation Based Bacteria Nanonetworks", IEEE Transactions on NanoBioscience, vol.12, no.1, pp.47,59, March 2013.

[52] B. Atakan, O.B. Akan, "On channel capacity and error compensation in molecular communication", Springer Transaction on Computational System Biology (2008).