MOLECULAR COMMUNICATION & NANO NETWORKING INVOLVING CELLULAR LEVEL COMMUNICATION PARADIGM EXPLAINED USING THEORETICAL MODELLING OF MOLECULAR COMMUNICATION

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Abstract - The ability of engineered biological nano machines to communicate with biological systems at the molecular level is anticipated to enable the future applications such as monitoring the condition of a human body, regenerating biological tissues and organs, and interfacing artificial devices with neural systems. From communication theory and engineering perspective, molecular communication is deemed as a new paradigm for biologically engineered nano machines along with natural biological nano machines to form a biological system. Molecular communication uses molecules as the carriers of information; sender biological nano machines encode information on molecules and release the molecules in the environment, the molecules then propagate in the environment to receiver biological nano machines and the receiver nano machines biologically react with molecules to decode the information. At present, molecular communication research is limited to small scaled networks of biological nano machines. Key challenges include development of robust nano machines, smart network mechanisms and efficient communication protocols. In this paper, we present state of the art in molecular communication in architecture, features, applications and design. Furthermore, real time challenges and applications are also discussed in developing network mechanisms and efficient communication protocols to create a network of bio machines for future applications.

IndexTerms - Biological nano machines, communication architecture and protocols, molecular communications, nano networks.

I. INTRODUCTION

Advancements in biomedical engineering and nano-technology has made it possible to create small scale functional devices from biological materials, that are capable interacting with other such devices in nano scale environments. Such biological devices are henceforth referred to as bio-nano machines1 this includes purified proteins molecules [1], genetically engineered cells [2], artificial proto cells and bio-silicon hybrid devices [3]. It is envisioned that these bio machines will enable many possibilities in the field of health, environment, information, communication systems and military applications. The interdisciplinary research area of molecular communication or nano-networks [4]-[6] is due to the rise of bio- nano machines interfacing.

Early research work in the field of molecular engineering was done in the year 2005 with the aim of establishing communication networks compatible with bio-nano machines design [7]-[9]. Initial efforts were taken to theoretically quantify the molecular communication characteristics [10]-[14]. The key challenge to the advance the area of molecular communication is to create a efficient network system capable of working with large number of biological nano machines.

In this paper we provide a comprehensive overview of the area of molecular communication and nano networks by reviewing the architecture engineering, features, applications and physical models. We also discuss the challenges and opportunities involved in developing network mechanisms efficient communication protocols and standardization for molecular communication. The main contributions of this paper with respect to other such survey and review papers.

[1]Nano machines are roughly defined as small-scale machines in this paper; no distinction is made between micro scale and nano scale.

Figure 1 Molecular communication architecture [4]

- **Overview of molecular communication:**
  In this paper, the architecture and real time application of molecular communication are briefly discussed and engineering efforts in molecular communication and its relevant areas are highlighted.
- **Methodology to examine basic properties of molecular communication:**
  A simple model is used to describe the process of molecular communication. The model describes key points such as average latency which may indicate the quality of molecular communication. The considered model characterises molecular communication as random walk, random walk with drift and random walk with reaction.
- **Discussion of recent research issue:**
  Various issues in development of molecular communication systems are discussed based on

approach and author's perspective of computer communication.

Further, this paper is organised as follows. In section II, the generic architecture and phases of molecular communication is discussed along with general features. Section III describes about the potential biological materials and methods that can be used to engineer molecular communication systems. Section IV uses a physical model to understand various properties of molecular communication. Section V discusses recent trends in advanced molecular communication and nano networking. A brief summary of key points of this paper is discussed in section VI.

II. MOLECULAR COMMUNICATION PARADIGM

The objective of molecular communication is to develop an abstract communication architecture to generalise communication process. The narrow examples f molecular communication can be seen in bio nano-machines which transport materials within a cell by communicating with each other. We classify the examples of communication between nano-machines on the basis of communication engineering, to identify and process the required molecular communication architecture. In this section, a brief overview of the molecular communication paradigm is described using an abstract architecture. The advancements in the existing methods and the potential application areas along with general characteristics of molecular communication systems is also discussed

A. Molecular Communication Architecture

Fig.1 Shows an architectural design for molecular communication. It represents components functioning in unity as information molecules that represent the information to be transmitted sender by a nano-machine that transmit information molecules and the medium in which the information molecules propagate from sender nano-machine to receiver nano-machine. The system also includes transport molecules to move information molecules, guide molecules to direct the movement of transport molecules. Interface molecules selectively allow certain transport information molecules using addressing molecules (not shown). Fig.1 also shows the general phases of communication that involves encoding of information, sending of information, propagating of information, receiving of information and decoding of information [15].

The basic components involved in above each phase are described as follows:

- Encoding is the phase during which a sender bio-nano-machine translates information into information molecules that the receiver bio nano-machine can detect. Information may be encoded in various forms within the information molecules, such as in the three-dimensional structure of the information molecule.
- Sending is the phase by which a sender bio nano-machine releases information molecules into the environment. A sender bio nano-machine may release information molecules by either unbinding information molecules from the sender bio-nano-machine.
- Propagation is the phase during which information molecules move from the sender bio nano-machine through the environment to the receiver bio nano-machine. An information molecule may diffuse passively through the environment without using chemical energy, or may bind to a transport molecule.
- Receiving is the phase during which the receiver bio-nano-machine captures information molecules propagating in the environment. One option for a receiver. Bio nano-machine to capture information molecules is to have a surface structure permeable to the information molecules.
- Decoding is the phase during which the receiver bio-nano-machine, upon capturing information molecules, decodes the received molecules into a chemical reaction. Chemical reactions for decoding at the receiver bio nano-machine may include the production of new molecules, the performing of a simple task, or the production of another signal.

B. Expected Characteristics

Table.1 compares certain key features of molecular communication to telecommunications in terms of propagation speed, range, signal types, devices and medium.

- Encoding and decoding with chemical signals: Molecular communication propagates chemical signals from a sender bio nano-machine to a receiver bio nano-machine, upon which the receiver bio nano-machine chemically reacts with the incoming chemical signals. Here information can be encoded within the physical properties or characteristics of information molecules, such as the type of information molecules used, their three-dimensional structure.
- Slow speed, limited range, large jitter, and high loss rate: The speed and range of molecular communication are extremely slow and short, and vary depending on the biological materials, mechanisms used, and the environment. In addition, molecular communication experiences large signal jitter and a high loss rate because the movement of molecules is often unpredictable and the molecules arrive at a receiver bio nano-machine after a widely varying period of time.

Moreover, the molecules may degrade in the environment and not even arrive at a receiver bio nano-machine.

- Biocompatibility: Sender and receiver bio nano-machines communicate by sending, receiving, and chemically reacting with information molecules. Bio nano-machine in molecular communication may be able to directly communicate with natural components in a biological system by using encoding and decoding methods available to the biological system. The biocompatibility of molecular communication may enable applications such as the implanting of bio nano-machines into a biological system for medical applications that require biologically friendly bio nano-machines.
- Energy efficiency, low heat dissipation, and chemically operated: Molecular communication uses mechanisms and materials from biological systems, and is therefore expected to be energy efficient and achieve low heat dissipation.

Table.1 Comparison between telecommunication and molecular communication

Communication	Telecommunication	Molecular Communication
Devices	Electronic devices	Bio-nanomachines
Signal types	Optical/electrical	Chemical
Propagation speed	Speed of light	Extremely slow
Propagation range	m - km	nm - μm
Media	Air/cables	Aqueous

C. Application Envision

Practical applications of molecular communication use bio nano-machines to sense molecules, transport molecules and modify molecules[16]. Applications are being considered in bio-medical environmental and manufacturing areas which are briefly described how molecular communication can be applied in real-time scenarios:

1. Biomedical Applications:

- Lab-on-a-chip: In lab-on-a-chip applications, the chemical analysis of biological samples is performed on a chip with dimensions in the mm to cm range. Analysis of biological samples is required for medical applications to diagnose disease or for general scientific studies of biological samples. Molecular communication provides techniques to transport specific molecules to specific locations of a chip. In addition, molecular communication may allow lab-on-a-chip applications to scale further down since molecular communication components can be at the nano-meter scale.
- Health monitoring: Monitoring performed within an organism (i.e. human, animal, or plant) enables identification of specific molecules in the body. The existence of specific molecules may serve as a bio-marker for a disease or a certain medical condition. More detailed information such as the spatial distribution of molecules can be used to provide information for further diagnosis. For such applications, bio nano-machines are implanted in the body, and molecular communication provides potential methods for gathering information about the molecules of the body, aggregating the information, and transmitting it to external devices.
- Drug delivery: Drug delivery systems facilitate the ad-ministration and distribution of drugs within an organism. Implanted bio nano-machine can use molecular signals within the organism, or molecular signals released by other bio nano-machines, to pinpoint target locations for drug delivery and thereby reduce the potential for side-effects at non-target locations.
- Regenerative medicine: Bio nano-machine made of living cells can divide and grow to form a functional structure (e.g., tissues and organs). Such bio nano-machine can be applied to aspects of regenerative medicine.

2. Environmental Applications:

- Environment monitoring: The environment may be exposed to toxic or radioactive agents. Information about these molecules could help to identify problems and to provide a map for cleaning up the environment in response to illegal contamination or an accidental spill.
- Waste/pollution control: The monitoring of molecules in the environment may provide information that is only of low-level resolution. Bio nano-machines could be deployed to monitor molecules in the environment and thus identify more precisely the location of a toxic source. For example, bio nano-machines can identify and use specific types of molecules to tag waste in the environment.

3. Manufacturing Applications:

- Pattern and structure formation: Molecular communication can be used to control the transport of molecules, and can be modified to produce novel patterns of molecules.

Table.2 Design and engineering of molecular communication system

Components	Examples Categorized by Materials
Bio-nanomachines	Modified cells [37], [38], [39], Artificial cells [3], [40], [41]
Information molecules	Synthetic particles [42]
Guide and transport molecules	Gap junction channels [16], [43], [44], Molecular motors and filaments [12], [15] [45], [46], Bacteria [47], [48], neurons [49]
Interface molecules	Liposomes [13], [50]
Addressing molecules	DNA molecules [10]

III. DESIGNING AND ENGINEERING FOR MOLECULAR COMMUNICATION

The molecular communication system described in previous section are designed and engineered from biological mechanisms and materials. In this section, we review recent research analysis concerning the design and engineering of molecular communication.

A. Sender and Receiver Bio Nano-machines

Sender and receiver bio nano-machines require chemical functionality for effective communication: sender bio-nano-machines must be able to synthesize, store, and release information molecules, while receiver bio nano-machines need to capture and react to specific information molecules. Two basic approaches for engineering bio nano-machines with functionality for communication are the modification of existing biological cells or the production of simplified cell-like structures using biological materials[17].

- **Modified biological cells:**
  The first approach for engineering bio nano-machines has been used and demonstrated in synthetic biology. Synthetic biology has also demonstrated that many other functions can be introduced into biological cells, such as logic gates, toggle switches, and oscillators. These functions can be used to increase the complexity of sending and receiving processes.
- **Artificial cells:**
  Another approach to engineering sender and receiver bio nano-machines is to create simplified cell-like structures using biological materials (e.g., by embed-ding proteins in a vesicle). One example is to start with a lipid bilayer and then add functionality as necessary. The lipid bilayer, which is similar to the membrane that encloses a cell, forms into a vesicle (a spherical lipid bilayer) in which functional proteins (e.g., a receptor) are either embedded or captured.

B. Information Molecules

Information molecules carry information and propagate from a sender bio nano-machine to a receiver bio nano-machine in the environment. The size and structure of the information molecules may affect how the information molecules prop-agate in the environment. Information molecules need to be chemically stable and robust against environmental noise and interference from other molecules.

C. Guide and Transport Molecules

Guide and transport molecules provide reliable mechanisms for propagating information molecules. A required functionality for these molecules is to direct the propagation of information molecules toward target locations (i.e., receiver bio nano-machines). Guide and transport molecules can be viewed as bio nano-machines specialized for transporting molecules.

D. Interface Molecules

Interface molecules allow bio nano-machines to transport a variety of information molecules using the same communication mechanism. The interface molecules allow any type of information molecule to be delivered to and concentrated at a target location. The interface molecules may also protect information molecules from environmental noise and prevent the information molecules from chemically reacting with other molecules in the environment outside the vesicle.

E. Addressing Molecules

Addressing molecules allow a sender bio nano-machine to specify the receiver bio nano-machine according to a generic addressing mechanism. A molecular communication system
with generic addressing is more flexible since it imposes fewer constraints on which information molecules are used.

IV. THEORETICAL MODELLING OF MOLECULAR COMMUNICATION

Theoretical models serve as a basic tool that can be used to quantify compare and improve the average propagation, variation in latency and loss rate. The domain of bio-physics as developed a number of theoretical models and computational methods that can be used for the advancement of molecular communication. This section is discusses the quality of molecular communication in terms of average latency, jitter and loss rate[18]. The fig.2 illustrates the variation in the latency in molecular communication.

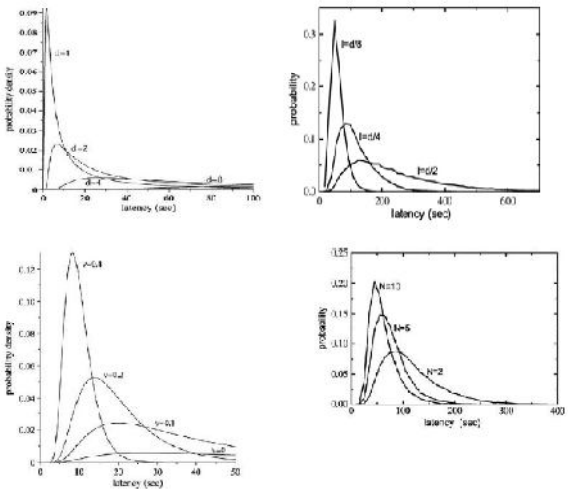


Figure.2 Comparison of latency rate

V. RESEARCH ISSUES AND CHALLENGES

Recent research in molecular communication remains limited to the design and analysis of small-scale networks of several bio nano-machine with simplistic assumptions about bio nano-machine and the environment. A key challenge to advance the area of molecular communication to the next stage is to develop robust and scalable techniques to create large-scale net-works which function in the environment of practical applications.

CONCLUSION

In this paper, we have provided a comprehensive overview of the emerging and interdisciplinary area of molecular communication. Molecular communication integrates techniques from biology for interacting with biological systems, from nano technology for enabling nano to micro-scale interactions, and from computer science for designing scalable and robust networks. Molecular communication has high potential capacity for impact, since biological systems pervade many environments and applications, but the current techniques available for molecular communication are limited. The area of molecular communication is in its infancy and numerous challenges and opportunities exist to advance this area as discussed in this paper.

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