# Recent Advancements in Molecular Communication among Nanomachines

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**Abstract**—Nanotechnology is an emerging field which provides opportunities in a vast range of areas. A nanomachine is an integrated device having nanoscale dimensions that can perform very simple tasks. However, it can be made to perform more complicated tasks provided these devices have means of communication. At these small sizes traditional electromagnetic waves are unable to perform their designated work. Hence some alternative means of communication need to be explored; Molecular Communication being one. In this paper, the concept of molecular communication and nanonetwork is introduced which uses biological molecules as information carriers. Molecular communication is a biologically inspired communication scheme in which the information is encoded onto molecules, which are then transmitted to the environment and reach the receivers which react chemically to the molecules and decode the information. This paper provides key concepts, architecture and potential applications of molecular communication.

**Keywords**—Nanonetworks; Nanomachines; Molecular Communication; Carrier/Information Molecules

## 1. INTRODUCTION

Nanotechnology provides a new set of toolsfor the engineering community to control the atomic and molecular scale entities. Foremostamong them are nanomachines which areintegrated functional devices consisting ofnanoscale components, envisioned to accomplishcomplex tasks as shown in Fig. 1.They need to cooperate with each other because a single nanomachine provides very limited functionality hence limited output. Nanonetworks are formed by enabling nanomachinesto communicate with each other to expand their application domains [1].There are many communication paradigms, but this paperfocuses onmolecular communication.In this communication, moleculesare used to encode, transmit and receive information[2].

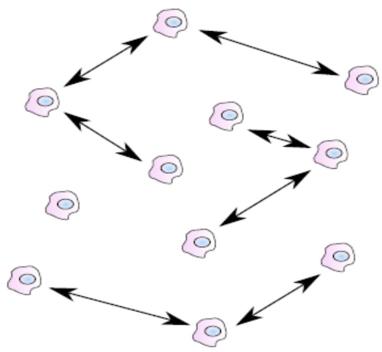

Fig. 1 Network of communicating cells

Molecular communication is a new communication paradigm in which the information is loaded (encoded) onto the information molecules which are carried away by the carrier molecules and propagated to the receivers through the communication channel as shown in Fig. 2. At the receiver, the information molecules are unloaded from the carrier molecules. Then the receivers react biochemically to the information molecules and decode the information that was encoded onto them. It is assumed that once the carrier molecules reach the receiver, they are removed from the environment i.e. they contribute to the communication once.

Molecular communication is inspired by the biological systems where communication is typically done through molecules [4]-[6]. Using molecules as carrier of information has not yet been, however, explored in the existing research. The current


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research effort in nanotechnology and biotechnology focuses on observing and understanding biological systems (e.g., observing and understanding how communication is done within a cell or between cells). Molecular communication extends the current effort to include artificially created communication systems based on communication mechanisms existent in the biological systems. There is a need to design a sender nanomachine which can generate information and encode them onto information molecules; a propagation channel which can loadinformation molecules onto carrier molecules, propagates the molecules and unloads the information molecules from carrier molecules and a receiver nanomachine which can receive the information molecules, decodes the information and react chemically to them.

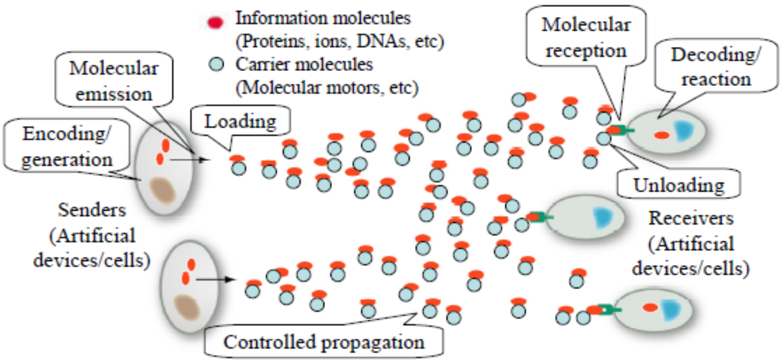


Fig. 2 Molecular Communication [3]

## I. NANOMACHINE DEVELOPMENT TECHNIQUES

As the name is self explanatory, nanomachines are miniscule devices. They are based on assembly of nanoscale components. Eric Drexler popularized the first concept of nanomachine technology and there is continuing effort to realize these concepts. A manufacturing approach has been currently provided for a sensornanomachine with a 1.5 nanometer switch which is able to detect and count a specific typeof molecule [7]. Biological cell is a naturally existing nanomachine. Dynein- molecular motors that walk along microtubules in a cell, F1ATPase- synthesizes ATP(energy) by using an influx of protons to rotate and bacterium- swims towards the chemicals(food) using flagellum are a few biological nanomachines. Nanomachines can be fabricated using any of the three popular approaches: top-down, bottom-up and bio-inspired approaches as shown in Fig. 3.

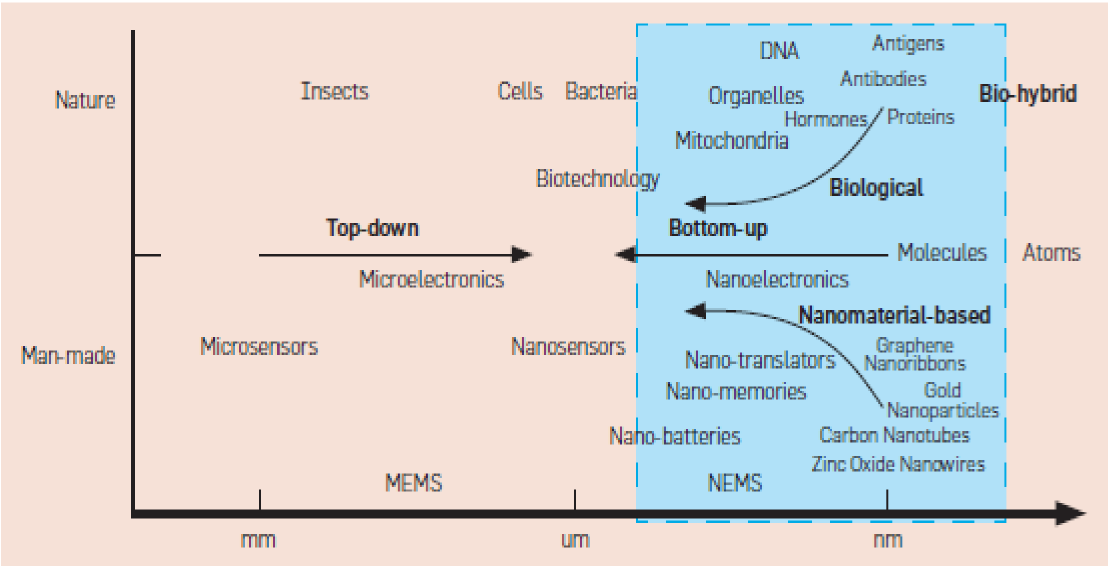


Fig. 3 Design of nanomachines [1]


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*A.* Top-down approach: It involves the downscaling of current microelectronic and micro-electro-mechanical devices to develop a nanomachine without atomic control level provided the resulting nanomachine retains the architecture of microscale components from where they are manufactured. Here techniques such as electron beam lithography and micro-contact printing are used [8].

*B.* Bottom-up approach: Here the nanomachines are realized from molecular components which are assembled chemically byprinciples of molecular recognition arranging molecule by molecule. This approach replicates the natural process of growth.

C. Bio-hybrid approach: Here the existing biological nanomachines act as the components of the development of newnanomachines.The many of the biological nanomachines can be found in cells, including nano-biosensors, nano-actuators and biological data storing components, tools and control units [2]. In future, the nanomachines will be developed using any of the above approaches. The existing biological nanomachines encourage their use as building blocks for new developments owing to their highly optimized architecture, power consumption and communication.

## 2. Communication Among Nanomachines

Realizing a nanonetwork is based upon the communication of nanomachines. Classical communication and network paradigms are limited for direct use in nanonetworks virtuethe new challenges and requirements introduced by the limited capabilities of nanomachines. Some of the main issues are as follows:

- Scale of the nanomachines is on the order of micro meter, hence traditional transceiver circuitries cannot be mounted into nanomachines.
- Use of current encoding and decoding techniques is not feasible due to very limited processing capability of nanomachines.
- For in vivo application scenarios, nanomachines need to be biocompatible so that they are not rejected by the biological systems.
- Mobility of nanomachines is governed by the physical rules in this regime [9].
- Nanomachines are extremely susceptible to any change in the communication environment such as dynamic concentration variations or quaking.
- Communication or noise signal characteristics cannot be easily anticipated due to extremely unreliable nature of the communication medium.

Nanomachine communication can be realized through nanomechanical, acoustic, molecular or chemical and electromagnetic means [9]. Nanomechanical communication takes place through the transmission of information by a mechanical contact between transmitter and receiver. But when the transmitters and receivers are remotely located, direct contact between the two is impossible. In acoustic communication, the transmission of information takes place through acoustic energy such as pressure variations. But due to their size constraints of the traditional acoustic transducers and radio frequency transceivers, their integration is not feasible at nanoscale. In molecular communication, information is carried through the molecules, in which the information is encoded, from the transmitter nanomachine to receiver nanomachine. Electromagnetic communication is defined as the transmission of information based on modulation and demodulation of electromagnetic waves. But this communication has high energy consumption as compared with the molecular communication. Molecular communication occurs in nature between nanoscale entities. Natural phenomena like intercellular and interbacterial communication provide a study ground to model nanonetworks. Therefore, the molecular communication is the most promising approach. Molecular communication possesses the following characteristics:

- Feasibility - regarded as easier to implement than other approaches in the near term
- Scale - appropriate size for nanomachines
- Bio-compatibility - integration with living systems possible
- Energy Efficiency - biochemical reactions have high efficiencies

Molecular communication presents the following challenges:

- Stochasticity - random propagation of molecules, environmental noise
- Delay - propagation times very long compared to speed of light
- Range - techniques can have very short practical ranges
- Fragility - biological components can be environmentally sensitive (temperature, pH, other reagents)


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## 3. MOLECULAR COMMUNICATION ARCHITECTURE

Molecular communication is an interdisciplinary field that spans Nano, ECE, CS, Bio, Physics, Chemistry, Medicine, and Information Technologies [10]. The transceivers here, due to their small size, are feasible to be used in nanomachines at nanoscale. There are five different architectures for molecular communication.

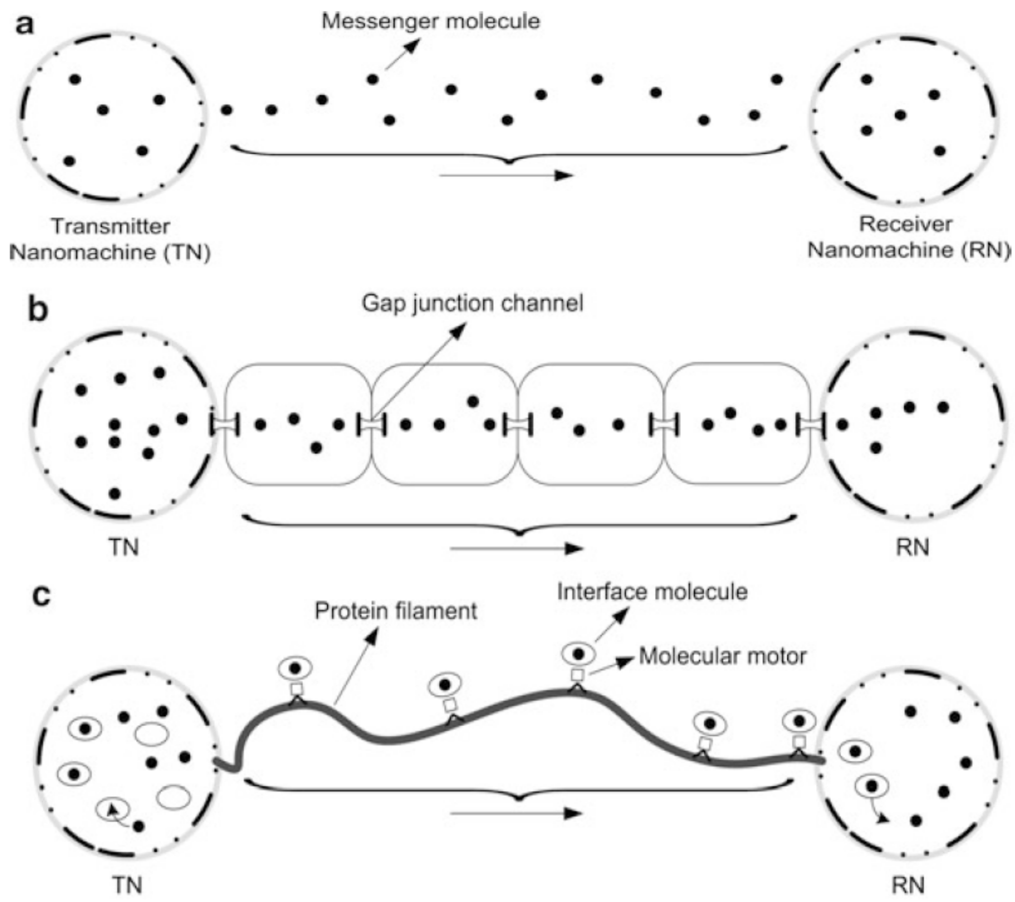
*C.* Free Diffusion- It is a kind of passive molecular communication. Here the emitted molecules diffuse freely in the medium and randomly hit the receiver as shown in Fig. 4 (a).

*D.* Gap Junction Channels- Gap junctions are aggregates of intercellular channels that permit direct cell–cell transfer of ions and small molecules. The channels mediate the diffusion of molecules through a pathway between transmitter and receiver as shown in Fig. 4 (b).

*E.* Molecular Motors- Communication using molecular motors is a kind on active molecular communication i.e. the transmission takes place over a well defined path. The information molecules are embedded in the vesicles, which are carried by the molecular motors over a microtubular chain as shown in Fig. 4 (c). e.g. dyneins and kinesins.

*F.* Flagellated Bacteria- It is a kind of flow-based molecular communication in which the messenger molecules are inserted into the bacteria. The attractant molecules are released by the receiver which directs bacteria towards itself as shown in Fig. 4 (d).

*G.* Random Collision- The messenger molecules remain attached to the transmitter and when there is a random collision or hitting with the receiver, the molecules bind to the receptors of the receiver as shown in Fig. 4 (e).





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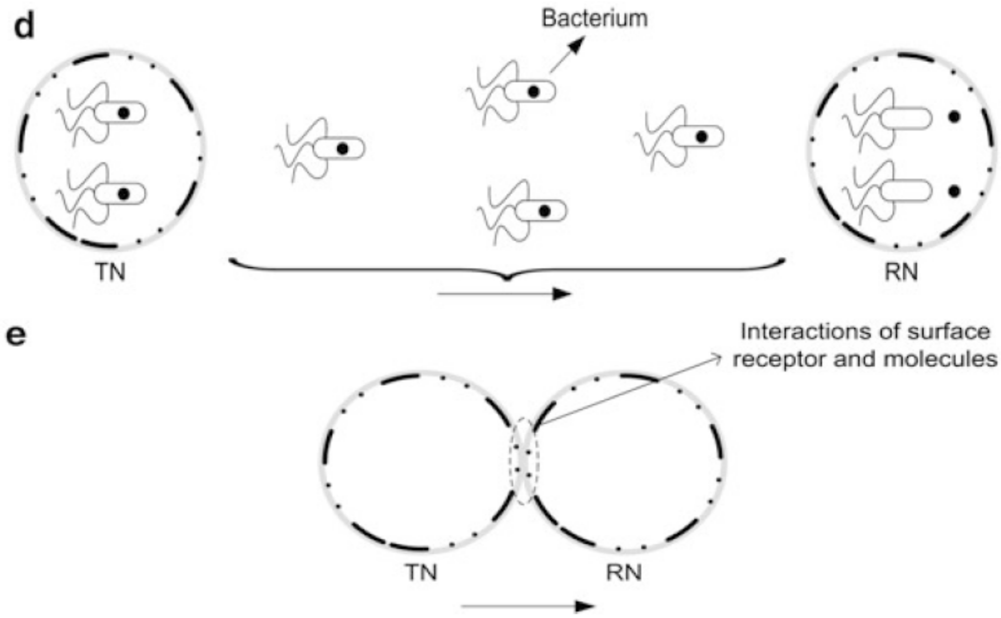


Fig.. 4 Architectures of Molecular Communication [12]

## 4. Applications of Molecular Communication

Molecular communication and nanonetworks have many biomedical, environmental, and industrial applications [2, 11, 12]. Some promising examples of these applications can be given as follows:

*H.* Biomedical Applications

*1)* Immune System Support: The immune system consists of blood cells responsible for protecting organisms from harmful pathogens. This is achieved by means of molecular communication and coordination among the blood cells in the immune system. This forms the biological immune network which is an excellent defense mechanism of organisms. Specific nanomachines may act as these blood cells to support the immune system when it works inappropriately. They may also detect and eliminate malicious agents such as cancer cells by communicating and coordinating with each other [13]. Surely, as in the molecular communication among blood cells of immune system, molecular communication is the most proper nanoscale communication paradigm for the coordination and self-organization of these nanomachines.

*2)* Drug Delivery: Drug delivery systems help the control and distribution of drugs in an organism. The controlled release and delivery of drug molecules to a specific tissue may be achieved through a molecular communication mechanism. This can reduce harmful side effects of the drug on other healthy tissues.

*3)* Health Monitoring: Molecular communication may be employed in order to identify and observe specific molecules for health monitoring purposes. For example, by deploying nanomachines that can sense a desired molecule in a body, spatial and temporal distributions of this molecule may be observed. For this application, molecular communication of nanomachines is essential to reliably gather information about the monitored molecules and to transmit this information to a central entity [3, 14].

*4)* Lab-on-a-Chip: In lab-on-a-chip applications, biological samples are chemically manipulated and analyzed on a chip with a dimension ranging from mm scale to cm scale. In these applications, molecular communication is required to move specific molecules to specific locations of a chip.

*I.* Environmental Applications

*1)* Environmental Monitoring: Similar to the health monitoring application given above, an environment can be monitored to identify and observe some specific molecules (including radioactive molecules) which cause environmental problems such as illegal contamination and radioactive leakage. Through nanomachines capable of sensing specific molecules, detection and localization of a non-desired molecule source can be achieved. For example, in order to monitor air, nano-filters which are able to monitor, detect, and remove harmful substances in air can be developed [15].

*2)* Animals and Biodiversity Control: Animal populations may be observed through a molecular communication system which can detect and follow specific molecules (e.g., pheromone molecules) emitted by animals. By synthetically releasing such molecules, it is also possible to interact with animal populations to control their presence in particular areas.


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*J.* Industrial Applications

*1)* Pattern and Structure Formation: Molecular communication systems can be jointly worked with chemical processes in order to produce novel molecular patterns and structures [16]. Molecular communication systems may be programmed to transport each molecule type to a predefined location. Then, chemical processes may be employed to complete a desired structure using the organized molecule species.

*2)* Functionalized Materials: Nanomachines interconnected through molecular communication (i.e., nanonetwork) can be incorporated into advanced materials to obtain new functionalities. For example, antimicrobial and stain repellent textiles are being developed using nanofunctionalized materials [17].

## 5. CONCLUSION

Molecular communication is integration of biology to interact with biological systems, nanotechnology to enable nanoscale and microscale interactions, and computer science to integrate into larger scale information and communication processing systems. Molecular Communication is another facet of communication engineering that tries to replicate natural communication protocols and apply them for various interesting applications. Molecular communication has significant potential and is at a critical stage, where some practical applications of molecular communication are required, which will only be possible with the collaborated effort of the scientists from all these different fields of science.

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