Molecular Communication*

A Nanotechnological Paradigm

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The importance of communication technology in day-to-day life and the impact of state-of-the-art miniaturization at the nanoscale on all-round progress are well recognized. Molecular communication, which is ubiquitous in natural biological systems, is a hybrid of these. We have described the basic concepts involved, the architectural aspects, and the applications of this emerging area of immense interest. The applications, both realized in practice as well as envisioned, cover biomedical (mainly healthcare), environmental, industrial and information technology realms.

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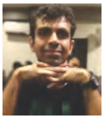

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1. Introduction

The word 'communication' signifies the exchange of information between individuals or groups at different locations through mutually understandable encoded/modulated symbols or signs. The message so transmitted from the sender to the desired destination may take values from a discrete or continuous set. On arrival at the receiver, the message is decoded/demodulated, and original information is reproduced with some deterioration caused by the disturbances in the intervening medium and imperfections in the system—the ever-present noise. Thus, the information reaching the end user may be somewhat distorted with respect to the one originating from the source. The physical arrangement or assembly of hardware components employed for accomplishing the task of transmitting and processing information is known as a communication system. It is generally presumed that this information is in the form of speech, music, picture, video, hieroglyphs, written

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text, or binary symbols, encoded in a format suitable for transmission across the physical medium or channel separating the sender and the receiver. However, it has recently been shown that biological and non-biological molecules flowing through various systems can also be used as carriers of information through these. This, in turn, has led to a change in the perspective on the subject of communication.

Reliable long-distance communication has been a cherished dream of humans since ancient times, and the efforts put in this direction make an impressive history (*Box* 1). As it stands now, communication systems have become part and parcel of our daily life (see *Box* 2). It is indeed fascinating that mankind has an inherent zeal for exploring and challenging itself and improving things by breaching the boundaries that separate the possible from the impossible. Following this tenet, the quest for developing cost-effective and sophisticated small-size devices giving good performance has culminated in the birth of nanotechnology (*Box* 3). However, it may be mentioned that nanotechnology is not a simple extension of relevant traditional technology because quantum effects become important in the systems at this scale (*Box* 4). The most basic functional units capable of carrying out a specific task in the nano-systems are known as nanomachines (NMs). However, an interconnected collection of these NMs is needed to perform a complex task and is called a nano-network. The exchange of information amongst NMs is referred to as nano-communication and can be realized through mechanical contact, pressure variations, electromagnetic waves, or the use of molecules.

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Nanoscale communication involving the transfer of information by encoding, transmitting, and receiving this as properties of molecules or nanoscale particles, is called molecular communication (MC). Its study as a mechanism of communication has been inspired by its existence in biological systems which are all around us. Some typical examples of these are the transfer of small biomolecules like hormones, peptides, lipids, etc., from one part of the human body to another and of neuron-generated action po-

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Box 1. A Bird's Eye-view of History of Long-distance Communication

The primitive attempts to communicate information from one place to another involved the use of smoke or fire signals, drum beaters, horn blowers, etc. This was followed by the deployment of horse riders as well as pigeons for carrying written messages and also the use of postal mail. A revolution in this direction was brought about by Morse, who concretized the earlier efforts by various people to develop the electric telegraph in 1837 using dedicated wires, and then put forward a messaging code that formed the basis of international telegraphic communication in 1851. This was followed by the formulation of electromagnetic wave theory by Maxwell in 1864 and experimental evidence of their existence by Hertz in 1887. In the meantime, Bell invented the telephone in 1875, which put the technology-based transmission of information (i.e., telecommunication) on a firm footing. Next, the development of radio by Marconi in 1901 led to the birth of wireless communication, which uses a part of the spectrum of electromagnetic waves for the transmission of information. Its numerous merits, like low cost, high speed, easy accessibility, constant connectivity, etc., made this a popular mode of communication. This technique got a strong boost from the invention of vacuum tube devices by Fleming, Forest, and others in the following few years, which laid the foundation of electronics. A further breakthrough came from Armstrong's development of superheterodyne receiver in 1918 and of television nearly 10 years later. A semiconductor-based, physically smaller, less power-consuming, more durable, and cheaper electronic component transistor, was invented in 1948 by Brattain, Bardeen, and Shockley. The technology so unfolded was significantly improved by the development of still cheaper silicon-integrated circuits with much better performance. This miniaturization has also dramatically affected the electronic computer technology, from the large-size vacuum-tube-based machine of the 1940s to the small chips-employing systems we now see around. This, in turn, has played an important role in the evolution of digital communication and its all-round progress due to its quite high transmission rate, compression, and ruggedness against noise. Furthermore, presently, besides electric conductors and wireless communication, clad glass fiber using laser light is also being used for communication. Before closing the content of this box, it may be mentioned that rigor-based theoretical foundation of digital communication was laid in 1948 by Shannon in his monumental publication 'A mathematical theory of communication', which provided the condition for error-free propagation of information carrying signal through the medium. This, in turn, brought him recognition as the 'father of information theory'.

tential to different nerve cells, muscles and glands, and so on. Obviously, it is drastically different from traditional communication as this involves the physical movement of information-carrying molecules from the sender to the receiver through a viscous medium. The resistive nature of the medium leads to higher-order disturbances and presents new conceptual challenges for design and architecture. Furthermore, because of its abundance in natural biosystems, it is generally illustrated by considering

Box 2. Communication Systems in Our Day-to-day Life

Some typical examples of communication systems we use as essential gadgets are telephone (landline, cordless, and mobile or cellular); radio and television (getting signals even from geostationary-orbit satellites, which makes these global); remote controls of television, audio devices, cars, etc.; bluetooth; wireless local area networks; Wi-Fi communication; computer, smartphone, tablet, etc., accessed internet and related applications; global positioning system; wireless computer mouse, keyboard, headset, etc.; and marine communication systems, aircraft communications addressing and reporting system, spacecraft communication systems. In fact, this list is certainly going to become more and more extensive as time passes.

Box 3. Nanotechnology – A Brief Historical Account

Strictly speaking, nanotechnology involves the use of materials with at least one dimension between 1 and 100 nm (1 nm, read as 1 nanometer, is one-billionth of a meter, or nearly one hundred thousandths of the average diameter of a human hair) for industrial purposes. However, this word is generally used to emphasize the smallness of the system involved, which may even be an order of magnitude larger than 100 nm. The idea of nanotechnology originated with the talk, "There's plenty of room at the bottom" delivered by 1965 physics Nobel Prize winner Feynman on 29th December 1959, at the annual meeting of the American Physical Society at Caltech. He dwelt upon the possibility of developing extremely small yet powerful devices through the manipulation of atoms in accordance with the laws of physics. In particular, he discussed writing the content of a book on the head of a pin in letters reduced by a factor of 25000 of the normal size and, thus, store and carry information in a minuscule space, and also, about miniaturization of computers. He also pointed out the wonderful characteristic of storing and communicating information of the biological systems as tiny as a cell. Though some efforts were made to develop semiconductor devices with sizes less than 100 nm in the early 1960s, the term 'nanotechnology' was first used by Taniguchi in 1974. However, it got recognition as a research field pertaining to the engineering of functional systems at the molecular level only in the mid-1980s. Since then, scientists have created numerous nanomaterials and nanodevices with applications in nanoelectronics, nanomedicine, industrial and purification processes, environmental remediation, energy harvesting, etc.

examples from this discipline and finds many novel applications in the related fields.

MC was put forward as an interdisciplinary research field involving communication engineering and molecular biology by Suda and coworkers in 2005. In their first two papers, published that

Box 4. Quantum Effects

At the nanometer scale, the behavior of particles is governed by principles of quantum mechanics rather than those of classical mechanics. Herein, the entities involved (viz. atoms, molecules, electrons, etc., and called quantum mechanical (QM) particles) are described in terms of a (complex-valued) wavefunction ψ, such that $|\psi|^2 dV$ gives the probability of finding the particle in a volume element dV. Mathematical treatment of the QM particles confined to a potential leads to discrete values of momentum and energy, which contrasts with what we observe in the things around us, say a ball for which these quantities have continuous values. The probabilistic behavior of QM particles also makes these follow the Heisenberg uncertainty principle and exhibit a tunneling effect. The former refers to a set of mathematical inequalities imposing an inherent basic limit on the accuracy with which the values for certain pairs of physical observables (such as position and momentum, angular position and angular momentum, etc.) of a quantum particle can be predicted. These aspects have no parallels in classical physics, and their manifestation gives rise to quantum effects. These, in turn, drastically influence various properties of materials when reduced from aggregated bulk to nanoscale. For example, unaggregated gold nanoparticles have a red color in solution and are not golden, and nanoparticles of the well-known semiconductor silicon behave as good conductors.

year, they described the basic concepts, the general architectural framework to develop a communication system for its practical realization, and the challenges to be faced while implementing the ideas. The first prototype MC system was experimentally demonstrated in 2008 by Hiyama et al. Some experimental work on recreating relevant functionalities and components in different biological systems was reported by some workers in 2009. Starting from 2010, researchers have also directed their efforts towards understanding various aspects of MC systems employing communication theory, statistical mechanics, and other mathematical techniques; on design, analysis, and computer simulations to create a robust network and to explore its different applications. Thus, MC has emerged as a remarkable hybrid nanotechnology based on principles of two very distinct disciplines digital communication and biology.

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The principal focus of this article is on the description of various aspects of molecular communication. To begin with, we point out the basics of a general communication system in the next section, followed by some details about the main aspects and typical char-

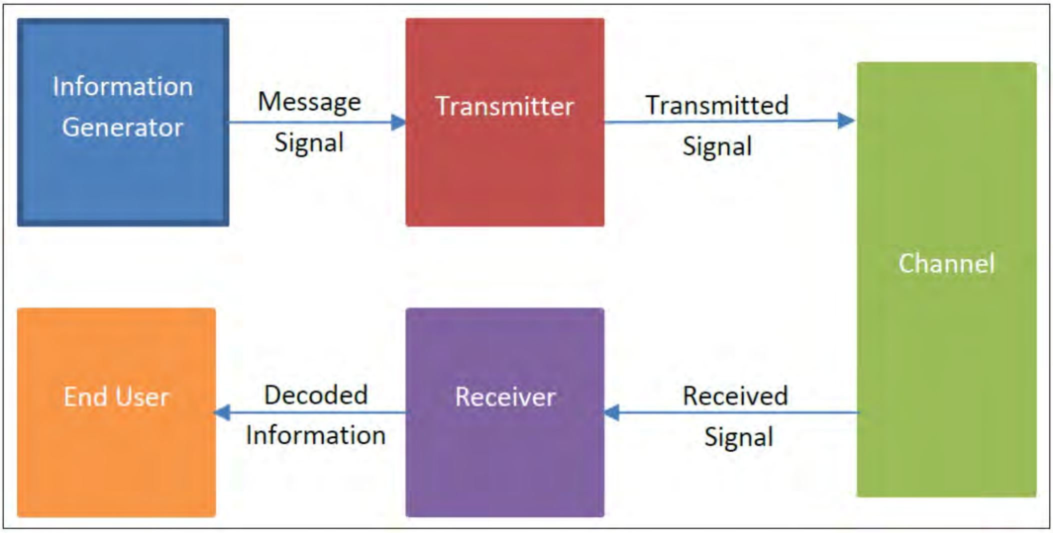

Figure 1. Essential constituents of a communication system.

acteristics of MC in sections 3 and 4. A comparative summary of its general features with those of traditional communication constitutes the content of section 5. Section 6 is devoted to different processes constituting MC and, thus, fundamentals of the design and architecture of an MC system. The article is concluded in section 7 with a brief discussion of its varied applications—both put into practice as well as envisaged. It is hoped that the article will help biology students achieve a coherent and comprehensive view of the subject of molecular communication. On the other hand, it should encourage students of physics and engineering to appreciate the relevance of communication theory to various biological problems.

2. General Communication System

The basic function of a communication system is to carry information from the location of a sender or transmitter to that of a receiver through the intervening medium or channel.

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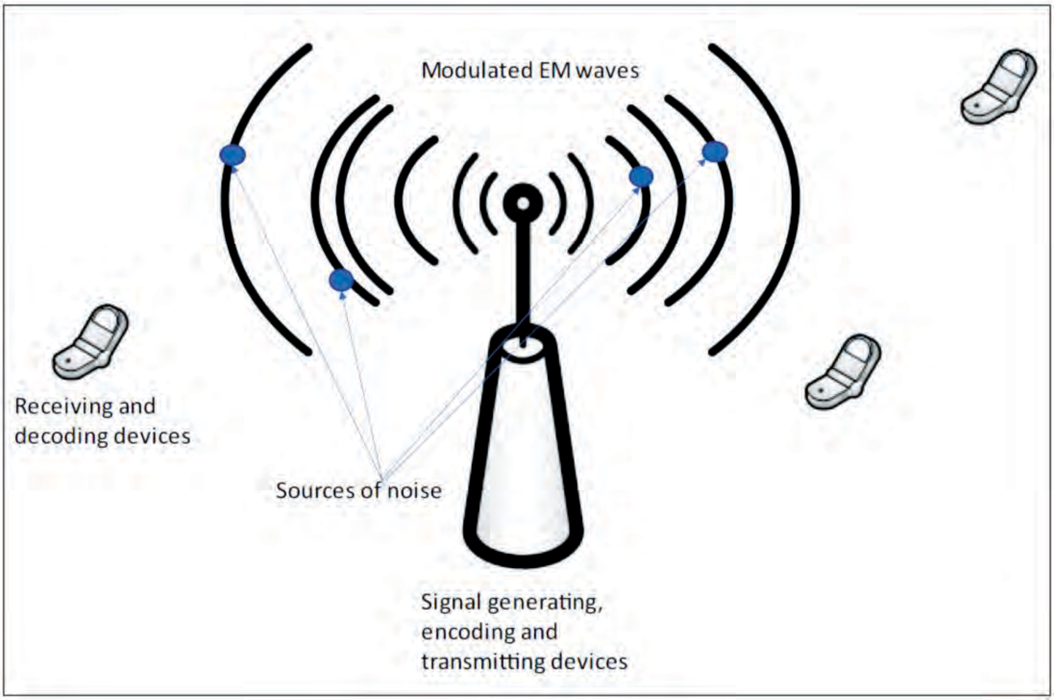

Figure 2. An outline of a telecommunication system.

3. Basic Aspects of Molecular Communication System

Molecular communication can be achieved by producing a system of sender and receiving devices at the nanoscale, which exchange information using molecules physically transported through the intervening medium. The key components of an MC system and the essentials of modes of propagation of the signal are discussed below.

3.1 *Nanomachines*

The tiny nano- to micro-scale entities comprising a small number of molecules, which can perform a particular simple task like the production of motion in and detection of molecules, are called nanomachines (NMs). These NMs constitute sender and receiver in an MC system. The NMs can be natural or artificially produced, and a collection of these can carry out multiple functions. The naturally occurring nanomachines composed of

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biomolecules (such as proteins, nucleic acids, lipids, biological cells, etc.) with or without non-biological materials (for example, magnetic particles, carbon nanotubes), and capable of implementing biological functionalities, are referred to as biological nanomachines or bio-nanomachines (BNMs). These can have the size of a few hundred nanometers (a macromolecule) to tens of micrometers (a cell) and are involved in the execution of many fundamental life processes. BNMs can also be made artificially using biological materials. Some typical examples of BNMs are mitochondria (organelles that convert oxygen and nutrients into energy-rich adenosine triphosphate (ATP) molecules in a cell), molecular motors or motor proteins like myosin, kinesin, dynein (that produce motion by converting chemical energy, derived from hydrolysis of ATP, into mechanical work), liposomes (spherical vesicles used for targeted delivery of nutrients and drugs), deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) (responsible for gene expression of cells), and prokaryotic (like bacteria) as well as eukaryotic (e.g., plant and animal cells) cells (in particular, these can sense specific type of molecules). Because of their biological origin, BNMs are inherently biocompatible, and some non-biological NMs can be engineered to be biologically friendly if needed. This unique feature, together with low invasiveness, makes nanomachines quite useful for biomedical applications. It may be mentioned that NMs and BNMs can be used as building blocks for developing complex systems, like nanorobots, capable of performing multiple functions.

3.2 *Information and Interface Molecules*

The molecules used for carrying the message from the sender NM to the receiver are called information molecules. To be faithful carriers of signal, these must be chemically stable and robust in respect of the physical medium through which these are to pass. Thus, the information molecules should have bare minimum interaction with the surrounding molecules. Also, these should not be affected much by thermal fluctuations. Some typical biological examples of these molecules are hormones (which control and coordinate internal metabolism, growth, development, and response to injury, stress, etc.), cytokines (that mediate and regulate immunity and inflammation), epidermal growth factor (a small polypeptide mitogen that stimulates proliferation of different types of cells), dopamine (which controls movement, memory, cognition, sleep, etc.), calcium ions (which play an important role in muscle contraction), DNA molecules (where a sequence of DNA nucleotides represents a message), and pheromones (which are used as signaling molecules by the plants, insects, and animals to activate a social response in members of the same species).

In view of the comments in the preceding paragraph, it is important that the information molecules are protected from different disturbances during their transmission from the sender to the receiver. Sometimes, this is accomplished by encapsulating these molecules during sending in such a way that the proper signal is delivered to the receiving NM. This vesicle-wrapped arrangement is known as interface molecules. Thus, the interface molecules not only safeguard the information molecules from the noise and chemical reaction with other molecules present in the environment but also make it possible to transport an assortment of information molecules through the same medium. Furthermore, the elimination of the possibility of a reaction between the information molecules and the surroundings also keeps the medium unaffected by the passage of the former. An example of this type of biomolecule is liposomes. In addition to the biological vesicles, nanomaterial capsules containing drugs (the information molecules) are used as interface molecules to deliver drugs to targeted tissues without producing any side effects on other tissues in the path.

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3.3 *Passive and Active Modes of Propagation of Information Carrying Molecules*

It is important to note that the information, as well as interface molecules, are physically transported from the sender to the receiver through the medium separating these, which, generally, is an aqueous solution. Thus, both types of these molecules travel through the viscous liquid environment experiencing a drag force and continuous random collisions with the surrounding molecules and ions. This makes the movement of the information-carrying agents irregular or Brownian. The resulting diffusion of these molecules (in all directions) is said to be a passive mode of propagation as this does not consume energy. Obviously, only a fraction of molecules starting from the sender move along the direction of the receiver and take quite a long to reach their destination, which means that the distance covered will be quite small. Also, this mode is relatively more suited for small molecules.

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It may be added that in a passive movement, the distance covered by a particle undergoing Brownian motion or free diffusion is not a linear function of time t. Rather, we talk about root mean square distance, which is given by $r_{\mathrm{rms}}(t) = \sqrt{6Dt}$. Here, D is the diffusion coefficient of the information-carrying molecule in the surrounding medium and is determined by its molecular weight and structure and by the viscosity and temperature of the medium. Thus, the time taken to cover a distance $l = r_{\mathrm{rms}}$ will be $t = \frac{l^2}{6D}$. For biomolecules like lysozyme protein, steroid hormones, and epidermal growth factor, the D values in aqueous media are 1.1×10^{-6}, 2×10^{-7}, and 5×10^{-7} $\mathrm{cm^2 s^{-1}}$, respectively. Thus, for illustrative purposes, taking $D = 10^{-6}$ $\mathrm{cm^2 s^{-1}}$, we find that time taken by such molecules to travel an rms distance of 1 cm will be of the order of 10^5 s, i.e., about 30 hours.

In contrast, to achieve directional transport of the information-carrying particles to specific sites, these must be subjected to a force supplied by the chemical energy. The motion so obtained is known as the active mode of propagation. This is comparatively fast (but still reasonably slow because of the presence of randomness arising from collisions with molecules of the medium). Also, it can be used to carry even larger molecules to somewhat greater distances and requires a lesser number of molecules to start from the sender (because these move in a particular direction rather than diffusion in all directions). However, the active mode does need a regular supply of energy and a track-like facility for directional motion.

In fact, in the case of biological systems, generally, the speed of the signal transport ranges from 10^{-6} ms^{-1} (1 micrometer per second or 1 μms^{-1}) to few ms^{-1} and the distance covered ranges from few μm to 2 m. Here, the fastest and the longest-range communication is observed in neural signaling, where the action potential is transmitted at nearly 100 ms^{-1} over a distance of nearly 2 m.

4. Main Characteristics of a MC System

(i) The sender and receiver NMs use the same communication mechanisms as prevalent in biological systems, making these capable of direct communication with the biological systems. This biocompatibility and consequent minimal invasiveness, together with its robustness in physiological conditions, make it feasible to implant such NMs in the human body for medical applications.

(ii) Since MC does not involve any kind of electrical consumption and consequent heat dissipation, and, rather, may involve biological processes which generate energy, this is more energy efficient. As an example, it may be mentioned that myosin converts ATP energy into mechanical work with an efficiency of about 90%.

MC is highly energy efficient because it does not involve any kind of electrical consumption and consequent heat dissipation.

(iii) The jiggle of the information and interface molecules caused by their random bombardment by the molecules of the medium of propagation makes the MC not only to be stochastic in nature but also a slow as well as short-ranged process. This is true whether the mechanism involved in the propagation of information carriers is passive or active.

(iv) In addition to the noise arising from the randomness mentioned above, the concentration of information molecules may be affected by the presence of the same species of molecules in the surrounding medium. Furthermore, these molecules may experience degeneration due to the existence of some molecules in the environment that affect their nature and because of factors like the pH and temperature of the medium. These, too, constitute noise for the system. A combined effect of these noises is that the molecules reaching their destination exhibit a spread about their mean properties.

(v) Using a group of sender NMs and a group of receiver NMs for transmission of information-carrying agents, particularly interface molecules and vesicles, through multiple channels, we can achieve enormous parallelism similar to multiple input multiple output (MIMO) system in wireless communication.

5. Comparison of Traditional Telecommunication and Molecular Communication Systems

Feature	Traditional	Molecular
Nature of signal	Electronic, optical	Chemical
Devices used	Electronic	Nanomachines
Encoded information	Voice, written text, video, computer data	Chemical states, phenomena
Propagation environment	Free-space, fiber glass, water, cables	Aqueous medium
Communication speed	Speed of light (3×10^8 ms^{-1} for free space and reduced by a factor equal to refractive index of the medium)	Very slow (10^{-6}–10^2 ms^{-1})
Propagation range	m–km	Quite small (10^{-6}–2 m)
Energy consumed	Electrical (high)	Chemical (low)
Noise types	EM fields, unwanted signals	Random collisions, Redundant molecules
Additional features	Accurate	Stochastic, biocompatible

6. Operational Aspects of Molecular Communication System

Broadly speaking, an MC system consists of a source (an NM or a group of these), the receiver NMs and the medium. The source provides information encoded molecules to be transmitted by the sender. The receiver NMs detect the information molecules and extract information useful for the end users. The medium separates the sender and the receiver, provides a channel for the propagation of the information molecules from the former to the latter and is viscous in nature. An outline of such a system representing

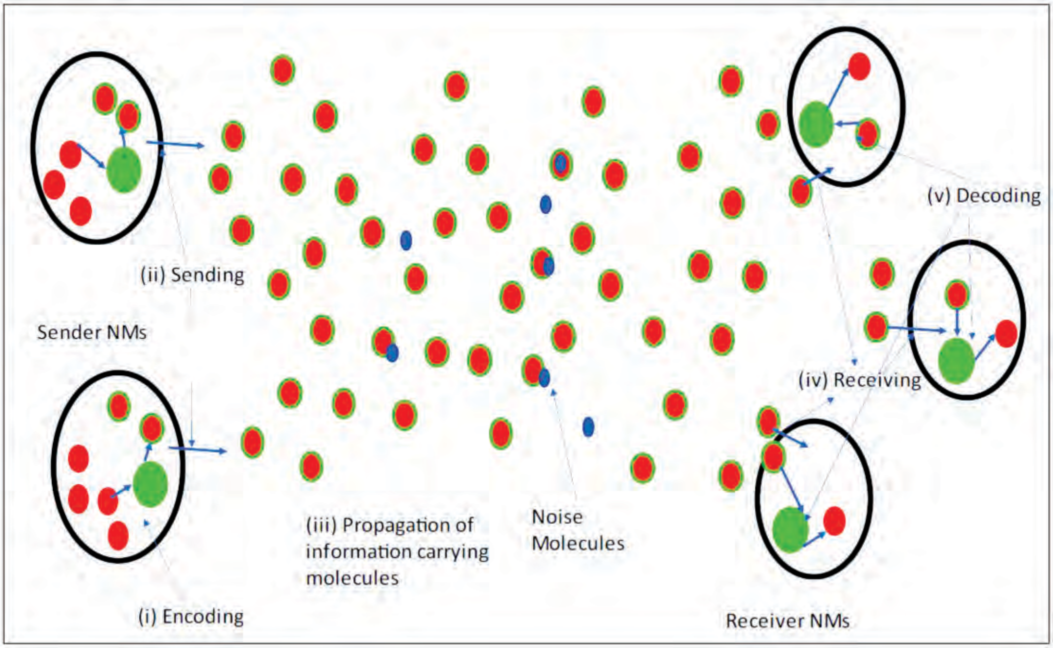

Figure 3. A schematic diagram for a molecular communication system and the processes involved.

the processes involved is shown in *Figure* 3. These processes are briefly described in the sequel.

(i) **Encoding**: The process by which a sender NM transcribes the message into information molecules in a unique form that can be detected and recognized by the receiver NM is called encoding. This can be implemented in different forms through modulation of physical and chemical properties of molecules, three-dimensional structure of molecules (e.g., protein structure), specific choice of the information molecules (e.g., DNA molecules having a specific sequence of bases), and the time-varying concentration of information molecules (as in calcium concentration).

(ii) **Sending**: It signifies the process by which a sender NM releases the information molecules into the medium for propagation. This release may be achieved by one of the following processes. (a) The information molecules undergo unbinding from the sender NM. (b) A molecular gate, such as an ion channel on the membrane, gets opened, which permits diffusion of the information molecules. (c) A chemical reaction is catalyzed, leading to the production of information molecules at the location of the receiver.

(iii) **Propagation**: It is the process of physical transportation of the information carrying agents from the sender NMs to the receiver NMs through the intervening medium. The information molecule may diffuse passively without consuming any chemical energy or may actively propagate as cargo by getting attached to a transport molecule or a molecular motor that physically travels over molecular rails (actin filaments on which myosin motors walk and microtubules on which kinesin and dynein travel), consuming chemical energy. These aspects make the transmission of a message by MC to be a slow and short-ranged phenomenon.

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(iv) **Receiving**: The process by which the information/interface molecules moving through the medium are entrapped by the receiver NMs is known as receiving. The mechanisms through which this detection can be carried out are as follows. (a) The receiver NM surface is such that the chosen coming molecules can get attached to this and produce reactions that lead to specific changes within the receiver NM. (b) The surface of the receiver NM is permeable to the input molecules so that these can enter the system and get attached to the user entity. (c) The surface has some type of chemically gated channels that permit passage of the information molecules into the NM. In general, the concentration of information carriers in the environment close to the sender is higher than that near the receiver.

(v) **Decoding**: Depending on the nature of the information encoded molecules captured by the receiver NM, different behaviors, such as structural changes, modification of chemical functionality, production of motion, or creation of new molecules, are triggered because of the chemical reactions between the two. This process is called decoding or demodulation. In the case of biological cells being used as receivers, protein synthesis and enzyme-catalyzed reactions are the usual mechanisms of decoding. It is worth mentioning that biological cells have a natural attribute of encoding as well as decoding chemical messages, which makes these quite useful BNMs.

7. Applications

The primary function of an MC system is to deliver information carriers from a source to a destination, which involves transporting, sensing, and modifying the molecules. These aspects are being exploited for their varied applications, detailed below.

7.1 *Biomedical Applications*

The main task of medical professionals is to reduce the suffering of human beings in a short time at low costs and make their life better. This mission has led to understanding the genesis of diseases at the cellular and sub-cellular level and to the development of smaller, efficacious, and cost-effective devices and systems for diagnosis and treatment. A consequence of this pursuit is the use of nanotechnology and, hence, to look for the applications of MC in health care. Some such activities are delineated in the next few paragraphs.

(a) ***Lab-on-a-chip***: Like the miniaturized micro-electromechanical and microfluidic systems, a lab-on-a-chip (LOC) is also a small-scale sample manipulation device (having a side of a few mm) that integrates and automates several laboratory functions (separation of a particular type of molecules from a mixture, reaction, and identification of molecules) into a single chip making this a fast, sensitive, and cost-effective arrangement. The LOCs having biochemical functionalities such as DNA sequencing, Polymerase chain reaction (PCR), etc., are useful for DNA analysis, human diagnostics, and general biological research. Integration of MC components in this chip provides nanoscale techniques to move molecules from one site to another on the chip, carry out chemical reactions in encased regions, and detect a tagged target. This, in turn, will make LOC a portable, cheap, reliable, and rapid medical diagnosis tool for future healthcare.

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(b) ***Health Monitoring***: The way to systematically check if the health of a human, animal, or plant organism is being affected by the prevailing conditions and, thus, to detect early signs of disease is called health monitoring. When implemented for human beings, this technique is also referred to as human body monitoring. The presence of specific molecules and their spatial distribution in the organism (say, the human body) provides information about a disease so that these molecules become a sort of biomarkers. This process can be executed more effectively by implanting BNMs in the body and using the MC processes to detect specific molecules (such as viruses and antigens) and to transmit the information to external devices for diagnosis. In fact, MC-based human body monitoring is being used to diagnose cancer and many other critical diseases in their early stages. The transmission of diagnostic information through telecommunication devices to health professionals not around makes it remote health monitoring and is in use for the care of heart and diabetes patients.

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(c) ***Molecular Imaging***: Molecular imaging is a fluorescent molecules based technique for visualization, characterization, and quantification of cellular functions and processes in vitro or in situ to collect information for diagnostic purposes. The generally used molecular probes that fluoresce on illumination with a characteristic wavelength are fluorescent proteins (green, yellow, red), and non-protein organic fluorophores like fluorescein, rhodamine, cyanine, etc. Recently, the quantum dots (which are semiconductor nanoparticles that fluoresce on being shined with ultraviolet radiation to give bright light, whose color depends on size and yields more accurate results), have also been added to this list. These probes get attached to specific proteins, and their location in a tissue can be traced using the property of fluorescence, thereby getting information about a disease like cancer. MC processes, when combined with this technique, improve coordination among the BNMs involved and provide more reliable results for a larger area in a patient's body.

(d) ***Targeted Drug Delivery***: Targeted drug delivery is a unique nanotechnological method of administering a drug at a specific site (diseased cells or tumors) in a human body so as to maximize the efficacy of drug molecules, producing the bare minimum side effects on the other non-targeted healthy tissues. This task is accomplished in three steps. First, the drug molecules are encapsulated in drug delivery carriers. Next, these carriers are transported to the desired location. Finally, the drug molecules are released at a controlled rate for absorption by the earmarked tissues enabling their therapeutic action within the chosen part. Obviously, the drug delivery carrier must be biocompatible, non-toxic, and biodegradable. These systems are being used in the treatment of cancer, cardiovascular diseases, diabetes, and tuberculosis. In conventional systems, the release of the drug molecules from the capsule is governed by the ambient conditions, like temperature, pH, etc., in the targeted tissue requiring medication. MC enables using BNMs (already present or implanted) as drug delivery carriers, whose transport can be coordinated in a better way by using molecular signals and BNMs having different functionalities. This, in turn, improves the accuracy of delivery by making it selective as well as more sustained and, hence, increases the effectiveness of the therapy. It may be added that if the pinpointed location for drug delivery is inside a cell, then the procedure is usually known as intracellular therapy. However, this is more challenging as the drug delivery carriers must overcome many biological barriers before releasing the molecules inside the infected cells.

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(e) ***Enhanced Immune Systems***: The immune system is a complex network of cells, proteins, and organs spread throughout the body that work together to defend it against outside invaders (called immunogens), by producing antibodies. These may be pathogenic organisms or germs (bacteria, viruses, fungi, etc.) that cause infectious diseases. These might be toxins or chemicals made by microbes. These could also be cells that have been damaged by cancer, sunburn, etc. The techniques of MC are being used to understand the mechanisms through which the germs enter the human body from outside, propagate within it, and are attacked by the antibodies to eliminate them. Thus, MC provides a methodology to understand the way the immune system acts and develops within the body over time. Besides, concepts of MC have been used to suggest ways to trigger and manipulate the immune responses in the host to intensify defense against specific immunogens by introducing artificial BNMs into the human body. This will, in turn, lead to planning better strategies for the treatment of immune system disorders, infectious diseases, and cancer.

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(f) ***Tissue Engineering***: Tissue engineering is an interdisciplinary area of activity that uses concepts and methodologies from biological science, material science, and engineering to develop a tissue structure that can be used to restore, maintain, and improve the functionality of or even replace damaged tissues and whole organs. Artificial skin, muscle, cartilage, bone, etc., are some examples of engineered tissues. When the procedure adopted for rebuilding tissues involves the use of stem cells, then it is usually called regenerative medicine. From the MC point of view, the engineered cells are BNMs that release molecules which on being differentiated by the relevant BNMs create patterns leading to the formation of a structure. This structure is then implanted into the patient's body to restore the affected tissue.

(g) ***Brain-machine Interface***: A brain-machine interface (BMI) is a neural implant that provides a direct communication pathway between a human brain and an external electrical device such as a computer or a robot to restore lost brain functions in respect of motor or sensory disability. To implement conventional BMIs, electrodes and electronic nanodevices are implanted in the brain. In the case of patients with BMI-based artificial limbs, motor signals produced in the brain are recorded through these electrodes and transmitted to an external device, which interprets these signals and operates the relevant limb to perform the desired activity. Similarly, in BMI-controlled treatment of brain disorders, signals generated in an external device are transmitted to electrodes in the brain, which, in turn, stimulate a specific part of the brain to manage neurodegenerative as well as neuromuscular malfunctions. For BMI applications, MC offers engineered BNMs for a less invasive and more biofriendly way of interaction with the brain through chemical means rather than the usual electrical signals.

7.2 *Environmental Applications*

The presence of harmful materials of any origin in the natural environment that has an adverse effect on routine activities and health is called environmental pollution. Information about the nature and distribution of contaminating substances can help pinpoint the problem in a proper perspective and to develop strategies to clean up the environment. The principles of MC can be used for this purpose by arranging different types of NMs or BNMs at various sites in the environment to detect the presence of contaminants and to identify the constituent molecules in a precise manner. The information gathered by this network of nano-sensors can be used to forewarn specific pollution. In addition, a group of NMs can also be deployed to process and, hence, degrade the toxic molecules into nontoxic forms, improving the quality of the environment.

By arranging different types of NMs or BNMs at various sites in the environment, one can detect the presence of contaminants and identify the constituent molecules in a precise manner.

7.3 *Industrial Applications*

The processes involved in MC can be used in some industries to improve the quality as well as output of their production. The agricultural industry can benefit from using BNMs to control the growth of different foods. In the manufacturing industry, MC can be used to monitor the transport and concentration of molecules and to get a variety of their patterns. This, in turn, can be used to produce a large variety of shapes and structures while using the same manufacturing machinery. This aspect can also be exploited to develop materials having specific functionalities.

7.4 *Information and Computer Technology Applications*

Information and communication technology will undergo a significant advancement by incorporating the NMs or BNMs into silicon-based chips.

It is contemplated that information and communication technology will undergo a significant advancement by incorporating the NMs or BNMs into silicon-based chips. For example, a mobile phone chip may be hybridized with a molecular lab-on-chip to carry out blood tests. Similarly, the integration of a network of NMs or BNMs capable of molecular communication into the internet will form an internet-of-nano-things or internet-of-bio-nano-things, which will be useful in collecting and monitoring real-time data related to healthcare (smart drug administration, nanoscale surgeries, etc.), environment, agriculture, and homeland security in a sophisticated manner. Furthermore, using NMs and BNMs for building novel computing architecture based on MC concepts will lead to the development of unconventional computation systems, which will be much smaller in size as compared to those that can be obtained from silicon technology.

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