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Wıreless Communıcatıons Beyond 5 g: Teraherzwaves, Nano-Communıcatıons and the Internet of Bıo-Nano-Thıngs

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Abstract

Two promising technologies cosidered for the Beyond 5G networks are the terahertz and nano-technologies. Besides other possible application areas they hold the commitment to numerous new nano-scale solutions in the biomedical field. Nano-technology, as the name implies, examines the construction and design of nano-sized materials. These two interconnected emerging technologies have the potential to find application in quite many areas, one of the most importan being healthcare. This overview paper discusses the specifics of these technologies, their most important characteristics and introduces some of the trends for their application in the healthcare sector. In the first section terahertz frequency radio waves and their specific properties depending on the surrounding environment are discussed, followed by an introduction to nano-scale communications. Terahertz waves mandate the use of nano-scale antennas, which in turn brings us to the concept of nano-scale nodes. Nano-scale nodes are units that can perform the most basic functions of nano-machines and inter-nano-machine communications, which allow distributed nano-machines to perform more complex functions. Beyond 5G the development of these nano-communications is expected to lead to the emergence of new complex network systems. In the second part of this paper the paradigms of the Internet of Nano Things, molecular commnications and the Internet of Bio-Nano Things are discussed followed by details on their integration in healthcare related applications. The main goal of the article is to provide an introduction to these intriguing issues discussing advanced nano-technology enablers for Beyond 5G networks such as terahertz and molecular communications, nano-communications between nano-machines and the Internet of Bio-Nano-Things in light of health related applications.

Keywords Nano-networks · Nano-technology · Molecular communication · Internet of bio-nano-things · Wireless nano-sensor networks · Terahertz band · Wireless body area network

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1 Introduction

In 1959, in his speech entitled "There's plenty of room at the bottom!" Nobel Prize-winning physicist Richard Feynman said "Many new discoveries will be born if nano-scale production is made possible" [1]. Today this centennial speech is considered the beginning of nano-science and nano-technology.

Some of his most important statements, astonishing at the time he shared them, created a roadmap for nano-scale related research. More than 60 years ago he urged people to consider the world of atoms as "the small world of atoms" and to "compare nano-things to hundreds of tiny hands that can rearrange atoms". He pointed out that "computers will be much smaller in size" and "the 24-volume Brittanica Encyclopedia can fit in a space physically as large as a pinhead"; that people will "be able to design extraordinary biological structures", where "miniaturization can be done by evaporation, and lubrication problems should be taken into consideration". He stressed on the utmost importance to "provide a clear definition of 'small imformation' and 'small size' when related to the nano-scale", which will mark the beginning of a total new engineering era.

Feynman concluded his speech with an interesting example: the students of a high school wrote on a pin head "Is it good?" and sent it to competing high school students. The rival high school wrote in the dot of one of the "i's": "It is not that good!" and sent it back. Feynman organized competitions at different levels for realizing the ideas he put forward and awarded hunderds of dollars to students who achieved the goals in the shortest time. His speech shows that important developments can be realized by people with wide imagination and open horizons. Today, many of Feynman's dreams are coming true, but there is still a long way to go.

The size of the computers, electronic elements and units used around us is getting smaller each year. The major driving force of this shrinkage trend is determined by the applications' requirements and the higher frequencies adopted. It has given rise to many new technologies in the 5G era and is envisaged to continue Beyond 5G where THz band communications will be actualized. With the increased frequencies used the wavelength of electromagnetic signals falls into the nano-meter scale, thus defining the so-called nano-communications as one of the major application areas of nano-technology. To be operational nano-networks will require nano-nodes, nano-routers and nano-gateways. An example is the so called in-body communication network where nano-nodes will ensure transmitting of information within the human body and between the human body and the outside world. This mandates that the size of the sensors is also reduced to nano-dimension. As wireless sensor networks are the major building blocks of many communication networks today (i.e. IoT and M2M) used in the world around us, the "in-body communication" will rely on wireless nano-sensor nodes and nano-networks for realizing communication within the body. Such communications can help administer vast number of functions, like directing body cells for disease defense or transporting medicine to specific organs. Besides healthcare applications, nano-technology and its derivatives can find applications in energy applications, environmental remediation, future transportation benefits [2–4].

The continuously increasing number of internet and mobile applications, their data volume and strict requirements both in terms of hgher data rates and lower latency make imperative the use of higher frequencies for realizing communications. In order to enable higher data rates, lower latencies and much greater overall capacity Beyond 5G networks are envisaged to operate in a higher frequency spectrum than 5G networks. Beyond 5G will use more advanced radio equipment and a greater volume and diversity of airwaves than today's networks. The use of extremely high frequency (EHF) spectrum, including the THz range is the one able to deliver ultra-high speeds and huge capacity over short distances. In light of this the research on THz communications in the last decade has immensely increased and continues to do so today.

The goal of this paper, different from other surveys, is to focus on the specifics of the THz frequencies and nano-communications from the point of view of their possible applications in the healthcare sector, the Internet of Nano-Things (IoNT) and the Internet of Bio Nano-Things (IoBNT) and provide a comprehensive overview of the related concepts, existing work and open research issues.

From here on the paper is structured as follows: in the next section the environmental behavior of the THz waves is discussed, succeeded by a short overview of the envisaged applications. Then the detailed consideration of communication issues in the THz band is provided and the IoNT and IoNBT are deliberated.

2 Behavior of Terahertz Waves in Accordance with the Environment

When designing nano-sensors, the frequency they operate at and the communication frequencies they will use are very important. Terahertz (THz) frequencies behave differently depending on the environment, so the communication distances vary quite a lot. This is due to the fact that atoms forming the medium show different vibrations in different ranges in the THz band.

This section focuses of the details and reasons of this varying behavior and its parameters. In the THz range molecules and atoms exhibit different vibrations as compared to other frequency ranges. Molecular vibrations can be divided into 3 groups; stress vibrations, angle bending vibrations and out-of-plane angle bending vibrations [5]. For example, a ring-forming molecule with an N atom has an N-1 bond. Of the 3 N-6 vibrations of such a molecule, N-1 are the binding strain vibrations and the remaining 2 N-5 are the angle bending vibrations.

2.1 Stress Vibrations

Stress vibrations are defined as the displacement of molecular groups. This displacement defines the length of the related vectors. When the simultaneous movement of different bonds in the molecule is realized in a synchronized manner it is called symmetrical stress vibration and if the movement is asynchronous it is called asymmetric vibration. Figure 1, illustrates the two types of stress vibrations: symmetrical and asymmetrical [6]. As a result of the asymmetric vibration, molecules tend to move asynchronously, resulting in increasing the frequency. Furthermore, frequency and energy are directly proportional.

2.2 Angle Bending Vibrations

Angle bending vibrations are the periodic change of the angle between two bonds. The displacement vectors are perpendicular to the bond direction (Fig. 2). Special forms of angle bending are: Shear, Swing, Ripple, Curl, Torsional vibration. These vibration types are shown in [6].

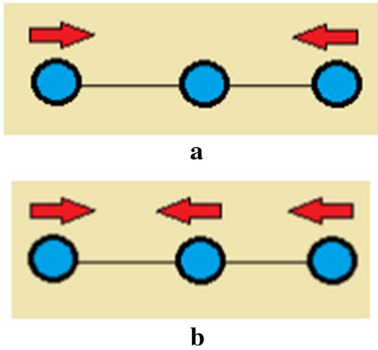

Fig. 1 Stress vibration. **a** Symmetric stress; **b** Asymmetric stress

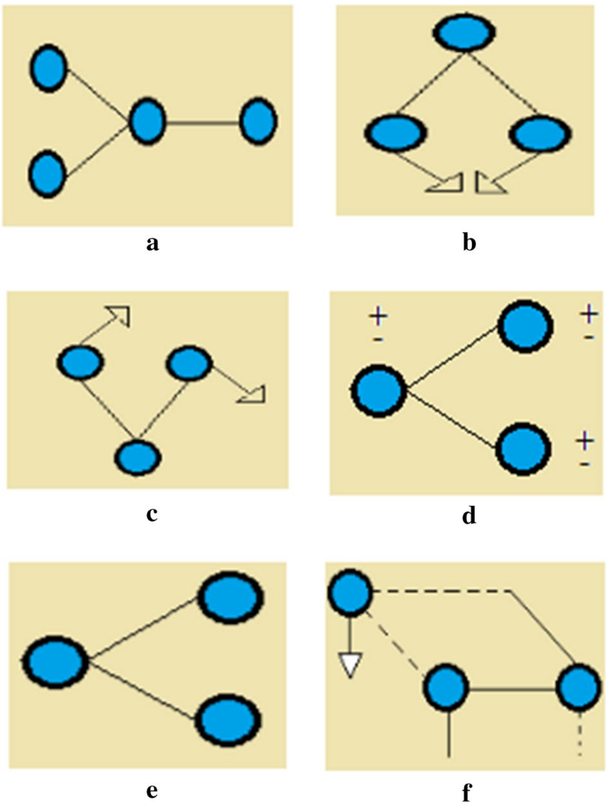

Fig. 2 Angle bending vibrations; **a** Angle bending; **b** Sheer; **c** Swing; **d** Ripple; **g** Curl **h** Torsional

2.3 Out-of-plane Angle Bending Vibrations

Another specific motion is the form of vibration that occurs in closed ring molecules which are umbrella-shaped [7] known as out-of-plane bending vibrations. An example is given in Fig. 3 below.

Electromagnetic waves at THz frequencies are affected by the vibrations of molecules as they move from one point to another also known as "flicker". Engineering design of

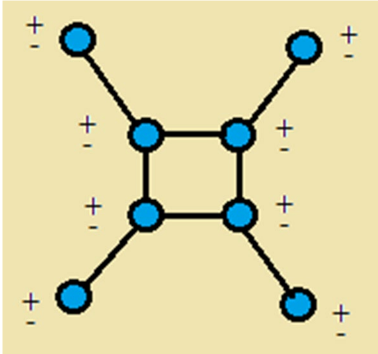

Fig. 3 Out-of-plane angle bending vibrations

systems transmitting in the THz frequency range should utilize flicker free zones. In such flicker free regions are investigated where the vibrations are at their minimum especially considering gas environments. This can be illustrated with a simple example: transmitting electromagnetic waves in the THz frequencies resembles the movement of people in crowded areas as comapred to the movement in non crowded spaces. Electromagnetic waves move more easily in flicker-free areas as it is simple to walk among fewer people or properly arranged groups of people.

THz waves can pass through almost every material to a certain degree, but the absorption of THz waves decreases in water and metal. THz waves cause the molecules they pass through to vibrate at certain frequencies. These vibrating molecules hinder the passage of THz reducing the transmission distance. So, in order to increase the communication range of THz waves, the vibration-free frequency range of the material to which THz waves are applied must be detected, i.e. material and media specific transmssion windows have to be determined. High frequencies are needed to transfer data at high speed. Thus Thz waves are indispensable for 5G and beyond. In addition, we need high frequency to make nanosensor networks with small antennas, which is also possible with THz waves, because the antenna size decreases as the frequency increases.

The technology based on THz frequencies finds application in different areas such as medical imaging, spectroscopy, MEMS (Micro Electrical–Mechanical Systems), communication systems, and wireless sensor networks. In almost all of these application fields, it is very important to take into consideration how the environment behaves at THz frequencies.

3 Applications of Terahertz Technology

3.1 Imaging Technologies

Thanks to its proximity to the infrared field, THz waves can be adapted and used for the design and construction of THz imaging in different imaging applications as i.e. harmless imaging. THz imaging applications have found a very important place in the field of security. THz imaging is especially used for scanning people at checkpoints in airports, as it can see behind and inside objects, while exhibitings quite high resolution. Compared to x-ray devices, it is less damaging to the human body and to the operator in charge. THz imaging systems are classified into active and passive source systems. Active source systems contain a source that can generate the THz wave; while passive source systems can only measure THz waves from solar energy [8].

In our country there are a number of current projects using THz's imaging technology. [8] developed a prototype called 'THz Wave Generator Spectroscopic Detection and THz Imaging Prototype ' which uses a passive source system method and achieves 3 cm resolution for up to 10 m distances in the range of 0.1 to 3. The authors also state that due to the use of THz waves the system can also operate quite successfully under fog condititons. The proposed design can also be used at airports for scanning purposes, checking whether there is a harmful object on the person without passing through special X-ray devices. The development of THz imaging technology shows that it can be utilized in different industries to test the quality of fiber composites [9]. Furthermore, thanks to its non-destructive measurement capability, THz imaging can be used to perform detailed quality control in food products.

3.2 Spectroscopy

Spectroscopy is a technology which examines the interaction of electromagnetic radiation with matter. The interaction of matter molecules with the electromagnetic waves, especially THz waves results in different vibration movements such as rotation, shear etc. This mobility of the molecules, in turn brings about changes in the energy levels of the molecules, which are the main field of study of spectroscopy. Spectroscopy is used to investigate different the behavious of THz frequencies, and molecules, and more specifically phenomena like superconductivity, plasmonic effects of conductive material and rotation phases. The resonance frequency of most materials is within the THz frequency band. The movements of molecules are generally divided into two, namely vibration and rotation [10]. As the name of the rotational movement implies, the rotation of molecules, like the rotation of a pendulum, creates a change in the dipole moment of an asymmetric molecule. Vibration movement is divided into tension and bending. Stress movement is the result of symmetrical or asymmetric stretching of bonds between two atoms, just like a spring. Bending vibrations are shear and torsional vibrations. Absorption of THz waves increases in areas where vibrations occur as it is more difficult for people to walk in crowded environment. Spectroscopy [11] is one of the important methods that show which molecule vibrates and where.

3.3 MEMS (Micro Electrical–Mechanical Systems)

Richard Feynmann believed that many new discoveries could arise if nano-scale production could be realized and emphasized how important it is to develop special measurement and production methods. One embodiment of his ideas is the development of Micro Electrical–Mechanical Systems, known as MEMS. This is a very dynamic, rapidly growing technology that can shape our future lives. Using this technology, microelectronic circuits or mechanical structures can be integrated in various elements and devices, reducing the size of the micro systems, while providing integration in one piece and ensuring the production of very low-cost devices [11]. Nano-nodes and the communication between them can be realized using MEMs technology. An example can be found in [12], as a communication unit with molecular or nano-electromagnetic nano-node and graphene-based antennas. Graphene is defined as the structure of carbon in a single atom thickness. It is an interesting material with great potential for use in a large number of application areas due to its combination of extraordinary mechanical strength, extraordinary electronic and thermal conductivity, sealing properties against gases and other special physical and chemical properties. Some of the important structural properties of graphene include purity, error density, thickness and size. Because of these superior characteristics it is a prime candidate for nano-nodes antennas allowing massive volumes of data to be transmitted in the THz band. Research activities carried out in Georgia Institute of Technology under the quidance of Professor Dr. Ian F. Akyildiz are testing the transmission of terabit sized data in seconds using antennas made of thin graphene. They also aim to realize this fast data transmission in the THz band [13].

3.4 Communication Systems

One of the main areas that THz waves are envisaged to be used in the future is wireless communications. As explained in detail in the Electromagnetic Modeling of THz Waves for Wireless Communication section, the communication distance of THz waves is short but the amount of information that can be transmitted is very high. THz waves have no problems passing through environments other than metals and liquids, but molecules exhibit different vibrations at specific frequencies. Absorption of THz waves increases in areas where vibrations occur and reduces the transmission efficiency. The answer to the question mentioned in the previous section, "how difficult it will be for a person to walk in a crowded environment" is that it "would be easier to pass among people who are lined up in a reverse manner". This is what is meant by the statement "THz waves prefer flicker-free zones". From engineering point of view it is important to determine which molecule vibrates and where it vibrates. To achieve this diverse methods can be employed. Infrared spectroscopy shows the frequency ranges with increased absorption [14]. Another method is HITRAN (High-Resolution Transmission Molecular Absorption) which is used to determine which molecule vibrates at which frequencies.

One of the main disadvantages of THz waves is the short transmission range. Due to the short communication distance, it is envisaged that in order to create THz based networks base stations can be installed in the streets in streetlamps, in office ceilings and in classroom environments close to available sources. These ultra-fast, ultra data volume connections hold great potential to become the main building block of the 5G and Beyond 5G infrastructure. [15]. Electronic storage capacity is one of the limeposts of how fast technology develops thorugh the years. In 2005 Toshiba announced the first 1 GB of portable memory, while during the same year Samsung made the world's first portable memory of 2 GB. [16]. Only 10 years later, the capacity of portable memory has increased by 10^7 times and Intel and Micron developed a 10 TB memory with the standard SSD size [17]. As we believe that technology is thought to continue to develop at this rate, it can be calculated that portable memory can reach 1 EB (exabit) ($10.^6$) TB in only five years from now. In line with these examples, it can be deduced that wireless portable memories supported by graphene antennas will be in the market in no more than 5 years. Thanks to THz communication, 1 TB data can be transferred wirelessly in 1 s depending to the specific bandwidth used. This speed is almost the lowest predicted communication speed [18]. Among the first applications that will mostly benefit from such ultra low latency data transfer are remote surgery, and holographic teleportation which are estimated to require close to 5 Tbps with an end-to-end latency of less that 1 ms. [19]

4 Electromagnetic Modeling of Terahertz Waves for Wireless Communications

Simulations and mathematical modeling come into play in cases where test environment has not been implemented yet and it is difficult to establish the environment for the application at hand. Simulations and mathematical models provide information about the results of experiments and make valuable predictions about their performance. In this section, the analysis of THz waves for different environments, which is not possible through real life experiemnts, is presented based on channel modeling and simulation of the communication properties of the media.

As radio waves travel over distances, they incur losses due to absorbtion in the surrounding environment and also in the air itself. The study in [20] investigates the specifics of THz waves absorbtion. The starting point in modelling the transmission of THz waves, is the Friss formula [20, 21] shown in Eq. (1). In Eq. (1) P_t is the power of the transmitter in free sapce, d is the distance, G_r and G_t are the gains of the transmitting and receiving antennas, L_0 is the free space loss which can be calculated as $L_0 = 32.4 + 20\log(d) + 20\log(f)$. Distance d is measured in km and the frequency in MHz.

$$P_r(dBm) = P_t(dBm) + G_r(dB) + G_t(dB) - L_0(dB) \tag{1}$$

While Eq. (1) is true for sub THz waves, in the case of communication using THz waves there is, in addition to the freespace loss, also the system loss caused the system noise and the absorption in the surrounding medium other than air. The formula with these additional losses is shown in Eq. (2) [22, 23].

$$P_r(dBm) = P_t(dBm) + G_r(dB) + G_t(dB) - L_0(dB) - L_{Noise}(dBm) - L_{Medium}(dB) \tag{2}$$

The loss due to noise can be expressed in dBm as shown in Eq. (3):

$$L_{Noise} = 10log_{10}(1000*k*T*B)(dBm) \tag{3}$$

Here T is the temperature in Kelvin, B is the frequency bandwidth in Hz, k is the Boltzmann constant, approximately 1.3801 × 10–23 j/K. The temperature is taken as 296 Kelvin which is the value of ambient temperature [22, 23].

The propagation of EM waves, especially in the THz bands, becomes obstructed by various additional phenomena as mentioned in the previous sections. Even if the constituent environment is gas, the loss due to absorption at some points may reach very large values enough to affect the results from data communication point of view. The vibrations of each molecule in the THz bands are different at different frequencies and respectively affect the absorption of EM waves. A method to observe these is the Fourier Infrared Spectroscopy (FTIR). It allows measurement of molecular bonds using infrared radiation. Infrared radiation is absorbed by the vibrational movements of molecules and leads to the formation of spectral peaks in the infrared section. These peaks are specific for different molecules as well as bacteria, and used for the separation and classification of molecules and bacteria. Whichever medium is modeled, the absorption coefficient of that medium should be obtained and the media absorption loss added to the system loss should be calculated as shown in Eq. (4).

$$L_{Medium}(f,d) = k(f)_{Medium}*d*10*log_{10}e(dB) \tag{4}$$

The coefficient k (f) in Eq. (4) gives the absorption coefficient of the medium, which varies with frequency[22, 23].

5 Constituent Parts of a Nano-Node

Nano-sized communication machines require nano-sized antennas and such antennas operate in the THz frequencies. On the other hand, from functional point of view, the main components of the nano-radio sensor nodes are no different from the existing radio sensor components. Nano-wireless sensor networks will be designed with nano-measurements. The main functionality and details of the nano-networks components are explained in more detail in the follwoing sections [3, 22].

5.1 The Sensing Nano-unit

The detection unit is intended to use graphene, an extremely strong material. Graphene is a single layer of carbon atoms arranged in honeycomb form, which is about 200 times more stronger than steel. Thanks to its structure graphene can be used to make ultra fast transistors, semiconductors, transparent electrodes and sensors. The components of the nano-node should fulfill the same functions as those of the existing wireless nodes. In the detection unit, physical quantities such as force, pressure, and displacement can be detected; chemical quantities such as chemical composition, molecular density can be evaluated; nano-detectors identifying biological entities and processes such as antibody/antigen interaction, DNA interaction and enzymatic interactions can be designed. Valuable entities that will be useful with this technology are the NTES (NTES—Nano-Technology Electromechanical Systems) [23, 24]. Nano-nodes can be divided into three main groups: physical, chemical and biological as shown in Fig. 4.

Carbon nano-tubes (CNT) are another alternative technology which can be used in the development of detection units for nano-radio sensor networks. The main features of the CNTs are their small size, their ability to respond precisely very quickly, and their ideal operation at room temperature. These basic properties allow the use of CNTs as gas molecule sensors. In addition, when CNTs are used as electrodes in electrochemical reactions, it is more advantageous to use them in the design of the detection unit due to their ability to remember and increase electron transfer. CNTs detect the nano-sized materials and

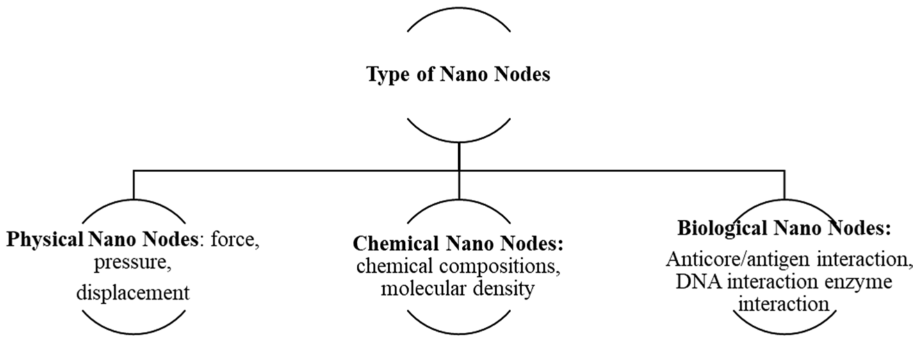

Fig. 4 Varieties of nano-nodes

reactions in terms of structure. In particular, semiconductor single-walled CNTs are highly susceptible to changes in the environment, they are 3 times more sensitive than existing sensors. The specific structure of the CNTs, will allow the construction of devices that are much smaller in size, much more sensitive, which react much better at room temperature and are more functional [24, 25].

The pioneering work regarding the application of nano-sensors for in-body communication belongs to Dr. Meyyappan. He was one of the first researchers to work on the design of CNTs as biosensors. In his work, Dr. Meyyappan aimed to generate and detect electrochemical signals in micro-working areas. [26, 27] Today it has been clearly demonstrated that nano-sensors produced using different methods can detect reactions in the body and give a predefined response. Thanks to a nano-sensing unit, implanted in the body as part of a nano-scale wireless sensor networks, recognition of serum biomolecules such as Glucose and DNA can be provided. When changes in the hormones within the body are detected, it is possible to calculate the concentration of the nano-sensing hormone and, if necessary, to produce nano-vehicles that will react to return it to normal levels. Studies are ongoing not only on hormones, but also on nano-machines capable of detecting intra- and extracellular events, and in an adverse situation that have the ability to interfere with enzymatic activity, drug delivery or mechanically [26, 27].

5.2 The Power Nano-unit

Given their extremely small sizes nan machines and nano-nodes will comsume much less energy as compared to current sensors and wireless sensor nodes. Many authors envisage that a major source of energy will be provided by self powering like for example through controlled vibrational energy harvesting using piezoelectric nano-generators [28]. Besides ensuring communication functions nano-nodes are expected to perform processing and data storage functions. Thus other forms of energy supplies are also considered. Lithium nano-baterries in nano-metric dimensions are contemplated for the power unit of the wireless sensor nano-node. The capacity of nano-batteries can go up to 45 µAh-1 cm–2 µm-1. Lithium nano-baterries are difficult to charge especially when in-body communication is taken into consideration. Recharging nano-batteries is not a simple task, luckily however, inspiration can be taken from many cases exsiting in nature. Another alternative to the formation of the power unit of nano-nodes in the body communication is the use of zinc oxide (ZnO) nano-wires. Zinc oxide nano-wires tend to return to their shape again when a certain force is applied. The vibrations thus generate current. For mobile phone technology and portable electronic devices, light and high energy capacity batteries are needed. In order to meet the needs in this field, sol–gel technique is being studied on nano-scale crystals. Batteries designed by using metal hydrate and nickel nano-crystals are another open research area [29, 30].

5.3 The Processing Nano-unit

It is also graphene that paves the way for the production of nano-processors. While the silicon processors we use today overheat and start burning at 9 GHz, graphene does not experience heat problems up to 500 GHz. Transistors, which provide a key to access to today's technology, enable the design of processors by being able to open or close an electronic gate according to the specific amount of electrical current they receive. Graphene transistors, on the other hand, can switch themselves on and off upon slightest current change and perform this operation thousands of times faster. Tests have shown that graphene-based processors can run up to 427 GHz. This means that even if the speed is calculated quite roughly, 100 times faster computers can be built. In addition, Prof. Dr. Engin Umut Akkaya showed in his studies that molecules can perform mathematical operations. With this invention, he paved the way for future micro- and nano-sized computers [31, 32].

5.4 The Storage Nano-unit

The famous projects proposed by Feynman that were discussed in the introduction were difficult to realize in the conditions of that day when he announced a prize of 1000 dollars to those who reach the result. The first of these projects was an engine to be produced in centimeter dimensions. The second was to reduce the size of a text page 25,000 times and in such a way that it can be read with an electronic microscope. Feynman's first project was realized by William McLellan, an electrical engineer, only a few months later in 1959. McLellan's engine features 250 µg, 0.3 mm in length and 33 cycles per second and is a cube-shaped engine. This engine, which earned McLellan the remarkable $ 1,000 prize, is on display at the California Institute of Technology, although it does not work today. The completition of the second project was not so fast. Twenty-five years later, Tom Newman, a graduate student, reduced the first page of Charles Dickens's novel "The Story of Two Cities" by 25,000 times and sent it to Feynman for $1000. Thanks to these projects, Feynman realized the first steps of nano-technology. "Nano-technology" as a term was coined in 1974 for the first time by Professor. Dr. Norio Taniguchi. Atomic memories are still a hot research topic today. As with CD-ROM and its derivatives, they preserve the information in the form of logical 0 s and 1 s.

A film was created using atoms in IBM laboratories. It was made by recording the snapshot of the molecules. In the film, a story is told with the movements of about 5000 atoms. The film is the world's smallest film made with a single-picture motion technique and contains the title of the Guinness Book of Records. If the film is expanded in size; and if the atoms were the size of an orange, the orange would be the size of the world. In other words, considering the magnification of the atom seen in the electronic microscope 100 million times, it can be estimated how difficult it was to create the film. It uses sound to move atoms. The intensity of the sound given to the atom was important because it helped to calculate how quickly the atom could advance. This example illustrates how far the nano- and atomic technology has come today. Returning to Feynman again, he said that each atom can carry information, so that when 125 atoms are equalized to one bit by $5\times5\times5$ atoms, 32 atoms can encode a bit of information in DNA [31]. Considering the density the carbon structure and taking the distance between two atoms to be 0.142 nm [32], then the storage capacity can be estimated to be greater than 1 bit per nm^3 or 1 gigabit per μm^3.

5.5 The Communication Nano-Unit

Communication of nano-nodes will be provided using molecules or nano-electromagnetically. Most prominent candidates are graphene based antennas. For general applications in 6G two major types are considered in [33–35]: the plasmonic reflectarrays and the electronically-controlled reconfigurable antenna arrays. The plasmonic reflectarrays are able to reflect signals in non-conventional ways, which include controlled reflections in non-specular directions as well as reflections with polarization conversion. On the other hand, electronically-controlled antenna arrays are based ion the possibility to change the resonnat frequency of graphene-based plasmonic nano-anetnnas by using small voltage to change their energy [14]. Graphene, defined as the structure of carbon in single atom thickness, is an interesting material which has a large application potential. It comes as a result of the combination of extraordinary mechanical strength, extraordinary electronic and thermal conductivity, sealing properties against gases and other special physical and chemical properties. Important structural properties of graphene include purity, error density, thickness and size. Because of these superior properties, it is such a promising candidate for antenna material in nano-nodes. In wireless data transfer, sending large data, such as 20–30 GB, can be troublesome and long. Under the leadership of Prof. Ian F. Akyildiz, at the Georgia University of Technology, researchers have reported that they were able to transfer data at a rate of 1 Tbps over a distance of several meters using graphene-based antennas. Prof. Akyildiz told journalists from the MIT Technology magazine that the graphene antennas are nano-structures with length of 1 μm and width of 10–100 nano-meters, which makes them suitable for the transmission of THz frequencies [36, 37].

6 Benefits of Nano-Communication for Health Care

Nano-communication is a new communication paradigm that has become a very hot research topic in recent years. The concept of connecting nano-things and especially the term "Internet of Nano-Things" (IoNT) was coined by Ian Akyildiz and Josep Jornet [37]. That early research defined the paradigm of nano-communications in general and the major research challenges along the way of its development in terms of channel modelling, information encoding and protocols for nano-networks. The concept of nano-communications refers to the construction of wireless sensor networks from nano-sized nodes which will be able to interact with cell-size or smaller units. It is very relevant to the healthcare sector where communication with cell-sized units (also called engineered cells or therapeutic nano-machines—NMs), and biological entities (i.e.living cells and bacteria) opens novel ways for the development of new diagnostic and treatment methods. Such nano-wireless sensor networks can be designed for destroying viruses or cells in the body by simply deploying them where the viruses or harmful cells are. With the help of nano-sized wireless sensor networks, various changes in the body can be monitored with utmost precision nearly in real time. As an example, we can consider a heart attack case where very accurate information can be instantly transmitted to the doctor and will enable him to intervene faster. Other specific benefits of nano-networks can be related to health applications with longer operation period, e.g. nano-nodes can enter the body's circulatory system, repair cells at the cell level and cure diseases, or provide early warnings about illness symptoms. Nano-sized wireless sensor networks will be able to intervene with the disruptions in the cells and be enabled to make changes in the DNA by micro scissors [36]. Nano-size wireless sensor networks may allow anti-cancer therapies to be developed with nano-nodes that can release DNA and chemotherapy in a precisely controlled manner only to cancerous tissues.

Even though such senarios might seem quite futuristic there are already several positive palpable developments in that direction. In a project carried out at the Massachusetts Institute of Technology, very small sensors have been developed to monitor chemical changes in the body that can lead to cancer. These sensors can also observe the effect of cancer drugs on living cells. The project leader, Prof. Michael Strano disclosed that his team has succeded in developing sensors made of thin strands of carbon molecules, coated with

DNA much smaller than the cells in the human body. These sensors can emit fluorescent light in the same spectrum as human tissue does and the method is used to receive data. The intensity of light changes when it interacts with DNA. This allows researchers to recognize specific molecules. The absence of any problems in the interaction of the sensors with DNA indicates that these sensors can be easily used in the body [38, 39].

By examining the neuro-nano-networks and the principles of electro-molecular design, nano-networks can lead to the development of new nano-communication methods inspired by biological systems. In this respect, nano-networks can provide intelligent personalized precision drug delivery solutions for patients with nervous system diseases which are not treatable today like spinal cord paralysis. Nano-networks can be used to help overcome side-effects of cancer treatment and provide sophisticated methods for cell-level health status examination [40, 41].

7 Nano-Communication Methods with Potential Use in Health Care

In [42] the authors indicate four possible methods for realizing nano-scale communication: nano-mechanical, acoustic, electromagnetic and molecular. The first two—nano-mechanical and acoustic communication are not suitable for in-body communication due to principle limitations and device size. Nano-mechanical communication requires mechanical contact between transmitter and receiver while acoustic communication poses size limitations due to the wavelengths used. So the two methods that are actually feasible for realizing in-body network communication and IoNT especially for healthcare applications are molecular communication (a new communication method) and electromagnetic THz wave based communication, which utilizes currently known communication principles.

7.1 Molecular Communications

Molecular communication is a promising method of communication for nano-scale networks. It is a kind of communication that predicts a chemical reaction or changes such as smell, light, taste etc. and provides communication among molecules by using nano-nodes. The major components of molecular communication comprise the transmitter, the receiver and the medium, similarly to classical communications. If we define the receiver and the transmitter in molecular communications as nano-machines, then the medium will be defined as a diffusion channel of molecules. Communication between molecules and nano-machines can be compared to the ligand-receptor adhesion phenomenon used in biology. The human endocrine system can be used as an example. It consists of hormones and secretory glands that produce hormones. The body's circulatory, digestive, excretory, respiratory and skeletal systems communicate through hormones building up the endocrine system. The communication realized in the endocrine system is very slow. Hormones are produced by the glands and transmitted to the blood stream. When the corresponding hormone reaches the target unit, the target unit secretes another hormone, reducing the hormone that triggers it. In this way, the body continues to work in a balance. Hormones in the endocrine system control many changes for example growth rate and development, the specific operation of our organs, the metabolism and the reproduction processes [43, 44].

Molecular communication is limited when considering the available nano-machines. Communication distances and studies of nano-machines are influenced by the dielectric properties of the environment, its density, water content and many other parameters. In this respect, new theories and techniques are needed to formulate and explain the mechanisms of how nano-machines communicate with each other. In molecular communication, the communication channel also has a variable signal/noise ratio. More details on research in this respect can be found in [45–47].

7.2 Electromagnetic Waves Communications

For many years one of the major network communication methods has been the one in which Electromagnetic (Radio) waves are used for signal transmissions. Various frequency ranges address the needs of various environment (transmission channel) requirements. While the KHz frequency range was used for wired communications, cellular and wireless communications in general utilize the licensed and unlicensed MHz and low GHz range. Electromagneic waves in the Thz range offer an alternative to molecular communication especially related to nano-networks and body communications. Developing high frequency processing technologies and reducing the antenna dimensions with materials such as graphene and CNT will allow for the construction of nano-nodes in nano-dimensions. The components of nano-nodes are detailed in chapter 2. But there are many problems that electromagnetic communication must overcome. Dielectric properties of molecules in very restricted and narrow areas are important in electromagnetic communication. At certain frequency ranges, the communication distance may increase, while at certain frequencies the communication distance may show a sudden decrease. Therefore, the structure of the molecules that make up the environment should be analyzed and modeled in detail, and the longest communication distance should be defined by determining suitable frequency bands. Electromagnetic waves communication will be influenced not only by the dielectric characteristics of the environment, but also by factors affecting the current electromagnetic communication, such as signal-to-noise ratio, power of the receiver and transmitter, free space loss. These components should be carefully considered and calculated when creating an in-bodynano- network [3].

7.3 Comparison of Communication Methods

Table 1 provides a summary of molecular communications in comparison to other existing wireless network communication methods.

The two most promising methods to be used with nano-networks are molecular and electromagineci wave communication methods. Each one however has its own advantages and disadvantages. Molecular communications for in-body networks are considered in great detail in [48]. As their main advantages the autors point out that molecular communications are biocompatible and are based on existing natural phenomena. It is also very important that their possibility to realize directed communication tasks has already been proven by some early system realizations. An example is using nitric oxide signaling elements for an artificially controlled cell-to-cell communication mammal cells reported in [49] Molecullar communication can also be realized by using molecules as communication carriers.

Molecular communications for in-body networks however pose some very serious challenges which are clearly summarized in [48] as: very slow propagation speed; channel characteristics are quite difficult to predict and very different than the traditional wireless cahnnels; molecules and respective nano-machines move according to Brownian motion and other cell and molecule specific laws; transmitted signals are very prone to noise,

Table 1 Comparing molecular communication method with other wireless communication network methods)

	Molecular communication	Electromagnetic communication	Magnetic induction	Optical communication	Acoustic communication
Information carrier	Molecule	Em wave	Em wave	Fiber optic	Environment
Signal type	Chemical signal	Electric signal	Electric signal	Optical signal	Audio signal
Spreading speed	Extremely low light speed	(3*108 m/s) light speed	(3*108 m/s) light speed	(3*108 m/s)	Sound speed
Spreading environment	Water environment	Air, soil, water	Air, soil, water	Air, water	Usually water

where noise comes for an array of factors like thermal noise, channel noise, molecular noise, drift and fading; nano-scale materilas and nano-machines production still has very high defect rates and operational uncertainties.

Electromagnetic based communications for nano-networks have also been considerably covered in recent years and there are a number of real life experiemnets with CNT, graphene anetnnas and antenna arrays. Their main disadvantage is that they are not naturally biocompatible. However, considering the IoNT it seems easier to provide a connection with the outside world while this is much more complicated in the case of molecular communications. Possible adoption of electromagnetic waves for in-body communication may simplify the interface with other out-of-the body-systems which is one of the critical points in IoNT. On the other hand, molecular communication has a great role to play in the emerging nano-medicine, which uses molecular knowledge of the human body to apply molecular tools for diagnosis, treatment and prevention of diseses. First gerenation nanopores [50] as well as synthetic cell tools [51] are some clear examples of the possibilities molecular communications has to offer.

8 Nano-Communications and the Internet of Nano-Things

Thanks to the development of various short and long range wireless technologies and standards [52] as well as the advances in M2M (Machine-to-machine communication) [53] and D2D (device-to-device communications (D2D), in the near future, most of the devices used today will be able to access the internet in an autonoumous way, independent of human beings. These developments have already given rise to many innovations in our daily life and a paradigm shift in communications from human-oriented to a more general human-benefitial communication. Most important of all is the concept of a new "Internet", the Internet connecting not humans but things, known as the IoT (Internet of Things). Briefly defined, the IoT represents a set of devices that can form an intelligent network, communicate with each other through various communication protocols to collect and analyze data in order to provide service to humans and their activities. Every object used in daily life, from refrigerator to television, washing machine to heater, can connected to the internet and communicate with other devices [54]. The term IoT technology was first introduced by Kevin Ashton in 1999, for covering devices that communicate with each via RFID (Radio Frequency Identification), but today this concept come to cover a much wider and much more comprihensive field [55]. In 2008, the number of devices that received IP addresses was higher than the world's population in that year. In 2020, this figure is expected to reach to 50 billion. IPv6 with a 128-bit address length is one of the major candidates to ensure connectivity to such huge numbers of devices.

It will be very simplistic to define the IoT only with the logic of smart devices in the home, office or city, which can communicate with each other. IoT will bring innovation not only into our homes it will result in fundamental changes in many other sectors like industry, transportation, logistics, energy management and the health services to name a few. While in the early years IoT was adopted in sectors like smart city, connected industry and smart energy, the trend shows increasing number of IoT projects related to healthcare in more recent years. A study done in [56] identified 1600 actual enterprise IoT projects in the top ten IoT segments, and compared the data for 2016 and 2018. While the number of projects related to smart city and connected building continue to rise, projects related to connected health have also joined their list.

8.1 Internet of Nano Things (IoNT)

While IoNT is functionally considered as a logical extension of the IoT into the nano-world, there are also a number of significant differences between the two. The IoNT, as first introduced in [37], requires novel medium access mechanisims, different addressing schemes, routing and association procedures. Besides the nano-nodes, described in Sect. 5, the IoNT network requires nano-routers, nano-micro interface devices and also gateways. Nano-routers are similar to nano-nodes but have larger computational resources, can control simple nano-nodes and are able to aggregate information coming from several nano-nodes. Nano-micro interface devices are another important component of IoNT, able to aggregate the information coming from nano-routers and convey it to the microscale or vice versa. These interfaces can speek the two languages—the language of classical communications and the language of molecular or nano-scale communication. Finaly the gateways are powerful components of the IoNT network which can ensure the communication with the outside world. A classical example of a gateway is a cellphone which can receive and process information from our wrist nano-micro interface and transmit it over the internet. Since 2010 when the groundbreaking work in [37] was published, many new advances have been made at the nano-scale and have pushed IoNT from hype closer to reality. Scientific research has in turn pushed the market expectations high. The healthcare industry is expected to hold a significant share. The Internet of Nano-Things Market is expected to grow at a CAGR of 24.12% over a forecast period from 2019 to 2024. [57] The high health care expectations especially in a world with quickly aging population have led to a a large increase in the demand for more efficient, more affordable and improved healthcare. There are already some examples of using IoNT in healthcare related scenarios.

Scientists at the Nano-Photonics Centre at Cambridge University together with Melville Laboratory for Polymer Synthesis have developedng a so called “intelligent lavatory” that can capture key data in users’ urine and use it to check levels of drugs, helping patients to adjust their medications accordingly. It uses gold nano-particles to collect molecules for analysis.

The developments and advances in nano-technology have allowed the detection of diseases in very minute amounts or in their initial stages. In April 2019, a pair of NJIT inventors Bharath Babu Nunna and Eon Soo Lee demonstrated nano-technology enhanced biochip which can detect cancers, malaria and viral diseases such as pneumonia early in their progression with a pinprick blood test.

The greatly increased investment in healthcare systems in emerging and developed economies is expected to boost the investment in the fields of IoNT as well. In the last twenty years significant progress has been achieved in the area of incorporating IoT in the healthcare.Monitoring data, electronic records and telemedicine are being successfully integrated at various levels with the national health systems in many countries. From here on the next step is forseen as integration with the IoNT, a step which will open new horizons in precision and personalization of medical care.

Thanks to IoT, the status of patients with chronic illness can be monitored continuously and communicated instantly to their doctors or relatives [58]. Even if the system cannot reach the doctor or his/her relatives in an emergency, the system will be able to contact the first aid team and ensure that the patient’s immediate blood values or other important biological parameters needed for the doctor to evaluate the situation are sent before the patient reaches the hospital. In this way, health specialists will be able to intervene more quickly and possibly save lives that could otherwise be lost. For example, a patient with increased likelihood of having a heart attack can be singled out automatically and much faster depending on specific changes in his vital biological parameters. If the patient is having a heart attack, his blood values will reach the hospital even before the patient is brought there. In this way, necessary first aid measures and medications will be prepared before the patient comes to the hospital and the chances of saving his life will be greatly increased. IoT and nano-communication technologies will merge together to ensure that emergency health situations in a patient are communicated to respective doctors instantly without the need of other people and services getting involved in the process. Many of these practices will be implemented on a daily basis and will be implemented quite soon (Fig. 5).

The intergration of IoT and nano-communications in the healthcare sector relies on a major component—the Wireless Body Area Network (WBAN). WBANs today comprise a number of non-intrusive small size devices (wearable ECG/EMG/EEG/SpO2, blood pressure, step counter and temperature meters [59]) used to collect information about various vital signs like temperature, blood pressure, oxygen saturation etc. [59]. These wearable devices have communication capabilities and can connect wirelessly to the outside world directly (smart watches) or through an external gateway (smart phones). Integration with nano-devices will open a whole range of new possibilities. Nano-devices (nano-sensors, nano-nodes, nano-actors etc.) will be placed inside the patient's body to provide much more detailed, accurate and timely information about his/her physiological state. Examples of applications close to this technology in daily life might be tablets swallowed for tracking the bacteria and microorganisms inside the body. IoNT will not only provide instant monitoring of the patient physical state, but will also allow detailed analysis and storage of large amounts of measurement data. The accumulated data will pave the way for more precise and personalized treatments. As an illustration we can consider the application presented in [60]. It is developed by using Zigbee nodes and ZigBee based wireless sensor networks. Another possible solution is to connect the pulse oximetry device to MicaZ wireless sensor nodes as done in a project in Ege University, EEE Department (Fig. 6). That application developed in Turkey, allows for current values of measurements of the patient's oxygen saturation, blood pressure and pulse to be displayed on a screen and at the same time sent to the medical staff if desired [61]. Details of the system are shown in Fig. 6. The developed prototype based on sensor networks has been tested in Ege University Hospital, Izmir, Turkey. The wireless nodes are programmed with nesC, the pulse oximetry device

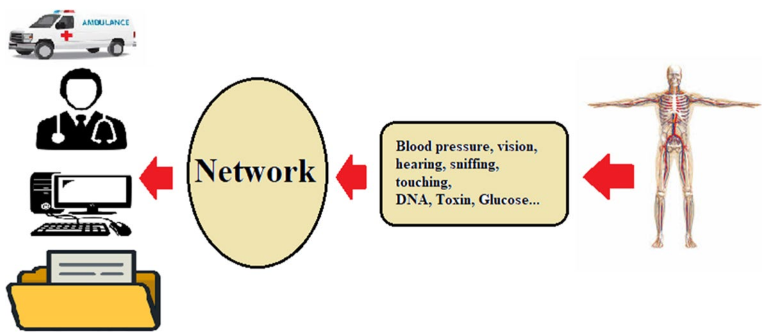

Fig. 5 Basic model of using IoT in the biomedical field

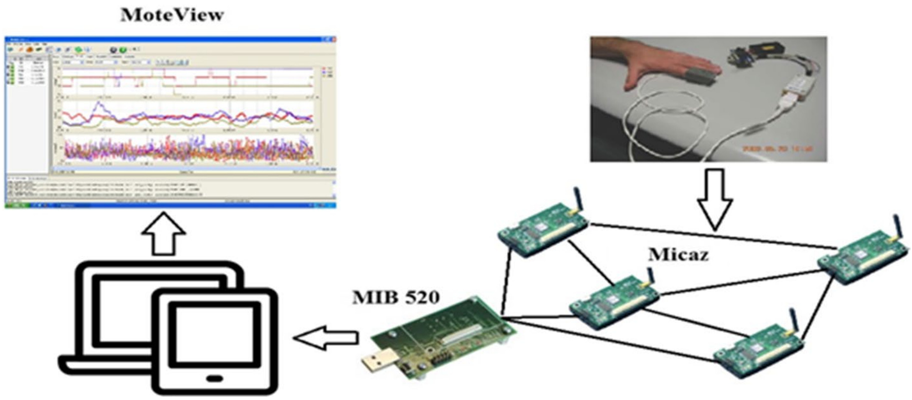

Fig. 6 Instant patient monitoring system with Micaz motes

is connected to MicaZ nodes and the data about the patient's pulse rate, plethysmogram and blood oxygen saturation are transferred to the central database via wireless network ustilizing the ZigBee standard. The performance of the system is measured in terms of the percentage of lossed packets in various network topologies. Today, such systems are quite widespread. Integration with IoNT can immensely enhance the capabilities and precision of such systems. The pulse oximetry device and MicaZ node shown in the figure can be realized by nano-nodes. Data accessibility, which in this project is realized by MoteView interface via a computer, can be diversified using more flexible IoNT and mobile interfaces.

8.2 Internet of Bio-Nano-Things (IoBNT)

At the intersection of IoNT and molecular communications a bold and futuristic vision is drawn in [62] by Akyildiz, Pierobon, Balasubramaniam and Koucheryavy—the Internet of Bio-Nano-Things (IoBNT). The concept is introduced focusing specifically on in-body communications. Despite the considerable success in studying and production of nanomaterials and nano-devices (especially graphene based ones), their artificial nature brings along compatablity problems when in body applications are considered. The novel concept introduced by Akyildiz and his colleagues is more related to synthetic biology and nano-technologies. It conceptualizes engineering of biologically embedded nano-devices that have communication capabilities within a specific range (biochemical domain) and are safe for use in human bodies. To illustrate the idea, Fig. 7 exposes the parallel between the components of a wireless node and the respective subsystems in the human cell. Nanonodes can be designed to implement the functions of wireless sensor nodes or embedded devices by using methods of synthetic biology and nano-technology. In addition to the essential nano-communication components described in the previous sections, the so called "actor nano-nodes" might also be required. These actor nano-nodes will be able to interfere actively inside the body's and cells' functions creating the required changes in targeted body cells. Such methods will provide precise, uninterrupted and highly personalized intervention inside the human body when required [63, 64].

Basically, the IoBNT communications is characterized as a specific derivative of molecular communications. The data collection, processing, encoding, transmission and

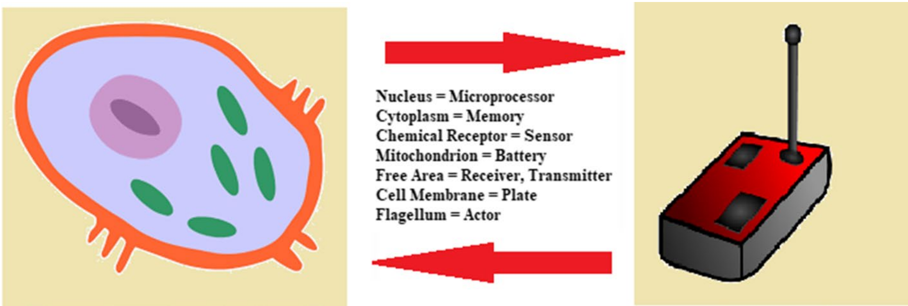

Fig. 7 Elements of a biological cell and components of a typical IoT device

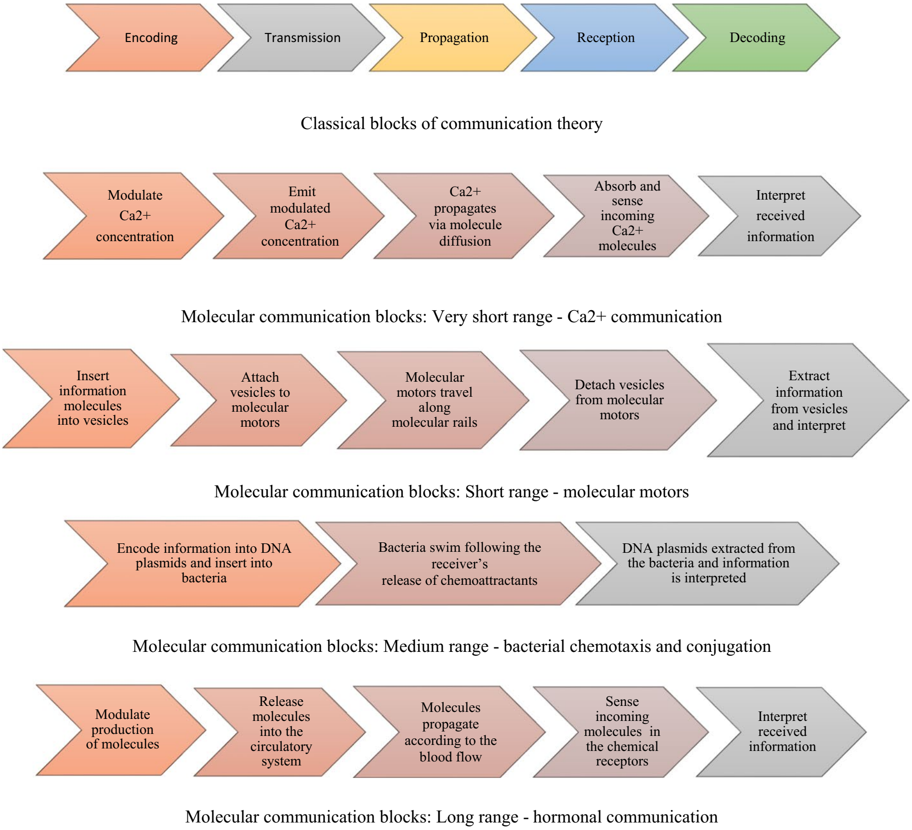

Fig. 8 Bio-IoT communication methods [54]

decoding can be engineered mimicking some specific biolocical funtionalities as illustrated in Fig. 8.

To epitomize the notions described above, Fig. 8 provides a comparison of the conventional communication steps with the bio-IoT communication methods. In many aspects the steps in molecular communication are quite similar to the classical communication steps. Specific to molecular communication is the fact that the communication method (transmission agent) differs according to the communication range. Transmission is provided using Ca2 + or molecules as carriers for short distances, while bacteria are used as carriers for medium range transmissions. Information molecules are inserted into vesicles or bacteria as carriers (similar to the encoding in classical communications) transmitted through molecular motors along molecular rails (communication channel), detached from the vesicles at the receiver end where information molecules are extracted (similar to decoding) and the information is interpreted accordingly (Fig. 9). Hormones and hormonal based communications on the other hand can be given as an example of a biological carrier which can realize long-range communications. [65, 66].

The suggested biological based networking concepts in [66] aim to extend the existing multifaceted communication that already exists between the organs and the systems in the human body with the purpose to collect and provide information in an externally controlled manner. The purpose is to inform the external health unit for extraordinary situations by adapting to the body's own system. In the human body, reporter molecules can be divided into two groups, primary and secondary messengers. Primary messengers are messenger molecules that enable intercellular communication, such as hormones and growth factors. Secondary messengers deal with intracellular communication. Primary and secondary messengers work in an organized way. The speed of this highly complex communication depends on the proximity of the cells. In the case of nerve cells the situation is very different—even though the cells are very far from each other the communication speed is very high. This is due to the specifics of the nervous system structure (neuron-based) and transmission agents [67, 68].

On the flip side, there area also lot of various problems to be solved regarding these new communication methods. For example, molecular signals, such as electromagnetic signals, cannot determine their direction. In molecular communication, signal communication is random. Therefore, new methods have to be designed for data transmission and new taransmission channel models should be developed. Nature is there to offer us ideas but there is still a long way to go.

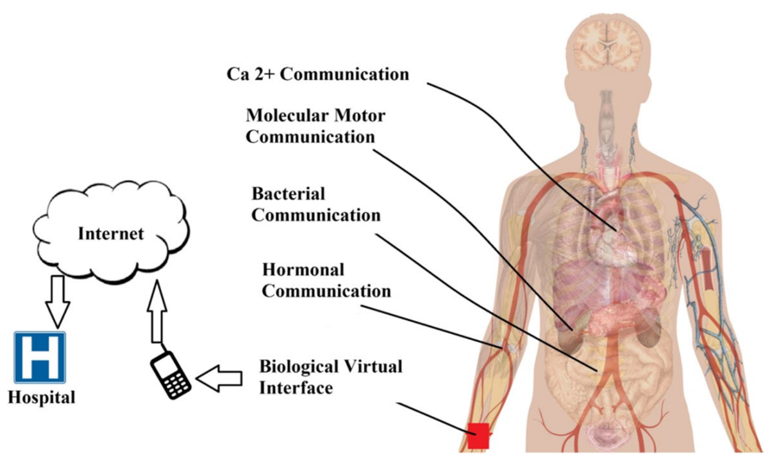

Fig. 9 Bio-IoT communicationnetwork architecture

Despite its resemblance to existing and already well-known in-body biological communication methods, the IoBNT still has a lot of blanks to be filled. Just think of the time when mobile phones were first introduced in the early 90 s—who could imagine that these useful but quite awkward and function limited devices would evolve in only a decade to become the most indispensable device we own today. The possibility that they would be able to make video calls and access the internet was totally out of scope at that time. The constantly increasing speed and variety of innovations has long surpassed many predictions. IoBNT might only be the next step not only into relieveing humans from current illnesses but maybe also perfecting them as Yuval Noah Harari says in his book "Homo Deus". However, it can bring many new problems with them. For example, the close monitoring of the human body may expose humanity to biological wars and terrorist attacks. Therefore, security measures should be considered and new standards should be developed. Precautions should be taken in case new viruses appear. This type of security measures requires re-thinking and re-designing the security measures considered and used in today's internet technology.

9 Conclusions

This paper discusses THz waves as one of the leading technologies of the future and considers applications they can support especially related to the health sector. In the first part details on the specifics of THz waves and network communication based on THz waves is presented.

The second part focuses especially on nano-communication and their applicationsin healthcare. Current state-of-the-art in in-body networks and transmission methods are presented followed by an in-depth discussion of the IoNT and the IoBNT. The communication methods proposed for biomedical communications—molecular and electromagnetic communication- are discussed and compared. Both methods are very important for in-body communication and each has its own pros and cons. The concepts of IoNT and IoBNT are presented including information about major components, technologies and node prototypes. Thanks to the the recent advancement in the design of nano-machines, nano-networks, nano-nodes and nano-sensors, the developments deliberated in this article are not too far in the future. Under the leadership of Professor Dr. Ian F. Akyildiz, the Georgia Institute of Technology, Broadband Communication Laboratory, projects are currently underway for the development these nano-technologies with a budget of nearly 3 million dollars. Another initiated ptoject is under the leadership of Professor Dr Özgür Barış Akan, from Turkey, the Minerva project, with a budget of 1.8 million-euro provided by the European Research Council (ERC). It focuses on examining the communication foundations of the nervous system for biological-based nano-structures and information-inspired neurological therapy. In this light, it is believed that the current article can serve as a guide for researchers who want to start work in this field and contribute to the exciting developments in nano-communications for medical applications that are just around the corner.

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Code Availability (Software Application or Custom Code) There is no code in this manuscript.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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