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From Nanocommunications to Body Area Networks: a Perspective on Truly Personal Communications

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Pawel Kulakowski, Kenan Turbić and Luis M. Correia

Abstract

This paper presents an overview of the problems related to really personal communications in a future perspective, i.e., ranging from communications inside the human body, to communication from a device on the human body to the outside environment. On the one hand, nanocommunications, understood as molecular communications (those performed in between groups of molecules or cells) will enable a range of applications that definitely will capture the attention of medical doctors, among others. The increase in scale will go through communication with nanodevices inside the body, followed by in-body communications (from these nanodevices to on-body ones), and then on-, off- and body-to-body communications (which address communication among devices on the body, and from these devices to external ones, being on the outside environment in general or on the body of another person). This paper intends to show how this gap can be closed by introducing proper interfaces, and also by referring some potential applications.

1. Introduction

The several successive generations of mobile cellular and wireless communications have basically been aiming at a single goal: to provide connectivity to people at their own pleasure. It started with the famous "anytime, anywhere" motto in the 1st Generation of mobile cellular communications for voice communications, and then it has been evolving to providing data and multimedia communications at higher and higher data rates. Of course, once the transfer of data becomes "instantaneous", the goal of increasing the data rate does not make too much sense anymore, which is why in fact the incoming 5th Generation aims at two other key goals: reduce transmission latency and increase connectivity capacity. These two other goals are not basically improving the direct user's experience (as it was the case for data rate), but rather enabling the use of machine-based applications and services. So, somehow, the evolution of mobile and wireless communications needs to address the truly personal dimension of communication, i.e., exchange of information within, through and outside the body.

Body Area Networks (BANs) have been explored for some time, concerning in-, on- and off-body communications. The proposed frequency bands to be used in these communication systems vary a lot, ranging from UHF to mm waves, depending on the system and application, among other aspects. Still, for the truly personal scale of communications, one needs to encompass nanoscale communications, enabling communications in between devices inside the body but not included in the in-body BANs' scale, but ultimately allowing for communications using the body. Of course, this ultrawide range of communications puts a quite large number of system issues, varying from power supply to distance, including aspects of frequency band, bandwidth, propagation speed, data rate, and modulation, among many others. In addition, one needs to address other technological matters, e.g., type of antennas, besides all the others concerning electronics, interfaces, materials, and so on.

The paper intends to provide first insights into these truly personal communications, with a survey addressing aspects on the how to integrate nanocommunications with other networks, how to create interfaces between nano/micro world and classical wireless networks, and other related problems. The paper is organised as follows: Section 2 presents nanoscale communication mechanisms, Section 3 looks into nano-micro-macro interfaces, while Section 4 addresses BANs at mm waves, and Section 5 discusses applications, before conclusions being presented in Section 6.

2. Nanocommunication mechanisms

There are few quite distinct approaches to the problem how the communication in nanoscale can be realised; here we describe three main ones which can be referred to as: (a) electromagnetic (EM)-based, (b) molecular and (c) FRET-based.

The first approach is based on the idea of **miniaturization** of existing electromagnetic solutions. Because of the small desired scale of devices, the EM frequencies must be very high. It is generally considered to use THz band (0.1-10 THz). It is feasible, if the antennas are made not from metal, but new materials like carbon nanotubes or graphene in general [Jornet2013]. Inside such materials, the EM propagation velocity is about 100 times smaller than in vacuum, so the wavelengths of the THz band are in micrometers range. Regarding the energy supply, having in mind that nanomachines should be able to perform their actions autonomously, it is very important to provide a local energy source or energy harvesting option. There are already proposed solutions based on of nanowires made of zinc oxide (ZnO). These nanowires, while bent e.g. because of a fluid flow in their vicinity, are able to generate electric voltage. It is assessed that for the purpose of supplying a single nanomachine, about few thousands of such nanowires are needed, each being 2 μm long and having 100 nm of diameter [Canovas2016].

These electromagnetic (working in THz band) solutions are currently intensively investigated; anyway, it should be noticed that both abovementioned aspects, i.e. the wavelength and the dimensions of the energy source, suggest that they are suitable rather for micro scale than for nano. On the other hand, these systems are quite easy to be integrated with networks in macro scale, as they share the same communication medium, which is the electromagnetic spectrum. Consequently, they could perform as gateways between macro and nano devices.

In the second approach, communication mechanisms known from the biological world are exploited. There are many ways how communication occurs in cells of living organisms. The information carrier in not an EM wave, rather a group of molecules, so these techniques are commonly named as **molecular communication**. One of the most widely considered molecular communication techniques is *calcium wave propagation* using diffusion (Brownian motion). It is just this mechanism which is used for signalling between living cells. Information is coded via modulation of concentration of sent calcium ions. Another option is using diffusion for broadcasting some larger particles. They could be *polymers*, carrying information coded in their modified structure, e.g. bits ‘0’ and ‘1’ might be coded modifying polymers with either hydrogen or fluorine atoms. In general, the diffusion process is rather a slow mechanism, e.g. the average velocity of calcium ions does not exceed 30 µm/s. It is why some scenarios are also considered where the diffusion velocity is increased by drift of the environment (which is also called flow assisted propagation) [Kadloor2012].

Another group of molecular communication techniques is realized with active (by contrast with passive diffusion) transportation of encoded information. Data bits can be encoded in the DNA chain (A, T, C and G nucleotides) of a plasmid located inside a *bacterium* or attached to a *catalytic nanomotor*. The bacterium, e.g. popular *Escherichia coli*, then travels using the force of its flagella. Catalytic nanomotors, which are usually gold and platinum nanorods, can, on the other hand, exploit chemical energy from the environment [Gregori2010]. All the mentioned carriers, bacteria and nanorods, are typically of 1-2 µm size.

There are, as well, solutions based on *molecular motors*, which are structures moving inside living cells. Molecular motors, kynesins or dyneins, are about 100 nm long and may carry cargo which can be encoded information, e.g. RNA or a sequence of peptides in a vesicle [Enomoto2011]. These motors ensemble wired communication, as they move along protein tracks called microtubules, so this type of communication is far more reliable than other approaches listed here. They are, however, quite slow, travelling only few µm per second or even slower.

Finally, the third approach is based on a phenomenon called **Förster resonance energy transfer** (FRET), which allows for non-radiative energy passing between two molecules. The first molecule, a nanotransmitter, being in high energy state (excited by an external radiation or a chemical reaction), may pass its energy to a neighbour molecule, a nanoreceiver. Applying FRET to nanocommunications, ON-OFF modulation is commonly accepted, what means that sending a bit ‘1’ is realized by a FRET transfer and sending bit ‘0’ – just not sending anything [Kuscu2012]. The phenomenon of FRET occurs only between spectrally matched molecules, i.e. the nanotransmitter emission spectrum should overlap the nanoreceiver absorption spectrum. There are, however, some possibilities to fill the energy gap between the molecules, if needed: e.g. with phonon-assisted energy transfer [Loscri2018]. FRET really operates in nano scale; the communicating molecules, usually fluorophores or quantum dots, are of 2-20 nm size, and it happens quite fast – the whole process lasts just few nanoseconds. At the same time FRET has clear limitations: its range is not greater than 5-15 nm, and this mechanism might not be very reliable, as instead of sending a signal to the receiver, the transmitting molecule might lose its energy emitting a photon. The solution is called MIMO-FRET with multiple molecules at both sides of the communication channel. It gives additional reliability via diversity, similarly as in wireless communications [Wojcik2015]. Routing techniques for FRET-based networks assume using molecules with specific properties, like photoswitched fluorophores, quenchers or proteins of changeable shape [Kulakowski2017].

This short survey shows that there is already proposed a grand variety of nanocommunication techniques, differing in scale, range, delay and, what most important, in communication mechanism. While FRET can provide communication between nano devices in a really short (nano) time, its range is limited to about a dozen of nanometers. On the other hand, EM-based solutions in THz band are quite compatible with classical wireless communication, but struggle to operate below µm scale. Finally, molecular communication provides a large number of methods that could be located somewhere between nano and micro worlds, but they are quire separated from each other, not sharing the same communication medium neither among themselves nor with FRET and EM-based solutions. It seems quite evident that **designing appropriate interfaces** between nano, micro and macro networks of various types is going to be a crucial challenge and turning point in the further development of nanocommunications. We will review a few of already existing concepts in the next section and show that we are really not so far from successful interoperation between networks of different scales.

3. Nano-micro-macro interfaces

While numerous communication mechanisms in both nano and micro scale were already proposed and thoroughly investigated, as referred in the previous chapter, they are still quite distinct and separated from each other. It is mainly due to the fact that they do not share the same physical medium, but use FRET/photons, THz waves, diffusing molecules or information coded in molecule structure or DNA chain. In consequence, it is really challenging to transfer data from one nano-network type to another or get the data from nano/micro scale to our macro world with wirelessly communicating devices. Yet, some solutions exist, based mainly on physical properties of specific molecules; they will be reviewed here (also see Fig. 1).

First, let us consider a case of information data generated at nano scale in a FRET-based network that is to be extracted to EM-based communication systems (e.g. THz graphene devices or BANs). Signals propagate through the network as FRET and the last-hop node may generate another FRET or a photon. A viable solution to convert this signal into an electrical one is a molecule called **channelrhodopsin**. This is a protein that could be excited with FRET energy or photon (in optical band). Channelrhodopsin (ChR), after its excitation, opens a channel for cations to flow through [Kmiecik2018]. As a consequence, the electrical potential on the opposite side of the channelrhodopsin increases and may be measured and treated as an input signal for EM devices. A single ChR size is about 5 nm, comparable with molecules communicating via FRET. If a larger solution is required, **photodetectors** might be applied, especially made of graphene. Graphene has very good detecting properties, absorbing photons or FRET signals from visible light to infra red EM range. New graphene photodetectors are also very fast, operating up to 50 GHz [Cakmakyapan2018], thus they can work as hubs gathering signals from multiple nano networks. Having in mind also how appropriate graphene is for building EM-based micro devices working in THz band, it seems this material might play crucial role in future nanocommunication systems.

An alternative for photodetectors might be exploiting a network of **nerve cells** (neurons) to gather data from nano networks. Human nervous system is an excellent example of a network collecting information from remote sensors (sensory neurons). A neuron may be activated when a *neurotransmitter*, e.g. coming from another nerve cell, binds a *receptor* on a neuron surface and thus opens an ion channel there. The ions from the environment can flow through the channel changing the electrical potential inside the neuron. This electrical potential then propagates inside the *neuron axon*, sometimes even over 1 meter long. The ions flowing into the neuron might be e.g. calcium cations used for molecular communication. Consequently, neurons may perform as interfaces converting molecular signals into electrical ones and carrying them over large distances. On top of that, neuron receptors may be replaced with layers of channelrhodopsin molecules [Kmiecik2018] and then neurons may receive signals from FRET networks as well. A neuron may then play role of a long-range connection transforming FRET and molecular signals into an electrical potential that can be further detected by EM-based devices measuring this potential at the far neuron end.

Information transfer from macro devices like BANs into nano world is viable as well. Due to the difference of scale, signals coming from macro devices are of **broadcast nature** for nano networks. Anyway, nano devices, if properly designed, are able to filter the forthcoming signals. Let us consider using optical source, e.g. a laser in order to transfer signals to FRET-based nano networks. FRET nano-transceivers are e.g. fluorophores like *Alexa, DyLight or Atto dyes*, which are biotechnologically engineered molecules currently available commercially. There is a wide variety of these dyes, characterized by very different absorption spectra in visible light range: from close to ultraviolet (380-400 nm) up to near infrared (700-750 nm). They might be applied for selective reception of optical signals upcoming from macro devices (similarly how narrow-band antennas are used in wireless communications). Optical signals might be received as well in molecular communication systems. An example is the abovementioned bacterium *Escherichia coli*, which, in response to optical stimulation, may export protons (H^+) changing pH of its environment [Grebenstein2018].

Finally, there are also some scenarios of cooperation and information exchange among molecular and FRET-based networks. First, molecular motors, e.g. kynesins, may carry not only cargo with encoded information, but also fluorophores. Such mobile fluorophores may forward signals to different FRET networks, depending on their actual location. Another group of solutions is related with specific molecular mechanisms initiating transmission in FRET networks. FRET might be started not only with a molecule excited by a photon. Instead, the required energy might be taken from a chemical reaction; in this case it is called **bioluminescence resonance energy transfer** (BRET). For the mentioned reaction to happen, *luciferin* (substrate), *luciferase* (enzyme), *oxygen* and *ATP* (energy source) are required. The delivery of them might be controlled by molecular mechanisms: the oxygen flow might be easily regulated, ATP might be transported in vesicles e.g. by molecular motors. As ATP can be also produced by *ATP-synthase* in a scenario of increasing proton concentration; it is again the bacterium *Escherichia coli*, which can initiate this process by generating a proton flux.

Consequently, the review presented in this section proves there is a large number of mechanisms that can be successfully coined into efficient interfaces linking nano, micro and macro worlds. These interfaces are clearly essential if nanocommunications is going to be not only a vague future vision, but an important part of current pervasive networking solutions.

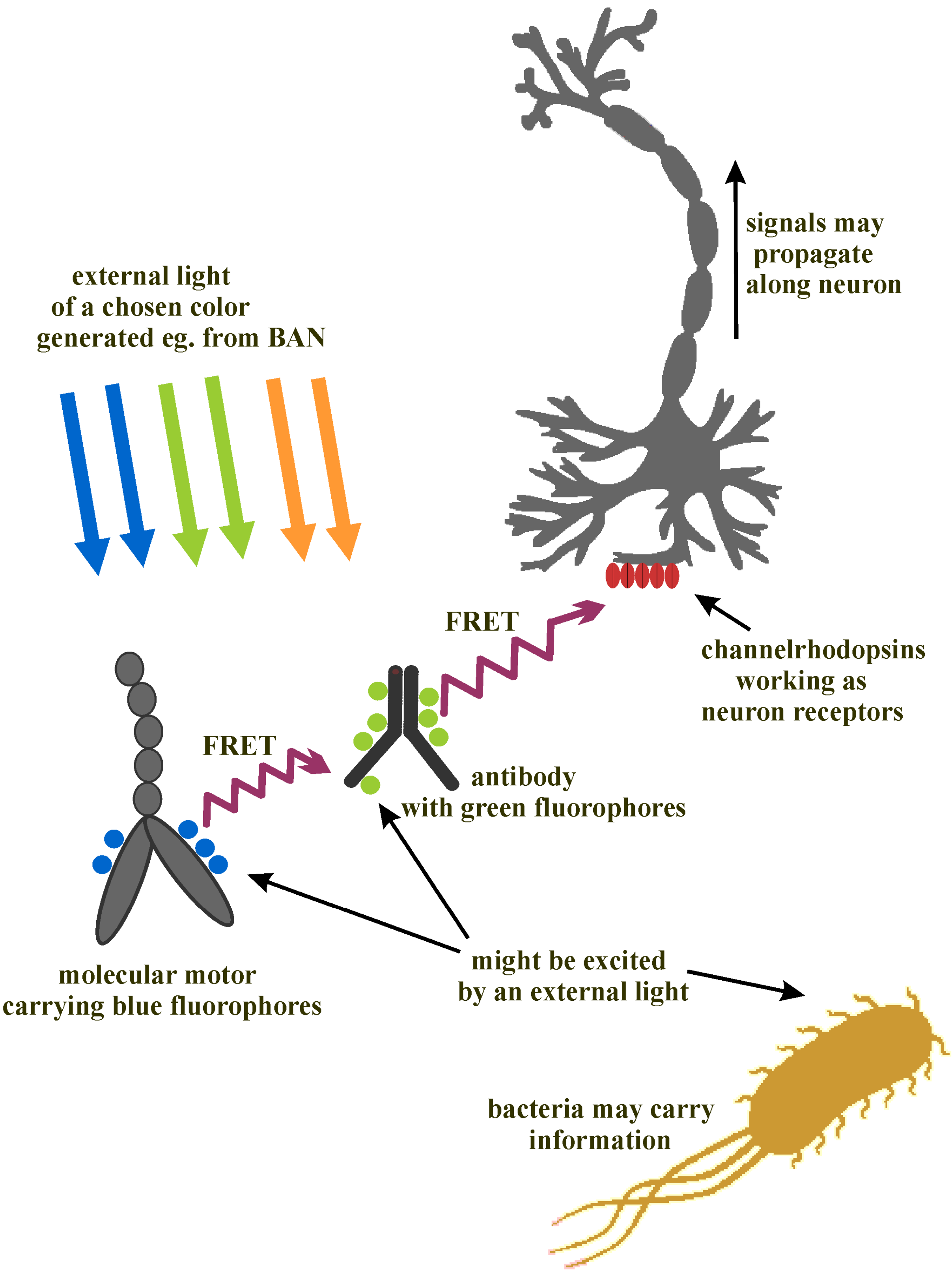

Fig. 1. Examples of communication mechanisms
between the molecular/FRET networks and external devices

4. About BANs: how they may fit and help here

Since BANs rely on the information exchange in between their nodes to achieve their potential, the communication channel is one of the central aspects of these systems [Cotton2014]. Three BAN communication scenarios are distinguished, i.e. on-, off- and body-to-body, facilitating the exchange of information in between the on-body nodes of the same BAN, an on-body node and an off-body one, or nodes on different BAN users (see Fig. 2). As they allow for the interaction of a BAN and the surrounding environment and in between different BANs, the latter two are particularly interesting for future applications.

In demanding applications, such as video streaming from an on-body camera, the off- and body-to-body channels face challenging high throughput requirements. In order to satisfy these demands, mm waves present themselves as a natural choice, due to the large available bandwidth. However, the propagation characteristics of mm waves are both attractive and challenging for BANs. On the one hand, the high propagation losses are favourable for BAN coexistence, secrecy and security reasons, as signals remain confined within the area in the user's close proximity. On the other hand, these losses pose a great challenge on preserving the information-bearing signal above the level required for satisfying communication quality.

BANs and mm waves have separately received a great deal of attention in the recent years, but studies of the former typically consider only frequencies below 6 GHz, while those of the latter neglect the important influence of user dynamics. A very few studies consider BANs operating at mm waves, and the available literature is scarce. The on-body channel has received the most attention so far [Pellegrini2015], With all of the available work considering the unlicensed bands at 60 GHz and 94 GHz (V- and W-band [IEEE2002], respectively), a variety of communication links were investigated, e.g., head-to-shoulder link [Ali2013], [Brizzi2013a], waist-to-torso [Brizzi2013a], helmet-to-all-body [Alipour2010], upper-body-to-hip [Brizzi2013b], among the others. Some authors have investigated the effect of clothes on the channel, where the considered materials include wool, cotton, felt and electro-textile [Brizzi2013b], [Guraliuc2014]. Except for the last one, which is designed to improve energy transmission in between the on-body antennas, the other materials have shown little influence. Due to the low penetration of mm waves, the effect of the body tissues beneath the skin is also found to be negligible [Ghandi2016], implying that the homogeneous phantoms are suitable for use at these frequencies. One should mention that most of the on-body channel studies consider a static user in the standing or lying-down posture [Alipour2010], [Li2014]. However, some reported works do consider the dynamic user case, where Motion Capture data was used to extract the human motion characteristics [Petrillo2015], [Nechayev2013].

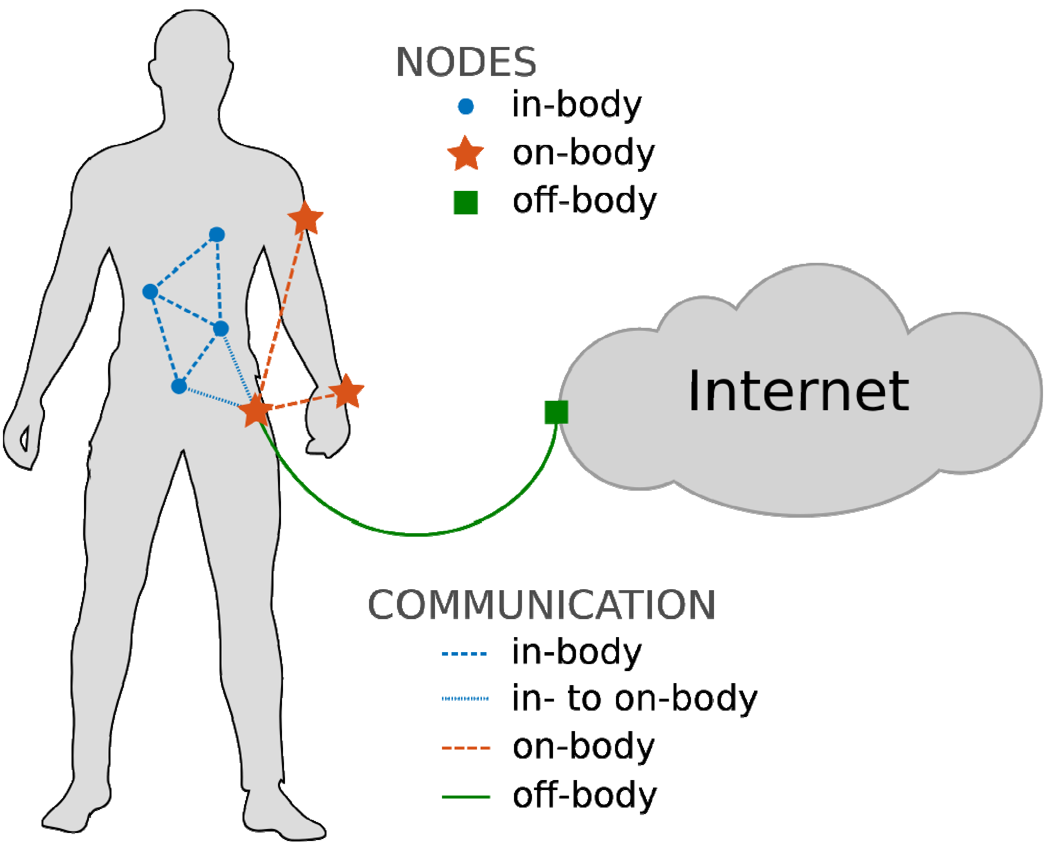

Fig. 2. Communication scenarios in body area networks

The consideration of type and placement of wearable antennas on the body is also of importance. One has to consider the connection to the antenna to the rest of the device circuitry, with all the challenges that one can think of, even with the level of miniaturisation that has already been achieved nowadays. Regarding the placement of antennas/sensors on a specific part of the body, there are two key aspects to consider: the mobility of that part of the body, the head and trunk being "more static" than arms and legs; the blockage of signals by the body itself and surrounding objects and people, the legs being the worse case and the head the best one [Turbic2018]. Only a few mobile off-body studies actually consider the user effects. In [Zhao2017], the investigate the influence of body-blockage from the user on the channel, where the blockage is represented as a part of the mobile terminal's radiation pattern; although a walking user scenario is investigated, only linear forward motion at constant velocity is considered. Body-to-body communication is the least explored BAN scenario, and the literature considering mm waves is extremely limited.

A number of challenges remains open, among which one can mention the interface between devices inside the body and sensors on or outside the body, network aspects of these communication systems, data transmission in a reliable way, power consumption and energy efficiency, just to mention a few.

5. Applications

Designing proper interfaces between nano-, micro- and macro- networks opens the space for a vast area of new applications going even beyond these ones envisioned for nanonetworks. The pivotal change is the fact that nanonetworks might be contacted and controlled from the macro world during the whole time of their functioning.

The largest group of applications is related to medical diagnostics and operations. Let us imagine a diagnostic system composed of nanoparticles deployed in a human tissue or the human vascular system. The data gathered by the system could be transmitted outside the human body and then through BAN connections to a doctor for a real time analysis. On the other hand, there could be a surgery operation performed using nanomachines controlled by a hospital staff remotely via BAN-to-nano interfaces, again, in the real time. The surgeons could supervise the nanomachines having access to the data collected inside the human body and steering the nanomachines actions. Besides these applications, one can envisage others encompassing patient monitoring, localised drug delivery, and aging care.

Sports is also another area where many applications can be envisaged, especially for high performance athletes. The monitoring of fitness-related activities, including the measurement of different physiological parameters, e.g., heart rate, energy consumption, fat percentage, or body water content, among many others. The measurement and display of real-time information and/or the control of follow-up reports may lead sports to a new level of professional well-being and safety.

Another very important application area is related to emergency, security and military personal applications, comprising smart suits for fire fighters, police, and soldiers in battlefields. Smart clothes use sensors that can measure the body's vital signals or detect bullet wounds, which can be essential for the safety of these personnel. The use of pills as sensors in some specific conditions may enable the detection of critical situations for the personnel, ultimately meaning the difference between life and death.

Entertainment is another area, where many applications can be envisaged, with the power of business and commerce behind them. On the one hand, requirements may not be as strict in the previous areas (and a person’s life is not at stake), but on the other hand, massification may represent a huge challenge. Tracking body movement via sensors (which can be stick to the skin) together with voice control or instead of it, will be a very powerful tool, for endless applications.

Business applications can also be foreseen, related to authentication and personal security. One example may be touch-based or near-field authentication services using the human body as a transmission channel, which can be used for payment services, business card exchange, and lock or login systems. User identification/authentication, associated to biometrics, play a key role in here, and the use of these technologies may substantially reduce the risk of a third person attack.

Other applications include people “thinking” directly to the Internet. Assuming the human nerve cells could be connected via nanonetworks to the external BANs and then to other networks, a person could send its emotions or requests for specific actions directly to the Internet, without the need for any intermediate devices like notebooks or smartphones. It might mean a real integration of a human and the Internet or, in another vision, a merge of Internet of Things with Internet of Nano Things [Akyildiz2015]. This might be the answer for the question what the truly personal communication should be and what could be direction for 6^{th} Generation of mobile networks.

Basically, the enhancement of advanced human-computer interfaces together with the trivialisation of the aforementioned applications will enable in the future that people will have access to a wide range of truly personal information, taking the use of current "health apps" existing in today's mobile phones to a level of human well-being and disease detection that is not possible today.

6. Conclusions

Nanocommunications, understood as molecular communications (those performed in between groups of molecules or cells) is definitely one of the hottest research areas in IT science in the last few years. The progress in this discipline is strenuous, especially as it requires cooperation of research from both IT and medical fields, but the potential applications are enormous, extending from medical ones, like remote diagnostics and surgery, localised drug delivery, and aging care, via sports, entertainment and military, to the final vision of human-Internet integration realised by getting signals directly from human nerve cells and sending them to the Internet. This is a vision of truly personal communications, where parts of the Internet are related to particular people, as they are located inside their bodies.

However, in order to have it happening, we should have not only mechanisms developed which enable networking in nano-scale, between molecules or cells, within a specific part of a human body. We need reliable interfaces connecting nanonetworks with external macro networks, like wireless body area networks. BANs are the networks specifically designed to collect signals from human bodies and send them further to the Internet.

This paper provided insights and first solutions of problems related to the integration of nano- and micro- networks with the whole wireless Internet, currently understood as Internet of Things. We reviewed the most important mechanisms of nano/molecular communications. We then presented what we know so far about possible interfaces between nano-, micro- and macro- networks. We also addressed the current development of body area networks, which are the most natural bridge between nano/molecular and macro/wireless communication systems. Finally, to make this picture complete, we characterised possible applications coming from such a fusion of networks of different scales. This looks to be the development direction of future mobile networks which is going to make them truly personal ones.

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