Feasibility Study of the THz Band for Communications Between Wearable Electronics

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Abstract—**Emerging wearable nano sensor networks enable a set of valuable applications in biomedical and environmental fields. At the same time, the current state of communication technologies significantly limits the processing capabilities of prospective nanomachines. Consequently, implying that all the analysis of collected data needs to be performed on a macro device. Therefore, to effectively enable long-awaited applications of nanonetworks their seamless integration into existing networking infrastructure is required, leading to the concept of Internet of Nano Things. In this paper, the interoperability between already deployed macro networks and emerging nano networks is preliminary investigated. The solution for this problem is non-trivial, as the existing macro wireless networks use primarily the carrier-based electromagnetic communications, while nanomachines must rely on ultra-low-power pulse-based EM radiation or inherently mobile objects as information carriers. Thus, the direct interaction between macro and nano networks is currently not feasible, forcing using special gateway nodes. Moreover, the modern solutions for nano communications have to be rapidly improved to enable construction of large-scale networks on top of existing link level techniques. Numerous theoretical questions are to be addressed to achieve this goal, ranging from the design of a proper modulation and coding technique to mitigation of noise and interference effects.**

I. INTRODUCTION

Wearable electronics are quickly becoming a part of our everyday life. According to the recent studies of World Economic Forum and Cisco [1] [2], the market of these devices grows every year having 60 Billion USD potential and we may expect hundreds of millions of devices in-use by the year 2018. Along with ever-increasing use of audiovisual applications and the growing trend to use them "on-the-move" wearable electronics could potentially become one of the most bandwidth-greedy networking scenarios we have ever witnessed [2] [3], see Fig. 1.

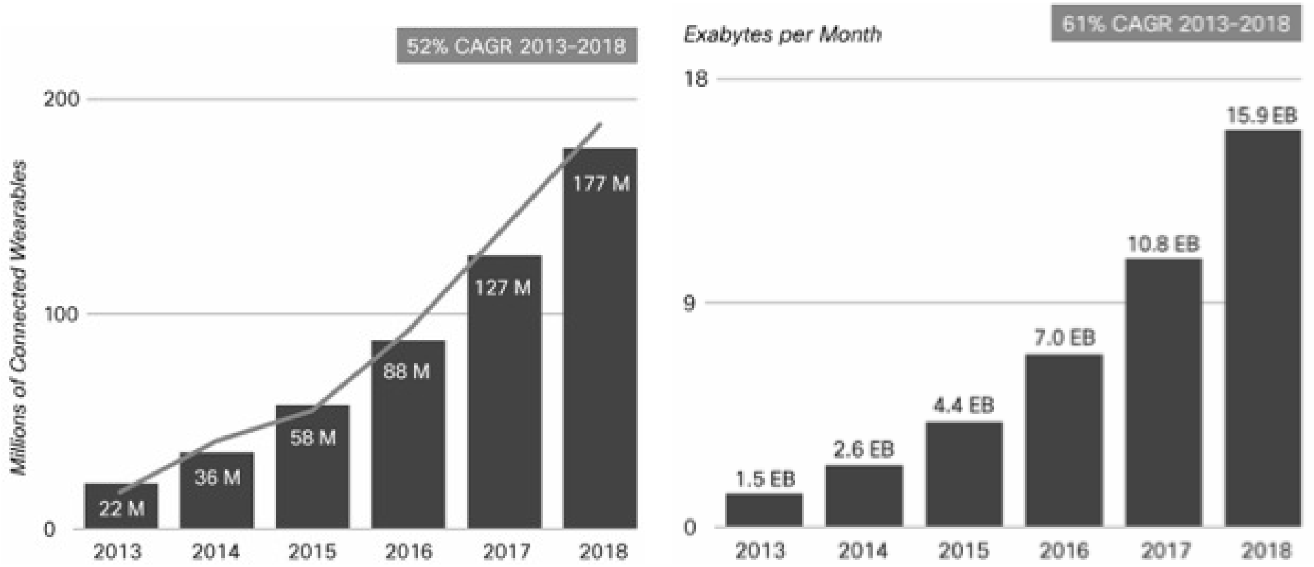
Inherent features of wearable electronics are small size of end systems, limited lifetime of batteries, high data rates of the imbedded wireless technologies and communications range sufficient for body area networking. Observing the development of wearable electronics in the past one could identify two major trends. First trend is directed at providing higher level of mobility for the user, achieved by miniaturization of end systems and increasing the energy efficiency of all the elements including the communication part. The best illustration of this trend is introduction of Blueetooth Low Energy (BLE), which became a de-facto standard for the current generation of wearable devices. However, the idea of adjusting the existing technology without changing the operational frequency range resulted in drastic reduction of the amount of available modulation and coding schemes and other power-greedy functionalities, such as the use of neighboring IEEE 802.11 ISM band. This naturally led to a reduction of maximum data rates from 24 Mbps (3 native and 21 2.4 ISM channels) in BT v3.0 to 1Mbps in BLE version. Thus, although the energy efficiency is increased, this approach limited the number of possible applications and user scenarios.

To mitigate this issue and support real-time wireless connectivity between head-mounted displays, wearable HD cameras, high-precision motion sensors and other recently announced devices [4] the second research direction has been initiated within the last few years. This trend is primary focused on substantial increase of capacity at the air interface, in particular, aiming at handling simultaneous transmission of uncompressed video over multiple links in the same contention environment. This helps avoiding devices with overlapping functionalities (coders/decoders, compression/recovery hardware, etc.) leaving them only at the central node, e.g. smartphone or tablet. As a result, the complexity and size of the peripherals – cameras/sensors/displays/etc. – decreases dramatically. Another effect of outsourcing processing-greedy tasks to the central entity is drastic decrease in power consumption.

Our recent investigations demonstrate that using Cortex-A9 and Intel Atom mobile processors the amount of power needed to compress even quarter-HD 540p video using MPEG-4 codec is several orders of magnitude higher that the power required to transmit it over the classic IEEE 802.11n network [5]. Finally, the accuracy of various operations such as pattern recognition, motion estimation and other data processing operations rapidly improves when working with the original content rather than with a version compressed with a lossy codec.

One of the prospective user scenarios for the next generation of wearable computing could be as follows: a smartphone in a pocket is collecting video streams from several high-resolution cameras, processing these data and transmit navigation, manual and warning information to head-mounted displays. Depending on the use case, the traffic flow might be supplemented by music, movie or a video conference. Another group of applications is in the area of gaming and virtual reality with high-accuracy sensors controlling the user motions and interpreting them accordingly. Although the two abovementioned use cases are claimed as reference scenarios, undoubtedly, the prospective applications of wearable devices are not limited only to video streaming, but enable a set of other bandwidth-greedy applications in the e-Health, military and environmental fields.

Motivated by the attractiveness of the use cases, as well as limitations of both existing cellular [6], [7], [8], WMAN [9],



(a) Connected wearables

(b) ”Wearable” traffic

Fig. 1. Growth in wearable devices, traffic and video traffic share (source: Cisco VNI 2014)

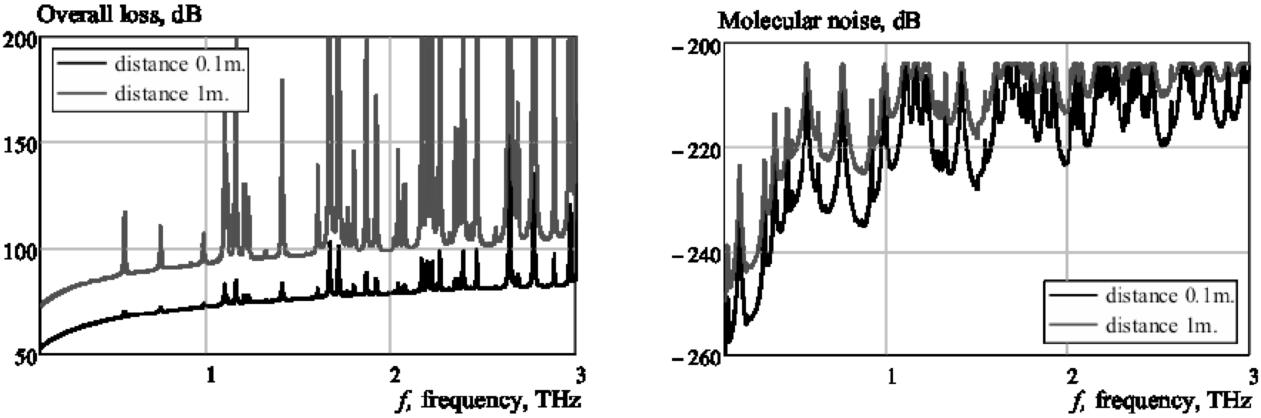
and WLAN solutions [10], the networking research community is currently moving forward with wireless technologies development for wearable electronics and discussing which particular way to follow. The process is expected to continue during the next few years due to a number of shortcomings in each of the proposed solutions. For instance, the evolution of IEEE 802.11 standards including 802.11ad WiGig (57-64GHz, 7Gbps, 10 meters) and 802.11ac (5GHz, 10-20 meters, 1.69Gbps), while providing full networking capabilities, are not energy efficient enough due to the use of complex modulations and coding schemes and OFDM. WirelessHD developed by SiBEAM to deliver uncompressed HD video (57-64GHz, 10-40GBps, 3-5 meters) relies on OFDM as well. The Wireless USB (3.1-10.6GHz, 0.5Gbps, up to 1 meter) is more energy efficient due to the use of ultra-wideband technology, however, similarly to WirelessHD, it does not provide networking capabilities. Finally, neither of the technologies that are currently under development can support the abovementioned bandwidth-greedy applications. Thus, despite there is definitely a room for further tuning of current and next generation solutions, the major breakthrough can only be achieved relying on principally new communications principles through the usage of novel materials and communications techniques for creating energy efficient user equipment without compromising the capacity and communications range requirements.

To keep up with the increasing capacity demands at short-range distances and, at the same time, satisfy the requirement of energy efficiency we propose to use the so far not well explored terahertz (THz) band, 0.1-10THz. By design, the use of these frequencies would allow for miniaturized end-user electronics, energy efficient communications while also providing extremely high capacity level, sufficient for any prospective applications. The only conceptual problem identified by the researchers when using the THz band is rather limited communications range of end systems. Thus, during the development and standardization of intermediate solutions for wearable electronics communications that are expected to last for the next few years, we propose to tackle the abovementioned issues from a different perspective. Instead of working on further improvements of energy efficiency, data rates and size minimization of the solutions having roots in ”macro” networks, we aim to solve an opposite problem: extend the communication range of THz millimeter-distance communications to support the prospective wearable electronics, which is, in principle, possible according to our recent investigations [11].

Short summary of the main results from the feasibility study is presented in the end of the section showing that, under certain assumptions, the communication range of THz wireless technology can be extended up to few meters, which is sufficient for wearable networking. The capacity at these distances is still extremely high amounting up to few Tbps while the potential energy efficiency is expected to be several times better than that offered by classical solutions. However, in order to come up with a fully operational wireless technology for wearable electronics numerous issues must be solved as the use of THz frequencies possesses a number of specific limitations and challenges. Among others, they are: (i) detailed description of the THz propagation properties in body area networks, (ii) antennas design for efficient communication over small distances, (iii) selection of the suitable low-complexity modulation and coding scheme and (iv) proposal of applicable medium access control techniques and (v) overall optimization of the selected communications mechanisms

II. RECENT ADVANTAGES IN BODY AREA NANO NETWORKS

The recent advances in nanomaterials, nanomechanical systems and microbiology have enabled design of small scale devices, capable of sensing, storing and processing of heterogeneous data. In the near future these so-called nanomachines will support crucial applications in medical and environmental fields. For instance, the recent proposal of Stanford Medi-



(a) Overall loss

(b) Molecular noise

Fig. 2. Overall loss (propagation and absorption) and molecular noise in 0.1-3 THz band

cal School can perform computing within living cells [12]; Dongjin Seo and Jan Rabaey et al. have presented their solution for low power chronic brain-machine interface [13]; while the Strano Research Group at MIT developed an nano sensor platform for measuring intra- and inter-cellular signaling pathways [14].

However, such tasks as human health monitoring, targeted drug delivery or air and water pollution control require cooperation between hundreds and thousands of nanomachines. To address this issue the concepts of of nanonetworks has been recently proposed in the beginning of the 21st century and extensively studied by leading research institutions since then. Over the last decade scientists have developed these concepts specifying basic communications principles while relying on either bio-inspired or electromagnetic (EM) approaches. The latest investigations have led the foundation for several communication techniques, feasible at nano scale. These include, but not limited to graphene-enabled electromagnetic wireless communications in the terahertz band (0.1 – 10 THz [15]), molecular diffusion where molecules are used to represent the encoded information [16], Forster Resonance Energy Transfer (FRET) [17], short range communication of calcium signaling between cells in a tissue [18], as well as the use of bacteria to carry DNA encoded information [19]. The current state-of-the-art suggests that EM nanonetworks will have communication range up to tens of centimetres with channel capacity up to 2-3 Tbps, while molecular-based techniques will work on distances of around 1-10 millimetres with data rates ranging from few Kbps to few Gbps [20], thus, supporting effective P2P streaming between nanomachines [21].

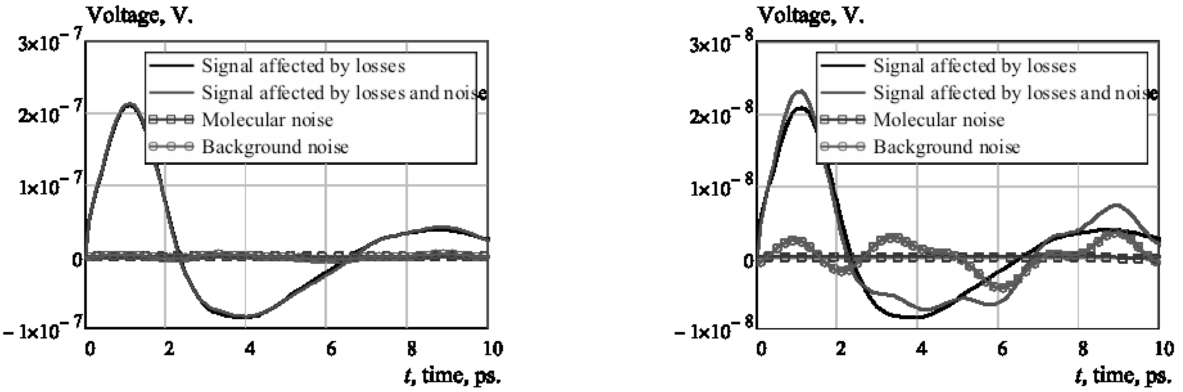
Motivated by a number of promising applications, the area of nano scale communications has recently attracted a huge interest from academia. The non-comprehensive list of events include an IEEE Transactions on Terahertz Science and Technology journal with an impact factor of 4.34; a dedicated Elsevier journal on Nano Communication Networks; two Special Issues of Journal on Selected Areas in Communications; Symposiums and workshops at IEEE GLOBECOM, ICC and INFOCOM, yearly ACM International Conference on Nanoscale Computing and Communication (ACM NANOCOM). Meanwhile, the leading industrial R&D centres are also contributing to the field of study by aiming to standardize communications over the THz band for short-range and body area networks via IEEE 802.15.3d Task Group [22], supported by Intel, NICT and Huawei on one side and recent achievements in Synthetic and Systems Biology by Microsoft Research, Cambridge, UK [23] and IBM Research, Zurich, Switzerland [24] on the other.

Despite the fact, the latest publications in the field have investigated in-depth the feasibility of point-to-point communications between nanomachines [25] [26] [27], substantial amount of work and vision is required before the first nanonetwork will become operational. Moreover, these networks in isolations bring very little benefits to the end users. As a result, in the majority of networking scenarios the nanonetworks are expected to interoperate with macro devices using some sort of gateways between them to relay information. These functionalities are silently presumed in most investigations due to their critical importance but have never been addressed so far.

Also while the applicability of the existing network layer model for wearable electronics is doubtful, the cross-layer design wearable networks is an important challenge [28]. Besides accurate interference-aware channel modelling [29]–[33], specific medium access protocols to to handle multimedia [34] and broadcast traffic [35], and power-related issues [36], the reliability issues with the untra-high frequency signal propagation through the prospective medium (atmosphere, skin, etc. [37]) has to be taken into account for protocols design and evaluation, like suggested in [38] and [39]. With respect to mentioned above, in the following section, we present a preliminary applicability assessment of the THz frequency band for communications between wearable electronics.

III. Feasibility Study of THz for Wearable Electronics

Nowadays, the THz band, 0.1–10THz, is already used for various purposes including imaging, spectroscopy, remote gas sensing, etc. First studies of THz band for wireless communications appeared in the beginning of 2000s showing that using the directional transmission, the received signal-to-noise ratio (SNR) could be very high. Nevertheless, there was only slight



(a) Distance 0.1 meter

(b) Distance 1 meter

Fig. 3. Received pulses and noises in the time-domain, pulse energy 10e-12

progress in THz communications so far. The reasons for slow adoption are due to complex way to generate THz waves and special propagation properties of these frequencies. Recently, researchers started to advocate the use of THz band for ultra-broadband networking between nano devices. It was stimulated by the recent progress in materials science and associated research on graphene THz antennas. One example is plasmonic antennas exploiting the behavior of Surface Plasmon Polariton (SPP, [40] [41]]) waves in graphene nanoribbons (GNR). However, the application of THz band communications was considered to be limited to extremely small distances on the order of few millimetres. The reason is that, to achieve high data rates (e.g. few Tbps) the authors usually suggest to use the entire band, 0.1–10THz. To understand principal limitations of this approach consider the link budget

$$P_{Rx}(f,d) = P_{Tx}(f,d) - L_P(f,d) - L_A(f,d), \qquad (1)$$

where P_{Tx} is the p.s.d. of the transmitted signal, P_{Rx} is the p.s.d. of received signal, $L_P(f,d)$ is free-space propagation loss, $L_A(f,d)$ is the p.s.d. of the molecular absorption loss. In addition to the losses in (1), the received signal at the receiver is affected by the molecular absorption noise as molecules re-emit a part of the absorbed energy back to the channel. The p.s.d. $P_N(f,d)$ of molecular absorption noise can be written as

$$P_N(f,d) = k_B\left(N_M(f,d) + N_B\right), \qquad (2)$$

where k_B is the is the Boltzmann constant, $N_M(f,d)$ is the equivalent molecular absorption noise temperature expressed via transmittance of the medium, and having maximum at approximately -204dB/Hz, N_B is the thermal noise that is constant for 0.1–10THz range [41] [11]. The overall losses and molecular noise in 0.1–3THz range shown in Fig. 2 highlight that the use of the whole range 0.1–10THz can only provide communications at extremely small distances (up to few millimeters) as the signal gets quickly absorbed by water vapor.

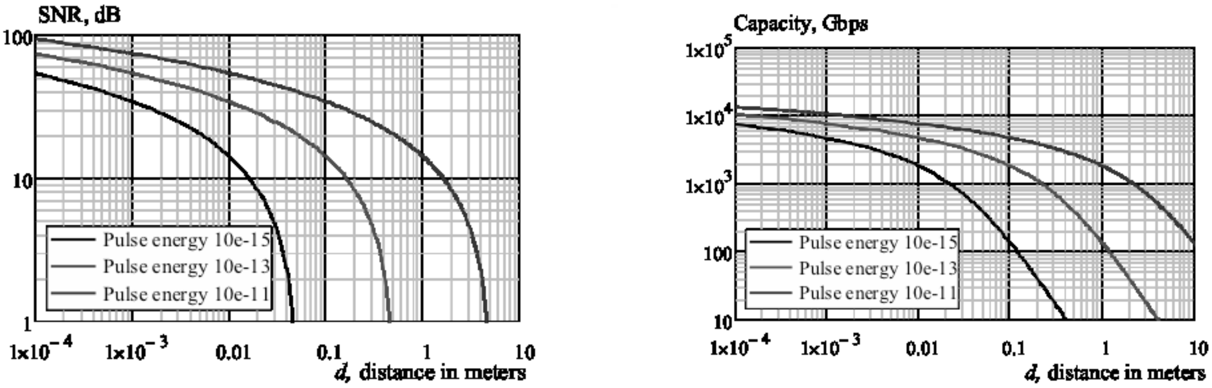
Taking another look at Fig. 2 one may observe that there are frequencies that are characterized by negligible absorption and molecular noise at distances suitable for short-range communications (1m.). We call these ranges as transparency windows and define them as a set of consecutive frequencies having transmittance of the medium higher than 95%. Fig. 2 shows the time-domain representation of received Gaussian pulse and associated noises at two distances. We see that at distances of interest only background thermal noise may affect the received waveform making the propagation conditions similar to those we used to work with at smaller frequencies. Thus, while the molecular absorption and noise play important roles when either the whole THz band, 0.1–10THz, is used for communications or low transmission energy is of interest (e.g., less than $10e-18$W, [9]) their effects becomes negligible in the transparency windows or at higher pulse energies.

Although there are a number of transparency windows available in 0.1–10THz range, the first 440GHz-wide window, 0.1–0.54THz, is of special interest as the propagation loss increases with the frequency. In our preliminary studies we computed the Shannon capacity (theoretical upper bound on achievable rate) and SNR for different transmission energies, see Fig. 3. Using 10e-11W one achieves distance of up to two meters with SNR at least 10dB and the corresponding capacity of more than 1Tbps. At slightly smaller distances even higher capacity is achievable, e.g. using 10e-11W we may provide 6Tbps with SNR 35dB at 0.1m.

This short discussion reveals that selected frequencies in THz band may indeed be of great use for communications at short distances potentially providing extremely high data rate in almost noise-free environment. The values of capacity and SNR reported above could be increased even further with the use of directional antennas. The use of novel materials, such as graphene and carbon nanotubes, may additionally improve performance allowing to get rid of thermal noise component and creating extremely reliable communication technology for wearable devices. Possible applications of such THz band communications include not only wearable electronics [42] [43] but broadband wireless access to the Internet using in-premises femto- and atto-cells.

IV. CONCLUSIONS

In this paper, a preliminary study of the wireless communications in the THz band for wearable electronics has



(a) SNR

(b) Theoretical channel capacity

Fig. 4. SNR and capacity for 440GHz 0.1-0.54THz channel

been performed. According to our investigations, the described technology has two major benefits, comparing to conventional gigahertz solutions: i) extremely high capacity on short distances (up to several Tbps) ii) ability to operate with narrow transceivers, including narrow antennas of several hundreds of micrometers size.

At the same time, to enable such type of communications, a considerable amount of research challenges has to be solved, including but not limited to cost-efficient transceivers design, throughput-oriented modulation and coding schemes proposal, and development of a medium access protocol suitable for ultra-dense networks.

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