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Terahertz Communications in Human Tissues at the Nano-scale for Healthcare Applications

G. Piro, *Member, IEEE,* K. Yang, *Student Member, IEEE,* G. Boggia, *Senior Member, IEEE,* N. Chopra, *Student Member, IEEE,* L. A. Grieco, *Senior Member, IEEE,* A. Alomainy, *Senior Member, IEEE*

***Abstract*—This letter investigates nano scale wireless communications in human tissues. Starting from propagation models, validated through real experiments, channel capacity and transmission ranges are derived for different physical transmission settings. Results highlight the challenges characterizing the communication in such a medium, thus paving the way to novel research activities devoted to the design of pioneering nanomedical applications.**

***Keywords*—Nano scale communications, THz band, channel capacity, human tissue**

I. Introduction

THe Internet of Nano-Things (IoNT) paradigm is quickly gaining momentum thanks to the recent advances of nanotechnologies. In its rationale, a potentially high number of nanometric devices, equipped with basic processing/communication capabilities, can be diffused in the environment for fine-grained data acquisition in extremely pervasive monitoring systems [1]. With reference to the healthcare domain, the objective is to deploy a network of *therapeutic* nanomachines able to operate either in inter and intra-cellular areas of the human body, thus enabling pioneering applications, including immune system support, bio-hybrid implant, drug delivering system, heath monitoring, and genetic engineering.While electromagnetic-based communications, handled in the terahertz band, are considered a viable technique for supporting data exchange in the IoNT [1], the study of wireless transmission schema at the nano-scale should be carefully addressed to sustain the progress of this technology.

The analysis of the channel capacity in the *lossy* air medium has been deeply investigated in [2], where it is demonstrated that terahertz communications offer very high physical transmission rates (i.e., more than 1 Tbps) and transmission distances in the order of few tens of millimeters. In the context of body-centric wireless communications, instead, only preliminary contributions, mainly focusing on propagation phenomena, can be found in literature. A comprehensive review of macro-scale propagation models is discussed in [3], whereas works in [4] and [5] address important aspects characterizing terahertz communications, that is, the measurement of dielectric properties of human skin tissues and the numerical analysis of propagation models, respectively. Unfortunately, to the best of the authors' knowledge, no scientific study better characterized the performance of terahertz communications in human tissues, expressed in terms of both maximum channel capacity and allowed transmission ranges.

To bridge this gap, the present contribution: (i) proposes a propagation model that encapsulates the attenuation of electromagnetic (EM) waves in the human skin tissues and (ii) derives the channel capacity and communication ranges. Path loss and molecular absorption noise temperature have been obtained from optical parameters of human skin tissues, verified through extensive experimental tests. Results of this investigation clearly show that, differently from the air medium, human tissues strongly and variably hinder EM communications in the terahertz band and novel communication schema are strongly required to enable IoNT-based intra-body systems.

II. Propagation models and transmission schema

EM communications in the terahertz band (i.e., 0.1-10.0 THz) can be supported by graphene-based nano-antennas. Regarding the transmission scheme, a promising approach is based on the Time Spread On-Off Keying (TS-OOK) modulation: a logical '1' is encoded with a short pulse and a logical '0' is encoded as a silence [2]. In what follows, let $B = f_M - f_m$ be the total available bandwidth, where f_m and f_M are the lower and the higher operative frequencies, respectively.

For what concerns the propagation model, as widely recognized, the terahertz band is highly frequency-selective and the molecular absorption noise is non-white. Moreover, the path loss, A, i.e., the power attenuation contributed by the human tissues on the transmitted EM wave, can be divided into two parts: the spreading path loss, A_s, due to the expansion of the waves in tissues, and the absorption path loss, A_a, due to the absorption of tissues. According to [5], it can be expressed as:

$$A = A_s + A_a = 20\log_{10} 4\pi d/\lambda_g + 10\alpha d \log_{10} e \quad [\text{dB}] \quad (1)$$

where, d, λ_g, and α, are the propagation distance of the wave, the wavelength in the considered medium, and the absorption coefficient measuring the amount of absorption loss of the EM wave in the medium, respectively.

Meanwhile, the noise power spectral density, $N(f, d)$, evaluated as a function of frequency f and distance d, is mainly influenced by the molecular absorption $T_m(f, d)$:

$$N(f, d) = B \cdot k_B T_m(f, d) = B \cdot k_B (1 - e^{-4\pi f d \kappa / c}), \quad (2)$$

where k_B, c, T_0, and κ are the Boltzmann constant, the speed of light, and the reference temperature (i.e., the general

G. Piro, G. Boggia, and L. A. Grieco are with the Dep. of Electrical and Information Engineering (DEI), Politecnico di Bari, v. Orabona 4, 70125, Bari, Italy; e-mail: {name.surname}@poliba.it.

K. Yang, N. Copra, and A. Alomainy are with Antennas & Electromagnetics School of Electronic Engineering and Computer Science Queen Mary University of London, London; e-mail: {name.surname}@pqmul.ac.uk.

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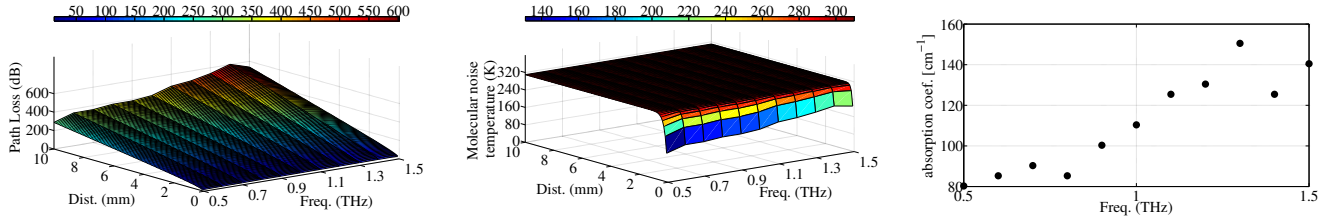


(a) (b) (c)

Fig. 1. Total path loss (a), molecular absorption noise temperature (b), and absorption coefficient (c) in human skin tissues.

human body temperature equal to 310 K), and the extinction coefficient, respectively [5].

The path loss and the molecular absorption noise temperature are shown in Figs. 1(a) and 1(b) as a function of the frequency and the distance. The values of absorption coefficient, α, used to generate these curves (see Fig. 1(c)) were obtained through real experiments carried out on human skin tissues having a refractive index equal to 1.73. Note that at the level of millimeters, the molecular noise temperature is not extremely high (approximately 310 K); this means that a communication link with acceptable signal to noise ratio can exist within the human tissue in the terahertz band.

Besides the effect of both path loss and noise temperature, communication capabilities are also strictly influenced by the way the power transmission, P_{tx}, is distributed in the frequency domain. In line with [2], three communication schemes (namely, *flat*, *pulse-based*, and *optimal*) are considered in this work and characterized in what follows.

1) Flat communication: The total power transmission, P_{tx}, is uniformly distributed over the entire operative band. Thus, the corresponding power spectral density is:

$$S_f(f) = \begin{cases} S_0 = P_{tx}/B & \text{if } f_m \le f \le f_M \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where, obviously, $\int_{f_m}^{f_M} S_f(f)df = P_{tx}$, that is, $S_0 = P_{tx}/B$.

2) Pulse-based communication: Taking into account capabilities of graphene-based nanoelectronic, the pulse generated by a nano-machine, i.e., the wave form used to transmit the logical '1', can be modeled with a n-th derivative of a Gaussian-shape: $\phi(f) = (2\pi f)^{2n} e^{(-2\pi\sigma f)^2}$ [2]. Hence, the power spectral density can be expressed as:

$$S_p(f) = a_0^2 \cdot \phi(f) \tag{4}$$

where σ, and a_0^2 are the standard deviation of the Gaussian pulse and a normalizing constant, respectively. Considering that $\int_{f_m}^{f_M} S_p(f)df = P_{tx}$, the normalizing constant is obtained as: $a_0^2 = P_{tx} \Big/ \int_{f_m}^{f_M} \phi(f)$.

3) Optimal communication: It aims at maximizing the overall channel capacity by optimally adapting the power allocation as a function of frequency-selective properties of the channel. The total bandwidth is divided in small sub-bands, so that in each of them the channel appears frequency-nonselective and the noise power spectral density can be considered locally flat. Accordingly, the total channel capacity as a function of the distance, $C(d)$, can be evaluated by the Shannon theorem[1]

$$C(d) = \sum_i \Delta f \log_2 \left[1 + \frac{S_o(f_i)}{A(f_i,d)N(f_i,d)}\right], \tag{5}$$

where Δf, and f_i are the bandwidth and the central frequency of the i-th sub-band; whereas, d, $A(f_i,d)$, and $N(f_i,d)$ are the distance between sender and receiver, the attenuation, and the noise power, respectively.

The optimal scheme is obtained solving the problem:

$$\text{maximize} \left\{ \sum_i \Delta f \log_2 \left[1 + \frac{S_o(f_i)}{A(f_i,d)N(f_i,d)}\right] \right\} \tag{6}$$

$$\text{subject to} \quad \sum_{i\in\Omega} S_o(f_i)\Delta f \le P_{tx} \tag{7}$$

$$S_o(f_i)\Delta f \le \gamma P_{tx};\ \forall i \in \Omega,\ \gamma \in]0,1] \tag{8}$$

$$\Omega = \left\{ i \,\middle|\, i_{\min_\Omega} \le i \le i_{\max_\Omega} \right\} . \tag{9}$$

In details, three main physical constraints have been considered due to technological issues: Eq. (7) means that the *total transmission power* cannot exceed the maximum available amount P_{tx}; Eq. (8) means that the *radiated peak power* in a single sub-channel should be a fraction, γ, of the total transmission power; Eq. (9) requires that sub-channels used for the transmission must be adjacent.

As well known, the maximization of a concave function, like the one in Eq. (6), can be done by using the Lagrange multipliers. Thus, the optimization problem, subject to the *total power* constraint in Eq. (7), can be rewritten as:

$$\max \left\{ \sum_i \Delta f \left(\log_2 \left[1 + \frac{S_o(f_i)}{A(f_i,d)N(f_i,d)} \right] + \lambda S_o(f_i) \right) - P_{tx} \right\} \tag{10}$$

The maximum is found by equating to zero the derivative of the argument of Eq. (10) with respect to $S_o(f_i)$ and λ. Thus:

$$\ln(2)[S_o(f_i) + A(f_i,d)N(f_i,d)] = \lambda^{-1} \qquad \forall i\ . \tag{11}$$

[1]Eq. (5) is valid because considering the transmission frequencies and refractive index of the present study,the investigation falls into the *far-field* region. In fact, it is possible to demonstrate that the wavelengths always remain below 0.35 mm and, at the same time, analysis focuses on propagation distances spanning from 1 mm to 10 mm (i.e., higher than the wavelength).

That is, the overall channel capacity is maximized when $S_o(f_i) + A(f_i, d)N(f_i, d) = \beta$, where β is a constant to be evaluated. The problem can be solved by using the *water-filling* principle, which adopts an iterative procedure for finding the most suitable power distribution on available sub-bands. In details, at the n-th step, β is computed as:

$$\beta(n) = \frac{1}{L(n)} \left[\frac{P_{tx}}{\Delta f} + \sum_i A(f_i, d)N(f_i, d) \right] \qquad (12)$$

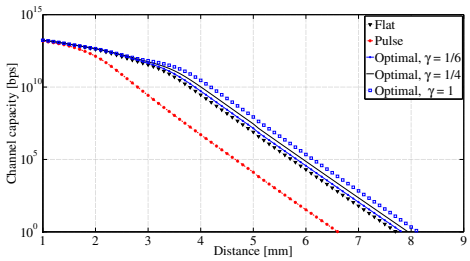
where $L(n)$ is the number of sub-bands at the n-th step. In particular, considering the i-th sub-band, the power spectral density is set as $S_o(f_i) = \beta - A(f_i, d)N(f_i, d)$. If it results $S_o(f_i) \leq 0$, then the corresponding value is set to 0 and Eq. (12) is computed again (excluding the considered sub-band) as long as there are no sub-bands with a negative $S_o(f_i)$ value. At the end, the procedure optimally distributes the total power transmission by assigning higher power spectral density values to sub-bands offering better channel conditions (i.e., lower path loss and lower noise power).

Then, the *radiated peak power* constraint in Eq. (8) is considered for adjusting the power profile resulting from the aforementioned procedure .Starting from the sub-channel with the highest power spectral density, the power transmission is reduced to the allowed peak values, γP_{tx}, thus spreading the residual power to unused sub-channels. Now, thanks to the monotonic trend of the path loss, the set of sub-channels selected for the transmission are always adjacent, thus respecting, at the same time, the last constraint in Eq. (9).

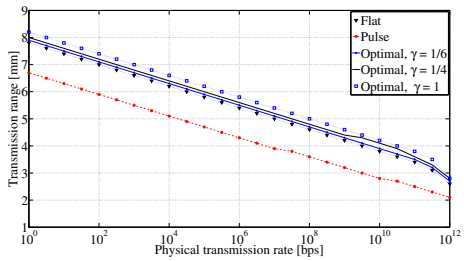
III. Performance Evaluation

The feasibility study of terahertz wireless communications in human tissues has been carried out through the NANO-SIM simulation platform[2]. In all the tests, the pulse energy has been set to 500 pJ. Moreover, when the *pulse-based* transmission scheme is used, the derivative order n and the standard deviation of the Gaussian pulse σ are set to 4 and 0.1, respectively. Figs. 2(a) and 2(b) show the upper bound of channel capacity and the maximum transmission range reachable in human tissues, respectively. From results, it is possible to observe that the *optimal* transmission scheme guarantees the highest performance thanks to its ability to optimally adapt the power distribution in the frequency domain as a function of the attenuation level. Nevertheless, as soon the allowed peak power transmission decreases, the channel capacity tends towards the one obtained with the *flat* approach. Moreover, the *pulse-based* approach exhibits the worst condition because it is not able to allocate a satisfactory amount of power in sub-channels experiencing the worst path loss. To provide a further insight, results demonstrates that the excessive attenuation provided by human tissues brings to very limited transmission ranges, i.e., lower than 9 mm, as well as to physical transmission rates lower thank 1 Tbps for transmission ranges above 3 mm. This means that multi-hop communications are required to extend the scope of this technology, together with novel MAC and routing protocols.

[2]Freely available at http://telematics.poliba.it/nano-sim.



(a)



(b)

Fig. 2. Estimated channel capacity (a) and transmission range (b).

IV. Conclusions

Focusing the attention on electromagnetic-based nanoscale communications in human skin tissues, this letter investigates the channel capacity and the transmission ranges achievable when deploying nano-machines in the human body. While it is expected to experimentally validate obtained results in the future, the reported analysis highlights how the communication in such kind of "medium" is really challenging and requires fully novel approaches, even combined with hybrid molecular communication techniques, to enable IoNT-based intrabody systems for healthcare applications.

Acknowledgments

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