Modelling of the Terahertz Communication Channel for In-vivo Nano-networks in the Presence of Noise

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***Abstract*—This paper focuses on the modelling of communication channel noise inside human tissues at the THz band (0.1-10THz). A novel model is put forward based on the study of the physical mechanism of the channel noise in the medium, which takes into account both the radiation of the medium and the molecular absorption from the transmitted signal. The derivation and the general concepts of the noise modelling is detailed in the paper. The results show that the channel noise power spectral density at the scale of several micrometres is at acceptable levels and the value tends to decrease with the increase of both distance and frequency. In addition, the channel noise is also related to the composition of the human tissues, with the result of higher channel noise in tissues with higher water concentration. The conclusion drawn from the conducted study and analysis paves the way for more comprehensive characterisation of the electromagnetic channel within in-vivo nano-networks.**

Keywords—Body-centric communication; nano-networks; noise modelling

I. INTRODUCTION

The recent interest in electromagnetic (EM) wireless nano-networks in the THz band stimulates the development of new models for performance assessment. Due to the advantages of size, bio-compatibility and bio-stability, this small-scale network is especially promising in biomedical fields [1]. For in-vivo nano-networks, EM communication is based on the transmission and reception of EM wave at the THz band to exchange information.

To date, some works have been performed on the channel characterisation and modelling of nano-communication at the THz band. Channel modelling of the THz wave propagating in the atmosphere with a different concentration of the water vapour was first studied in [2, 3]. Subsequently, both numerical and analytical EM channel modelling at the THz band for in-body nano-communication was investigated in[4] . In order to quantify the potential of the THz communication, channel capacity is used as an important performance metric and to proceed with realistic and accurate representation of the actual capacity and channel model in the THz band, consideration of channel noise model is necessary.

For the time being, some studies have been conducted for THz channel noise characterisation [2-4]. A noise model for nano-communication channels in the atmosphere was first introduced in [2], approximating the noise temperature as the molecular absorption noise, which is considered as a basis in [5, 6]. Same noise model was applied in [4] as well to characterise the in-vivo nano-communication channel. This noise model only takes into account the radiation energy of the medium and focuses on the transformation of the energy directly into antenna temperature, while ignoring the molecular absorption from the transmitted signal. Furthermore, the noise model was updated in [7] and it had been pointed out that the molecular absorption of the transmitted signal should be an additional noise source in the THz band. Then, such models were further investigated and applied in [8-10]. The different physical causes and mechanisms behind the absorption and emission were also studied in [11]. However, the molecular absorption noise model proposed by [8] is not fully comprehensive, since the distance-dependent spread path loss is not considered, which should also be added in the energy conservation.

In this paper, the channel noise model of in-vivo nano-networks at the THz band is proposed, which is considered as a combined result of the body radiation noise and molecular absorption noise. At the same time, the basic physical mechanisms behind the body radiation noise and molecular absorption noise are discussed and analysed.

The remainder of this paper is organized as follows. Section II presents the core background on molecular absorption and path loss models for EM communication at the THz band. The channel noise model for in-vivo nano-networks is proposed with the consideration of the physical background and derivation of the model in section III. Finally, a brief conclusion is drawn in Section IV.

II. Background

In this section, the analysis of the end-to-end noise model including transmission, propagation and reception of the EM wave is performed. Considering the complexity of the real human tissues, two assumptions are made here. A spherically symmetric propagation environment is assumed and the receiver is at the centre of a sphere while the transmitter is at distance r from the receiver, and the antennas of the transmitter are assumed to be ideal isotropic ones.

A. Molecular Absorption

Molecular absorption causes attenuation to the signals, since the EM energy is partially transformed into internal energy of the molecules in the medium. This process can be described stochastically by the absorption coefficient $\alpha(f)$ [2]. This quantity depends on the frequency and gives the THz band a unique frequency selective spectral absorption profile. Given the absorption coefficient, the amount of incident EM radiation that is capable of propagating through the absorbing medium at a given frequency can be calculated. This parameter is defined by transmittance, which is obtained by using the Beer-Lambert's law as [12],

$$\tau(r,f) = e^{-\alpha(f)r} \quad (1)$$

where f is the frequency of the EM wave and r stands for the total path length. The molecular absorption when travelling a distance r can be obtained from the transmittance of the medium τ given by Eq.1 as [2, 3],

$$A_{abs}(r,f) = \frac{1}{\tau(r,f)} = e^{\alpha(f)r} \quad (2)$$

B. Path Loss

The path loss in human tissues is divided into two parts; the spreading loss and molecular absorption loss [2]. The spreading loss is a part of attenuation, caused by the expansion of a wave propagating through the medium and it can be calculated from the modified Friis transmission equation [4],

$$A_{spr}(r,f) = \left(\frac{4\pi n\mathrm{fr}}{c}\right)^2 \quad (3)$$

where c is the speed of light in vacuum, f is the frequency of the EM wave and n is the corresponding refractive index of the THz wave in the human tissue medium. Considering the attenuation, the total path loss can be described as,

$$A_{PL}(r,f) = A_{spr}(r,f)A_{abs}(r,f) = \left(\frac{4\pi n\mathrm{fr}}{c}\right)^2 e^{\alpha(f)r} \quad (4)$$

The details on the calculation of the absorption coefficient and path loss of human blood, skin and fat tissues can be found in [13]. It is demonstrated that the total path loss increases with both the distance and the frequency, independently of the molecular composition of the channel. There are also some fluctuations in each figure. The reason is that the major contribution of the total absorption in a regular medium comes from the molecules of water vapour and the water vapour molecules also partially absorb the energy at frequencies slightly deviating from their resonant frequencies [7].

III. Channel Noise in the Terahertz Band

There are several sources of noise in the THz channel within human tissues. The transmission noise generated by the molecular absorption from the transmitted signal is the main contribution. There are also other contributors, such as the thermal noise caused by the surrounding nano-devices and the noise generated by the energy radiation from the molecules in the medium [2, 3]. By the conservation of energy, it is predicted that the absorbed energy can be divided into two parts. A fraction of the energy absorbed by the molecules in the medium shifts the molecules to a higher energy state and stays in the absorbing frequencies, therefore the medium experiences a temperature increase, which can be considered as heat. The other part of the energy is re-emitted in random directions and becomes the noise to the received signal [11]. The proportion of these two parts is very difficult to clarify, because the real human tissue is a very complex medium and it may be different in various environments.

To proceed with THz channel noise analysis, heat in the transmission channel needs to be specified. If all the absorbed energy is assumed to be transformed into heat, the increase in temperature of the medium due to the energy can be calculated. The temperature increase of the atmosphere was calculated in [11], which is a minute increase. Essentially, each point in the medium experiences a temperature increase due to the absorption from the transmitted signal, and at the same time radiates according to the Planck's law [11]. Nevertheless, the minute increase in temperature has a relatively small influence on the value of Planck's function; thus, it is possible that the heat contribution to the noise caused by the radiation will remain slight. Following the similar physical mechanism, this conclusion can also be applied to human tissues. Therefore, the heat contribution to the channel noise can be disregarded and Planck radiation of the molecules can be considered in the medium to be generated by the original temperature of the medium.

Moreover, with regard to the device noise, a number of prototypes of antennas emitting at the THz band available today are built with conventional materials. In this case, the Johnson-Nyquist thermal noise should be taken into account as a source of noise [6]. However, with the development of new materials, it is possible that the thermal noise can be neglected with the use of graphene and its derivatives to create THz antennas. Though very few studies of the noise at the THz band in graphene devices were reported to date, it is reasonably expected that the noise is small [13]. Therefore, the channel noise in the transmission is the only source of noise at the receiver, which is applicable to the human tissue model.

A. Body Radiation Noise

According to the physical fundamental in [11], it can be concluded that the molecular absorption noise model in [3] is based on the sky noise. The sky noise is caused by the temperature of the absorbing atmosphere, making the atmosphere (or any medium) as an effective black body radiator in homogenously absorbing medium (in the frequency domain). The sky noise is therefore known as a background noise which is independent of the transmitted signal. Besides, for the situation in the atmosphere, the temperature is simply treated as power in the Rayleigh-Jeans region of the spectrum, producing a noise temperature T_{mol}. The model can be derived following the explanation in [11],

$$T_{mol}(r,f) = T_0(1 - e^{-\alpha(f)r}) \quad (6)$$

where T_0 is the reference temperature.

However, this noise model is only a background noise instead of the molecular absorption noise in the atmosphere. For in-vivo scenario, this model is not sufficient due to the fact that it is not reliable to use the molecular temperature as a parameter to evaluate the radiation from the absorbing medium in human tissues.

In this paper, Planck's law is used to evaluate the background radiation noise and the molecular absorption noise is considered as an additional noise source. Similar to the sky noise which is caused by the atmosphere in the sky, in this paper the noise caused by the radiation of the human tissues is referred as body radiation noise. Therefore, the body radiation noise is described with the Planck's function in human tissue medium,

$$B(T_0, f) = \frac{2h\pi(nf)^3}{c^2}\left(e^{\frac{hf}{k_B T_0}} - 1\right)^{-1} \quad (7)$$

where k_B is the Boltzmann's constant and h is Planck constant. Planck's function is multiplied with π to transform the unit from $W/Hz/cm^2/sr$ to $W/Hz/cm^2$.

For simplicity, the human tissue is assumed as an isothermal and homogeneous layer with thickness r. As mentioned before , body radiation noise is generated by the radiation of the local sources of the human tissue medium and it is assumed that this radiation is only from the original energy state of the molecules before transmission happens, thus it is independent of the transmitted signal. And it can be described as,

$$N_b(r,f) = \lim_{r \to \infty} \int_0^r B(T_0,f)\alpha(f)e^{-\alpha(f)s}\, ds \quad (8)$$

The integral in the equation describes the noise intensity at the centre of a sphere with a radius r, given all the points s in the medium contribute to the noise intensity. And the limit accounts for the radiation of the entire medium. By calculating the integral, it could be obtained,

$$N_b(f) = \lim_{r \to \infty} B(T_0,f)\left(1 - e^{-\alpha(f)r}\right) \sim B(T_0,f) \quad (9)$$

Since this is obtained by the Planck's function, the unit of the body radiation noise p.s.d is $W/Hz/cm^2$. The body radiation noise can be further approximated by taking into account the (ideal) antenna aperture term $c^2/4\pi(n_0 f_0)^2$ to get body radiation noise p.s.d with the unit W$/Hz$ [11],

$$N_b(f) = B(T_0,f)\frac{c^2}{4\pi(n_0 f_0)^2} \quad (10)$$

B. Molecular Absorption Noise

Indeed, the internal vibration of the molecules turns into the emission of EM radiation at the same frequency of the incident waves that provoked this motion [2, 3]. It is considered as a noise factor that affects the propagation of EM waves in the THz band. However, it is demanding to specify the proportion of the absorbed energy turns into the emission. For simplicity, it can be assumed that all the absorbed energy from the transmitted signal received at the receiver would turn into molecular absorption noise p.s.d at point r. Hence, the molecular absorption noise can be expressed as,

$$N_m(r,f) = S_{Tx}(f)\left(\frac{c}{4\pi nfr}\right)^2\left(1 - e^{-\alpha(f)r}\right) \quad (11)$$

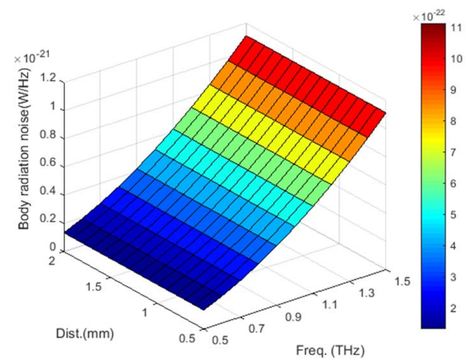
where $S_{Tx}(f)$ is the transmitted signal p.s.d and $(4\pi rnf/c)^2$ accounts for the spreading loss.

C. Total Channel Noise

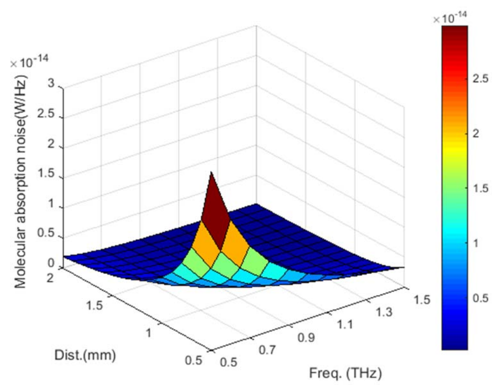
From the previous sections, the total channel noise p.s.d. for in-vivo nano-networks can be obtained as,

$$N(r,f) = N_b(f) + N_m(r,f) \quad (12)$$

The body radiation noise and molecular absorption noise p.s.d of human skin tissue are shown in Fig. 1. Because the molecular absorption noise is dependent on the transmitted signal, and for simplicity, in this paper only transmitted signal with flat p.s.d over the entire frequency is considered. The pulse energy and pulse duration are set to 1 pJ and 100 fs, respectively.



(a) Body radiation noise p.s.d

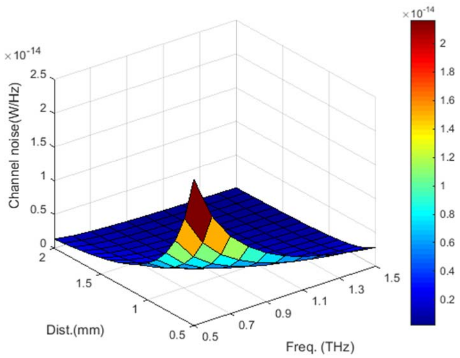


(b) Molecular absorption noise p.s.d

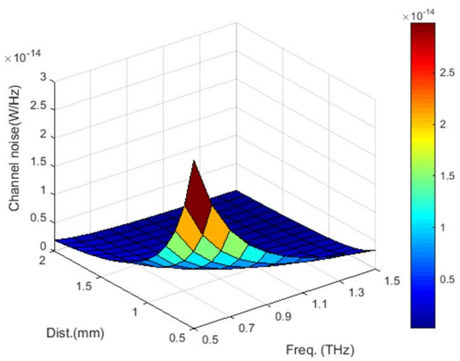
Fig. 1. (a) Body radiation noise p.s.d and (b) Molecular absorption noise p.s.sd for human skin tissue

From Fig. 1, it can be clearly seen that the molecular absorption noise p.s.d is about seven orders of magnitude higher than the body radiation noise p.s.d in human skin, which is due to the fact that the molecular absorption coefficient of the human tissue is considerable. This result is also valid in other types of human tissues. Hence, it can be concluded that the molecular absorption noise is the dominant noise source in the THz band for in-vivo nano-networks and the total channel noise can be approximated using the molecular absorption noise.

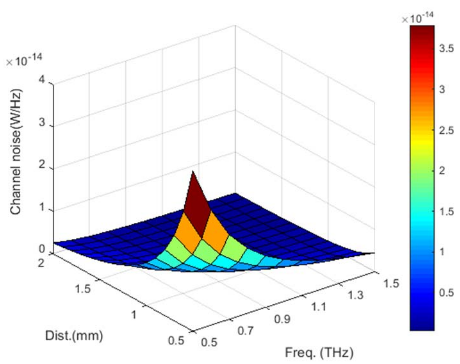
The total channel noise p.s.d of the THz wave in different human tissues is shown in Fig. 2. It is illustrated that the noise p.s.d increases with the decrease of the water concentration in the medium. The reason is that the noise p.s.d is inversely proportional to the square of the refractive index in (11), and the refractive index increases when the water concentration in the tissues rises. At the same time, the channel noise is decreasing with the rise of both distance and frequency for all three tissues, because the spread path loss increases when the distance and frequency go up and the loss is a substantial attenuation to the transmitted signal. Furthermore, because the absorption coefficient is considerable, the noise power is much bigger than the received energy power.



(a) Blood



(b) Skin



(c) Fat

Fig. 2. Total channel noise p.s.d as a function of distance and frequency for different human tissues (a) Blood, (b) Skin and (c) Fat

IV. CONCLUSION

In this paper, we focused on the induction mechanisms behind the channel noise contributions in the in-vivo nano-communication links and investigated the physical principles and mathematical derivations of the body radiation noise and molecular absorption noise. The channel noise is dominantly contributed by the molecular absorption noise. The noise tends to be at reasonable levels with the increase of both the distance and the frequency. In addition, the channel noise is also related to the composition of the human tissues; the noise p.s.d is higher in tissues with higher water vapour. What's more, the complete channel noise model including the real human tissue compositions and contributions will be developed and investigated as a follow-on study and further measurement campaigns are planned for the next steps in the research.

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