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NUMERICAL ANALYSIS OF THE ALVEOLAR SPACES AND HUMAN TISSUES FOR NANOSCALE BODY-CENTRIC WIRELESS NETWORKS

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Abstract: This paper investigates the propagation of Terahertz (THz) electromagnetic waves inside the human body and discusses a model of the system performance of Nanoscale Body-Centric Wireless Networks inside the alveolar spaces and human tissues. THz band wireless communication enables new applications especially in nanoscale wireless communication. The model developed in this paper calculates the total absorption loss, path loss and capacity properties of EM waves propagating through the Alveolar Spaces and Human Tissues in nanoscale environment for THz band wireless communication. Based on the modeling of noise level and path losses, the channel capacity is calculated. The results show that Wireless Nanosensor Networks (WNSNs) can communicate through the human body. According to the numerical analysis of the model several transmission windows which are ω1 = [0.01 THz – 0.5 THz], ω2 = [0.58 THz – 0.74 THz] and ω3 = [0.77 THz – 0.96 THz] have been found for Nanoscale Body-Centric Wireless Networks. The longest and lowest transmission window which is in the range of 0.01 THz – 0.5 THz values have been analyzed for blood, plasma, RCBs and water to design universal nanonode for Nanoscale Body-Centric Wireless Networks at gases in lungs and blood.

Keywords: Nanoscale Body-Centric Wireless Networks, Internet of Bio-Nano Things, Molecular Communication, Nanonetwork, Health Monitoring Systems

Nano Boyutlu Vücut Merkezli Kablosuz Ağların Alveolar Alanları ve İnsan Dokuları İçin Numerik Analizi

Öz: Bu makalede, insan vücudu içerisinde Terahertz (THz) elektromanyetik dalgalarının yayılımı araştırılmış ve alveolar boşlukları ve insan dokuları içindeki Nano Ölçekli Vücut Merkezli Kablosuz Ağların sistem performansının bir modeli tartışılmıştır. THz frekans bandı kablosuz iletişimde, özellikle nano ölçekli kablosuz iletişimde yeni uygulamalar sağlamaktadır. Bu makalede geliştirilen model, THz bandının kablosuz iletişimi için nano ölçek ortamında Alveoların boşluklarında ve insan dokularından yayılan EM dalgalarının toplam emilim kaybı, yol kaybı ve kapasite özelliklerini hesaplamaktadır. Gürültü seviyesi ve yol kayıplarının modellenmesine dayanarak, kanal kapasitesi de hesaplanmıştır. Sonuç olarak, Kablosuz Nano Telsiz Duyarga Ağlarının, insan vücudu üzerinden iletişim kurabildiği gösterilmektedir. Modelin sayısal analizine göre 3 iletim penceresi olan ω1 = [0.01 THz - 0.5 THz], ω2 = [0.58 THz - 0.74 THz] ve ω3 = [0.77 THz - 0.96 THz] bulunmuştur. Kablosuz Ağların THz iletişimde en uzun ve düşük geçiş penceresi olan olan 0.01 THz - 0.5 THz aralığı akçigerlerde ve kan için Nano Ölçekli Vücut Merkezli Kablosuz Ağlar evrensel nano düğüm tasarlayabilmek için modellenmiştir.

Anahtar Kelimeler: Nano Ölçekli Vücut Merkezli Kablosuz Ağlar, Biyo-Nano Nesnelerin İnterneti, Moleküler İletişim, Nanoağlar, Sağlık İzleme Sistemleri

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1. INTRODUCTION

The history of nanotechnology follows the development of concepts and experimental studies in the broad category of nanotechnology since it was put forward in 1959 (Feynman, 1960). The main aim for nanosensor is to develop battery free nodes which can sense the environment changes (Bush, 2010). A nanosensor is a sensor which detects and measures new types of events in the nanoscale (Akyildiz and Josep, 2010). However, by combining these basic units, the capacity of these nanosensors can be greatly expanded and more complex tasks can be realized that emphasize the nanonetworks concept (Akyildiz et al., 2008). The magnitude of the node needs to be in the nanometer size because the place where WNSNs are placed is too small in biomedical applications. Nano nodes require THz antennas for their dimensions because when the frequency increases dimension of the antenna decreases for instance Nano sized antennas can just propagate at THz range. THz wave has to propagate from the environment where the absorption is minimum. The band spectrum which is frequency band where the path loss is minimized and the transmission distance is maximized is called transmission window. Here in this paper useful transmission windows within the human body especially in the lungs and blood are calculated. There are related works in the literature like (Zarepour et al., 2015), (Yang et al., 2015) so in this work different model have been used to contribute to literature.

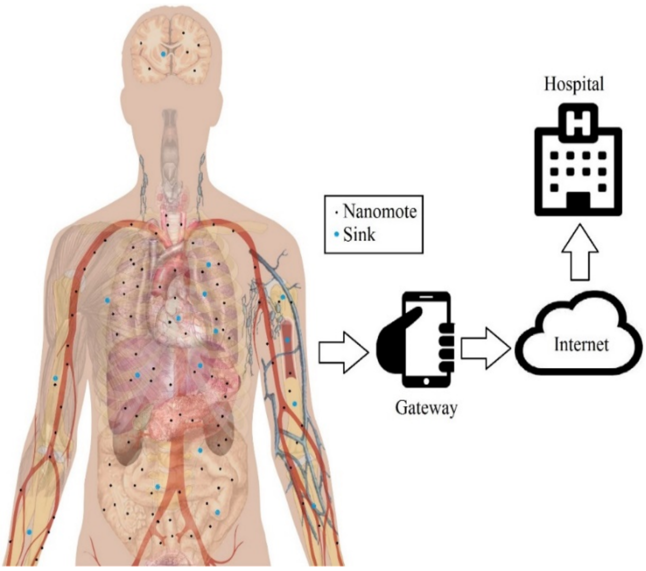

Figure 1:
Internet of Bio-NanoThings via WNSN for Intra-body applications

IoBNT (Bio-Nano Internet of Things) is a paradigm-changing concept for communication and network engineering; Here new challenges are faced with the development of effective and safe techniques for information exchange, interaction and networking in the biochemical area (Akyildiz et al., 2015). So far, two paradigms have been developed to complete the communication process. These are molecular communication (MC) and electromagnetic communication (EM). Table 1 summarizes MC and EM network features. MC is a wide range research area that covers biocommunication and nanocommunication technology.

The transmitting biological nanomachines encode information about the molecules and release them to the environment, the molecules then spread to the biological nanomachines which react biochemically with the molecules to dissolve the information. In MC for very short range communication the carrier is Ca^{2+}, in short range communication the carrier is molecular motors, in medium range communication the carrier is bacteria chemotaxis and conjugation, and in long range communication the carrier is hormones (Akyildiz et al.,2015), (Pierobon and Akyildiz, 2010), (Nakano, 2012).

For instance in MC an antenna is not necessary as in EM. As previously mentioned nano nodes require THz antennas for their dimensions. THz antennas are also a very revolutionary issue because the demand for increased and irregular bandwidth for wireless communication systems will inevitably lead to a widening of operating frequencies towards the lower THz frequency range. Higher carrier frequencies will enable fast transfer of large amounts of data when needed for emerging applications (Kleine and Tadao, 2011). There are some existing antenna design studies in literature such as (Llatser et al., 2012), (Jornet and Akyildiz, 2013), (Llatser et al., 2012) for WNSNs.

Table 1. Comparisons of key features of EM and MC.

	EM	**MC**
Communication Carrier	EM Wave	Molecule
Signal Type	Electronic Signals	Chemical Signal
Propagation Speed	Light Speed ($3*10^8$ m/s)	Extremely slow
Propagation Environment	Air, water, soil…	Aqueous Medium

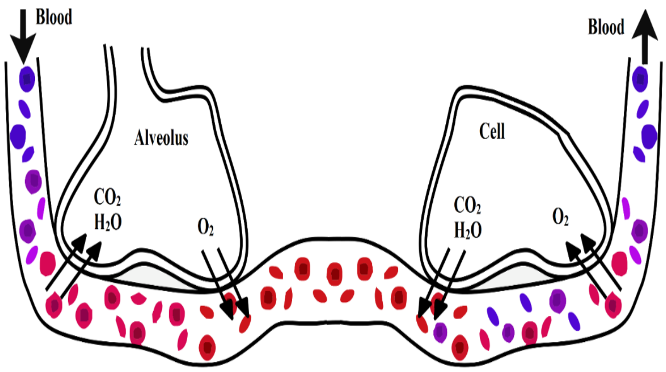

Figure 2:
Gas Exchange between Alveolar Spaces and Capillaries

The paper also calculates the transmission window optimal for the human body especially in the lungs and blood at THz range. Fig. 2 shows that the function of the respiratory system is to exchange three gases: oxygen, carbon dioxide and water vapor. As shown in Fig. 2, the inhaled oxygen moves from the alveoli in the capillaries to the blood and the carbon dioxide moves from the blood in the capillaries to the air in the alveoli. According to the paper Jornet ve Akyildiz, 2011 and Akkaş et al., 2012 it has been shown that some molecules vibrate strongly in specific THz frequencies. These vibrations cause EM loss and cannot therefore be used as a transmission window frequency. You can think vibrations as an example for human it is difficult to walk in crowded place like time square New York city but it is easy to walk and go far distance in an empty football field. You can find more details in Jornet ve Akyildiz, 2011 and Akkaş et al., 2012 papers for vibration of molecules at high frequencies. Here, numerical analyses of electromagnetic waves due to attenuation are given for the absorption loss, path loss and capacity properties in lungs and blood. Blood is selected for modelling because the blood cells suspend the blood plasma that constitutes 92% water. Previous publications prove that water has higher attenuation Akkaş et al., 2012 and Yang et al., 2015 as in blood. For this reason, in this study, the blood is analyzed which has the minimum capacity, transmission distance and maximum path loss. At THz range from publications (Akyildiz et al., 2014), (Akkas, 2016) several transmission windows have been found for one medium. This work investigates the propagation of electromagnetic waves from 0.01 to 10 THz and proves that the best transmission windows which are ω_1 = [0.01 THz – 0.5 THz], ω_2 = [0.58 THz – 0.74 THz] and ω_3 = [0.77 THz – 0.96 THz] have been found for Nanoscale Body-Centric Wireless Networks. The longest and lowest transmission window which is 0.01 THz – 0.5 THz range values have been analyzed for blood, plasma, RCBs and water to design universal nanonode for Nanoscale Body-Centric Wireless Networks at gases in lungs and blood.

This article is organized as follows. Related studies have been given in Section II. Section III shows the absorption characteristics of gases in the lungs and blood. Section IV provides an analysis of power allocation and channel capacity. In Section V, numerical results are given graphically. The paper is summarized in Chapter VI.

2. RELATED WORK

Javed and Ijaz (2013) I. T. Javed, et al. discover SimpleNano, a simple and new channel model for WNSN applications in the THz frequencies. SimpleNano is an approach to log-distance path loss with random (log-normally distributed) attenuation caused by molecular absorption.

Zarepour et al. (2015) reviews the characterization of time-varying characteristics of THz communication over a time-varying channel. Using existing propagation models for WNSNs, the paper then investigates the reliability of communication over the changing channels of communication as the main class of time-varying WNSNs. The chemical reactor used WNSN for monitoring and health monitoring as two case studies in which channel compositions changed over time.

In their project Petrov et al. (2015), developed an analytical framework for prediction of signal-to-noise-plus-noise ratio (SINR) in dense THz networks. First, they applied the mathematical devices of stochastic geometry to obtain a closed form equation for the total interference level in the receiver. Then, for the SINR value, the nodes provided an approach as the density and the transmission power function.

Yang et al. (2016) investigated the effects of the interface type between the epidermis and dermis layers in human skin tissue, and examined the paper by introducing two models with different interfaces (ie 3-D sine and 3-D sinc function).

Akkas (2016) calculated the capacity and SNR according to estimation of transmit paper. This paper gives a guideline for readers to calculate their transmit power for body-centric nano-communications.

Abbasi et al. (2016) proposed a new channel model for the skin that takes into account all the above-mentioned parameters. In addition, the proposed model was also confirmed by comparison with the measurement results of the skin sample using THz time domain spectroscopy (THz TDS).

Most of the studies given above explain the THz propagation in different environments. But none have proposed THz channel modeling of WNSNs using electromagnetic waves for producing a universal nanonode working at a specific frequency inside the alveolar spaces and human tissues. In this work THz channel modeling of WNSNs using electromagnetic waves for producing a universal nanonode working at a specific frequency inside the alveolar spaces and human tissues have been proposed.

3. NUMERICAL ANALYSIS OF THE MODEL

In THz band attenuation, THz wave propagation is changed according to environment. So electromagnetic waves need to transfer where the absorption loss properties is minimum. The Friis equation (1) calculates the received power from antennas which is shown as P_r with gain G_r, when transmitted from another antenna which is shown as P_t with gain G_t (Friis, 1946).

$$P_r(dBm) = P_t(dBm) + G_r(dB) + G_t(dB) - L_{FSPL}(dB) \quad (1)$$

L_{FSPL} equals $20log_{10}(d) + 20log_{10}(f) - 27.55$ where d express the distance from the transmitter in meters and f express the signal frequency in megahertz (Rappaport and Theodore, 1996). In THz communication the medium in which the EM wave will propagate needs to be added to the Friis equation (1) as additional loss (L_{medium}) and the noise power (L_{NP}) added is given in equation (2):

$$\begin{aligned} P_r(dBm) = {} & P_t(dBm) + G_r(dB) + G_t(dB) \\ & \underbrace{- L_{FSPL}(dB) - L_{NP}(dBm) - L_{medium}(dB)}_{System\ Loss} \end{aligned} \quad (2)$$

In equation (2) L_{NP} is given in terms of dBm calculated as (Couch and Leon., 1994):

$$L_{NP} = 10\log_{10}(1000 \cdot k \cdot T \cdot B)\ (dBm) \quad (3)$$

In equation (3) B, k and T express bandwidth, Boltzmann constant and the temperature respectively. Temperature unit is taken in Kelvin. T is calculated as 310.15 Kelvin in this paper which is equal to body temperature. To compute the L_{medium} in gases in the alveolar spaces and capillaries EM theory is used (Goody and Yuk, 1989) and the absorption coefficient is taken from (Rothman et al., 2009) database. The transmittance of an environment is calculated by (Beer-Lambert Law). So in equation (4), L_{medium} can be expanded as:

$$\begin{aligned} L_{medium}(f,d) &= \frac{1}{\tau(f,d)} = e^{k(f)d} \\ L_{medium}(f,d) &= k(f)\, d\, 10\log_{10} e(dB) \\ &\Downarrow \\ k(\omega) &= N(p,T)\sum_{i=1}^{q} n^{(i)} \sum_{j=1}^{s(i)} I^{(ij)}(T)\phi(\omega, \omega^{(ij)} - \omega, \omega^{(ij)} + \omega; p, T) \end{aligned} \quad (4)$$

Table 2. Constants and Parameters in equation (4)

Symbol	Quantity	Units
k(ω)	absorption coefficient	calculated by line-by-line method
N	volume concentration of gas molecules	at temperature T and pressure P
$\Phi^{(ij)}$	line shape of the j^{th} line	for the i^{th} isotopic
$I^{(ij)}$	integral intensity of the j^{th} line	for the i^{th} isotopic
$\omega^{(ij)}$	center position of the j^{th} line	stored in spectral line parameter database
$n^{(i)}$	mixing ratio of the i^{th} isotopic species	determined both by the gas mixing ratio ($N^{(i)}/N$)

Table 2 shows the parameters and constants in equation (4).

$$N(p,T) = p/(kT), \tag{5}$$

In equation (5) how volume concentration of gas molecules calculated has been shown (4).
For example, to calculate an enriched isotopic mixture, the user should indicate the artificial abundance (artab) of the given isotopic species, and the system recalculates the new intensity value as follows:

$$I^{(ij)} = I^{(ij)} artab(i) / natab(i) \tag{6}$$

Last of all, final formula which contain all the equation above in gases inside the alveolar spaces and capillaries can be rewritten as:

$$\begin{aligned} P_r(dBm) &= P_t(dBm) + G_r(dB) + G_t(dB) \\ &- \left(20\log_{10}(d(m)) + 20\log_{10}(f(MHz)) - 27.55\right) \\ &- \left(10\log_{10}(k \cdot T \cdot B) + 30 \ \ (dBm)\right) \\ &- \sum_{i,g} \frac{p}{p_0} \frac{T_{STP}}{p_0} \frac{p}{RT} q^{i,g} N_A \sigma^{i,g}(f) d 10\log_{10} e(dB) \end{aligned} \tag{7}$$

The final formula in human tissues given as:

$$\begin{aligned} P_r(dBm) &= P_t(dBm) + G_r(dB) + G_t(dB) \\ &- \left(20\log_{10}(d(m)) + 20\log_{10}(f(MHz)) - 27.55\right) \\ &- \left(10\log_{10}(k \cdot T \cdot B) + 30 \ \ (dBm)\right) \\ &- k(f) d 10\log_{10} e(dB) \end{aligned} \tag{8}$$

k(f) refers to absorption coefficient, which changes according to *f*. In this paper *k (f)* values calculated from Demirhan et al., (2010), for human tissues. Blood, plasma, RCBs and water have been also analyzed in this paper.

4. POWER ALLOCATION AND CHANNEL CAPACITY

To calculate the channel capacity SNR is given in equation (9) (Llatser et al., 2012):

$$SNR(d) = \frac{S(f_i)\,A(f_i,d)^{-1}}{N(f_i,d)} \tag{9}$$

In equation (9) $N(f_i,d)$, $P_r(f_i,d)$, $S(f_i)$ show the noise, total path loss and the transmit power respectively.

$$C(d) = \sum_i \Delta f \log_2\left[1 + \underbrace{\frac{S(f_i)\,A(f_i,d)^{-1}}{N(f_i,d)}}_{SNR}\right] \tag{10}$$

In equation 10, the SNR is calculated as $SNR=P_t-P_r-P_n$. P_t express the transmit power, P_r express the total path loss, and P_n express the noise energy calculated from equation (3) (Akyildiz et al., 2009). In this paper P_t is assumed to be 0 dBm (0.001 watt) for the evaluations which is low enough for a nanosensor. And finally capacity result is given at (10) which's unit is in bits/s (Akyildiz et al., 2009). As explained in the introduction, THz channel is sensitive to frequency so that the capacity calculated by dividing bandwidth (Goldsmith, 2005). In this paper Δf (centered on frequency) is taken as $1\text{x}10^{-2}$ THz.

5. NUMERICAL RESULTS

The electromagnetic absorption mathematical method which has obtained at section 3 and 4 have been used to get graphs in this section. In all models in this paper T is taken as 310.15 K (Body Temperature) and P is taken as 1 atm (Standard Atmospheric Pressure). Equation (4) has numerically calculated the absorption loss of the gases and blood medium in THz wireless medium which have been used in Fig. 3 to Fig. 6. Equation (7) and equation (8) have numerically calculated the total path loss of the gases and blood medium in THz wireless medium which have been used in Fig. 7a - Fig. 7b. Equation (10) have numerically calculated the capacity loss of the gases and blood medium in THz wireless medium which have been used in Fig. 7c.

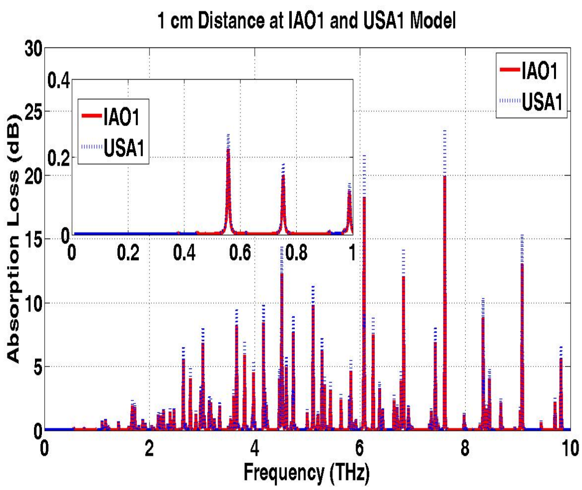

Figure 3a:
Frequency vs. absorption loss in the 0.1–10 THz at air model

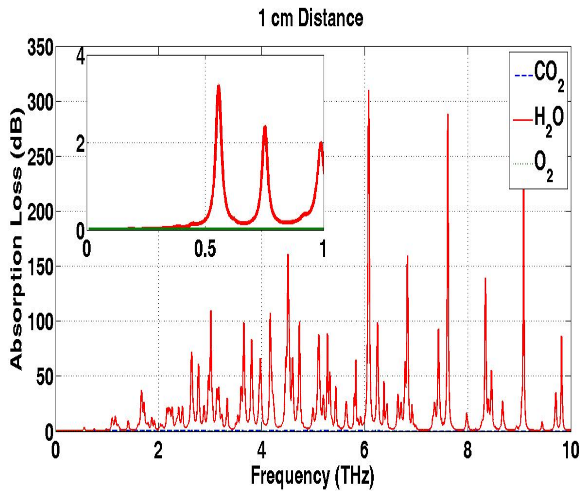

Figure 3b:
Frequency vs. absorption loss of gases exchange between alveolar spaces and capillaries

Figure 3:
Frequency vs. absorption loss

Fig. 3a. shows frequency vs. absorption of air and Fig. 3b. shows frequency vs. absorption of CO_2, H_2O, O_2 in the 0.1–10 THz respectively. In Fig. 3a. USA and IAO is the model that change according to temperature, pressure, density and viscosity over a large range of elevations or altitudes. USA1, IAO1: mean latitude of summer season. In all models in this paper T is taken as 310.15 K (Body Temperature) and P is taken as 1 atm (Standard Atmospheric Pressure). In Fig. 3. *k (f)* values calculated from (Couch and Leon., 1994) for gases. Examining the Fig. 3a. in detail several transmission windows have been found at Fig.3.

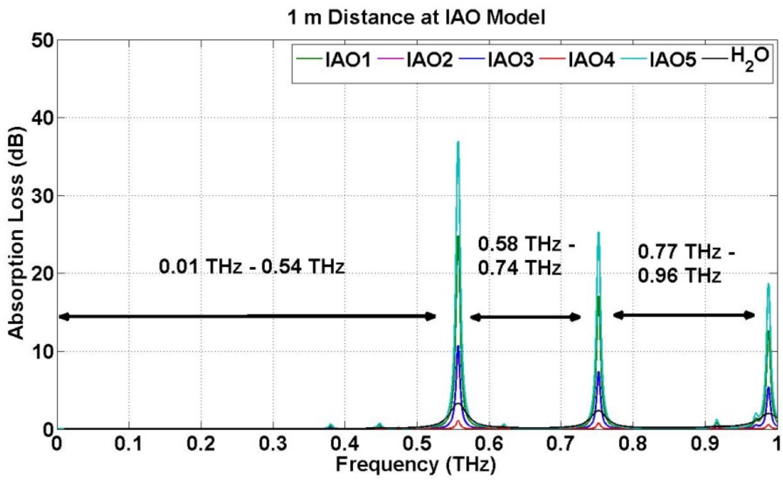

Figure 4a:
Absorption loss of IAO air model

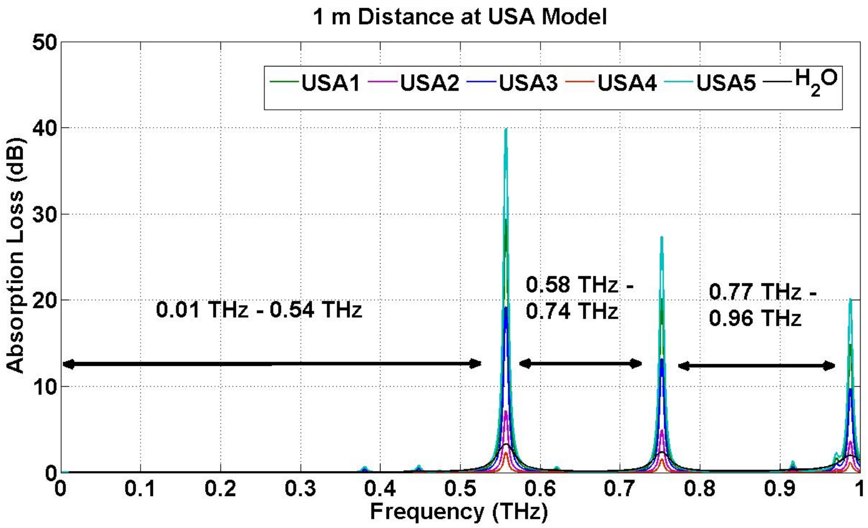

Fig. 4b:
Absorption loss of USA air model
Fig. 4:
Absorption loss of IAO and USA air model

Fig. 4a. shows frequency vs. absorption of air and Fig. 4b. shows frequency vs. absorption of CO_2, H_2O, O_2 in the 0.1–1 THz respectively which are more suitable and is the lowest band for transportation of signals in air and gases which are exchange between alveolar spaces and capillaries. Just H_2O is added to Fig. 4 because we know that from the Fig. 3b. CO_2 and O_2 has almost no absorption between 0.1–1 THz. The simulation results that have been given at Fig. 3. and Fig. 4 are given as a guide to other readers. Fig. 4c. and Fig. 4d. proves that nano communication data is possible from 0.01 THz to 1 THz frequency range and the best transmission window in this range is ω_1 = [0.01 THz – 0.5 THz], ω_2 = [0.58 THz – 0.74 THz] and ω_3 = [0.77 THz – 0.96 THz].

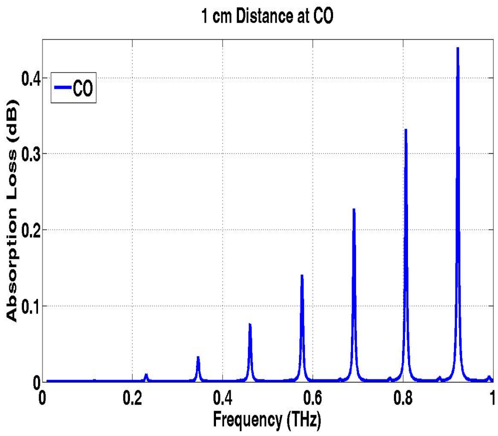

Figure 5:
Absorption loss of CO

Fig. 5. is given as an example of how the transmission window should also be used to design special sensors to detect dangerous gases like CO. To summarize the transmission window, w = [0.01–1 THz] may provide less attenuation but the other gases that can be involved should also be considered for specific sensor design.

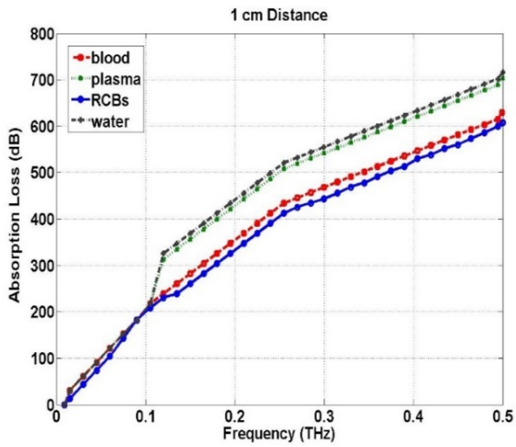

Figure 6a:
Absorption loss of blood, plasma, RCBs and water in the 0.1–0.5 THz

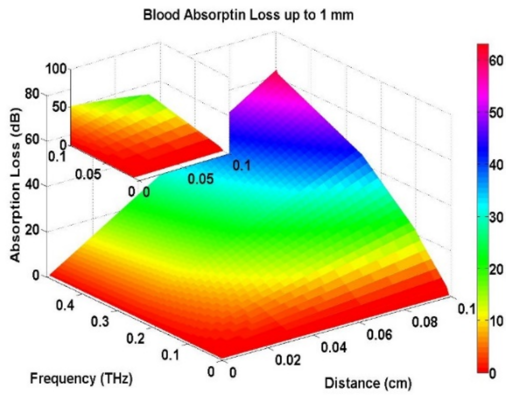

Figure 6b:
Absorption loss of blood in 3D dimension

Figure 6:
Frequency vs. distance and absorption loss of different body parts

Fig. 4. gives the values of absorption loss for air and gases exchange between alveolar spaces and capillaries in the band from 0.01–1 THz band. Best transmission window in this range have been found ω_1 = [0.01 THz – 0.5 THz], ω_2 = [0.58 THz – 0.74 THz] and ω_3 = [0.77 THz – 0.96 THz]. 0.01 THz – 0.5 THz range values have been given in Fig. 6. for blood, plasma, RCBs and water to design universal nanonode for Nanoscale Body-Centric Wireless Networks at gases in lungs and blood. Fig. 6a. gives the values of frequency vs. absorption loss of blood, plasma, RCBs and water in the 0.01–0.5 THz band. Fig. 6b. is a 3D version of Fig. 6a.. As a result, the absorption loss increases with increased frequency so the communication distance is decreases. If the reference value of 10 dB is considered, then from Fig. 6b. the "yellow" field can be tracked providing the best communication status. In Fig. 6a. and Fig. 6b. have given a detailed graph for loss of absorption due to the weakening of electromagnetic waves in the blood.

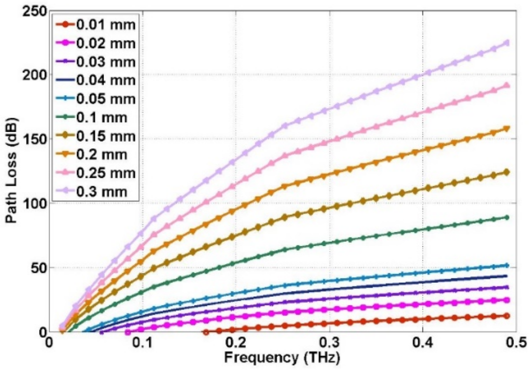

Figure 7a:
Frequency vs. path loss of blood in the 0.01–0.5 THz band at 0.01-0.3 mm distance

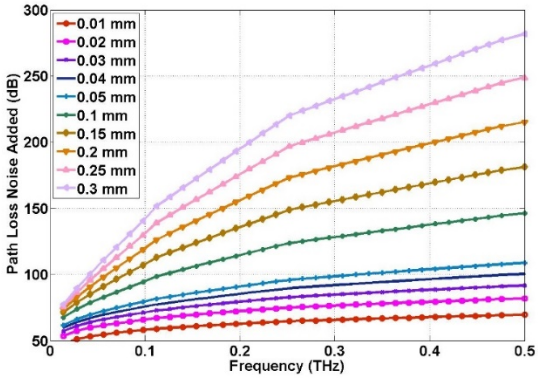

Figure 7b:
Frequency vs. noise added path loss of blood in the 0.01–0.5 THz band at 0.01-0.3 mm distance

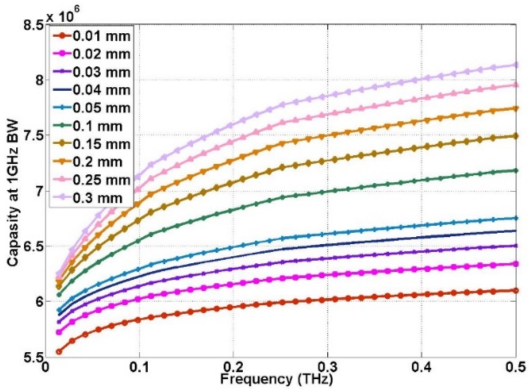

Figure 7c:
Frequency vs. capacity in the 0.01–0.5 THz band at 0.01-0.3 mm distance

Figure 7:
Frequency vs. other parameters in the 0.01–0.5 THz band at 0.01-0.3 mm distance

Equation (7) and (8) have numerically calculated the total path loss of the gases and blood medium in THz wireless medium. The results for path loss and noise added path loss is given in Fig. 7a. and Fig. 7b. respectively. Increase in path loss when noise is added as shown in Fig. 7b.. 0.01 - 0.5 THz band have 0.01 mm communication distance around a system loss of 10 dB. Fig. 7c. gives the relation between frequency and capacity in the 0.01 - 0.5 THz band at 0.01 -

0.3 mm distance. Fig. 7. tell us that there is not capacity problem at the THz range. But designers also need to consider that the nanosensors have nano magnitude and limited power source. Therefore, this paper also shows that new THz wave propagation models need to be found. Numerical evaluations show data communication is possible over the 0.01 THz to 0.5 THz band but to reach more communication distance modern THz propagation techniques have to be found.

6. CONCLUSION

The development of nanotechnologies and wireless nanosensor networks will have a major impact in almost all areas of our society, especially in the field of health. In this article, we focus on the electromagnetic option for communication between nanosensor gases in the body and blood. We have calculated an electromagnetic based wireless THz channel model to compute the losses and capacity. The paper calculates that 0.01–1 THz is more suitable for propagation of EM waves in air in lungs, gases exchange between alveolar spaces and capillaries and blood. Best transmission window in this range have been found ω1 = [0.01 THz – 0.5 THz], ω2 = [0.58 THz – 0.74 THz] and ω3 = [0.77 THz – 0.96 THz]. The longest and lowest transmission window which is 0.01 THz – 0.5 THz range values have been analyzed for blood, plasma, RCBs and water to design universal nanonode for Nanoscale Body-Centric Wireless Networks at gases in lungs and blood. Analyzes also show that there are limitations to data transfer in the THz band with today's technology. However, designers also need to think that the nanonodes have nano magnitude and limited power source so that new THz wave propagation models need to be found. As a result, this study is primarily in the first theoretical and numerical phase focusing on the communication or communication between alveolar spaces and nano-devices in human tissues inside the body. Nevertheless, the results at section 5 in gases inside the body and blood medium also presents a guideline for other researches that will be working in WNSNs. In future studies, experimental evaluation using THZ spectroscopy was planned for the next step to confirm the numerical findings and suggest a more comprehensive and evaluated human tissue feature. In future works, also thermal noise effect will be added to results and we can compare how useful the modeling for humanity.

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