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Breaking Barriers in-Vivo THz Communication Analysis for Nano Networks in Human Tissues

Ban A. Asi[1], Farhad E. Mahmood[2*], Nada I. Najim[1]

[1] Department of Computer Engineering, College of Engineering, University of Mosul, Al Majmoaa Street, 41002 Mosul, Iraq
[2] Department of Electrical Engineering, College of Engineering, University of Mosul, Al Majmoaa Street, 41002 Mosul, Iraq
[*] Corresponding author, e-mail: farhad.m@uomosul.edu.iq

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Abstract

Body Nano-Communication based on RF radio communication in the terahertz band supports health and fitness industry applications. Nano communications primary facilitate real-time monitoring of biological and chemical substances inside the human body, helping an early detection of stroke and heart attack risks. Monitoring small communication range inside the human body via electromagnetic propagation is not an easy task; thus, in this paper, we investigate the path loss of radio propagation in three human tissues: blood, skin, and fat using a Tera-Hertz frequency range in between 0.5 and 1.5 THz. The results support the idea that the path loss inside the human body depends on the dielectric loss of human tissues and the function of frequency and distance. It also shows that increasing the distance and the frequency of the signal inside the tissues, such as blood, fat, and skin, the path loss increases because the attenuation increases when the frequency increases. Furthermore, the study examines the effect of Doppler as a method of measuring the speed of blood flow to predict the early risks being considered.

Keywords

nano communications, human body, terahertz (THz), spreading loss, absorption loss

1 Introduction

Nanotechnology has many applications that include the manufacture of particles in the Nanoscale range. Nanotechnology is an emerging and attractive technology for future applications that received great attention since 1959, when it was invented by Richard Feynman cited in [1:p.1]. Ramsden [2] provides a comprehensive introduction to Nanotechnology, by highlighting the principle and some applications. While Al-Tayyar and Mohammed Ali [3] provide some challenges in the design of an antenna for such a technology.

Nanotechnology is science, engineering, and technology conducted at the nanoscale. Nanotechnology finds applications across various science fields, including martial engineering, physical science, chemistry, etc. [4, 5]. Nanoscale must be extremely small to reduce antenna size, and to meet the needs of higher frequencies, such as those between 0.5 and 1.5 THz [6, 7].

Nano or micronized machines can communicate with each other using THz waves. The impact of Nanotechnology, Nano networks, and Nano communication on human life and health is very significant in these days. The communication process is carried out using two models of communication, namely molecular communication and electromagnetic communication. The first is one of the promising techniques where information is transferred through molecules and the communication distance short. This design prevents delays and reduces the channel unreliability caused by random movement of particles. Electromagnetic communication, in which information is disseminated by Nano transmitters and receivers addresses the challenges of the former [6–8].

Afsana et al. [4] presented a scheme that enhances the performance of Nano networks communication over terahertz frequency bands for wireless body sensor networks, making it apt for smart e-health applications. However, they do not consider the change in human tissue and the impact of speed on the measurements.

Akkaş [6] presents an evaluation of the propagation of electromagnetic waves within human tissues, including blood, skin, and fat, for both single-path and multi-path layers, based on calculations of Nano sensor transmit power. Specifically, the characteristics of wave propagation within the Intra-Body Nano network communication pathway are

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determined through a theoretical method. Nevertheless, adjustments for variations in blood speed are not included.

Kulakowski et al. [9] conducted a concise review of significant nano-communication mechanisms, encompassing molecular mechanisms, the Förster resonance energy transfer phenomenon, and electromagnetic micro-devices. The article also offers a summary of Body Area Networks (BANs) communication technologies, covering smart textile applications, inductive and body coupling techniques, along with a variety of suitable radio technologies.

Lemic et al. [10] presented a network architecture capable of supporting precise localization of energy-harvesting in-body Nano nodes, in addition to facilitating their bidirectional communication with external environments. Furthermore, they introduced the use of location-aware and Wake-up Radio based wireless Nano communication paradigms, alongside Software-Defined Metamaterials, to enhance the proposed functionalities within THz-operating energy-harvesting in-body Nano networks.

Canovas-Carrasco et al. [11] introduced a hierarchical BANs architecture that comprises two distinct types of Nanodevices: Nano nodes and a Nano router. These devices are conceptually formulated utilizing currently available electronic components. The authors proposed a communication paradigm employing the THz frequency band for information exchange among the Nanodevices. This communication system was implemented within a human-hand scenario. Furthermore, the deleterious effects of path loss and molecular absorption noise on electromagnetic wave propagation within biological tissues were effectively mitigated in this context.

Salem and Azim [12] developed an electromagnetic model for blood, enabling the specification of the volume fraction and particle shape of its Red Blood Cells through Effective Medium Theory. They also examined how variations in the volume fraction of Red Blood Cells, also known as hematocrit, influence its characteristics and impact the level of signal degradation experienced during wireless transmission. Notably, they evaluated blood as a transmission medium for wireless signals in the THz band, considering different bandwidths and parameters such as path loss, molecular noise, signal-to-noise ratio (SNR), and information rate.

In this paper, we investigate the feasibility of body nano communication for health and fitness applications, focusing on real time monitoring of biological substances to detect stroke attack risks. It specifically examines radio communication in the terahertz band within the human body. The key contributions of the paper include:

1. Conducting path loss analysis in human body in terahertz frequency to explore the radio propagation in three human tissues: blood, skin, and fat, using frequency range between 0.5 and 1.5 THz.
2. Calculating frequency and distance dependency while taking into consideration the influence of different dielectric properties of the different tissues in terms of frequency and distance.
3. Using Doppler effect to measure the blood flow speed inside the human body to predict early risk factors for stroke and heart attack. By incorporating doppler measures, the system gains the ability to monitor physical parameters dynamically, thus enhancing its predictive capabilities.

The remainder of this paper is **structured** as follows: in Section 2, the system model for path loss is introduced, the BER in human tissues and the Doppler effect in human are discussed. In Section 3, the numerical results are elaborated, and subsequently, Section 4 presents the conclusions.

2 Research methodology

In this section, we discuss how to calculate the path loss of electromagnetic waves in the terahertz range inside the human body.

2.1 Total path loss

The Friis equation serves as a tool for determining the path loss experienced by THz channels within human tissues, characterized by two distinct components: spread path loss and absorption path loss. Spread path loss arises from the wave's expansion through the medium, whereas absorption path loss results from the medium's absorption properties, closely associated with the optical parameters of the material, particularly the extinction coefficient [11–15]. The total path loss PL can be calculated using the modified Friis equation as follows [11, 12]:

$$PL_{dB} = PL_{spr\ dB} + PL_{obs\ dB}\,. \quad (1)$$

Equation (1) provides a simplified mathematical method for calculating path losses, where PL_{spr} is the spread loss caused by the wave's expansion and propagation in the medium and PL_{obs} denotes the loss brought by the medium's absorption.

2.2 Spreading loss

The spread path loss is introduced by the expansion of the wave in the medium, which is defined as [11, 12]:

$$PL_{spr} = 20\log_{10}\frac{4\pi d}{\lambda_g}\,, \tag{2}$$

where d represents the propagation distance, the wavelength in the medium λ_g is determined by the relationship between the free-space wavelength, λ_0, and the material's refractive index n, as follows [11, 12]:

$$\lambda_g = \frac{\lambda_0}{n}\,. \tag{3}$$

2.3 Absorption loss

The path loss quantifies the attenuation resulting from molecular absorption. In general, when electromagnetic waves traverse a material medium, a portion of the electromagnetic energy emitted by a Nano antenna is transformed into the internal kinetic energy of the molecules. The molecular absorption path loss of waves in lossy media can be described using Beer-Lambert Law, which provides a fundamental understanding of absorption loss [12–14]. According to the law, the intensity of the electromagnetic wave decreases exponentially with propagation distance d as follows:

$$I(d) = I_0 e^{-\alpha d}\,, \tag{4}$$

where I_0 is the initial wave intensity, α is the absorption coefficient, which can be described using the following formula and the use of the extinction coefficient k, which aligns with the Beer-Lambert Law, capturing the wave energy loss as it propagates through biological tissues:

$$\alpha = \frac{4\pi k}{\lambda_0}\,.$$

Hence, we can write the electromagnetic wave's absorption loss (PL_{obs}) as it travels through the medium is measured by the extinction coefficient k:

$$L_{\text{absorption}} = \left(\frac{4\pi k}{\lambda_0}\right) d\,. \tag{5}$$

Moreover, the model used in this paper is a modified version of the Friis equation, which combines free-space loss and absorption loss, making it suitable for biological tissues. This approach is validated through the inclusion of dielectric properties, for example refractive index and extinction coefficient, which determine wave behavior in tissues like blood, skin and fat. Similar approaches have recently been adopted in prior works [6–16] to model wave propagation in lossy biological media, thereby supporting the relevance of our model.

To model the absorption loss, we begin with the medium loss (L_{medium}) caused by propagation through varied lossy medium, as well as the noise power (L_{NP}) at the receiver due to environmental factors. The received signal can be therefore expressed using the modified Friis equation, accounting for various propagation environments

$$P_r = P_t + G_r + G_T - L_{\text{NP}} - L_{\text{medium}} - L_{\text{FSPL}}\,. \tag{6}$$

L_{NP} is calculated as:

$$L_{NP} = 10\log_{10}\left(1000 * T \times K \times B\right). \tag{7}$$

Table 1 shows the constants and parameters of Eqs. (6) and (7).

L_{medium} can be calculated as:

$$L_{\text{medium}} = L_{\text{spread}} + L_{\text{absorption}}\,, \tag{8}$$

where $L_{\text{spread}} = 6.4 + 20\log(d) + 20\log(\beta)$ is spread attenuation loss due to the difference of wavelength of the signal of the medium. And $L_{\text{absorption}}$ is as in Eq. (5), hence

$$L_{\text{medium}} = 6.4 + 20\log(d) + 20\log(\beta) + \left(\frac{4\pi k}{\lambda_0}\right) d\,, \tag{9}$$

where

$$\beta = 2\pi f \sqrt{\frac{\mu\varepsilon'}{2}\left[1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2 + 1\right]}\,.$$

Dielectric properties are represented by the complex permit trinity of the medium. Optical properties are represented by the refractive index and the extinction coefficient of the medium [13].

The data listed in Table 2 can be used to compute the dielectric characteristics. The refractive index n, which we need in Eq. (3) and the extinction coefficient k according to Beer-Lambart Law can be calculated as in Eqs. (10) and (11), respectively [11–14]:

Table 1 Constant and parameter

Symbol	Quantity	Units
P_r	Received power	dBm
P_t	Transmitted power	dBm
G_r	Received antenna gain	dB
G_T	Transmitted antenna gain	dB
L_{NP}	Receiver noise power	dBm
L_{FSPL}	The free space loss	dB
K	Boltzmann constant	J/K
B	Bandwidth	Hz
C	2.99×10^8 m	m/s
T	Ambient temperature	310 K

Table 2 Dielectric parameters of blood, skin and fat at THz

Tissue	Blood	Skin	Fat
ε'	3.5781	2.9240	2.2130
ε''	2.0109	0.9085	0.5732

$$n = \sqrt{\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon'}{2}} , \tag{10}$$

$$k = \sqrt{\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'}{2}} , \tag{11}$$

where ε' represents the real part of the relative primitively and ε'' represents the imaginary part of the relative.

2.4 The signal to noise ratio

The signal to noise ratio (SNR) in dB can be given as

$$\mathrm{SNR} = P_t - L_f - P_n , \tag{12}$$

where P_t is the transmit power, L_f is the total path loss, and P_n is the noise energy. In this paper, P_t is assumed to be −15 to 5 dBm, which are low enough for Nano-node [6–16].

The 2 PSK modulation has a wider range: due to this, 2 PSK modulation is taken into consideration in this paper. The BER rate for 2 PSK with additive white Gaussian noise is [6–17]:

$$\mathrm{BER} = 0.5 erfc \sqrt{\mathrm{SNR}} , \tag{13}$$

where *erfc* is the error function formula [14].

2.5 Doppler effect on the speed of blood in the body

A Doppler ultrasound (Fig. 1) represents an imaging modality that employs sound waves to visualize blood in motion within blood vessels. In contrast, a standard ultrasound utilizes sound waves to generate images of bodily structures, but it lacks the capability to depict blood flow [18, 19]. The functionality of Doppler ultrasound is predicated on the measurement of sound waves that are reflected from moving entities, such as erythrocytes. This phenomenon is referred to as the Doppler effect.

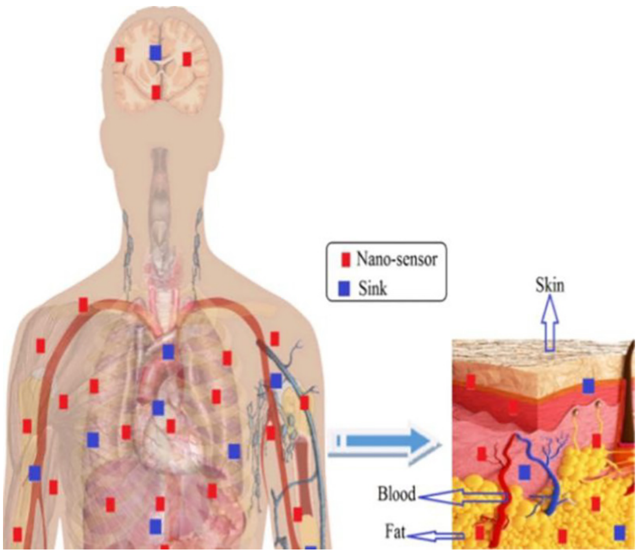

Fig. 1 Nano network for intra-body

This paper measures the speed of blood flow in humans using the Doppler effect *fr*, according to Eq. (14):

$$fr = \frac{c}{c - d} f , \tag{14}$$

where the propagation distance is d, the speed of blood is c. Doppler effect is utilized to calculate the blood flow speed based on the frequency shift using Eq. (14).

3 Results and discussion

The MATLAB program [20] is utilized to perform data analysis and compute the path loss and absorption coefficients of human tissues such as blood, skin, and fat at terahertz (THz) frequencies, serving as a critical component in the comprehension of nanoscale networks. By using dielectric parameters of blood, skin and fat at THz. Taken from the sources and at frequencies between 0.5 and 1.5 THz, we calculated the values of the path loss vs. distance for the signal inside tissues such as blood, fat and skin. Moreover, SNR and BER were also calculated for signals inside the tissues.

3.1 Path loss analysis

The finding reveals that path loss varies significantly among different tissues due to the unique dielectric properties of blood, skin, and fat. It is worth noting that blood exhibit the highest path loss across the frequency range of 0.5 to 1.5 THz, as shown in Figs. 2 and 3. This is attributed to the high-water content in blood plasma, which increases attenuation. Plasma constitutes 55% of blood fluid, is mostly water of the volume of 92%. In contrast, fat tissue demonstrates the lowest path loss due to its low water content compared to other tissue and simpler molecular structure. These results confirm the critical role of tissue composition in determining the feasibility of Nano communication at terahertz frequencies.

Interestingly, the study also highlights the nonlinear relationship between path loss and distance. For shorter distances (below 2 mm), path loss is relatively manageable, supporting the capability of intra-body Nano communication within small-scale networks. However, as the distance increases, the attenuation effect becomes more pronounced,

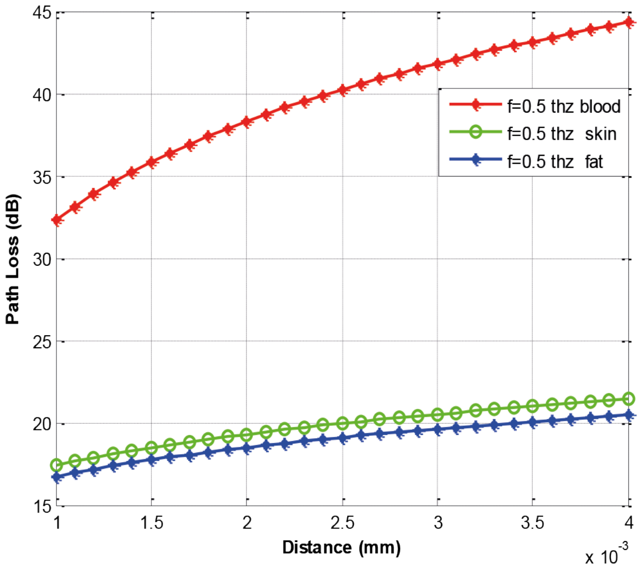

Fig. 2 The path loss vs. distance at frequency 0.5 × 10^{12} Hz, as calculated in Eq. (3)

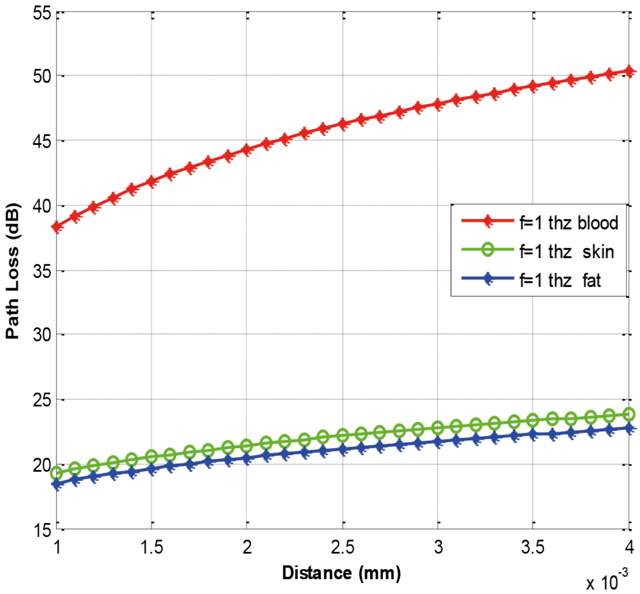

Fig. 3 The path loss vs. distance at frequency (1 × 10^{12} Hz)

emphasizing the need for optimized transmitter placement and enhanced power control in practical applications.

Fig. 4 illustrates that with a frequency equal to (1.5 THz), the path loss will increase, because the path loss is directly proportional to frequency.

While scattering and reflections can contribute to overall path loss, particularly in heterogenous or multi-layered tissues, this study focuses on dominant losses – spreading and absorption losses – in homogenous tissue media. Future work can extend this analysis to include scattering effects caused by inhomogeneities, such as cellular structures, and reflections at tissue interferences.

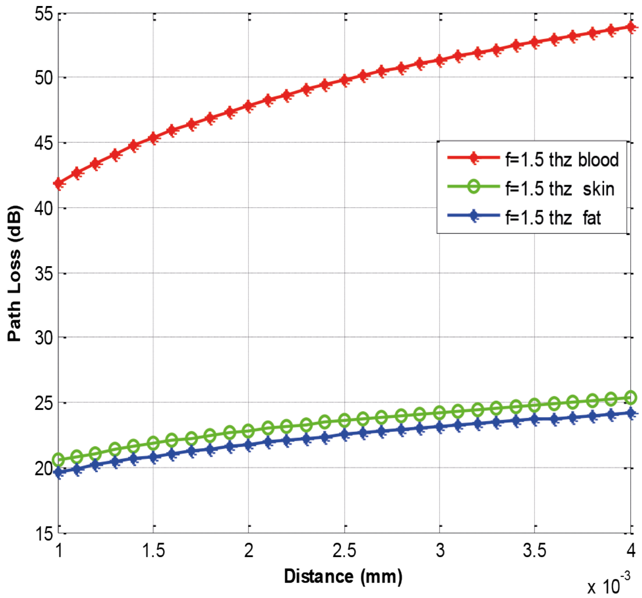

Fig. 4 The path loss vs. distance at the frequency (1.5 × 10^{12} Hz)

3.2 Frequency impact on path loss

The results in Fig. 5 indicates a positive correlation between frequency and path loss. At higher frequency, such as 1.5 THz, the absorption loss becomes the dominant factor due to increased molecular interaction. This trend underscores the trade-off between achieving higher data rates and managing signal attenuation. Future implementations of Nano communication systems should balance these factors to optimize performance.

The comparison between path loss and frequency, as simulated through MATLAB [20], demonstrates that

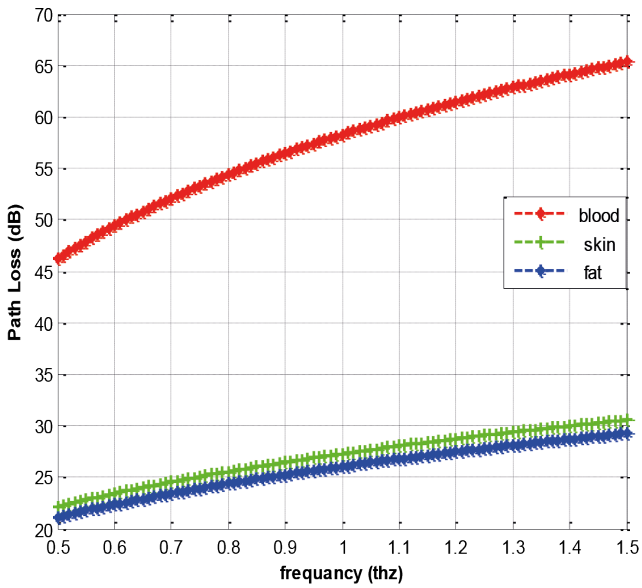

Fig. 5 The path loss vs. frequency

the path loss is subject to variation across different body parts owing to the disparate values of certain parameters, specifically the refractive index and absorption coefficient, and further elucidates that path loss intensifies with an increase in frequency.

3.3 SNR and BER evaluation

The SNR analysis in Fig. 6 demonstrates the blood exhibits a high BER because the attenuation in the blood is more than it is in the skin and the fat, especially at longer distance range of (0.4–2.2 mm). This finding suggests that communication through blood is more susceptible to noise and attenuation, which could impact the reliability of Nano sensors deployed in vascular environments. To mitigate these effects, advanced error correction algorithms and adaptive modulation techniques can be employed.

3.4 Doppler effect

The Doppler effect analysis, depicted in Fig. 7, illustrates how changes in blood flow velocity impact the frequency shift and the performance of the communication system. Faster blood flow rate results to frequency shifts, that introduce extra challenges in maintain synchronization between Nano devices, incorporating real-time Doppler measurements into the communication protocol may enhance the system adaptability to physiological variations.

3.5 Broader implication

These finding have significant implications for the design of Nano communication systems in healthcare. For instance, understanding the path loss dynamics within different tissues can inform the development of optimized implantable devices for monitoring blood glucose levels, detecting early signs of stroke, or administering targeted drug delivery. Moreover, the study highlights the need of more research of antenna design in biological environments.

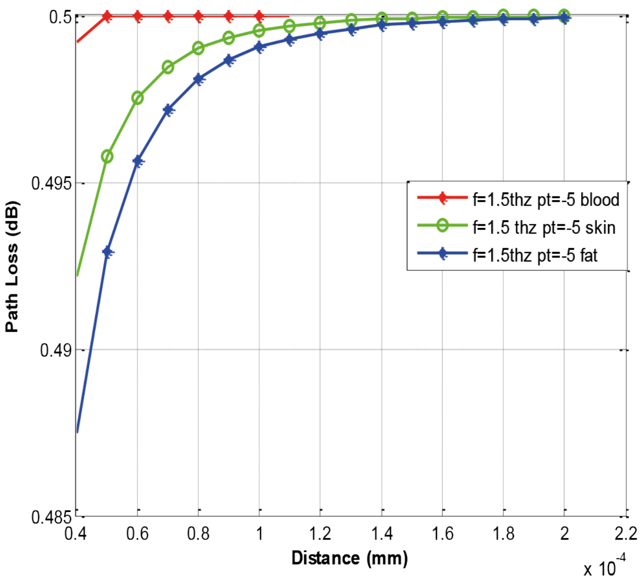

Fig. 6 BER vs. distance at frequency (1×10^{12} Hz)

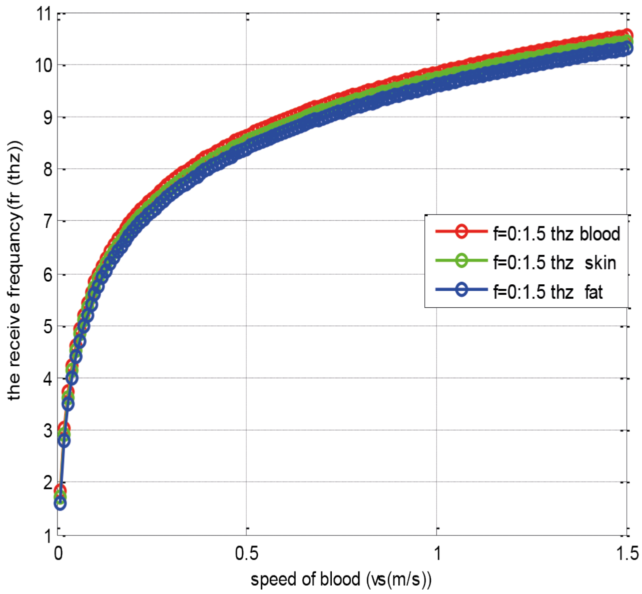

Fig. 7 Doppler effect vs. speed of the body

4 Conclusions

This paper presents a novel approach for estimating path loss in-vivo in THz channel within human tissues, across frequencies ranging between 0.5 and 1.5 THz. Our finding shows that at millimeter-scale distances, path loss remains manageable, highlighting the feasibility of electromagnetic communication among Nano devices. However, as distance increases, so does path loss within blood, skin, and fat tissues due to heightened attenuation. Path loss is more pronounced in blood than in skin or fat, likely due to blood plasma's composition – 92% water – which increase attenuation. Furthermore, our investigation includes an assessment of the BER of Nano sensors propagating THz electromagnetic waves within blood, skin, and fat. Additionally, we proposed a novel methodology of using Doppler effect to gauge the impact of varying bodily speeds on blood flow, thereby increasing our understanding of physiological dynamics. The contributions underscore the potential of intra body Nano communication for advancing healthcare monitoring and diagnostic capabilities.

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