Stochastic Noise Model for Intra-body Terahertz Nanoscale Communication

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ABSTRACT

The development of miniature plasmonic signal sources, antennas and detectors are paving the way towards advanced healthcare networks, namely, in-vivo Wireless Nanosensor Networks (iWNSNs). These networks are expected to enable a plethora of applications ranging from intra-body health-monitoring to drug-delivery systems. The state of the art of nanoelectronics, nanophotonics, and nanoplasmonics points to the Terahertz (THz) band (0.1-10 THz) as the frequency range for communication among nano-biosensors. Several propagation models have been recently developed to study and assess the feasibility of intra-body electromagnetic (EM) nanoscale communication. These works have been mainly focused on understanding the propagation of EM signals through biological media, but do not present extensive formulation which quantify the noise contributions in the intra-body channel. In this paper, a stochastic noise model for iWNSNs is presented upon analyzing the individual noise constituents that affect intra-body systems operating in the THz frequency band. The identified noise sources include Johnson-Nyquist noise, Black-body noise as well as Doppler-shift-induced noise. The probability distribution of each noise component is derived and a comprehensive noise framework is established which allows the total noise power-spectral density of the iWNSN in the THz frequency band to be computed. The proposed analytical model is fundamental as noise is an important metric which affects both the intra-body channel capacity and data rate in the THz band.

CCS CONCEPTS

• **Computer systems organization → Sensors and actuators**;

KEYWORDS

Nanonetworks, terahertz band, noise model, intra-body

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1 INTRODUCTION

Nanotechnology is expediting the development of novel nanosensors that are capable of detecting various types of events at the nanoscale with unprecedented sensing and actuation capabilities. In-vivo Wireless Nanosensor Networks (iWNSNs), which have the potential to operate inside the human body in real time, have been recently proposed as a technique to provide faster and more precise disease diagnosis and treatment in comparison to traditional technologies [5]. Meanwhile, researchers have effectively deployed surface plasmon resonance sensors to investigate circulating biomarkers in body fluids for the diagnosis of deadly diseases [22]. By means of communication, nanosensors will be able to autonomously transmit their sensing information to a common sink, be controlled from a command center, or coordinate joint actions when needed [2].

The cutting edge paradigms of nanoelectronics, nanophotonics, and nanoplasmonics points to the Terahertz (THz) band (0.1-10 THz) as a promising frequency range for communication among nano-biosensors. Though most nano-biosensing applications rely on the use of light, the study of the THz band propagation within the human body is still at its infancy. Numerical analysis and characterization of THz propagation through various body tissues have been presented in [23]. A genuine model that accounts for the intra-body signal degradation has been demonstrated in [8]. Starting from these, the development of comprehensive architectures and protocols for intrabody nanonetworks comprise the path of research that ought to be addressed.

Noise is a controlling quantitative influence on the development of systems. It basically degrades the signal transmission quality and affects the system throughput, for it may require re-transmission of data packets or extra coding to recover data in the presence of errors. Existing research in terms of the analysis and quantification of noise in the THz frequency band can be found in [12][13]. Yet, in the context of in-vivo wireless networks, few works exist to tackle this fundamental parameter which ought to be studied in order to assess the communication link [15][24]. In our recent previous work, a deterministic thermal noise analysis for intra-body communication based on the diffusive heat flow theory has been developed [7].

In this work, we present a novel stochastic noise model for intra-body wireless communications in the THz frequency band by identifying the three main noise sources inside the body. These include the Johnson-Nyquist noise, Black-body noise as well as Doppler-shift-induced noise. Detailed analysis of the underlying physical fundamentals of each noise source is illustrated. In addition, the probability distribution of each noise component is given and a complete noise model is derived, allowing to compute the total noise power-spectral density of the in-vivo medium in the THz frequency band.

The rest of the paper is organized as follows. In Sec. 2, the characterization of intra-body noise is presented. In Sec. 3, an intra-body detailed noise analysis is established, in which the Johnson noise, Black-body noise as well as Doppler- shift-induced noise are intensively discussed. In Sec. 4, the numerical results of the developed noise model are demonstrated. Finally, we draw our conclusions in Sec. 5.

2 CHARACTERIZATION OF INTRA-BODY NOISE

Our system of interest is composed of a medium full of both biological cells as well as liquid-surrounded heat sources larger than tens of nanometers (nm), as illustrated in Fig. 1. The heat sources in this work are considered to be nano-antennas in nano-biosensing implants in the human body. Throughout this paper, we will use the general term "particle" to refer to both the biological cells and the nano-antennas. As the nano-antennas radiate electromagnetic (EM) waves, cells will capture part of this EM energy through the process of molecular absorption. Hence, subsequent to such exposure, the cells also become heat sources. The absorbed EM energy will be converted into heat which will result in temperature increase around the cells, as has been extensively discussed by the authors in [7]. Fundamentally, temperature is a key factor in computing the noise associated with a communication system.

The noise sources in our medium of interest include Johnson noise, Black-body noise and Doppler-shift-induced noise. Johnson noise exists as a result of the detecting nano-receiver at the receiver side. Black-body noise arises as a natural contribution of the thermal EM radiation within or surrounding a body. In the case of the Doppler-shift-induced noise, the propagation between the nano-receiver is not only by a direct line-of-sight route, but via many paths as different scatterers change the plane waves incident on the receiver. Consequently, the received signal at any point consists of a large number of horizontally travelling uniform plane waves whose amplitudes, phases and angles of arrival have each a random component.

3 ANALYSIS OF INTRA-BODY NOISE

In this section, a comprehensive analysis of the identified noise sources available in an intra-body medium is provided.

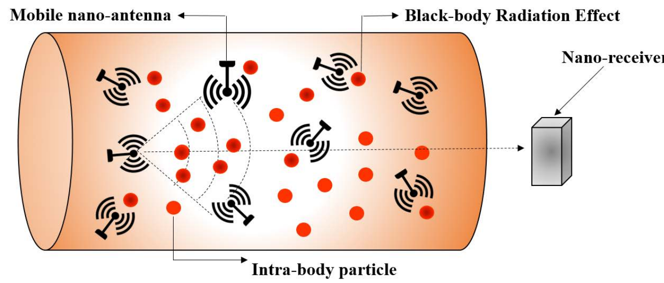

Figure 1: Proposed intra-body system model.

3.1 Johnson-Nyquist Noise

Within every communication system, particularly at the front-end, components that contribute noise to the detection process exist. This results in degrading the ultimate detectability of the signal. The majority of this noise arises from electronics, particularly mixers or direct detectors as well as transistors in amplifiers that follow these devices. Thermal noise, also referred to as Johnson-Nyquist noise, is produced by fluctuations of charged particles (usually electrons) in conducting media [3]. Any component in the system that dissipates power generates thermal noise. When a resistor R is at temperature T, random electron motion produces noise voltage, $V(t)$, at the open terminals. Consistent with the central limit theorem, $V(t)$ has a Gaussian distribution with an rms voltage of [3]

$$V_{rms} = \sqrt{4k_b TRB}, \tag{1}$$

where k_b is Boltzmann constant, h is Planck constant and B is the bandwidth of the measuring system. The probability density function (PDF) of the noise voltage, V_{rms}, is given by

$$p(x) = \frac{1}{V_{rms}\sqrt{2\pi}} \mathbf{exp}\left(-\frac{x^2}{2V_{rms}^2}\right), \tag{2}$$

with a zero mean and variance of [3]

$$\sigma_v^2 = \frac{2(\pi k_b T)^2}{3h} R. \tag{3}$$

The theory further shows that the mean square spectral density of thermal noise is [3]

$$G_v(f) = 2Rhf \cdot \mathbf{exp}\left[-\left(\frac{hf}{k_b T} - 1\right)\right]. \tag{4}$$

Instead of dealing with mean square voltage, the available spectral density at the load resistance could be found using the maximum power transfer theorem as

$$G_a(f) = \frac{G_v(f)}{4R}. \tag{5}$$

Thus, the first source of noise that is always found in an in-vivo wireless communication system arises from the thermal cycle of heat exchange between the receiver, which is a nano-antenna in our assumed scenario, and the environment.

3.2 Black-Body Noise

Every physical body spontaneously and continuously emits EM radiation. The emitted radiation is described by Planck's law [16]. The higher the temperature of a body, the more radiation it emits at every wavelength. The intra-body medium could be denoted as a Black-body since it is associated with temperature above absolute zero. Therefore, the intra-body channel always has background noise even without signal transmission.

The spectral radiance of a body, E_f, describes the amount of energy radiated from a body at different frequencies. It is measured in terms of the power emitted per unit area of the body, per unit solid angle that the radiation is measured over, per unit frequency as [11]

$$E_f(f,T) = \frac{2hf^3}{c^2}\mathbf{exp}\left[-\left(\frac{hf}{k_bT}-1\right)\right], \tag{6}$$

where c is the speed of light in the medium. The power spectral density, $H(f)$, is the product of the spectral radiance, $E_f(f,T)$, and the effective aperture area, A_{eff}, of the nanoantenna, i.e.

$$H(f) = E_f(f,T)\cdot A_{eff}, \tag{7}$$

where A_{eff} is inferred from the amount of noise that the antenna intercepts and is given by

$$A_{eff} = \frac{\lambda_g^2}{4\pi}. \tag{8}$$

λ_g is the effective wavelength given as λ/n', in which n' and n'' are the real and imaginary parts of the tissue refractive index n, respectively. The tissue refractive index is given as

$$n = n' - jn''. \tag{9}$$

In classical physics, Black-body radiation is considered as chaotic EM radiation. Hence, the electric field strength and the magnetic induction of a mode of the thermal radiation (in a small spatial region) have a Fourier series representation given by [10][21]

$$x(t) = \frac{1}{2}a_0 + \sum_{n=1}^{N} a_n\mathbf{cos}(2\pi f_n t) + b_n\mathbf{sin}(2\pi f_n t). \tag{10}$$

Thereby, the phenomenon is described by a characteristic set of frequencies or harmonics, f_n. If we take a particular mode of the radiation field, a_n as an example, we have [10]

$$a_n = \frac{2}{T}\int_0^T x(t)\mathbf{cos}(2\pi f_n t)dt. \tag{11}$$

Next, we consider the characteristic function of this particular mode given as

$$\varphi_n(A) = \left\langle e^{-ja_nA}\right\rangle. \tag{12}$$

The term $\left\langle a_n^2\right\rangle$ is related to the correlation function by

$$\left\langle a_n^2\right\rangle = \frac{4}{T^2}\int_0^T\int_0^T \left\langle x(t')x(t'')\right\rangle \mathbf{cos}\omega_n t'\mathbf{cos}\omega_n t'' dt'dt''. \tag{13}$$

Using the properties of a Gaussian random process, it is known that

$$\left\langle x(t')x(t'')\right\rangle = 2D\delta(t'-t''), \tag{14}$$

in which D refers to the diffusion coefficient. It then follows that

$$\langle\mathbf{exp}(-ja_nA)\rangle = \mathbf{exp}\left[-\frac{1}{2}A^2\left\langle a_n^2\right\rangle\right], \tag{15}$$

where

$$\left\langle a_n^2\right\rangle = \frac{4D}{T}. \tag{16}$$

The probability that a_n^2 has a particular value of a_n follows from the Fourier Transform, and the form of the characteristic function indicates that the distribution is Gaussian. The PDF of the excitation of the amplitude, a_n, is given by [10]

$$p(a_n) = \frac{1}{\langle a_n\rangle\sqrt{2\pi}\mathbf{exp}\left[-\frac{a_n^2}{2\langle a_n^2\rangle}\right]}. \tag{17}$$

3.3 Doppler-Shift-Induced Noise

The internal fluctuations which result from the heat transfer mechanism experienced by the intra-body system are characterized by the cells' random and irregular velocity. To assess such scenario, consider the one-dimensional motion of a spherical particle with radius r, mass m, position x, and velocity $v(t)$ in a fluid medium having a viscosity η. Newton's equation of motion for the particle is [14]

$$m\frac{dv(t)}{dt} = F_{tot}(t), \tag{18}$$

where $F_{tot}(t)$ is the total instantaneous force on the particle at time t, arising from the interaction of the particle with the surrounding medium. This force is governed by a friction force, F_{fric}, proportional to the velocity, $v(t)$, of the particle and given as [20]

$$F_{fric} = -\zeta v(t), \tag{19}$$

where the friction coefficient, ζ, also referred to as the drag constant, is described by Stokes law as [14]

$$\zeta = 6\pi\eta r. \tag{20}$$

A random force, $\xi(t)$, represents the rapidly fluctuating part of F_{tot}. For such scenario, the analysis could be modeled using the Brownian particle equations of motion, referred to as *Langevin equations*, given by [20]

$$\begin{aligned} m\frac{dv(t)}{dt} &= -\zeta v(t) + \xi(t),\\ \frac{dv(t)}{dt} &= -\gamma v(t) + \frac{1}{m}\xi(t), \end{aligned} \tag{21}$$

where $\gamma = \zeta/m = 1/\tau$ and τ is the Brownian timescale for the relaxation of the particle velocity. The force during an impact is supposed to vary with extreme rapidity over the time of any observation, i.e. in any infinitesimal time interval, which cannot be strictly true in any real system. Therefore, the effect of the fluctuating force can be illustrated by providing its first and second moments as time averages over infinitesimal time interval [25]

$$\langle\xi(t)\rangle_\xi = 0, \quad \langle\xi(t_1),\xi(t_2)\rangle_\xi = 2\beta\delta(t_1-t_2), \tag{22}$$

where $\langle\ldots\rangle_\xi$ is an average with respect to the distribution of the realizations of the stochastic variable $\xi(t)$, and β is a measure of the strength of the fluctuation force. If $\xi(t)$ is continuous, the existence of a local solution for (21) is guaranteed. An explicit formal solution of (21) can be obtained as [20]

$$v(t) = v(0)e^{-\gamma t} + \frac{1}{m}\int_0^t e^{-\gamma(t-x)}\xi(x)dx. \tag{23}$$

The mean squared velocity can be found from (23) as [25]

$$\left\langle v(t)^2\right\rangle = v(0)^2e^{-2\gamma t} + \frac{\beta}{\zeta m}(1-e^{-2\gamma t}). \tag{24}$$

In the long time limit, the exponential drops out and the mean squared velocity must approach its equilibrium value k_bT/m. Consequently, we have [25]

$$\beta = \zeta k_b T. \tag{25}$$

The changing velocity of the source (nano-antennas in nano-biosensing implants in the human body) results in Doppler-shifts to the transmitted frequency of light originating from a source that is moving in relation to the observer (receiver). Therefore, the wave is observed to have frequency, f_d, for a signal arriving at an angle, ϕ, given as

$$f_d = f_m \mathbf{cos}\phi, \tag{26}$$

where

$$f_m = \frac{\langle v(t)\rangle}{\lambda_g}. \tag{27}$$

f_m is the maximum Doppler-shift at the particle speed and carrier wavelength, λ_g.

The received signal $R(f,t)$ is a result of many plane waves each shifted by the Doppler contribution appropriate to the particle motion relative to the direction of the plane wave [19]. The power contributed to the received signal by plane waves constitutes of the power, $f(\phi)d(\phi)$, arriving in the angular interval that would be received by an isotropic nano-antenna of the same polarization, multiplied by the nano-antenna gain, $G(\phi-\alpha)$, multiplied by the square of the parallel fraction of polarization $\left[p_u(\phi)\cdot p_g(\phi-\alpha)\right]$ as [9]

$$f(\phi)d(\phi)\left[p_u(\phi)\cdot p_g(\phi-\alpha)\right]^2 G(\phi-\alpha), \tag{28}$$

where α is the antenna bearing of the antenna beam. From (26), we find $d\phi$ as

$$d\phi = -\frac{1}{f_m\sqrt{1-\left(\frac{f_d}{f_m}\right)^2}}df. \tag{29}$$

By substituting (29) into (28) and combining the two angles $\binom{+}{-}\phi$ from which the Doppler-shift, f_d arises, the power-spectral density of $R(f,t)/\sqrt{2}$ is given as [19]

$$S(f) = S_1(f) + S_2(f), \tag{30}$$

in which

$$S_1(f) = \frac{f(\phi)G(\phi-\alpha)\left[p_u(\phi)\cdot p_g(\phi-\alpha)\right]^2}{f_m\sqrt{1-(f_d/f_m)^2}}, \tag{31}$$

and

$$S_2(f) = \frac{f(-\phi)G(-\phi-\alpha)\left[p_u(-\phi)\cdot p_g(-\phi-\alpha)\right]^2}{f_m\sqrt{1-(f_d/f_m)^2}}, \tag{32}$$

where $\phi = \mathbf{cos}^{-1}\left|\frac{f_d}{fm}\right|$. Similar to mobile-radio reception, both the in-phase and quadrature components at any given time, t, are independent Gaussian random variables with the following PDF [19]

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\mathbf{exp}\left[-\frac{x^2}{2\sigma^2}\right]. \tag{33}$$

x in this case is the in-phase component of $R(f,t)$ and σ is the RMS value given as [19]

$$\sigma = \sqrt{\int_{-f_m}^{f_m} S(f)df}. \tag{34}$$

3.4 Combined Noise Model

In order to formulate an end-to-end noise model, the total noise power spectral density should be calculated. From the analysis presented above, it is clear that the three noise sources are probabilistically independent. Thereafter, the resulting PDF is the convolution of (2), (17) and (33). As we are dealing with three Gaussian PDFs, we should recall that the convolution of Gaussian functions is also a Gaussian, with variance being the sum of the original variances [6]. This can be proved by knowing that the Fourier Transform of a Gaussian, $f_X(x) = \mathcal{N}(x;\mu_X,\sigma_X^2)$ is given as

$$F\{f_X\} = F_X(\omega) = \mathbf{exp}[-j\omega\mu_X]\mathbf{exp}[-\frac{\sigma_X^2\omega^2}{2}]. \tag{35}$$

According to the convolution theorem and by considering three Gaussian PDFs we have

$$\begin{aligned} f_Z &= f_X * f_Y * f_W = \mathcal{F}^{-1}\left\{\mathcal{F}\{f_X\}\cdot\mathcal{F}\{f_Y\}\cdot\mathcal{F}\{f_Z\}\right\} \\ &= \mathcal{F}^{-1}\Bigg\{\mathbf{exp}\left[-j\omega\mu_X\right]\mathbf{exp}\left[-\frac{\sigma_X^2\omega^2}{2}\right]\mathbf{exp}\left[-j\omega\mu_Y\right] \\ &\qquad \mathbf{exp}\left[-\frac{\sigma_Y^2\omega^2}{2}\right]\mathbf{exp}\left[-j\omega\mu_W\right]\mathbf{exp}\left[-\frac{\sigma_W^2\omega^2}{2}\right]\Bigg\} \\ &= \mathcal{F}^{-1}\Bigg\{\mathbf{exp} - j\omega\left(\mu_X+\mu_Y+\mu_W\right) \\ &\qquad \mathbf{exp}\left[-\frac{\left(\sigma_X^2+\sigma_Y^2+\sigma_W^2\right)\omega^2}{2}\right]\Bigg\} \\ &= \mathcal{N}(z;\mu_X+\mu_Y+\mu_W). \end{aligned} \tag{36}$$

To compute the total power spectral density, we add the spectral densities of the individual noise sources. To do so, we consider the simplest nano-antenna structure demonstrated to date, i.e., a nano-dipole antenna, with $G(\alpha) = 1.5$. By substituting the gain of the antenna, (30-32) will lead to

$$S_{sim}(f) = \frac{3}{f_m\sqrt{1-\left(\frac{f_d}{f_m}\right)^2}}. \tag{37}$$

Next, we sum of the individual noise contributors in the in-vivo system as

$$N_{tot}(f) = G_a(f) + H(f) + S_{sim}(f). \tag{38}$$

4 NUMERICAL RESULTS

In this section, we numerically evaluate the intra-body noise model presented in Sec. 3. Despite the fact that our analysis is valid for any homogeneous medium, in this section, we provide numerical results for the specific case of blood, as it is considered a good example of a medium with various components. Blood plasma is the liquid component of the blood which has tiny particles of dissolved protein, glucose, and minerals, among others. Blood plasma also holds different types of blood cells in suspension, namely, platelets, red blood cells, and white blood cells. As mentioned in Sec. 2, the primary energy source in the system is a nano-antenna, which radiates an EM wave at a distance. As a result of the absorption, cells become heat sources. To calculate the temperature, T, of the cells, which is a key parameter in computing the different noise constituents, we follow the same approach presented in [7]. We consider red blood cells in our analysis due to the fact that their physical properties are available in the literature, as given in Table 1. Nonetheless, the simulation could be extended taking into account other body particles and tissues.

Table 1: Simulation Parameters

Parameter	Symbol	Unit	Value	Ref.
Red blood cell radius	r	m	4×10^{-6}	[4]
Red blood cell mass	m	pg	33	[17]
Red blood cell viscosity	η	Pa·s	0.00278	[1]
Initial cell velocity	$v(0)$	mm/s	1.1	[18]

The Johnson-Nyquist noise power spectral density in the high frequency regime including the THz frequency band is presented in Fig. 2. We specifically selected a large range of frequencies to understand the receiver impact on the communication link. It can be noticed that noise in electrical resistors has a flat power spectrum; hence, white noise could be easily utilized as a model without compromising accuracy. Although such noise power spectral density value is small, it is significant in the context of nanonetworks as they rely on the transmission of low-energy, very-short pulses.

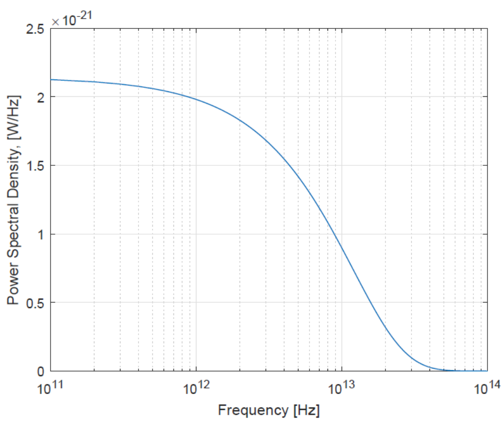

Figure 2: Johnson-Nyquist noise power spectral density in the high frequency regime.

In addition, as we are interested in the behavior of noise, Planck's function, given in (6), is used to approximate the intra-body background radiation. This noise is stimulated by the temperature of the absorbing molecules, causing the intra-body medium to become a Black-body radiator. Similar to [13], in order to focus on the radiative behavior of the intra-body noise, the antenna effective area is discarded. Thus, we plot the intra-body spectral radiance, E_f, in the THz frequency band as shown in Fig. 3. It is to be noted that the Black-body hemispherical emissive power is π times the Black-body intensity, which should be considered when converting units.

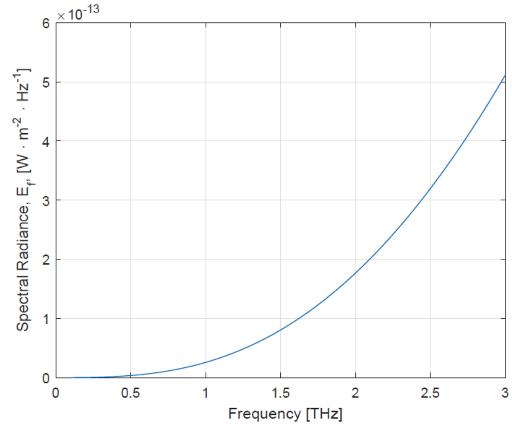

Figure 3: Intra-body spectral radiance, E_f, as a function of the THz frequency band.

Further, calculating the mean squared velocity, $\langle v(t)^2 \rangle$, presented in Fig. 4, is essential for computing the Doppler-shift-induced noise power spectral density. Actually, Fig. 4 reinforces the "Fluctuation Dissipation Theorem" [25] that expresses the balance between "friction" which tends to drive any system to a completely dead state and "noise" which keeps the system alive. This balance is necessary to maintain a thermal equilibrium state at long times.

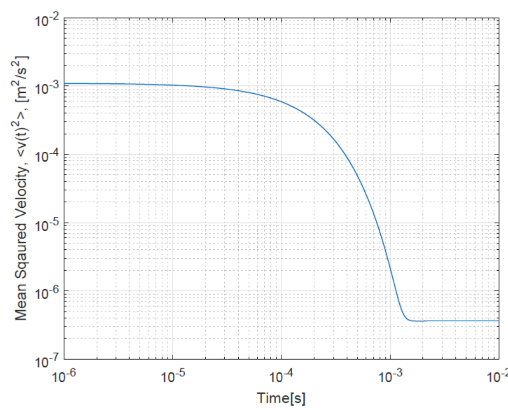

Figure 4: Mean squared velocity, $< v(t)^2 >$, of intra-body particles (red blood cells in our assumed scenario) versus time.

In Fig. 5, the Doppler-shift-induced noise power spectral density is presented. This noise contribution shows how a pure frequency, e.g., a pure sinusoid, which is an impulse in the frequency domain, is spread out across frequency when it passes through the intra-body channel. It is to be noted that the 'bowl shape' is the classic form of this Doppler spectrum. The frequency range where the power spectrum is nonzero defines the Doppler spread. The sharpness of the boundaries of the Doppler spectrum viewed in Fig. 5 are due to the sharp upper limits on the Doppler shift produced by a nano-antenna travelling among the scatterers of the intra-body model. Due to multiple scattering, the incident light may have its direction partly randomized before interacting with red cells, and frequency

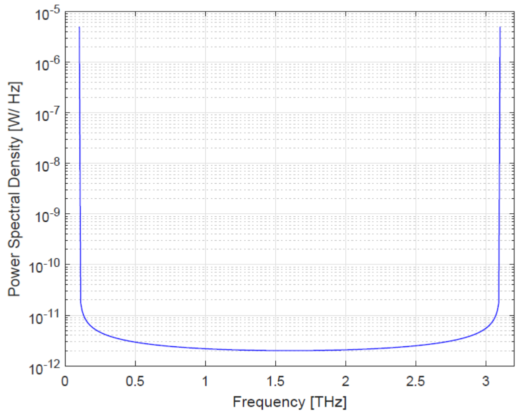

Figure 5: Doppler-shift-induced noise power spectral density of an intra-body medium in the THz frequency band.

multiples can be produced by scattering from multiple red cells. Such complex effects preclude exact calculation of the shape of the Doppler spectrum. Since the Doppler shift induced noise constitutes the larger contribution in comparison to the Johnson-Nyquist and Black-body noise, the overall noise power spectral density takes the form of the Doppler spectrum as seen in Fig. 6.

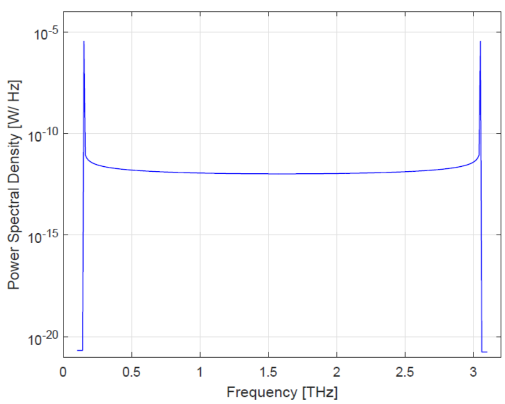

Figure 6: Total noise power spectral density of an intra-body medium in the THz frequency band.

5 CONCLUSIONS

In this paper, a stochastic noise model for intra-body systems operating in the THz frequency band has been developed. A comprehensive analysis illustrating the physical fundamentals associated with each noise source and the probability distribution of each noise component was presented. The noise sources include Johnson-Nyquist noise, Black-body noise as well as Doppler-shift-induced noise. As a result, the total noise power-spectral density of the iWNSN in the THz frequency band has been computed. It has been concluded that the Doppler-shift-induced noise has the largest impact in comparison to both the Johnson and Black-body noises. The importance of the presented framework lies in comprehending the intra-body channel model to ensure viable wireless nano-communication. It will aid in accurately predicting the number of received bits that have been altered due to noise, interference, distortion or bit synchronization. The proposed model will actually extend the application scope of nano-networks and guide the development of practical communication strategies among intra-body nanosensors.

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