Reliability Analysis of Time-Varying Wireless Nanoscale Sensor Networks

Eisa Zarepour*, Mahbub Hassan*, Chun Tung Chou*, Adesoji A. Adesina† and Majid Ebrahimi Warkiani ‡

* School of Computer Science and Engineering, University of New South Wales, Sydney, Australia
Email:{ezarepour, mahbub, ctchou}@cse.unsw.edu.au

†ATODATECH LLC, Brentwood, CA 94513 USA
Email:ceo@atodatech.com

‡Laboratory of Microfluidics & Biomedical Microdevices, School of Mechanical and Manufacturing Engineering,
University of New South Wales, Sydney, Australia, Email:m.warkiani@unsw.edu.au

***Abstract*—Advances in nanotechnology is paving the way for wireless nanoscale sensor networks (WNSNs), promising radically new applications in medical, biological, and chemical fields. The small nanomaterial-based antennas communicate in the terahertz band, which coincide with the natural resonance frequencies of many molecule species causing severe molecular absorption and noise. The problem is particularly more complicated when the channel condition (composition, pressure and temperature) changes over time, causing time-varying absorption. This paper aims to characterise the time-varying property of terahertz communication over a channel whose condition varies over time. Using existing propagation models for WNSNs, we then investigate the reliability of communication over composition varying channels as a major class of time-varying WNSNs. We use WNSN for chemical reactor monitoring and health monitoring as two case studies where channel compositions vary over time. Our simulation results show that for a given transmitted power, the Signal-To-Noise (SNR) and Bit Error Rate (BER) vary over time in a given distance from the transmitter and that is highly sensitive to the composition of the channel.**

Keywords: Nanoscale communication; Time-varying WNSN; Reliability analysis; Composition varying channels.

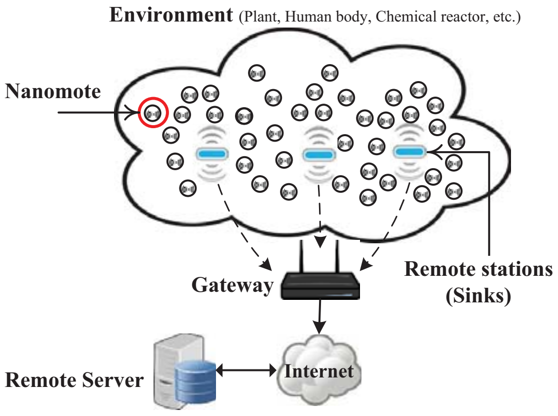

Fig. 1: A schematic architecture for environmental monitoring via WNSN.

I. Introduction

With recent advances in nanotechnology, researchers are now seriously contemplating the possibility of electromagnetic wireless nanoscale sensor networks (WNSNs) [1]. Since a WNSN can operate at molecular levels, they can be used for totally new kinds of nanotechnology applications which cannot be realised with conventional sensor networks. Akyildiz and Jornet [1] have outlined a number of possible interesting new applications of WNSN in biomedical (health monitoring and drug delivery), environmental (plant monitoring and defeating insect plague), industrial (ultra-sensitive touch interfaces), and military (biological and chemical defense) domains. Figure 1 illustrates a general schematic architecture for online microscopic environmental monitoring using the WNSNs. The data collected by nanomotes will be transmitted to a nearby micro or macroscale sink, then it will be transferred to a remote server via a macroscale gateway connected to the Internet. Using such an architecture, a WNSN has been demonstrated for nanoscale monitoring tasks such as plant monitoring [2] where a network of nanmotes have been deployed in a crop field to monitor the interaction of the plants with the environment.

In [3] we have demonstrated that how a network of nanomotes can be used to monitor and control chemical reactors with the ultimate goal of increasing the performance of the synthesis i.e. the ratio of desired product in the output. In all aforementioned WNSN applications, reliable wireless communication among nanomotes, or between nanomotes and a macroscale sink is required [4]. However, at nanoscale, achieving reliable wireless communication poses several chal-

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lenges, because the nanoantenna operates over the terahertz band and this frequency band is severely affected by the molecular absorption.

In addition, radio communication in the terahertz band is affected by the presented molecules in the channel in two different ways. First, radio signal is attenuated because molecules in the channel absorb energy in certain frequency bands. Second, this absorbed energy is re-radiated by the molecules which creates noise in the channel [5]. Molecular absorption is highly sensitive to the channel condition inducing its composition, pressure and temperature and also the communication frequency. In some environments that WNSN are envisaged to be used, the condition of the channel might dynamically change over time that leads to dynamic molecular absorption over time.

In this paper, we introduce the time-varying WNSNs and investigate the reliability of communication in composition varying channels as a major class of time-varying WNSNs.

The rest of this paper is structured as followed. In Section II, time varying WNSN is introduced followed by two detailed examples. Section III presents terahertz channel modelling for time-varying WNSNs followed by the simulation results in Section IV. Conclusion will be presented in Section V

II. TIME-VARYING WNSNS

Small antenna size dictates that WNSN operate over very high frequencies, namely the terahertz band ranging from 0.1-10 THz. Because this frequency band coincides with the natural resonance frequency of many molecules, communication in this band is mainly affected by molecular absorption. Moreover, molecular absorption, as a new source of noise and path loss in WNSN, is highly sensitive to the type of existing molecules in channel, pressure and temperature of the medium, and communication frequency. The effect of each molecule on the terahertz propagation is characterised by its molecular absorption coefficient, $K(f)$, which can be obtained from publicly available databases such as HITRAN [6].

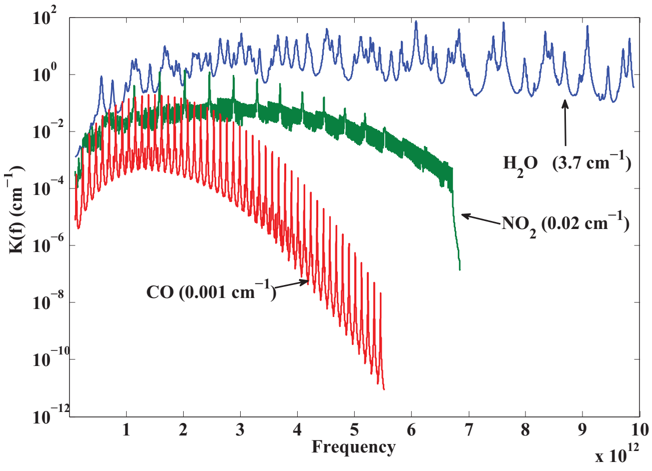
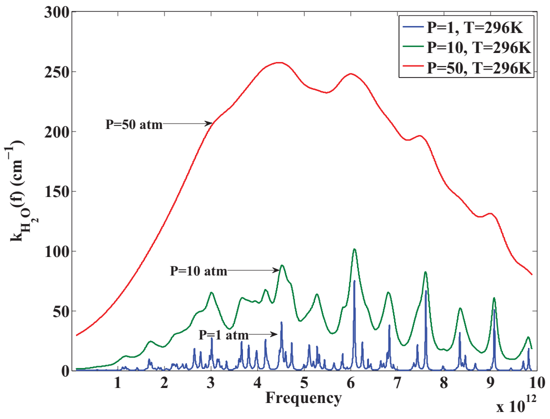
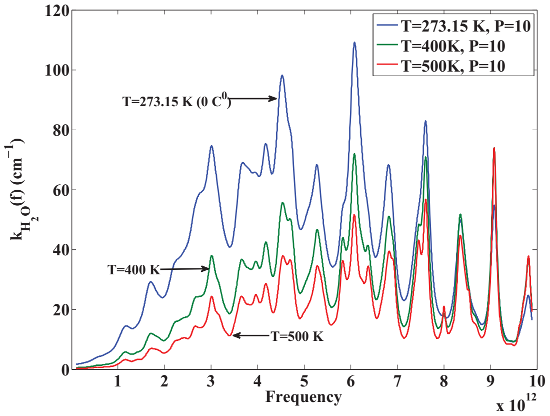


Fig. 2: The log-scale spectrum of molecular absorption coefficient (in cm^{-1}) for three chemical species over the terahertz frequency band ranging from 0.1-10 THz.



(a) Increasing the pressure intensifies molecular absorption at a given temperature.



(b) Temperature has a reverse effect on the molecular absorption.

Fig. 3: The effect of pressure and temperature of the medium on the molecular absorption.

Figure 2 shows the log-scale representation of the absorption coefficient over the entire terahertz band for three molecules, water vapour (H_2O), nitrogen dioxide (NO_2) and carbon monoxide (CO). The numbers in parentheses are the average absorption coefficient over the terahertz band in cm^{-1}. Firstly, Figure 2 shows that molecules might have different absorption spectra. For example, while CO mainly resonates at frequencies less than 5.5 THz, water molecules absorb energy over the entire terahertz band. Secondly, the amplitude of the absorption is different for different molecules, so the terahertz band is differently affected by various molecules. For example, the average absorption coefficients of water vapour and carbon monoxide molecules are 3.7 and 0.001 cm^{-1} which show a difference of four orders of magnitude.

To study the effect of the temperature and pressure of the medium on molecular absorption, we extract the $K(f)$ for water vapour as an example at three different pressure (1, 20 and 50 atm) and temperatures levels (273.15, 400 and 500 K), depicted in Figure 3. Figure 3a shows that increasing pressure increases absorption at a given temperature. The average absorption coefficients over the entire terahertz band are 3.7, 36, 168 cm^{-1} for pressure of 1, 10, 50 atm, respectively, so the average absorption over the terahertz band increases with the pressure of the medium. On the other hand, Figure 3b shows the effect of temperature. While the average absorption of water vapour at a temperature of 273.15 K over the terahertz band is 40 cm^{-1}, it drops to 18 cm^{-1} for a temperature of $500K$, which means that temperature has an inverse effect on the absorption coefficient.

In many applications in which WNSN are envisaged to be used, the channel condition (composition, pressure and temperature) could be dynamic over time, which means the molecular absorption and thus noise and path loss would be variable over time. We refer to this type of channel as *time varying WNSN*.

For example, a WNSN monitoring a chemical reactor might experience different types of molecules during the synthesis, due to the occurrence of different reactions. Figure 4 shows three snapshots of the simulation of a given chemical reactor. The reactor starts with only carbon and hydrogen molecules but after few steps it contains more than 15 different molecules. In addition, the temperature of a chemical reactor could be also variable because the exothermic and endothermic reactions release and consume heat respectively, changing the temperature of the medium.

TABLE I: Few examples for applications of WNSN whose terahertz channel is time-varying. ✓confirms variation.

	Chemical Reactor Monitoring	**Human cell monitoring** [1], [7]	**Plant Monitoring** [2]
Composition	✓	✓	✓
Pressure	✓	✓	✓
Temperature	✓	✗	✓
Time scale	pico second	second	minute
Source of variation	Occurrence of different reactions	Mainly respiration process and blood pressure	Photosynthesis & Respiration - Dehydration & Rehydration
Dominant molecule	OH	H_2O	H_2O

Table I highlights the key parameters that lead to a dynamic channel in few time varying WNSN. It also presents the origin of the variation in channel condition and introduces the most dominant molecule that holds the highest average absorption coefficient in each application.

A. Composition varying channels

In this paper, we study composition varying WNSNs as a subclass of time-varying WNSNs whose type and concentration of molecules in the channel are dynamic over time.

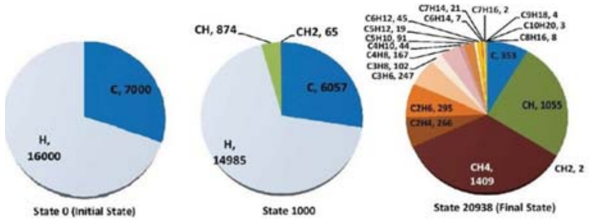


Fig. 4: Three compositions of a given chemical reactor over time; obtained from our SSA simulation.

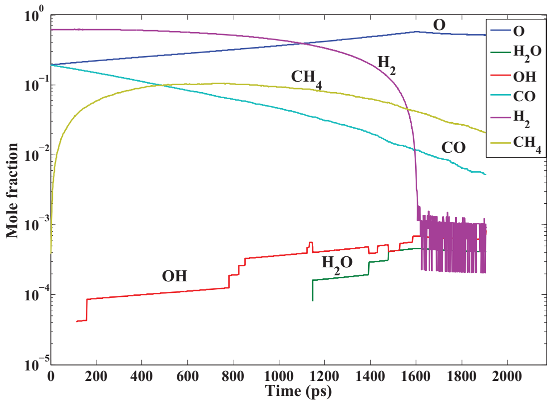


Fig. 5: Evolution of concentration of different molecules during a FT process. CO and H_2 are consumed while other species are gradually produced.

We investigate two case studies including chemical reactor monitoring and human body health monitoring systems both using WNSNs. Then, in the following Section (III), we investigate the effect of composition variation on the quality of communication in the terahertz band.

1) Monitoring Chemical Reactor: Microscopic monitoring of chemical reactors at the molecular level using WNSNs has been recently demonstrated in the literature [3], [8]. In order to make our discussion concrete, we consider a WNSN that has been used to monitor the progress of a Fischer-Tropsch (FT) synthesis. FT synthesis is a major process for converting natural gas to liquid hydrocarbons in a batch chemical reactor. The reactor starts with a specific amount of carbon monoxide CO and hydrogen H_2. Many chemical species are produced and consumed, via many different chemical reactions, during the synthesis. The synthesis stops when no more new products are produced.

The chemical composition within a FT chemical reactor changes over time. We use the Stochastic Simulation Algorithm (SSA) [9], which is a standard algorithm to simulate chemical reactions to study the variation of composition during FT synthesis. Figure 5 shows the mole fraction, i.e., concentration of 6 selected species over time during the course of FT catalysis with initial composition consisting of 500 molecules

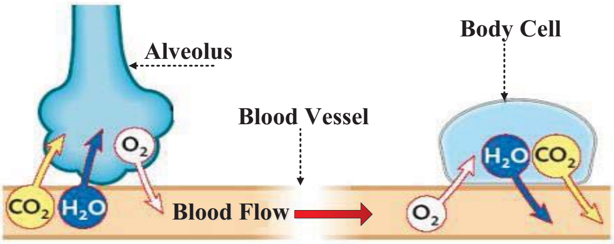


Fig. 6: Respiration process affect the composition of body cells, blood itself and alveolus cells in lung [10].

of CO and 1200 molecules of hydrogen. It shows that the chemical composition in the reactor changes over time.

2) A nanomote monitoring human body cells: In this section, we want to demonstrate the existence of the time-varying property of the terahertz channel for intrabody WNSN applications. Human bodies, as the communication channel between nanosensors, could have different compositions depending on the type of body. These compositions could also vary over the time. For example, the amount of some species (specifically oxygen, carbon dioxide, CO_2 and water molecules) change during the respiration process in all human body cells. The blood circulatory system circulates the blood through the body; carrying oxygen to the cells; collecting the excess water and CO_2 which has been produced during cell respiration; and carries them to the alveolus cells in the lungs (Figure 6). This process affects the composition of the most of living cells. To get more insight into the effect of variations in the human body on the quality of the terahertz communication, we assume a scenario that two nanorobots need to communicate with each other within the blood [11]. The communication channel therefore is mainly affected by the blood composition which is dynamic over time due to respiration process. Although the chemistry of the blood composition has a complicated form, for the sake of terahertz communication, we consider three main reactions that affect the mole fraction of the most absorbent molecule in the blood, i.e. water. Table II shows these reactions. During the cell respiration (R_1), water will be produced. A fraction of this water then will be used by the blood bicarbonate buffering system (R_2 and R_3) to regulate the pH of the blood and the rest will be carried to the lung to be exhaled [12].

TABLE II: A simple model for the variation of the blood composition

Cell respiration	R_1:$(CH_2O)_6$(Glucose)$+6\,O_2 \longrightarrow 6\,CO_2+6\,H_2O+$ Energy
Buffering system	R_2:$CO_2 + H_2O \longrightarrow H_2CO_3$
	R_3:$H_2CO_3 + H_2O \longrightarrow H_3O^+ + HCO_3^-$

We simulate these reactions via SSA. We assume the initial blood is composed from 7% oxygen (from inhalation), 80% water, Glucose: 7% (absorption from the intestine) and 6% other molecules. Figure 7 shows the evolution of species during one breathing cycle. It shows that the mole fraction of the water increases towards the inhalation and then approaches to the initial amount at the end of exhalation because the extra produced water (during the cell respiration) will be exhaled from lung.

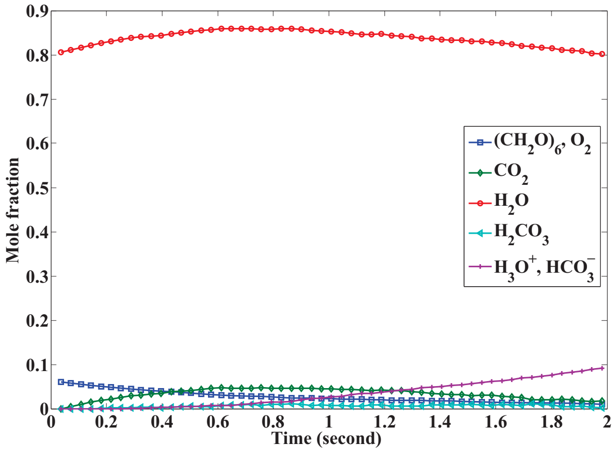


Fig. 7: Variation of the blood composition over one respiration cycle.

III. CHANNEL MODELLING FOR COMPOSITION VARYING WNSNS

This section introduces the channel modelling of time-varying WNSNs based on radiative transfer theory presented in [5]. We assume the radio channel is a medium consisting of N chemical species $S_1, S_2, ..., S_N$. The effect of each chemical species S_i on the radio signal is characterised by its molecular absorption coefficient $K_i(f)$ of species S_i at frequency f which can be obtained from the *HITRAN* database [6]. We consider a radio channel in a medium which has time-varying chemical composition. Let $m_i(t)$ be the mole fraction of chemical species S_i in the medium at time t. The medium absorption coefficient $K(t, f)$ at time t and frequency f is a weighted sum of the molecular absorption coefficients in the medium:

$$K(t, f) = \sum_{i=1}^{N} m_i(t) K_i(f) \tag{1}$$

The total attenuation, attenuation due to spreading and attenuation due to molecular absorption at time t, frequency f and a distance d from the radio source is [5]:

$$A(t, f, d) = e^{K(t,f)d} \times \left(\frac{4\pi f d}{c}\right)^2 \tag{2}$$

The molecular absorption noise, $N_{\text{abs}}(t, f, d)$, which is due to the re-radiation of absorbed radiation by the molecules in the channel, is given by [5]:

$$N_{\text{abs}}(t, f, d) = k_B T_0 (1 - e^{-K(t,f)*d}) \tag{3}$$

where T_0 is the reference temperature 296K and k_B is the Boltzman constant.

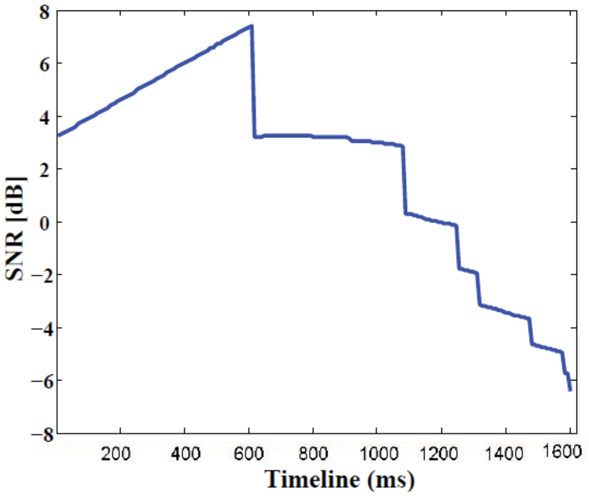
Let $U(t, f)$ be the power spectral density of the transmitted radio signal at time t and frequency f. The signal-to-noise ratio (SNR) at time t, frequency f and distance d is:

$$\mathrm{SNR}(t, f, d) = \frac{U(t, f)}{A(t, f, d)N_{\mathrm{abs}}(t, f, d)} \tag{4}$$

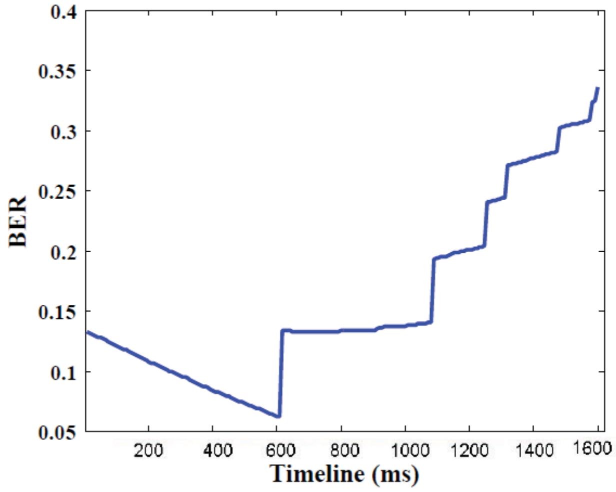
IV. RELIABILITY ANALYSIS

In this section, we study the reliability of a communisation for both case studies, i.e. terahertz WNSN within human blood and chemical reactors.

A. Methodology



(a) SNR



(b) BER

Fig. 8: Reliability of communication during a FT synthesis with initial CO=500, H=1200.

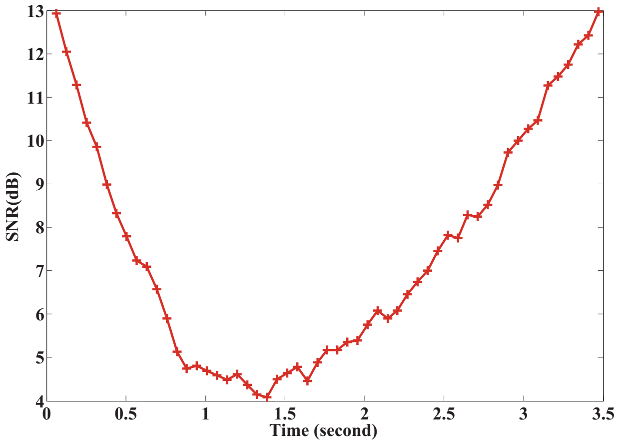


Fig. 9: BER within the blood for an adult person (18 years, respiratory rate: 15 per minutes)

In the first case, we use the simulation setup that we have used in Section II-A2 to calculate the evolution of blood composition over time. For the second one, we consider a FT reactor with initial feeding molecules of 500 carbon monoxide and 1200 hydrogen. The chemical production continues until no more new chemicals can be produced. Molecular absorption coefficients of the chemical species of the both blood and FT reactor are obtained from the *HITRAN* database [6]. Then, we follow the procedure in Section III to compute the medium absorption coefficient, attenuation, molecular noise and *SNR*. BER is calculated using the recently proposed modulation schema for WNSN, TS-OOK [13]. The transmitted power has been set to 1pW $(10^{-12}W\ )$ and the distance between two nanomotes is 1mm.

B. Results

First we investigate the reliability of communication within the chemical reactor. Figure 8 shows the *SNR* and *BER* during the FT synthesis and as it can be seen, both are fluctuated. *SNR* starts from 3.2 dB at the beginning of the catalysis, reaches to 7.8 dB in t=600 ms and finally drops to less than -6dB at the end of the synthesis that makes *BER* been fluctuated between 0.05 and 0.4.

Figure 9 presents the SNR within the blood over one respiration cycle. As it can be seen, because the water has the highest molecular absorption coefficient among other species, the SNR follows its reverse pattern, i.e. falls when the water increases and vice-versa. It starts at 13dB and gradually decrease to around 4dB in the middle of the respiration process and then returns to the initial value at the end of cycle. This pattern is modulated by the respiration process, so we expect that it would be repeated over time. In order to investigate this hypothesis, we calculate the corresponding BER for an adult person with respiration rate of 15 cycle per minutes. As it can be seen from Figure 10, the BER fluctuated over time follows a fixed pattern which is modulated by the respiration process.

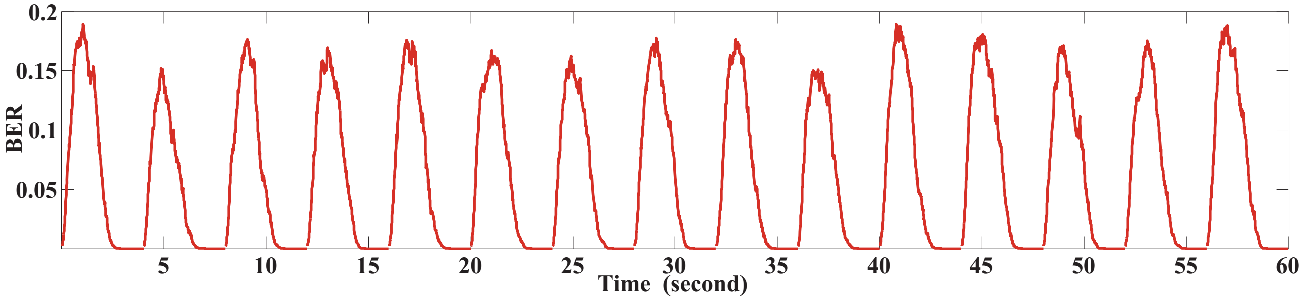


Fig. 10: BER within the blood for an adult person (18 years, respiratory rate: 15 per minutes)

C. Discussion and future work

Given that terahertz channel is critically dependent on the chemical composition of the medium, how to guarantee reliable communication in environments that exhibit time-varying composition is challenging. Intuitively, WNSN might be required to implement some form of adaptive communication to guarantee reliability in such environments. However, adaptive communication requires accurate channel estimation, which is challenging at nanoscale due to the extremely limited resources of nanomotes. Recently, some offline adaptation techniques such as open loop power adaptation and offline dynamic frequency hopping have been proposed to address this issue [14], [15], [16]. These techniques use the prior knowledge of the channel to derive the offline policies. However, in some applications the prior knowledge of the channel might not be available or it may be difficult to obtain. In such cases, we need to design a system to perform online estimation of the channel state, but how to do this is a challenge. In addition, designing a mechanism which allows the nanomote to self-synchronised the transmission parameters with the prior offline channel estimation is still an open problem which is considered as a future work.

V. CONCLUSIONS

Given that WNSNs operate over terahertz band and the terahertz channel is highly sensitive to the channel conditions (chemical composition, pressure and temperature of the medium), we analyse the reliability of communication in WNSNs whose channel conditions vary over time causing time varying noise and attenuation in the medium. As two case studies for time-varying WNSNs, we analysed the reliability of the terahertz nano-scale communication in chemical reactors and human blood as two envisaged contexts for using WNSN. We found that *SNR* and *BER* are fluctuated over time in both cases which highlight the need for designing efficient adaptive communication protocols for time-varying WNSN.

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