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Power Distribution and Performance Analysis of Terahertz Communication in Artificial Skin

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ABSTRACT
Apart from the effect of path loss and signal-dependent molecular absorption noise, the capabilities of in-vivo nano-communication at the Terahertz (THz) frequencies are also strictly influenced by the distribution of power transmission in the frequency domain. In this paper, artificial skin with different fibroblast cell densities are considered as THz communication mediums, signal-to-noise ratio (SNR) and channel capacity as a function of the transmitted signal power for flat and Gaussian-shaped distribution is quantified. In addition, the achievable communication distance of THz communication inside the artificial skin is evaluated. The results show that -30 dBW using flat distribution and -40 dBW with Gaussian distribution can provide optimal SNR without posing more energy requirement on nano-transceivers. The achievable communication range in dermal equivalent is strictly limited to about 1 to 2 mm. Gaussian-shaped power distribution can provide higher SNR but lower capacity comparing with flat distribution. These results provide fundamentals in building future intra-body nanonetworks.

Keywords
Power distribution, Terahertz, Artificial skin, SNR, Capacity

1. INTRODUCTION
In-vivo nanonetworks have been presented to provide fast and accurate disease diagnosis and treatment. Despite the fact that nanotechnology has been witnessing great advancements, enabling the communication among nanomachines is still a major challenge. An increasing number of research of THz channel modelling is conducted in literature such as [6, 7, 11, 1]. It is highlighted that the primary noise source of THz communication is the molecular absorption noise, which severely pollutes the transmitted signal in the communication channel in literature [3, 8, 14]. For the general communication systems, apart from the effect of path loss and noise, communication capabilities are also strictly influenced by the distribution of power transmission in the frequency domain. Especially as the molecular absorption noise of THz communication is signal-dependent, hence it is necessary to investigate the effect of power distribution on the communication performance.

In order to provide an accurate characterisation of THz wave propagation inside the human body, the THz properties characterisation of communication medium, human tissues is crucial. Because performing experiment on a living human skin tissue is carefully regulated. Alternatively, artificial human skin samples allowing repeatable measurement are often used for experimental investigation. In terms of human skin, dermal equivalent (DE) is widely used as a substitute for human skin in various fields of skin biology, pharmacotoxicology and clinical applications [10]. DE is developed by seeding dermal fibroblast cells in collagen gel to progressively re-organise the lattice [2]. The measurement of DEs with three kinds of fibroblast cell densities was performed using THz Time Domain Spectroscopy (TDS) in transmission mode. The details of sample preparation, measurement and optical parameters extraction are provided in [13].

2. THZ COMMUNICATION MODELS
In this section, the THz propagation channel models inside human tissues are briefly reviewed. The path loss of the THz wave inside human body is composed of the spreading loss and the molecular absorption loss as [11],

$$PL(r,f) = (\frac{4\pi nfr}{c})^2 e^{\alpha(f)r} \tag{1}$$

where c is the speed of light in vacuum, n is the refractive index, r is the total path length, and $\alpha(f)$ is the absorption coefficient. The absorption coefficient of human tissues at THz frequencies is much higher than the case of air because of the high concentration of liquid water, which gives in-vivo communication some peculiarities. The received signal power from the targeted transmitter in the channel is significantly degraded by the path loss, which can be represented by,

$$P_R(S,r) = \int_B S(f)(\frac{c}{4\pi nfr})^2 e^{-\alpha(f)r} df \tag{2}$$

where B is the bandwidth of the communication channel, $S(f)$ refers to the transmitted signal power spectral density (psd) from the transmitter antenna.

The noise in the THz communication channel is primarily contributed by the molecular absorption noise [7]. The molecular absorption noise N_m for the THz communication in the human body is composed of the background noise N_b and the self-induced noise N_s, and the noise power power can be represented by [14],

$$N_b(r) = \int_B B(T_0, f)(\frac{c}{\sqrt{4\pi} n_0 f_0})^2 df \quad (3)$$

$$N_s(S, r) = \int_B S(f)(1 - e^{-\alpha(f)r})(\frac{c}{4\pi n f r})^2 df \quad (4)$$

$$N_m(S, r) = N_b(r) + N_s(S, r) \quad (5)$$

where T_0 is the reference temperature of the medium, and $B(T_0, f)$ stands for the Planck's function.

Thereafter, the SNR of the channel can be described as a function of transmission signal and distance as,

$$SNR(S, r) = \frac{P_R(S, r)}{N_m(S, r)} \quad (6)$$

When the transmitted signal power is low, the background noise power and the self-induced noise power is at the same scale, so both of them play a significant role in the communication performance. Because the molecular absorption noise is non-white. The THz channel capacity can be obtained by dividing the total bandwidth into many narrow sub-bands and summing the individual capacities [5]. The i^{th} sub-band is centred around frequency $f_i, i = 1, 2, ...$ and it has width Δf. If the sub-band width is small enough, the channel appears as frequency non-elective and the noise psd can be considered locally flat. The resulting capacity in bits/s is then given by [6],

$$C(r) = \sum_i \Delta f log_2[1 + \frac{S(f_i) PL^{-1}(f_i, r)}{N(f_i, r)}] \quad (7)$$

3. POWER DISTRIBUTION

In the simplest case, the total transmitted signal power P_T is uniformly distributed over the entire operative band. Thus the corresponding transmitted signal psd is,

$$S_{flat}(f) = P_T/B for f \in B, 0 \quad \text{otherwise} \quad (8)$$

In addition, considering the limited capabilities of a single nanoscale device. The advancements in graphene-based nanoelectronics [4], point out to the possibility of transmitting 100 fs pulses. In light of the state of the art in nanotransceivers, nano-communication is envisaged to achieve based on the exchange of ultra-short pulses. For simplicity, the transmitted signal can be modelled with an n^{th} derivative of a Gaussian-shape: $\phi(f) = (2\pi f)^2 n e^{(-2\pi\sigma f)^2}$ [9]. Thus, the signal psd can be expressed as [6],

$$S_p^{(n)}(f) = a_0^2 \phi(f) \quad (9)$$

where σ and a_0^2 are the standard deviation of Gaussian pulse and a normalising constant, respectively. Considering that $\int_{f_m}^{f_M} S_P^{(n)}(f) df = P_T$, the normalising constant is obtained as [9],

$$a_0^2 = \frac{P_T}{\int_{f_m}^{f_M} \phi(f)} \quad (10)$$

Typically, the power requirement for nanoscale biological sensors varies from less than a few nW to a few μW [12]. Therefore, in this paper, the transmitted signal power is set as -90 dBW to 0 dBW. n and σ are 6 and 0.15, respectivey.

4. ARTIFICIAL SKIN

Among the tissues, skin is a promising candidate because it is the most abundant human tissue and it has various hydration levels throughout the human body. Since THz wave is sensitive to water concentration of the propagation medium, the diversity in the optical parameters of skin at different spots can influence the THz transmission. It motivates this study on the influence of fibroblast cell density of dermal equivalent on the optical parameters and then on SNR and channel capacity of THz communication under different power distribution schemes.

Skin can be divided into three major layers: epidermis, dermis, and subcutaneous fat with definitive thicknesses and functionality. The thickest of all three layers is dermis with a range of 0.6 mm to 3 mm as shown in Fig.4. It enables DE to be a replacement of human skin in applications of skin biology. The absorption coefficient and refractive index of DE with three kind of cell densities is obtained in [13] as shown in Fig.4.

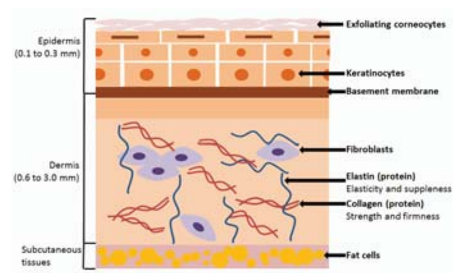


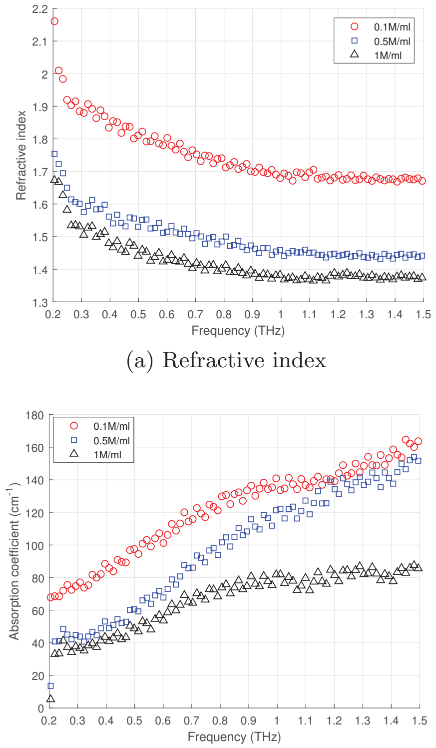
Figure 1: Schematic of human skin structure and constituent cell types. Dermis is the thickest layer.

5. ANALYTICAL RESULTS

5.1 Signal-to-noise ratio

The relationship between SNR and the transmitted signal distribution schemes of THz communication inside dermal equivalent with different cell densities is illustrated in Fig. 3. It is clearly shown that SNR increases rapidly with pulse power from -90 dBW, and tends to be constant after a certain value. The threshold is -30dBW for flat communication and -40 dBW for Gaussian pulse-based communication. It implies that flat power with a value of -30 dBW and pulse power with a value of -40 dBW can provide optimal SNR without posing more strict requirement on nano-devices and saving energy. It is also found that SNR can be independent of the power allocation schemes when the transmitted signal power is high enough. It is because that when the transmitted signal is high enough, so that the self-induced noise is the only noise source in the channel, and after simplifying Eq 6, SNR is independent of the transmitted signal.

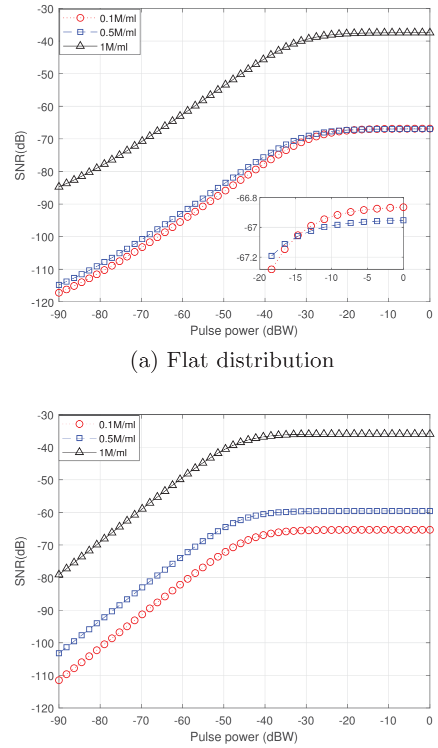
Considering Gaussian pulse-shaped distribution with a power of 1 muW, SNR as a function of the path length for THz communication inside three kinds of dermal equivalent is



(a) Refractive index

(b) Absorption coefficient

Figure 2: Frequency-dependent refractive index and absorption coefficient of dermal equivalent with three different cell densities, namely, 0.1 M/ml, 0.5 M/ml and 1 M/ml.



(a) Flat distribution

(b) Gaussian-shaped distribution

Figure 3: SNR versus transmitted signal power for THz communication inside artificial skin using (a) flat and (b) Gaussian-shaped distribution, and the communication distance is 1 mm.

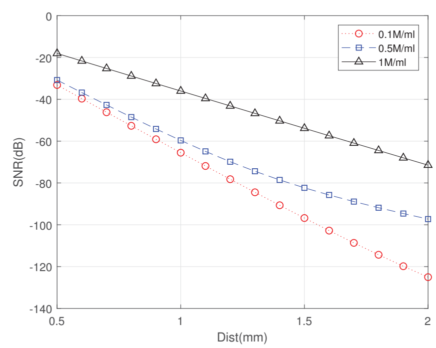


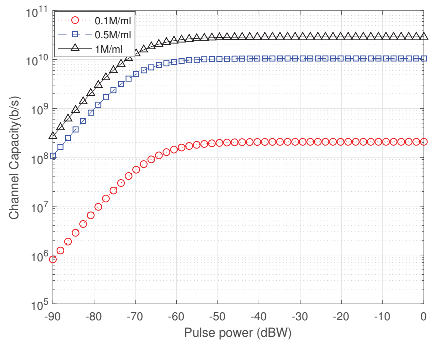
Figure 4: SNR versus path length in dermal equivalent with three cell densities using Gaussian-shaped power distribution.

shown in Fig. 4. It can be seen that DE with higher cell density has lower SNR. For example, when the path length is 1 mm, SNR of THz communication in DE with 1 M/ml fibroblast cell is about -36 dB, and it drops to about -60 dB and -65 dB, when the cell density goes down to 0.5 M/ml and 0.1 M/ml, respectively. The difference caused by the cell density increases with the path length. Besides, the achievable communication distance of THz within these samples is limited to 1 to 2 mm, and the specific distance significantly depends on the tissue composition.

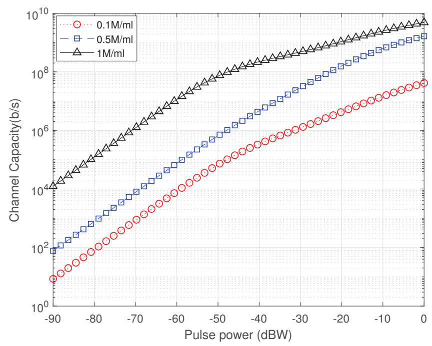
When transmitting the same signal power, Gaussian-shaped power distribution can provide higher SNR than flat for THz communication inside the same type of tissue. For instance, when the signal power is -60 dBW, SNR of THz communication inside DE with 1 M/ml cell density is -62 dB using flat, while the one using Gaussian is -50 dB. Similar conclusion can drawn for other tissue type and power values.

5.2 Channel Capacity

The channel capacity as a function of the transmitted signal is studied and the results for two power distribution schemes are shown in Fig. 5. It can be seen that channel capacity in flat distribution case increases with pulse power until -60dBW, it tends to be a constant when further rises the signal power. However, the capacity using Gaussian-shaped distribution steadily rises with the signal power. The capacity in both scenarios can be at the scale of Gigabits per second (Gbps) with a path length of 1 mm. Furthermore, at the same transmitted signal power, Gaussian-shaped power distribution provides lower capacity comparing with flat distribution.



(a) Flat distribution



(b) Gaussian-shaped distribution

Figure 5: Information rate versus transmitted signal power for THz communication inside dermal equivalent using (a) flat and (b) Gaussian-shaped distribution.

6. CONCLUSION

In this paper, the effect of the transmitted signal power distribution on the in-vivo THz communication performance, including SNR and channel capacity has been analysed. It is found that -30 dBW using flat distribution and -40 dBW with Gaussian distribution can provide optimal SNR. In addition, SNR degrades about 30 dB when the fibroblast cell density decreases a scale from 1 M/ml to 0.1 M/ml, and SNR drops more sharply with the increase of path length. The capacity in both flat and Gaussian-shaped distribution can be at the scale of Gbps with 1 mm transmission distance. Gaussian-shaped power distribution can provide higher SNR but lower capacity comparing with flat distribution. The findings obtained in this paper provide a basis for further practical experiment in the artificial skin samples using nano-devices and can help design future intra-body nanonetworks.

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