URSI AP-RASC 2019, New Delhi, India, 09 - 15 March 2019

Capacity Evaluation of In-Vivo Nano-Sensors at Terahertz Frequencies Using Multiple Antenna Techniques

Qammer H. Abbasi[1,3] Aya Abdelaziz[2], Rui Zhang[3],
[1]School of Engineering, University of Glasgow
[2]Cairo University, Egypt
[3] Queen Mary University of London, London
Contact email: Qammer.abbasi@glasgow.ac.uk

Abstract

This paper presents an experimental based study on capacity evaluation of 2x2 multiple input multiple output in-vivo communication channel at terahertz (THz) frequency, with a potential of applicability in future nano-networks based healthcare systems. During the study, equal power and water-filling power allocation techniques are being used and compared for inside the skin channel, where transmitter was placed in dermis layer and receiver was in epi-dermis layer. Results show that water-filling capacity outperforms the equal power allocation scheme. It is observed that at low SNR water-filling power allocation has 50% improvement over equal power. However, above 10 dB SNR, this difference reduces and eventually becomes negligible at SNR of 20 dB and above. The results presented in this paper will help system designer in link budget calculation for enhanced nano-health systems.

1. Introduction

The Internet of Nano-Things (IoNT) is a future paradigm where nano-scale devices will be connected to existing communication networks and ultimately internet [1]. Fig. 1 shows an envisioned IoNT architecture integrating nano-communication with wireless body-area networks (WBANs). The nano-devices talk to each other by nano-communication (which can be using high frequency) and have capability to perform several tasks. This concept can be applied in connectivity with miniature devices such as nano-scale robot, which can be connected with numerous other nano-robots that can form a network. This feature can also be applied in ultra high speed on chip communication, biological defenses and health monitoring systems [2]. For the connectivity of nano sensors, EM-based techniques at terahertz (THz) and sub-THz frequencies [3] are considered as a promising candidate due to its ability to detect molecular changes and its strong liquid-water absorption, specifically in the 1 to 10 THz band. With the evolution of new materials like Graphene, Graphene Nano-ribbons (GNRs) and Carbon Nano-tubes (CNTs) [4], motivates the nano-devices connectivity by using THz band (0.1-10 THz) due to their ability to slow the propagating wave making compatible at these frequencies in comparison to the nano-scale. In addition, THz has capabilities to represent characteristic

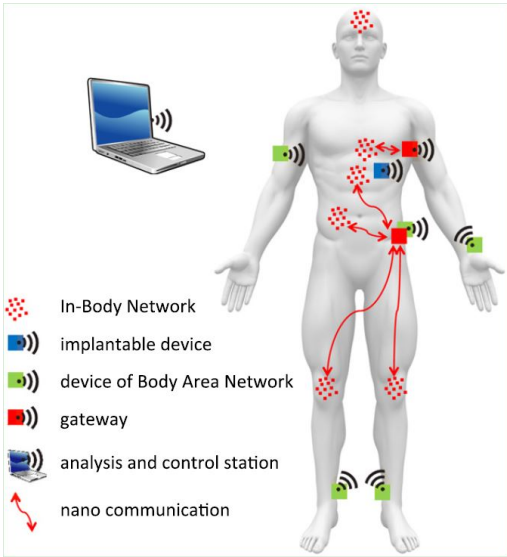

Fig. 1. Nano-sensor based future healthcare system [1].

fingerprints for many chemical substances in this spectrum [4] on top of its attractive features of non-ionizing hazards for biological tissues, and less-susceptibility to certain propagation phenomena [5,6]. Due to shorter wave length and sensitivity against water, terahertz channels have much higher propagation loss and extra molecular absorption loss compared to the gigahertz channels [7]. Applying multiple input multiple output techniques (MIMO) to over come this fading seems an attractive solution at terahertz [8]. Some studies in literature have been presented for applicability of MIMO to THz [10-16] including initial study on in-vivo

communication at terahertz for multiple antennas. In [11] a graphene based reconfigurable MIMO system for THz has been proposed. Massive MIMO means large number of serving antennas working adaptively and coherently at the base station to simultaneously serve large number of wireless broadband terminals. More transmitting and receiving antennas contribute to the higher spectral efficiency as well as the physical layer security. In [12], authors presented the prospect of massive MIMO (m-MIMO) as a solution to overcome the short range and limited power devices for THz. In order to enable multiple access in THZ, [13] presented a Per-beam synchronization (PBS) technique. In [14], m-MIMO system in the THz were compared, where 55 dB channel gain at 1 THz was achieved with more system complexity for beam forming technique. None of the literature paper discusses about the capacity enhancement using MIMO for in-vivo communication at terahertz as per authors knowledge. In this paper, authors presented a capacity gain for MIMO-aided terahertz in-vivo system for two power allocation schemes, namely, water-filling and equal-power (where water-filling is applied in current scenario due to low signal-to-noise ratio (SNR) for capacity improvement). The studies presented in this paper are based on numerical modelling data for inside the skin from 0.1- 4 THz. Rest of paper is organized as: Section II details about the model used in this study for in-vivo MIMO, Section III, details about the capacity result and Section IV, draws the conclusion.

2.. System Model

The human skin is anisotropic medium, which is complex and can be mainly divided in to three layers namely: dermis, epidermis and stratum corneum, which is the thinnest layer among all. The detailed skin model was first presented and discussed by Abbasi *et al.* (author of this paper) in [8], which takes into account, distance between transmitter and receiver, frequency, sweat ducts and interface between dermis and epidermis layer (as the wavelength is comparable to the size of roughness interface). The three layer skin model, with non-flat interface between dermis and epidermis used in this study (as per [8]) is shown in Fig. 2. It can be seen in the figure that the sweat duct is represented by helix. A 2x2 MIMO (two transmitting and two receiving antennas) is used in this study as shown in Fig. 2 with transmitter being in dermis and receiver in epidermis. Three ducts are used in the model for mimicking real scenario. More details about model and dimensions are given in [8].

3. MIMO Capacity for In-Vivo at THz

This research assumes that transmitter does not know the channel state information, hence the capacity for uniform power allocation and water-filling can be written as [17]:

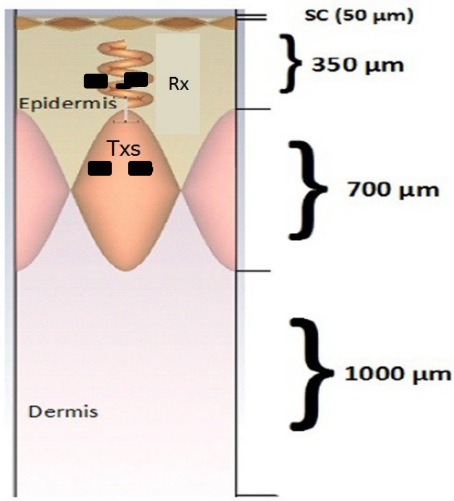

Fig. 2. A three layer skin model used in this study by applying 2x2 MIMO (Tx and Rx location shown above)

$$C = \log_2\left(\det\left[\mathbf{I} + \frac{\zeta}{\ }\mathbf{H}_{\mathrm{NF}}\mathbf{H}_{\mathrm{N}}^{\mathrm{H}}\right]\right) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

$$C = \sum_{i=1}^{K} \log_2(1 + \lambda_i P_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Whereas eq. 1 is for channel capacity of equal power and eq. 2 is for water filling technique. In eq. 1, H_F, represent frobenius transform, and in eq., 2, λ, represent eigen values. In this paper, the 10% outage for 2x2 MIMO in addition to ergodic capacity is calculated for water-filling and equal power combining techniques. The ergodic and outage capacity for the water-filling and uniform power allocation are illustrated in Fig. 3. Results show that at low-signal to noise ratio (SNR) range, the achievable capacity is limited, which increases with increase in average SNR.

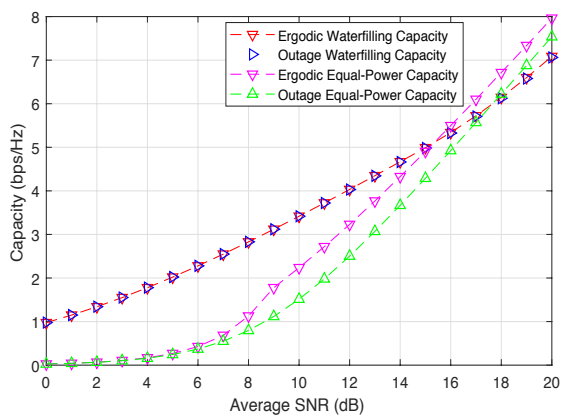

Figure 3. Ergodic and 10% outage capacities of in-vivo channel for equal-power and water-filling schemes at THz.

It can be seen that the water-filling technique provides higher capacity as compared to the uniform power allocation. The reason for this is optimal power distribution among the eigen channel in case of water filling scheme. However, no major enhancement at high SNR is due to reason that in capacity enhancement SNR is considered as a major factor. Fig. 4 shows the comparison of achievable ergodic channel capacity of the in-vivo channel for both power schemes. The results in Fig. 4 shows the comparison of equal power and water filling and clearly illustrates an improvement of 150% improvement for water-filling at SNR equal to 1 dB. Whereas, at higher SNR=20 dB, this improvement reduces to 1.6% only. Alternatively, it can be said that, there is an average improvement of 1.6 b/s/Hz for water-filling as compared to equal power at SNR less than 10 dB.

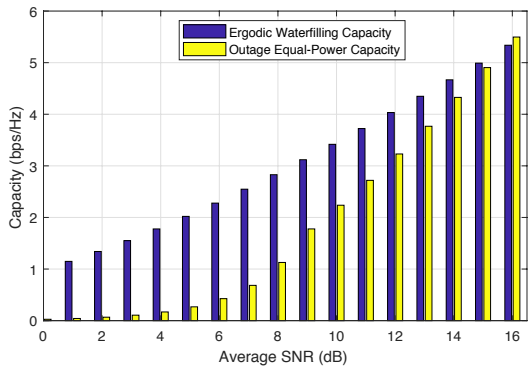

Figure 4. A comparison of water-filling and equal-power allocation scheme for in-vivo channel at THz

4. Conclusion

This paper presents for the first time the capacity of 2x2 MIMO for in-vivo nano-scale communication at terahertz. In addition, performance comparison of two power allocation techniques namely equal power and water-filling has been presented. Results show that 2x2 MIMO can provide enhancement in capacity for nano-scale in-vivo communication and water-filling outperforms equal power combining technique at low SNR but at higher SNR both techniques perform equally well. The study in this paper will be helpful for designing enhanced nano-scale in-vivo communication system by applying MIMO at terahertz to overcome the high losses in such medium.

5. Acknowledgements

Authors would like to acknowledge Ke Yang and Akram Alomainy for their support.

6. References

[1] F. Akyildiz and J. M. Jornet, "The internet of nano-things," IEEE Wireless Communications, vol. 17, no. 6, 2010.

[2] J.M. Jornet and I.F. Akyildiz, "Graphene-based plasmonic nano-antenna for terahertz band communication in nanonetworks," IEEE JSAC, vol. 12, pp. 685–694, 2013.

[3] R. Gente and M. Koch, "Monitoring leaf water content with THz and sub-THz waves," Plant Methods, vol. 11, 2015, Art. no. 15.

[4] Markus Walther, Bernd M. Fischer, Alex Ortner , Andreas Bitzer, Andreas Thoman and Hanspeter Helm, "Chemical sensing and imaging with pulsed terahertz radiation", Anal Bioanal Chem, Vol. 397, pp. 1009–1017, 2010.

[5] Liebe HJ, Hufford GA, Manabe T., "A model for the complex permittivity of water at frequencies

[6] below 1 THz", Int J Infrared Millimeter Waves. Vol. 12(7), pp. 659–75, 1991.

[7] Rønne C, Åstrand P-O, Keiding SR., "THz spectroscopy of liquid H2O and D2O". Phys Rev Lett. Vol. 82, pp. 2888–91. 1991.

[8] Q. H. Abbasi, H. El Sallabi, N. Chopra, K. Yang, K. A. Qaraqe, and A. Alomainy, "Terahertz channel characterization inside the human skin for nano-scale body-centric networks," IEEE Transactions on Terahertz Science and Technology, vol. 6, no. 3, pp. 427–434, 2016.

[9] G. Piro, P. Bia, G. Boggia, D. Caratelli, L.A. Grieco, and L. Mescia, "Terahertz electromagnetic field propagation in human tissues: A study on communication capabilities," Nano communication networks, Else- vier, vol. 10, pp. 15–59, 2016.

[10] Abdelaziz, A., Yang, K., Qaraqe, K., Boutros, J., Abbasi, Q. H. and Alomainy, A., Multiple Antenna Techniques for Terahertz Nano-Bio Communication, IEEE MECBME, Gammarth, Tunis, Tunisia, 28-30 Mar 2018, pp. 67-71.

[11] Z. Xu, X. Dong, and J. Bornemann, "Design of a reconfigurable MIMO system for THz communications based on graphene antennas," IEEE Transactions on Terahertz Science and Technology, vol. 4, pp. 609–617, 2014.

[12] K. I. Bolotin, K. J. Sikes, Z. Jiang, M. Klima, G. Fudenberg, J. Hone, P. Kim, and H. L. Stormer, "Ultrahigh electron mobility in suspended graphen," Solid state communication, vol. 146, pp. 351–355, 2008.

[13]] I. F. Akyildiz and J. Jornet, "Realizing ultra- massive MIMO(1024 x 1024) communication in the (0.06-10) terahertz band," Nano Commu- nication Network, Elsevier, vol. 8, pp. 46–54, 2016.

[14] LiYou, Xiqui et al., "BDMA for millimeter-wave/terahertz massive MIMO transmission with per-beam synchronization," IEEE Journal on Selected Areas in Commu- nication, vol. 35, pp. 1550–1563, 2017.

[15] S. Hoseini, M. Ding, and M. Hassan, "Massive MIMO performance comparison of beamforming and multiplexing in the terahertz band," IEEE Globecom Workshops, 2017.

[16] Z. Xu, X. Dong, and J. Bornemann, "A statistical model for the MIMO channel with rough reflection surfaces in the THz band," *IEEE Transactions on Terahertz Science and Technology*, vol. 4, pp. 609–617, 2014.

[17] Qaraqe, M., Abbasi, Q. H. , Alomainy, A. and Serpedin, E. , Experimental evaluation of MIMO capacity for ultrawideband body-centric wireless propagation channels. *IEEE Antennas and Wireless Propagation Letters*, 13, pp. 495-498.