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Multiple Antenna Techniques for Terahertz Nano-Bio Communication

Aya Abdelaziz[1,4], Ke Yang[2], Khalid Qaraqe[1], Joseph Boutros[1],
Qammer H. Abbasi[3], and Akram Alomainy[2]
[1]Electrical and Computer Engineering, Texas A&M University at Qatar, Doha, Qatar
[2]Antennas Electromagnetics School of Electronic Engineering and Computer Science Queen Mary University of London, London,
[3]School of Engineering, University of Glasgow
[4]Department of Electronics and Electrical Comm., Cairo University, Egypt

***Abstract*— Using higher frequency bands becomes an essential demand resulting from the explosive wireless traffic needs and the spectrum shortage of the currently used bands. This paper presents an overview on the terahertz technology and its application in the area of multi-input multi-output antenna system and in-vivo nano-communication. In addition, it presents a preliminary study on applying multiple input-single output (MISO) antenna technique to investigate the signal propagation and antenna diversity techniques inside the human skin tissues, which is represented by three layers: stratum corneum (SC), epidermis, and dermis layers, in the terahertz (THz) frequency range (0.8 - 1.2) THz. The spatial antenna diversity is investigated in this study to understand MISO system performance for two different in-vivo channels resulting from the signal propagation between two transmitting antennas, located at the dermis layer, and one receiving antenna, located at epidermis layer. Three techniques are investigated: selection combining (SC), equal-gain combing (EGC), and maximum-ratio combining (MRC). The initial study indicates that using multiple antenna technique with THz might be not useful for in-vivo nano-communication.**

I. INTRODUCTION

Multi-input multi-output (MIMO) antenna system is a method for multiplying the capacity of a radio link to exploit the multipath propagation and the spectral efficiency for a given total transmit power for the wireless communication systems. The advantages of MIMO antenna system can be maximized either by increasing the system diversity gain by applying effective diversity antenna system, or by transmitting multiple parallel data streams for increasing the spectral efficiency and data rates [1].

The research of THz spectroscopy and imaging has gain a great importance in the past twenty years [2]. THz technology can support terabit-per-second (Tbps) links that can not be supported by technologies below 0.1 THz. Moreover, THz band will contribute to the area of macro-scale and nano-scale communication due to its very large bandwidth. Macro-scale communication applications include 5G cellular networks, terabit wireless area networks (T-WLAN), terabit wireless personal area network (T-WPAN), and secure wireless communication. Nano-scale communication will support nano-scale machines which are nano-devices that are able to perform several tasks at the nano-scale and can communicate at this very high frequency band. This feature has some great applications in health monitoring systems, nuclear and biological defenses, the Internet of nano-things, and ultra high speed on chip communication [3]. One of the practical application of THz link is the short range communications such as nano-sensors and wireless personal area networks as shown in Fig. 1 [3].

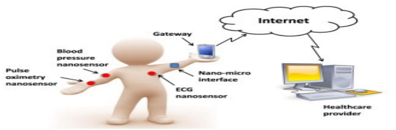

Fig. 1. An envisaged nano-sensor network for health care [3].

Terahertz band antennas will be required to be ultra-band and multi-band to enable multi-giga bit per second and tera bit per second links in the THz band. Applying MIMO system with terahertz band will be highly recommended to overcome the very high path loss of the channel. Moreover, the very small size of the designed antenna at this frequency band enables the integration of very large number of antennas with very small footprint.

There is an increasing interest in applying THz for in-vivo communication because of its non ionizing properties, and the strong absorption of water at terahertz frequencies. The water content of a healthy skin is around 70% by weight and this makes THz frequency range particularly useful in dermatology [4]. The normal human skin tissue is represented by three main layers: stratum corneum, epidermis, and dermis (outermost to intermost). The signal path loss and radio channel model inside the human skin at terahertz frequency was proposed in [5]. Pulsed electric field propagation in a stratified media stack consists of SC, epidermis, dermis, and fat has been modeled in [6], and losses due to spreading and molecular absorption noise temperature have been evaluated as a distance function between node pairs. The spatial antenna diversity is investigated in this study to understand MISO system performance for two different in-vivo channels resulting from the signal propagation between two transmitting antennas, located at the dermis layer, and one receiving antenna, located at the epidermis layer. The system model is simulated using the CST microwave studio by fixing the distance between the transmitting antennas and study the effect of changing the distance between the receiver antenna and the two transmitting antennas at different frequencies. As the antenna diversity can be realized in several ways, three techniques are investigated in this study: selection combining (SC), equal-gain combing (EGC), and maximum-ratio combining (MRC). Although MIMO is a method for multiplying the capacity of a radio link to exploit multipath propagation and the spectral efficiency for a given total transmit power for the wireless communication systems, the initial study indicates that multiple antenna technique might be not useful for in-vivo nano-commuinacation.

The paper is organized as follows. Section II presents an overview about using MIMO in terahertz band and its applications. In section III, a review about the existing technology of applying terahertz MIMO for biomedical applications has been presented. The study of skin layers with MISO channels and the results are presented in section IV. Finally, conclusions are given in section V.

II. MIMO ANTENNA SYSTEM IN TERAHERTZ BAND

Huge propagation loss is considered as the main problem with THz band resulting from the signal attenuation by the molecular absorption of the waves. MIMO represents a solution to improve the THz communication and provide Tbps for a few meters distance.

Recently, novel plasmonic materials such as graphene and metamaterials are used to design miniature nano antennas and nano transceivers that operate in THz band [7], [8]. Reconfigurable MIMO graphene antenna system was designed for THz communication (1-10) THz [9], the beam width and the direction can be controlled by each graphene patch in the antenna such that the radiation properties can be programmed dynamically. THz channel models are different than those at GHz band as the THz signal loss is resulting from the spreading loss as well as the molecular loss. MIMO systems can enhance the performance, if both the antenna size and the separation between antennas decrease. Graphene-based antennas represent a great solution to design the nano-antennas due to the graphene unique structure, wherein, electrons are able to move with minimal resistance and hence create electromagnetic wave atop the graphene layer [10]. Authors demonstrated in [10] that the graphene based Yagi-Uda patch antennas have higher spectral efficiency than the omni-directional metallic antennas. Massive MIMO means having very large number of serving antennas that are functioning coherently and adaptively at the base station. More transmitting and receiving antennas contribute to the higher spectral efficiency. However, the antenna size and separation between the elements are the two main factors that limit the MIMO system. Massive MIMO becomes practical at the higher frequency bands because this means that the antenna design is very smaller and can be packed in a smaller area. Massive MIMO network will also make it far more resistant to interference and intentional jamming than current systems that only utilize a handful of antennas because these antennas focus the transmission and reception in a very directed regions of space. In addition, massive MIMO overcomes the problem of very short communication at THz band due to the limited power of the compact solid state THz transceivers [11]. Per-beam synchronization (PBS) in time and frequency was applied to beam division multiple access for massive MIMO system in terahertz band for mobility scenarios. This technique overcomes the problem with the classical wireless channels as the doppler spread of these channels is large at the THz band while the delay spread does not change much over different frequencies leading to system implementation difficulties [12]. The study discussed the beam domain channel characteristics, authors showed that the channel elements are independent of time and frequency with the massive MIMO technique i.e., number of antennas at both the transmission and reception sides tends to infinity. Introduction of PMS reduces the effective delay and doppler frequency spreads compared to the ordinary synchronization schemes. This reduction depends on the number of terminal antennas [12]. Two suggested massive MIMO systems were compared in [13]: beamforming and multiplexing in the terahertz band. Although beamforming antenna technique represents a channel gain up to 55 dB at 1 THz taking into account the assumption that the THz communication channel is line of sight with no significant multipath rays [11], it increases the system complexity and cost. Moreover, achieving a high gain at this high frequency will result in a pencil beam, which will be affected by any movement of the transmitter and receiver. In spite of the belief that MIMO systems contribute to the beam forming gain but limited multiplexing gain improvement [14], multiplexing technique adds to the channel gain by the molecules absorption and re-radiation of the electromagnetic waves in the THz band such that it creates multi channels [3], [15] and can add to the channel gain more significantly than the beam forming techniques in certain circumstances such as high SNR and high transmit power . However, beyond limited distance as 10 meters, the transmit power should be increased to avoid the zero capacity drop [13].

III. TERAHERTZ MIMO FOR BIOMEDICAL APPLICATIONS

Terahertz band has great applications in biomedical area due it its unique properties as it doesn't damage the tissues because of its law energy photons, water strong absorption of THz light, and resonances in biomolecules [16]. Recently, THz proves its advantages for in-vivo applications, especially for in-vivo imaging of skin burns, melanoma, corneal pathologies, and cancer [17], as the skin locates at the body surface thus easing the penetration and the imaging technique. Dielectric function changes have been detected for different types of tissues, and the mean reason is the water absorption changes of these tissues [18]. Terahertz molecular imaging (TMI) technique and applications were reviewed in [19]. TMI application advantage depends on the idea of safety as the energy is much lower than the ionization energy of biological molecules compared to the hazardous x-ray radiation especially when accompanied with nanoparticle contrast agent probes to increase its sensitivity to realize the contrast between the cancerous and healthy tissues [19]. Moreover, communication which based on electromagnetic waves to exchange the data between the nano-devices is a promising technique for medical applications and e-health monitoring due to the unique properties of THz that were discussed before and the emerging new technology materials like Carbon Nano Tube (CNT) and Graphene [20], [4], [21], [22]. Magneto-inductive (MI) nanoscale transceivers, which based on multi-layer graphene (MLG), operating at THz were proposed in [23] as a mean of intra-body communication. It was proven that they have some advantages such as: achieving nano-scale size, universal operation environment that not suffering from propagation medium and absorption but only coupling loss, some features compatible with the intra-body communication as bio-compatibility, and low THz resistance [23].

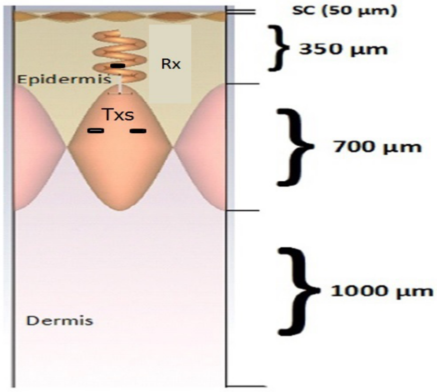

Fig. 2. Model representing the layers and their thickness with one receiving and two transmitting antennas.

Tissue	**Epidermis**	**Dermis**
$\grave{\varepsilon}_r$	4	3.27
$\grave{\grave{\varepsilon}}_r$	1.63	1.23

TABLE I

THE DIELECTRIC PARAMETERS OF THE SKIN TISSUES AT 1 THZ.

IV. DIVERSITY MODELING AND SIMULATION RESULTS

The skin is a complex heterogeneous and anisotropic medium. In our skin model, the skin tissues are represented by three layers: stratum corneum (SC), epidermis, and dermis. The detailed skin model was first presented and discussed in [24]. The path loss model and the electromagnetic modeling inside the human skin at terahertz band was first proposed in [25] taking into consideration sweat ducts, frequency, and distance dependent factors. The roughness of the boundaries between the skin layers has be taken into consideration i.e., between SC and epidermis, and between epidermis and dermis layers because the used frequency ,and consequently the wavelength, and the roughness dimensions are in the same order of magnitude. The sweat duct is modeled in the epidermis layer by a helix as shown in Fig. 2. Figure 2 represents the skin layers with the dimensions. Three ducts are simulated inside the model to increase the accuracy. For real skin tissues, the thickness of each layer differs according to the position all over the body, ranging from very thin when covering sensitive areas of the body, such as eyelids, to very thick when covering the tough areas, such as the hand palm. The skin tissue dimensions in the model were taken to be average between the skin dimensions of the sensitive areas and the tough areas.

Maxwell equations are solved throughout the skin layers by applying finite element analysis, using a commercial software CST ® Microwave Studio package. The model was analyzed at a frequency range (0.8 - 1.2) THz. Three dipole antennas with length 76 μm and radius 5 μm were used. One of the antennas was inserted and simulated inside the epidermis layer as a receiving antenna, while the other two antennas were inserted and simulated in the dermis layer as transmitting antennas. The distance between the two transmitting antennas is fixed to 40 μm such that the mutual coupling is below -17dB for the whole frequency band and consequently the two transmitting antennas are suitably decoupled. The distance between the receiving antenna and the two transmitting antennas is varied from 30 μm to 600 μm. A perfect matched layer (PML) was set as the boundary condition for the model as it operates like a free space and waves can pass this boundary with minimal reflections. The values of the skin dielectric layers properties used in simulation were reported by Pickwell *et al.* [26], [27] and represented in Table 1.

The diversity gain (DG) for two different in-vivo channels resulting from the signal propagation between two transmitting antennas, located at the dermis layer, and one receiving antenna, located at epidermis layer, is calculated to evaluate the system performance. Different diversity combining techniques are applied in this study: selection combining (SC), equal-gain combing (EGC), and maximum-ratio combining (MRC). S-parameters magnitude and phase, which represent the input output relationship between the two channels, are extracted from the simulation software and then converted to the time domain using an Inverse Fast Fourier Transform (IFFT). Diversity combining is achieved by using the expressions given in [28] for combing the time domain signal:

$$SC(t) = max(r_1(t), r_2(t)) \tag{1}$$

$$EGC(t) = \frac{r_1(t) + r_2(t)}{\sqrt{2}} \tag{2}$$

$$MRC(t) = \sqrt{r_1^2 + r_2^2} \tag{3}$$

where $r_1(t)$ and $r_2(t)$ are the two received branch signal envelopes. The DG is calculated by plotting the cumulative distribution functions (CDFs) of the two branch signals and the diversity-combined signals. The DG is the difference between the strongest of the two branch signals and the diversity combined signal at 10% assumed outage probability. In MRC and EGC, the two branch signals are co-phased to provide coherent signal addition using the simple technique in [28].

Although MIMO antenna systems are used in wireless communication to enhance data throughput, from the initial study it is predicted that might be multiple antenna technique is not useful in in-vivo nano communication. Results demonstrate that there is a high cross correlation between the two channels. Fig. 3 shows the CDF plot for the two channel with different diversity combining techniques used in the study.

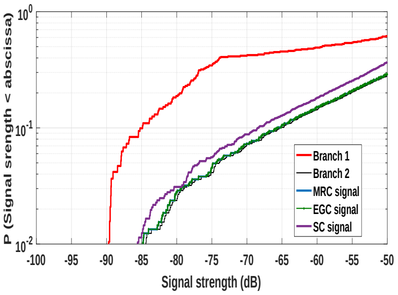

Fig. 3. CDF plot for diversity gain calculation.

V. CONCLUSION

The paper presented a preliminary simulation study for using MISO technique in Terahertz band (0.8 - 1.2 THz) inside the human skin tissues. The skin model consists of three layers: SC, epidermis, and dermis layers; taking into consideration, the sweat ducts effect and roughness between layers. One dipole antenna was inserted in the epidermis layer as a receiving antenna, while two dipole antennas were inserted in the dermis layer as a transmitting antenna. Spatial diversity techniques for in-vivo channels were investigated. Distance between transmitting antennas was chosen to guarantee that the mutual coupling is always below -17 dB. The distance between the Rx antenna and the two Tx antennas was varied to study the distance effect. In spite of the fact that MIMO antenna system supports enhanced data throughput even under conditions of interference, signal fading, and multipath, it might be not useful to use multiple antenna technique for in-vivo nano-communication. This early conclusion emphasize the difference between the in-vivo communication channels and the classical ones.

In addition, the paper presented an overview for using MIMO in THz band with applications and advantages, and using THz MIMO for in-vivo nano-communication. Still challenging research is needed for investing THz biomedical applications for the area of in-vivo communication with MIMO antenna system such that we can gain the maximum achievable channel capacity by studying the spatial correlation inside the body medium and implementing the MIMO antenna systems inside the body.

VI. ACKNOWLEDGMENT

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REFERENCES

[1] Ezio Biglieri, Ropert Calderbrank, Anthony Constantinides, Andrea Goldsmith, Arogyaswami Paulraj, and H. Vincent Poor, *MIMO Wireless Communication*, Cambridge University Press, 2007.

[2] A. Redo-Sanchez and X. Zhang, "Terahertz science and technology trends," *IEEE Journal of Selected topics in quantum electronics*, 2008.

[3] Ian Akyildiz, Josep Jornet, and Chong Han, "Terahertz band: Next frontier for wireless communications," *Physical Communication, Elsevier*, vol. 14, pp. 260–269, 2014.

[4] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3211–3221, 2011.

[5] 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.

[6] 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, Elsevier*, vol. 10, pp. 15–59, 2016.

[7] K. Yao and Y. Liu, "Plasmonic metamaterials," *Nanotechnol. Rev.*, vol. 3, pp. 177–210, 2014.

[8] 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.

[9] 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.

[10] 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.

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

[12] Li You, Xiqi Gao, Geoffrey Ye Li, Xiang-Gen Xia, and Ni Ma, "BDMA for millimeter-wave/terahertz massive MIMO transmission with per-beam synchronization," *IEEE Journal on Selected Areas in Communication*, vol. 35, pp. 1550–1563, 2017.

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

[14] 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.

[15] J. Kokkoniemi, J. Lehtomaki, and M. Juntti, "A discussion on molecular absorption noise in the terahertz band," *Nano communication networks*, 2015.

[16] S S Dhillon et al, "The 2017 terahertz science and technology roadmap," *J. Phys. D: Appl. Phys.*, vol. 50, 2017.

[17] Z. Taylor, R. Singh, D. Bennett, P. Tewari, C. Kealey, N. Bajwa, M. Culjat, A. Stojadinovic, H. Lee, J. Hubschman, E. Brown, and W. Grundfest, "THz medical imaging: in vivo hydration sensing," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, pp. 201–219, 2011.

[18] E. Pickwell and V. P. Wallace, "Biomedical applications of terahertz technology," *J. Phys. D:Appl.Phys.*, vol. 39, pp. R301–R310, 2006.

[19] J. Son, "Principle and applications of terahertz molecular imaging," *Nanotechnology*, vol. 24, 2013.

[20] S. Balasubramaniam and J. Kangasharju, “Realizing the internet of nano things: challenges, solutions, and applications,” *computer*, vol. 46, pp. 62–68, 2013.

[21] Q. H. Abbasi, , K. Yang, N. Chopra, J. Jornet, . Abuali, K. A. Qaraqe, and A. Alomainy, “Nano-communication for biomedical applications: A reiview on the state of the art from physical layers to novel networking concepts,” *IEEE Access*, vol. 4, no. 3, pp. 3920–3935, 2016.

[22] Q. H. Abassi, M. Ur-Rehman, K. Qaraqe, and A. Alomainy, *Advances in body-centric wireless communication: applications and state-of-the-art*, Series: IET telecommunications series. Institution of Engineering and Technology: London, 2016.

[23] B. Gulbahar, “Theoritical analysis of magneto-inductive terahertz wireless communications and power transfer with multi-layer graphene nano coils,” *IEEE Transactions on molecular, biological, and multi-scale communications*, vol. 3, pp. 60–70, 2017.

[24] I. Hayut, A. Puzenko, P. B. Ishai, A. Polsman, A. J. Agranat, and Y. Feldman, “The helical structure of sweat ducts: Their influence on the electromagnetic reflection spectrum of the skin,” *IEEE Transactions on Terahertz Science and Technology*, vol. 3, pp. 207–215, 2015.

[25] Q. Abbasi, H. Sallabi, N. Chopra, K. Yang, K. Qaraqe, and A. Alomainy, “Terahertz channel characterization inside the human skin for nano-scale body-centric network,” *IEEE Transactions on Terahertz Science and Technology*, vol. 6, pp. 427–434, 2016.

[26] E. Pickwell, B. E. Cole, A. J. Fitzgerald, V. P. Wallace, and M. Pepper, “Simulation of terahertz pulse propagation in biological systems,” *Applied Phys. Letters*, vol. 84, pp. 2190–2192, 2004.

[27] E. Pickwell, B. E. Cole, A. J. Fitzgerald, M. Pepper, and V. P. Wallace, “In vivo study of human skin using pulsed terahertz radiation,” *Phys. Med. Biol.*, vol. 49, pp. 1595–1607, 2004.

[28] W. C. Jakes, *Microwave mobile communications*, John Wiley and Sons, New York, 1974.