On and Off-Body Radio Channel Performance of a Dual Band and Dual Mode Antenna

Mohammad Monirujjaman Khan [1,2]

[1] Department of Electrical and Computer Engineering
North South University, Bashundhara, Dhaka, 1229, Bangladesh
monirkhan.qmul@gmail.com

[2] School of Electronic Engineering and Computer Science
Queen Mary University of London, Mile End, London E1 4NS, United Kingdom

Abstract **─** In this paper, measurement results of on-body radio propagation channels at 2.45 GHz and off-body radio propagation channels at 1.9 GHz using dual band and dual mode (DBDM) antenna are presented. The proposed antenna works at two different frequencies with different radiation modes. Experiments are performed first in the chamber and then in an indoor environment. The path loss has been characterized for ten different on-body radio channels at 2.45 GHz. Five off-body radio channels are studied at 1.9 GHz. The path loss was modeled as a function of distance for on-body radio propagation at 2.45 GHz and off-body radio propagation at 1.9 GHz. For on-body propagation, the path loss exponent is noticed to be 2.48 and 2.22 in the camber and sensor laboratory, respectively. For off-body radio propagation case, the path loss exponent is noticed to be 1.27. The proposed antenna shows very good on-body and off-body radio propagation channel performance.

Index Terms **─** Body-centric wireless communications, dual band and dual mode antenna, on/off-body communications, path loss.

I. INTRODUCTION

The rapid development of biosensors and wireless communication devices brings new opportunities for Body-Centric Wireless Networks (BCWNs) which has recently received increasing attention due to their promising applications in medical sensor systems and personal entertainment technologies. Body-centric wireless communications (BCWCs) is a central point in the development of fourth generation mobile communications. In body-centric wireless networks, various units/sensors are scattered on/around the human body to measure specified physiological data, as in patient monitoring for healthcare applications [1-5]. A body-worn base station will receive the medical data measured by the sensors located on/around the human body. In BCWCs, communications among on-body devices are required, as well as communications with external base stations.

Antennas are the essential component for wearable devices in body-centric wireless networks and they play a vital role in optimizing the radio system performance. The human body is considered an uninviting and even hostile environment for a wireless signal. The diffraction and scattering from the body parts, in addition to the tissue losses, lead to strong attenuation and distortion of the signal [1]. In order to design power-efficient on-body and off-body communication systems, accurate understanding of the wave propagation, the radio channel characteristics and attenuation around the human body is extremely important.

Researchers have been comprehensively investigating narrow band and ultra wideband on-body radio channels recently. In [6-11], on-body radio channel characterisation was presented at the unlicensed frequency band of 2.45 GHz. In body-centric wireless communications, there is a need of communications among the devices mounted on the body as well as off-body devices. In previous study, researchers have designed the antennas for on-body communications and investigated the on-body radio channel performance both in narrowband and ultra wideband technologies. However, in common healthcare monitoring scenarios, it is very important for the antenna to radiate over the body surface omni-directionally and also directive towards off the body units in order to get the best on body and off-body radio channel performances, i.e., minimise the link loss to ensure power efficiency. Body-centric wireless devices need to offer low power consumption in order to extend the battery life of the body worn devices and also need to provide power-efficient and reliable on-body and off-body communications [12]. Antenna with omni-directional radiation pattern over the body surface improves the path gain for the on-body links while antenna with directive off-body radiation pattern

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improves the path gain for off-body channels.

This paper presents experimental results of on-body and off-body radio propagation channels of dual band and diverse radiation pattern antenna. The antenna used in this study works at two different frequency bands as 2.45 GHz (ISM band) with omnidirectional radiation pattern over the human body surface and 1.9 GHz (PCS band) with off-body radiation mode from the human body. The 2.45 GHz is used for the communication over human body surface (on-body) and 1.9 GHz is used for the communication from body mounted devices to off-body units (off-body communications). Experiments were performed in the Body-Centric Wireless Sensor Laboratory and Anechoic Chamber in Queen Mary University of London. In this study, a frequency-domain measurement set-up was applied. For on-body case, the path loss for ten different on-body radio channels is shown and analysed. For off-body case, the path loss for five different radio propagation channels at 1~6 meter distance locations in indoor environment is investigated.

The rest of the paper is organized as follows; Section II discusses about the antenna, on-body radio channel measurements setting and on-body results, Section III presents off-body radio channels measurement settings and results, and finally Section IV provides the conclusion.

II. ON-BODY RADIO PROPAGATION CHANNEL STUDY AT 2.45 GHz

A. On-body radio channel characterisation at 2.45 GHz

The on-body radio channel performance at 2.45 GHz of the dual band and dual mode (DBDM) antenna has been experimentally investigated. Figure 1 shows the fabricated dual band and dual mode antenna. The antenna was modelled on FR4 substrate with a thickness of 1.57 mm and a relative permittivity of 4.6. There is a full ground plane at the backside of the substrate with the size of 60×60 mm. The antenna contains two radiating elements, a disk loaded Monopole and circular Patch [12].

The antenna was designed using Computer Simulation Technology (CST) Microwave Studio™ and then fabricated in the antenna laboratory in Queen Mary University of London. The antenna is simulated both in free space and on the human phantom (ground plane 4 mm away from right chest) using Computer Simulation Technology (CST) Microwave Studio™. The human body employed is the commonly available detailed multi-layer model namely the ‘visible male model’ developed by the US Air Force [13]. The resolution of the model applied is 4 mm with the electrical properties of human tissues defined at 2.45 GHz and 1.9 GHz, respectively, for all organs and tissues used including heart, lungs, muscle, fat, skin, etc. [14-15]. The on-body performances (return loss and radiation pattern) of the antenna were measured on the real human body (4 mm away from right chest). Figure 2 shows the free space and on-body return loss responses of the proposed antenna. The antenna works at 2.45 GHz and 1.9 GHz. The antenna is proposed to use in body-centric wireless communications where communication is necessary both to the devices on body and to the external off body networks nodes. The top loaded disk Monopole structure is to get the resonance at 2.45 GHz with omnidirectional radiation pattern over the body surface to communicate with other body worn devices whereas the lower circular patch on the FR4 board is for 1.9 GHz with off the body directive radiation mode to communicate power-efficiently from on-body device to off-body units. At 2.45 GHz, this dual band dual mode antenna radiates omnidirectionally over the body surface of the human body which is good to set up power-efficient on-body communication with other collocated devices on the body and at 1.9 GHz it produces directional radiation pattern towards off the body which will be good for power-efficient communication from on-body device to off-body units. The free space and on-body radiation patterns of the proposed DBDM antenna are shown in Figs. 3 and 4, respectively. The antenna shows very good bandwidth, radiation efficiency and gain when it is placed on the human body. More details about the free space and on-body performance parameters (radiation pattern, bandwidth, gain and radiation efficiency) of this antenna are available in [12].

Fig. 1. Fabricated version of the dual band and dual mode (DBDM) antenna [12].

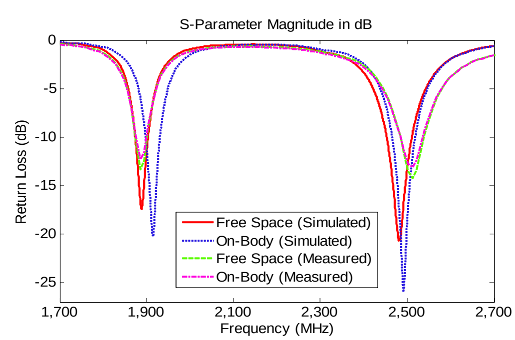
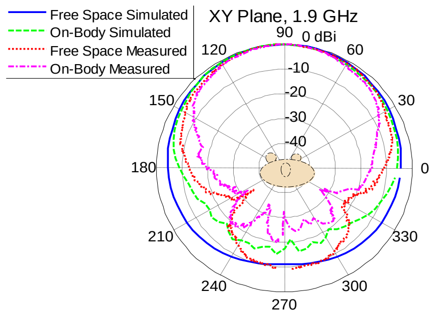
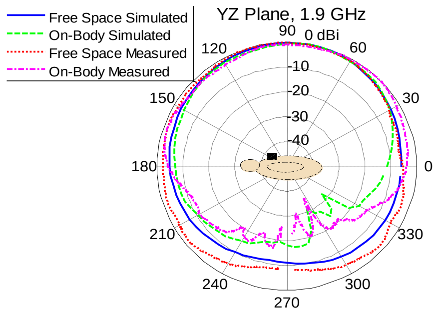


Fig. 2. Simulated and measured free space and on-body return loss responses of the proposed dual band and dual mode antenna [12].

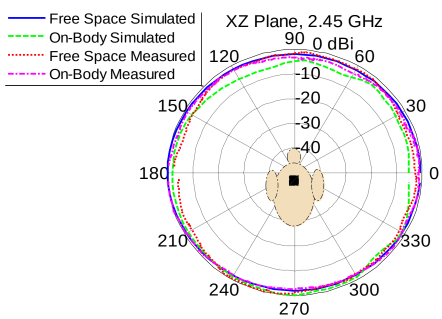


(a) XY plane at 1.9 GHz

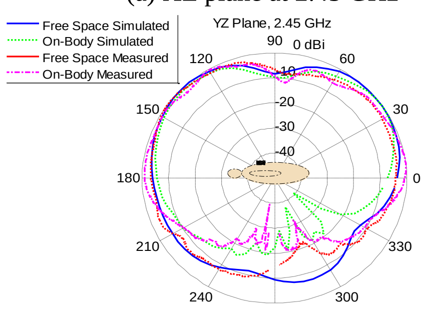


(b) YZ plane at 1.9 GHz

Fig. 3. Simulated and measured free space and on-body radiation patterns of the proposed dual-band and dual mode antenna: (a) XY plane at 1.9 GHz, and (b) YZ plane at 1.9 GHz.



(a) XZ plane at 2.45 GHz



(b) YZ plane at 2.45 GHz

Fig. 4. Simulated and measured free space and on-body radiation patterns of the proposed dual-band and dual mode antenna: (a) XZ plane at 2.45 GHz, and (b) YZ plane at 2.45 GHz.

In this study for on-body radio propagation channel study at 2.45 GHz, the S21 measurements of the proposed DBDM antenna were performed in an anechoic chamber and in the indoor environment. An average-sized real male test subject, with a height of 1.74 m and a weight of 80 kg was used. In this study, a pair of DBDM antenna was used. A HP8720ES vector network analyser was used to measure the transmission response (S21) between two DBDMs placed on the body.

The transmitter antenna connecting with the cable was placed on the left waist, while the receiver antenna connecting with the cable was successively placed on 10 different locations on the front part of the standing human body; as shown in Fig. 5. The test subjects were standing still during the measurements and, for each receiver location and measurement scenario, 10 sweeps were considered. The effects of the cable were calibrated out.

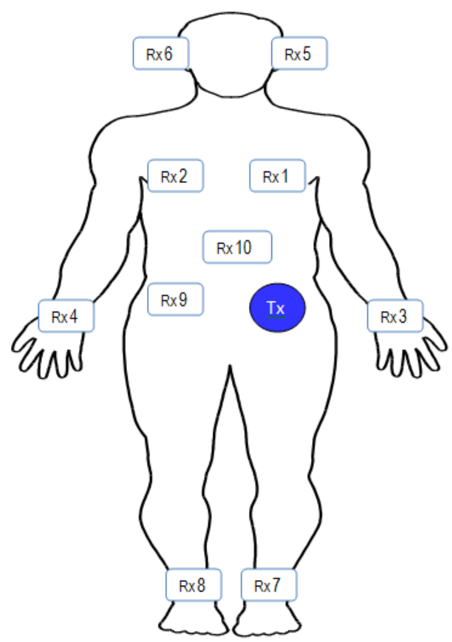


Fig. 5. On-body radio propagation channel measurement settings at 2.45 GHz showing the transmitter antenna is on the left waist while the receiver antenna is on 10 various locations of the body.

The on-body measurements were first performed in the anechoic chamber and then repeated in the Body-Centric Wireless Sensor Laboratory at Queen Mary, University of London. The total area of the laboratory is 45 m^2 which includes a meeting area, treadmill machine, workstations and a hospital bed for healthcare applications [16-17].

The path loss for the different receiver locations was computed directly from the measurement data of S21 (10 sweeps) averaging at 2.45 GHz. Figure 6 shows the comparison of path loss for left waist to ten different on-body links measured in the chamber and in an indoor environment.

Results show that for both in the chamber and in indoor environment cases, the lowest path loss value is observed for the left waist to left chest and left wrist links while the highest is noticed for the right ear and right wrist channels. This is so happened because for left chest left wrist channels, the communication distance between the transmitter antenna and the receiver antenna is less and there is direct Line-Of-Sight (LOS) communication but for the right ear and right wrist the communication distance between the Receiver (Rx) antenna and Transmitter (Tx) antenna is higher moreover the communication is blocked by human body and the presence of Non-Line-Of-Sight (NLOS) communication. The average path loss of ten different on-body channels is noticed to be higher in the chamber than in the sensor laboratory. The higher path loss value for on-body links in the anechoic chamber may be due to the non-reflecting environment. The average of ten different on-body link's path loss in the sensor laboratory is noticed to be 44.48 dB, while in the chamber it is noticed to be 42.05 dB. Based on the results and analysis, it is noticed that this antenna shows very good on-body radio channel performance at 2.45 GHz.

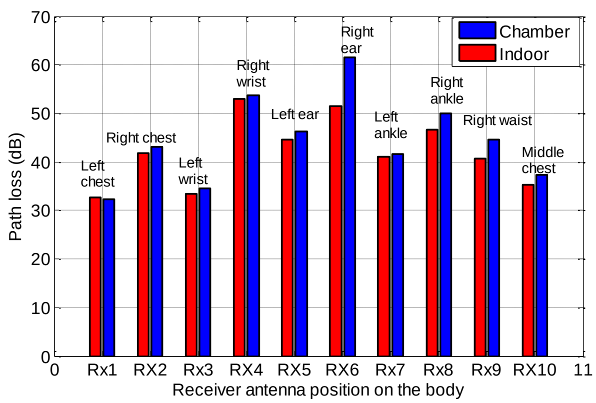


Fig. 6. Comparison of path loss for left waist to 10 different on-body links measured in the chamber and in an indoor environment.

B. Path loss vs. distance

The path loss was modelled as a function of distance for 31 different receiver locations for propagation along the front part of the body. In this case, the transmitter DBDM antenna connecting with cable was placed on the left waist and the receiver DBDM antenna was attached on 31 different locations on the front part of the body; as shown in Fig. 7.

The average received signal decreases logarithmically with distance for both indoor and outdoor environments as explained in [18]:

$$PL_{dB}(d) = PL_{dB}(d_0) + 10\gamma \log(\frac{d}{d_0}) + X_\sigma, \qquad (1)$$

where d is the distance between transmitter and receiver, d_0 is a reference distance set in measurement (in this study it is set to 10 cm), $PL_{dB}(d_0)$ is the path loss value at the reference distance, and X_σ is the shadowing fading. The parameter γ is the path loss exponent that indicates the rate at which the path loss increases with distance [15].

In order to extract the path loss exponent a least-square fit technique was performed on the measured path loss for the 31 different receiver locations, (Fig. 7).

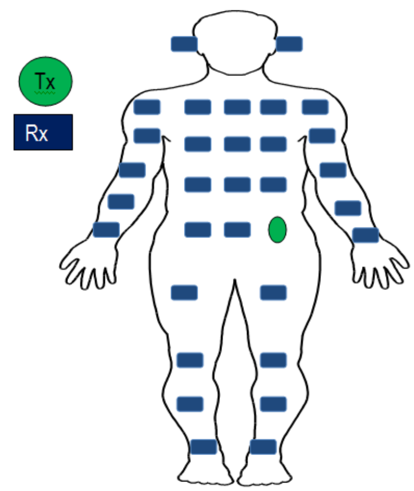


Fig. 7. On-body measurement settings at 2.45 GHz showing the transmitter is on the left waist and the receiver antenna is on 31 different locations of the body.

The measured value and modelled path loss for on-body channels versus logarithmic Tx-Rx separation distance are shown in Fig. 8. The path loss exponent was found to be 2.48 in the chamber and 2.22 in indoor (Table 1). In the indoor environment, the path loss exponent was found to be lower compared to chamber. Results and analysis show that when measurements are performed in indoor, the reflections from surroundings scatters increase the received power, causing reduction in the path loss exponent. A reduction of 10.48% was noticed in indoor compared to the chamber in this case.

X_σ is a zero mean, normal distributed statistical variable, and is introduced to consider the deviation of the measurements from the calculated average path loss. Figure 9 shows the deviation of measurements from the average path loss fitted to a normal distribution for both measurement cases. The standard deviation of the normal distribution value is noticed to be slight smaller in the indoor environment (Table 1).

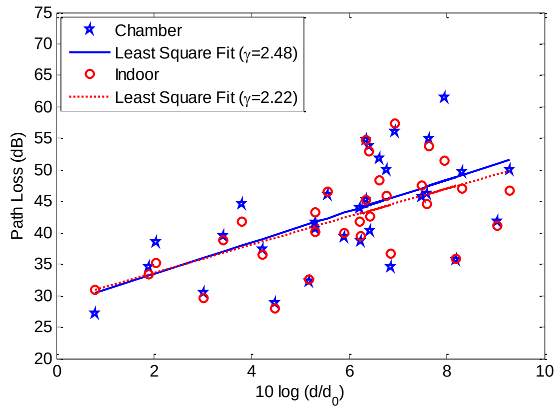


Fig. 8. Measured and modelled path loss for on-body channel versus logarithmic transmitter (Tx) and receiver (Rx) separation distance for the DBDM antenna at 2.45 GHz.

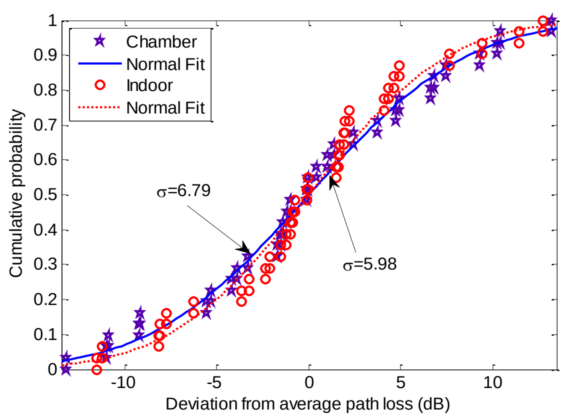


Fig. 9. Deviation of measurement from the average path loss (fitted to normal distribution) for the dual band and dual mode antenna at 2.45 GHz.

Table 1: On-body path loss parameters at 2.45 GHz

Path Loss Parameters	Chamber	Indoor
γ	2.48	2.22
$PL_{dB}(d_0)$ (dB)	28.45	29.22
σ (dB)	6.79	5.98

III. OFF-BODY RADIO PROPAGATION CHANNELS STUDY AT 1.9 GHz

A. Off-body radio channel characterisation at 1.9 GHz

In this section, off-body radio propagation measurement at 1.9 GHz is performed in the Body-Centric Wireless Sensor Laboratory at Queen Mary, University of London using the same dual band dual mode (DBDM) antenna. Five different off-body radio channels were considered. A receiver antenna connected with Vector Network Analyser (VNA) was placed on the ceiling near the wall, as shown in Fig. 10 (b). During measurement, the transmitter antenna connecting with the other port of the VNA was attached on five different locations on the human body as right chest, left waist, left wrist, right ear, left ankle, as shown in Fig. 10 (a). During the measurement, the test subject was standing still at 1 to 6 metre locations with the interval of 1 metre facing towards the receiver antenna. The VNA transmission power was set to 0 dBm. For each location and measurement scenario 10 sweeps were considered.

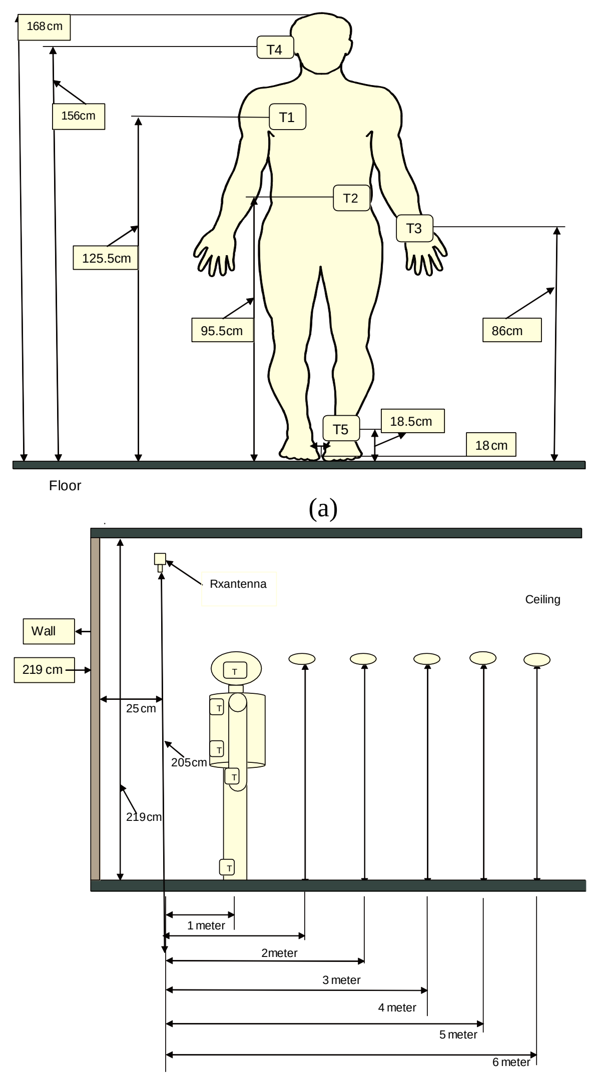


Fig. 10. Off-body measurement settings at 1.9 GHz, (a) locations of the antenna on the human body, and (b) measurement scenarios and side view showing transmitter antenna and the antenna on the human body.

The path loss for each different off-body channel is calculated directly from the measurement data S21 (10 sweep) averaging at 1.9 GHz. Figure 11 shows the comparison of path loss for five different off-body channels, when subject was standing still at 1~6 metre locations measured in indoor environment. At one metre distance location, the lowest path loss is noticed for the receiver to the chest link and the highest is noticed at the ear and ankle links. The chest link has the lowest communication distance and LOS communication with the receiver antenna as compared to the ankle link resulting the lowest path loss value for this link. Though, the communication distance between the receiver antenna and the right ear link is less but higher path loss value is noticed which is due to the different orientation of the transmitter antenna located on the right ear. At one metre distance, the average path loss of five off-body links is 45.84 dB, while at six metre distance it is noticed to be 54.27 dB. Results show that as the distance increases, the path loss for most of the off-body radio channels increases. This antenna shows good off-body radio channel performance at 1.9 GHz.

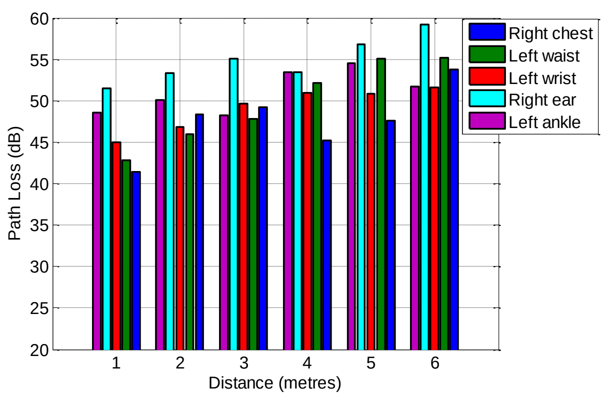


Fig. 11. Comparison of path loss for five different off-body channels, when subject was standing still at 1~6 metre locations measured in an indoor environment.

In this case, the path loss was modeled as a function of distance for 30 different receiver locations at 1.9 GHz. A least square fit technique is performed on measured path loss for all 5 off-body channels (1-6 metre) at 30 different transmitter locations to extract the path loss exponent (see Table 2). Figure 12 shows the measured value and modelled path loss for off-body channel versus logarithmic Tx-Rx separation distance showing path loss exponent for the dual band and dual mode antenna at 1.9 GHz. In this study, the path loss exponent is found to be 1.27. Results and analysis show that this proposed dual band and dual mode (DBDM) antenna shows very good path loss exponent value at 1.9 GHz for off-body radio propagation.

Figure 13 shows the deviation of measurements from the average path loss fitted to a normal distribution for dual band antenna dual mode antenna at 1.9 GHz. In the indoor, the standard deviation of the normal distribution for this antenna is σ =3.11.

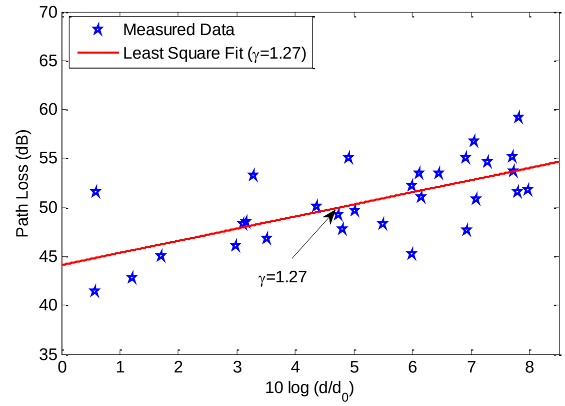


Fig. 12. Measured and modelled path loss for off-body channel versus logarithmic transmitter (Tx) and receiver (Rx) separation distance for the dual band and dual mode (DBDM) antenna at 1.9 GHz.

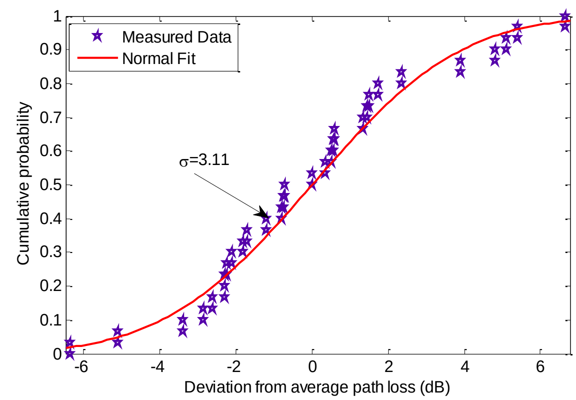


Fig. 13. Deviation of measurement from the average path loss (fitted to normal distribution) for the dual band and dual mode antenna at 1.9 GHz for off-body case.

Table 2: Off-body path loss parameters at 1.9 GHz

Path Loss Parameters	Results
γ	1.27
$PL_{dB}(d_0)$ (dB)	44.11
σ (dB)	3.11

IV. CONCLUSION

The on-body radio channel performance at 2.45 GHz and off-body radio channel performance at 1.9 GHz of a dual band and dual mode (DBDM) antenna is experimentally investigated in this paper. Measurements are performed both in the anechoic chamber and in an indoor environment. On and off-body radio channels have been characterized and analyzed. For on-body case, the path loss for ten different on-body radio channels measured in the anechoic chamber and sensor laboratory is shown and analysed. For off-body case, the path loss for five different off-body radio channels at 1 to 6 metre distance locations measured in indoor environment is investigated. A least square fit method was performed on the measured path loss results for on-body radio propagation at 2.45 GHz and off-body radio propagation at 1.9 GHz. The proposed dual band and dual mode (DBDM) antenna shows very good on-body and off-body radio channel performance; hence it will be suitable candidate for body-centric wireless communications in order to set up power-efficient communication between body mounted devices and also with the off-body units.

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Mohammad Monirujjaman Khan received his Ph.D. degree from Antenna and Electromagnetic Group, Queen Mary University of London (QMUL). He is working as an Assistant Professor in the Department of Electrical and Computer Engineering, North South University, Dhaka, Bangladesh. His main research interests include compact and efficient antennas for medical and sports applications in wireless body area networks and wireless personal area networks, radio propagation channel modelling and characterization, small antennas design, cognitive radio and system and wearable systems. He has authored and co-authored more than 60 technical papers in leading journals and peer-reviewed conferences. Khan is acting as a reviewer for many leading IEEE and IET journals in the area of antennas, radio wave propagation and communication systems.