Path loss variation of on-body UWB channel in the frequency bands of IEEE 802.15.6 standard

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The wireless body area network (WBAN) has gaining tremendous attention among researchers and academicians for its envisioned applications in healthcare service. Ultra wideband (UWB) radio technology is considered as excellent air interface for communication among body area network devices. Characterisation and modelling of channel parameters are utmost prerequisite for the development of reliable communication system. The path loss of on-body UWB channel for each frequency band defined in IEEE 802.15.6 standard is experimentally determined. The parameters of path loss model are statistically determined by analysing measurement data. Both the line-of-sight and non-line-of-sight channel conditions are considered in the measurement. Variations of parameter values with the size of human body are analysed along with the variation of parameter values with the surrounding environments. It is observed that the parameters of the path loss model vary with the frequency band as well as with the body size and surrounding environment. The derived parameter values are specific to the particular frequency bands of IEEE 802.15.6 standard, which will be useful for the development of efficient UWB WBAN system.

1. Introduction: The statistics provided by World Health Organization (WHO) has indicated that the non-communicable dieses such as cardiovascular diseases, respiratory diseases, diabetes etc. are the leading cause of death in all over the world [1]. It is also predicted that the chronic diseases will account for three-quarters of total deaths by 2020. Statistics also reflects that the chronic diseases are found more among old peoples. The old people (65 years and over) have been comprised a greater proportion worldwide. The projected proportion of old people in 2050 is 15.6%, which was 5.1% in 1950 [2]. Alternatively, the proportion of young people (below 15 years) has been decreasing significantly, which was 34.4% in 1950 and projected proportion in 2050 is 21.3%. It indicates the shifting of young old balance throughout the world. The aged persons are more likely to have difficulties in mobility and require assistance of other people to continue their normal activities. Thus, the efficient management of healthcare is becoming a challenging task due to the increasing demands for service. It is expected that the wireless body area network (WBAN) system will be an efficient tool for effective management of healthcare service especially for providing long-term care to the peoples suffering in chronic diseases. WBAN is a network of intelligent wireless sensor nodes strategically placed on key portions of body for providing various services. The sensor nodes placed in, on or around the body will continuously sense the physiological parameters of interest and wirelessly transmit it to the care providers or hospitals. The care providers will continuously monitor the patient parameters and will take required action as necessary. The action may be a wireless instruction to the patient to take certain drug at required quantity, automatic injection of medicine to the patient through actuator system or they may instruct the ambulance on the network to shift immediately the patient to hospital. The use of WBAN system in healthcare service is a cost effective information and communications technology driven solution to the challenges of modern healthcare needs. It allows ubiquitous monitoring of patients vital parameters by removing the restrictions on patient mobility. The WBAN systems must be safe for body, compact in size and low weight so that patient can wear it without any discomfort as well as it must be secure and reliable. The ultra-wideband (UWB) radio is the appropriate air interface for WBAN systems due to its low level of radiated power, high data rate, low power consumption, robustness against multipath, compact and simple transceiver architecture etc. The IEEE 802.15.6 standard [3] has included UWB as one of the physical layer for body area network (BAN) applications. In [3] the unlicensed UWB frequency band (i.e. 3.1–10.6 GHz) defined by FCC [4] was divided in two frequency groups namely low band and high band. The low band is divided in three sub bands whose centre frequencies are 3494.4, 3993.6 and 4492.8 MHz. The high band is divided in eight sub bands whose centre frequencies are 6489.6, 6988.8, 7488.0, 7987.2, 8486.4, 8985.6, 9484.8 and 9984.0 MHz, respectively. The bandwidth of all sub bands is 499.2 MHz. Sub bands with the centre frequency of 3993.6 and 7987.2 MHz are considered as mandatory band for low and high band, respectively, while the other sub bands are considered as optional.

For development of a reliable wireless communication system, it is always prerequisite to characterise the propagation channel. The mathematical model of the channel is utmost prerequisite to remove the effect of channel from the received signals. The UWB channel characteristics in BAN environments have significantly differs from typical indoor UWB channel due to the proximity of human body. In-body to on-body channel model reported in [5] is based on measurements performed in living animals for the frequency band of 1–6 GHz. An in-body channel model was reported in [6] for the frequency band of 2.36–2.5 GHz. The dynamic behaviour of UWB around-body channel characteristics reported in [7] are based on measurements performed in time domain. Amplitude variation of arrival paths are reported in [8] for the pseudo dynamic on-body UWB link based on measurement performed in an anechoic chamber for the frequency band 2–8 GHz. Variation of path loss of on-body channel at different frequencies are reported in [9] for a limited number of radio links based on measurement performed in anechoic chamber for the frequency band 2–8 GHz. On-body channel model reported in [10] is based on frequency dependence finite difference time domain simulation. On-body channel models reported in [11–13] are based on measurements performed in anechoic chamber. Off-body UWB channels are characterised to

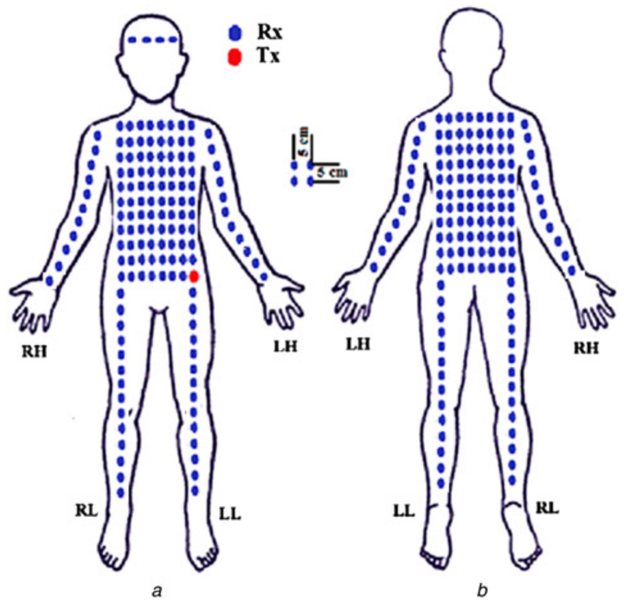

Fig. 1 *Positions of antennas on the body*
a LOS
b NLOS

certain extends in [14–16]. On-body and off-body preliminary channel study is reported in [17]. Channel characteristics reported in [18–20] are based on measurements performed in anechoic chamber. Around-body channel models reported in [21–23] are based on measurement performed on human torso. Taparugssanagorn *et al*. [24] provides the model for path loss and delay dispersive parameter for on-body and off-body channels based on measurements performed for a limited number of channel links. However, all the parameters of reported path loss models for on-body UWB channel in the literature represent the frequency averaged path loss of the entire frequency band of corresponding measurement. Furthermore, the permittivity and the conductivity of human body are frequency dependent. Therefore, it is expected that the characteristic parameters of path loss models might be dependent on the frequency band of applied radio wave. In these circumstances, the frequency averaged path loss derived for the entire UWB frequency band may not reflects the actual channel characteristics on the specific operating frequency band. This will introduce non-reliability in the system. In this Letter, we have experimentally determined the path loss parameters of on-body UWB channel for each frequency sub band standardised in [3]. Variation of path loss parameter values at each sub band in line-of-sight (LOS) and non-line-of-sight (NLOS) channel conditions are examined. The variation of parameter values with the size of human body is also analysed and reported. Furthermore, the variations of parameter values at each sub band with the surrounding environments are analysed based on measurement data. The objective of this study is the experimental determination of path loss model parameters for on-body UWB channel, which will be more appropriate for the specific frequency band of interest defined in the IEEE 802.15.6 standard. The derived parameter values will be useful for the UWB WBAN system designers for efficient realisation of the system.

The remaining of this Letter is organised as follows: the Section 2 provide the description of measurement setup, procedures of measurement and different channel scenarios. The description of the antenna characteristics on the human body is also described in this section. Section 3 provides the data analysis and corresponding results. The conclusion of this Letter is drawn in Section 4.

2. Description of measurement setup, scenarios and antenna characteristics

2.1. Measurement setup: Channel measurements setup consists of a Rohde and Schwarz ZVA24 vector network analyser (VNA), monopole UWB antennas and triple shield low loss RF cables with shielding effectiveness >100 dB from mini-circuits (CBL-10FT-SMSM+). The VNA was controlled from a computer connected to it through local area network. The antennas used are small (18 mm × 12 mm) printed monopole with T-shaped notch in the ground plane with omnidirectional radiation pattern in H-plane [25]. The VNA was configured to S21 parameter measurement setup with the radio channel as device under test. The frequency bandwidth (B) used in our measurement is 7.5 GHz (i.e. 3.1–10.6 GHz) and the number of frequency sampling point (M) chosen was 1601, which provides the maximum detectable delay ($\tau_{\max}$) of the channel as

$$\tau_{\max} = \frac{(M-1)}{B} \tag{1}$$

The resultant maximum detectable delay from (1) in our measurement is 213 ns. The time resolution of the measurement setup is given by the reciprocal of the frequency bandwidth that is 133 ps in this configuration. The intermediate frequency (IF) bandwidth and the transmit power of the VNA was kept at 1 kHz and 10 dBm, respectively. The resultant display averaged noise level is −120 dB. A full two port (TOSM) calibration of the VNA was performed with the cables used in the measurement to remove all systematic errors.

2.2. Measurement scenarios: Channel measurements are performed in a typical laboratory environment. The laboratory is consisting

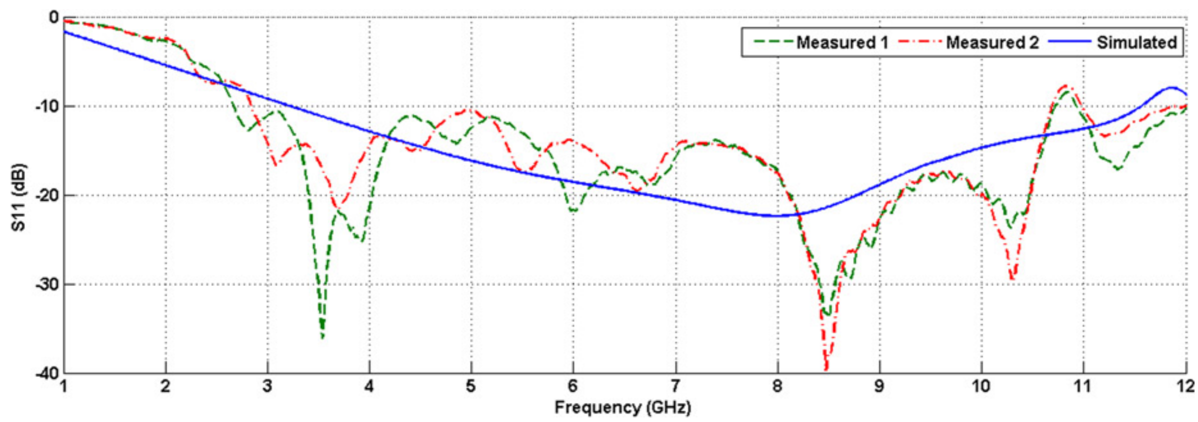

Fig. 2 *Simulated and measured return loss of the antennas*

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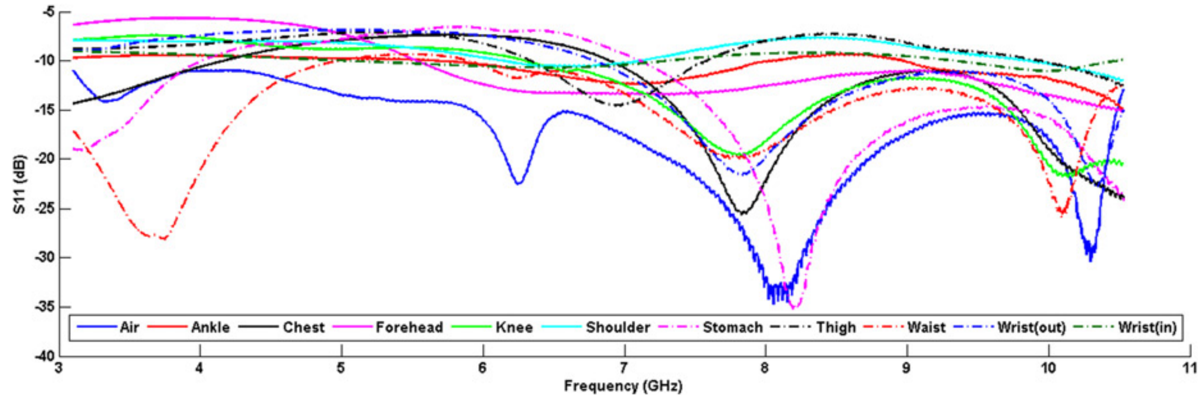

Fig. 3 *Measured return loss of the antenna on the body without dielectric*

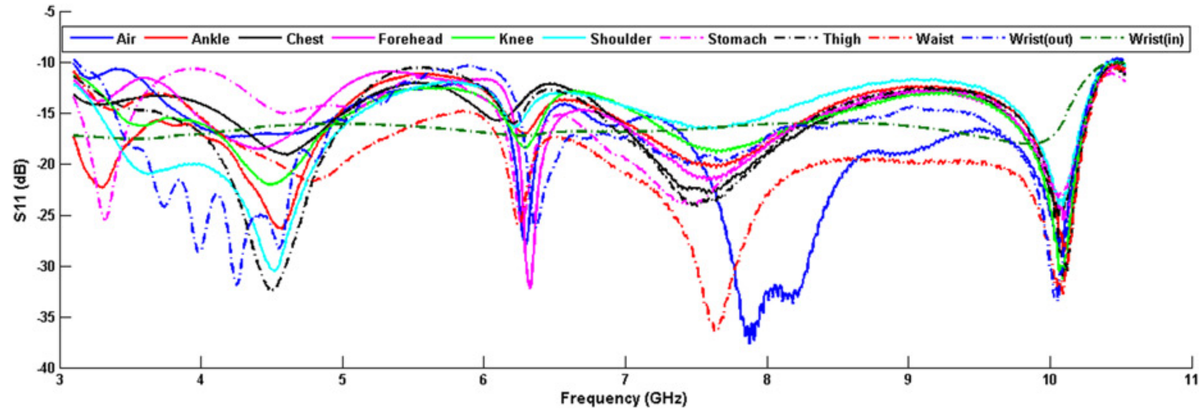

Fig. 4 *Measured return loss of the antenna on the body with dielectric*

of different laboratory instruments, computers, workbenches, bookshelves, tables, chairs etc. The floor and roof of the laboratory is made of concrete with a ceiling of plasterboard. Sidewalls are made of concrete with two-third of its height covered with glass windows having aluminium frame. Total six set of measurement campaigns are carried out for the determination of path loss in LOS and NLOS scenarios on the body of three persons having different size to get the trend of path loss parameters with the size of body. The heights of three persons classified as 'thin', 'normal' and 'fat' in our measurements are 175, 178, 170 cm, respectively and corresponding weights are 52, 65 and 64 Kg, respectively. The circumference of the thin, normal and fat persons at waist are 71, 81, 81 cm, respectively, while the corresponding circumference at chest are 79, 91 and 85 cm, respectively. In LOS scenario the transmit and receive both antennas are kept on the front side of the body whereas in NLOS scenario the transmit antenna was in the front side and the receive antenna was placed on the rare surface of the body. The placements of antennas are shown in Fig. 1. Separation between two consecutive receiver antenna positions was maintained at 5 cm, which is sufficient to get detail variation of path loss information. In all measurements, both the

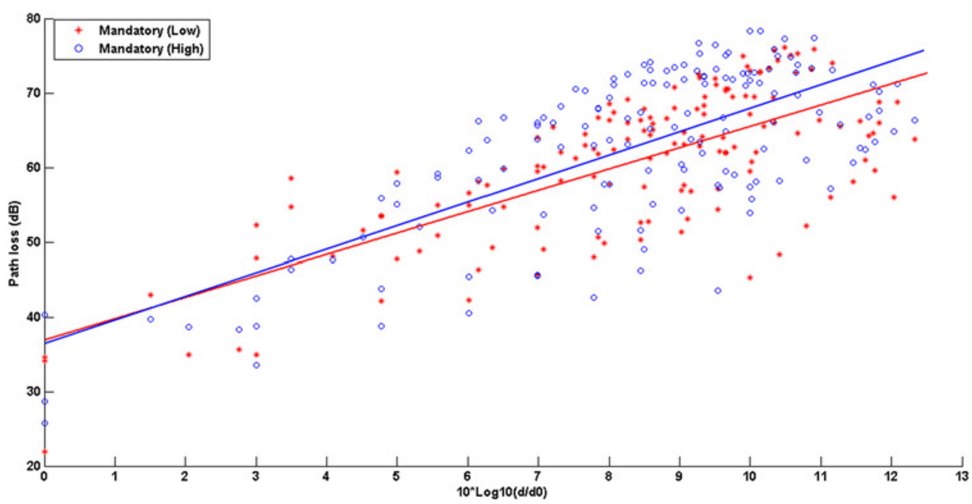

Fig. 5 *Scatter plot of path loss for the mandatory bands in LOS*

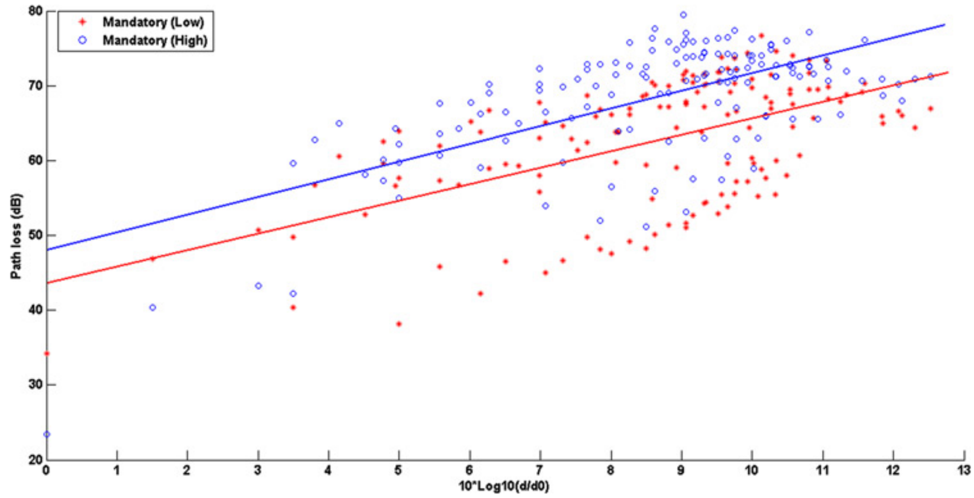

Fig. 6 *Scatter plot of path loss for the mandatory bands in NLOS*

antennas are separated from the body by 10 mm for optimum coupling of the antenna and the body [26]. The person on whom the measurements were performed was asked to stand straight without any movement during the measurement period at a relatively free space of the room. In all channel links total 10 consecutive channel frequency responses are averaged to remove random noises and saved in computer for further analysis. Numbers of averaged channel responses recorded from thin, normal and fat person in LOS are 136, 145, 125, respectively, and the same in NLOS are 132, 142, 108, respectively. To study the variation of path loss with surrounding environments measurements are performed on the body of same person at five different places in the laboratory. Different places are selected based on the number of scattered objects and their arrangements near the body.

2.3. Antenna characteristics: The antenna required for WBAN application should be compact in size, lightweight, highly efficient in radio transmission, robust, and inexpensive. Tremendous research works are going on all over the globe for development of appropriate wearable antenna. Textile antennas are one type of antenna used in body worn systems. It is observed that the characteristics of an antenna significantly changes when placed on the body. The frequency of operation, impedance matching and radiation pattern of the antennas having ground plane, experiences less effect when placed on body [27]. Similarly, the front–back ratio of antennas having ground plane have no significant difference when placed in free space and on the body [27]. The small UWB antenna structure reported in [25] is simulated in Ansoft HFSS, fabricated and tested for application in our measurement. The measured and simulated return losses (S11) of the antennas are shown in Fig. 2. It is observed that the placement of antenna on human body affects the reflection efficiency of the antenna. To test the coupling of the antenna with the body, the return loss of the antenna at different position of the body was investigated. Due to the change in composition of different part of human body, the return loss of the antenna is different at different position on the body. Fig. 3 shows the variations in return loss of antenna on different position on the body. To get an optimum coupling of the antenna with the body a 10 mm thick dielectric material was attached at the rare side of the antennas. The dielectric used in our measurements is hard thermocol. Similar method was adopted in most of the literature whereas in [28] a cardboard of 5 mm thick was used as dielectric. Fig. 4 shows the return loss of the antenna on different parts of the body after attaching the dielectric.

3. Data analysis and results

3.1. Path loss variation with body size: The path loss model is the preliminary requirement for wireless communication system designers to get the knowledge of attenuation of transmitted power as it propagates away from the transmitter. The path loss, at a distance can be calculated by averaging the squared term of

Table 1 Variation of path loss parameters

Body size	Channel number	Path loss parameters			
		LOS		NLOS	
		n	Pl(d_0)	n	Pl(d_0)
Thin	0	1.8	40	2.0	50
	1	**1.7**	**46**	**2.0**	**52**
	2	1.8	45	2.3	50
	3	1.8	43	2.8	44
	4	2.0	43	2.6	46
	5	2.1	43	2.6	48
	6	**2.2**	**43**	**2.7**	**47**
	7	2.3	42	2.8	47
	8	2.3	43	2.8	47
	9	2.1	45	2.7	50
	10	1.8	48	2.6	52
Normal	0	2.8	36	2.2	42
	1	**2.9**	**37**	**2.2**	**44**
	2	2.8	37	2.3	44
	3	3.0	34	2.5	42
	4	2.9	36	2.4	45
	5	3.1	36	2.4	46
	6	**3.2**	**36**	**2.3**	**48**
	7	3.2	37	2.2	50
	8	3.2	38	2.2	51
	9	3.3	39	2.2	52
	10	3.3	39	2.3	53
Fat	0	3.1	33	1.8	57
	1	**3.2**	**33**	**1.6**	**60**
	2	3.4	33	1.9	59
	3	3.4	31	1.9	57
	4	3.5	32	1.9	57
	5	3.4	34	1.6	61
	6	**3.4**	**35**	**1.6**	**62**
	7	3.6	35	1.4	64
	8	3.6	35	1.5	65
	9	3.5	37	1.5	66
	10	3.4	38	1.6	67

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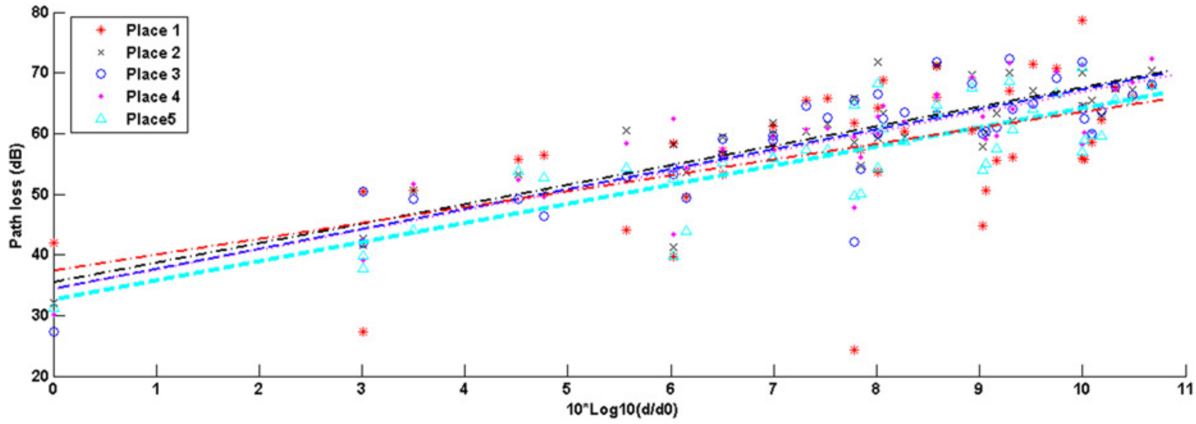

Fig. 7 *Path loss at different positions in the mandatory low band*

the channel frequency response over the number of frequency sweep points (N) as

$$Pl(d) = 10 \cdot \log_{10}\left(\frac{1}{N}\left(\sum_{1}^{N}\left|H(f_i, d)\right|^2\right)\right) \quad (2)$$

where $H(f_i, d)$ is the recorded frequency response of the channel. The distance dependent path loss may be expressed as

$$Pl_{\rm dB}(d) = Pl_{\rm dB}(d_0) + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right) + \chi \quad (3)$$

where d_0, n and χ are the reference distance, path loss exponent and shadow fading, respectively. In this measurement, the channel frequency responses are recorded for entire UWB frequency band as stated in Section 2. The frequency response for each sub bands defined in [3] have been extracted in Matlab and corresponding frequency averaged path loss for particular bands are calculated using (2). It is observed that the path loss parameters frequency dependent varies in each frequency band. Figs. 5 and 6 show the scatter plot of path loss for two mandatory bands for a person of normal size for LOS and NLOS channel conditions, respectively. Linear regression lines by least square means are fitted to the measured path loss for obtaining path loss parameters. Table 1 provides the path loss parameters for all sub bands for both LOS and NLOS conditions for three persons of different body size.

3.2. Path loss variation with surrounding environment: To study the dependency of path loss parameters with the surrounding environment, total five set of measurements are conducted in the same measurement room in LOS condition. The subject on whom the antennas were attached was asked to stand in the same way as in the previous measurement campaigns at five different places in the room. The different places are chosen based on number of scatters near the body and their geometrical arrangement. Figs. 7 and 8 represent the variation of path loss at different places for the mandatory low band and high band, respectively. Detail variations at each band are shown in Table 2.

3.3. Shadow fading: Deviations of measured path loss from the estimated path loss are calculated for all frequency bands for all individual for both LOS and NLOS channel conditions. The Kolmogorov Smirnov (K–S) test was performed to find the statistical distribution of fading term. The candidate distributions considered in K–S test are normal, lognormal, Weibul, Rayleigh and Nakagami. The parameters of the specific distributions are estimated from the measured values using maximum likelihood estimation technique. Random numbers of sufficient length are generated for a specific distribution with the estimated parameters for the distribution and K–S test was performed with the measured data. Test was performed for 1000 times for each distributions and average passing rate of the test is observed for all channel. From the observation, it is found that the lognormal distribution gives the highest passed distribution in all channels.

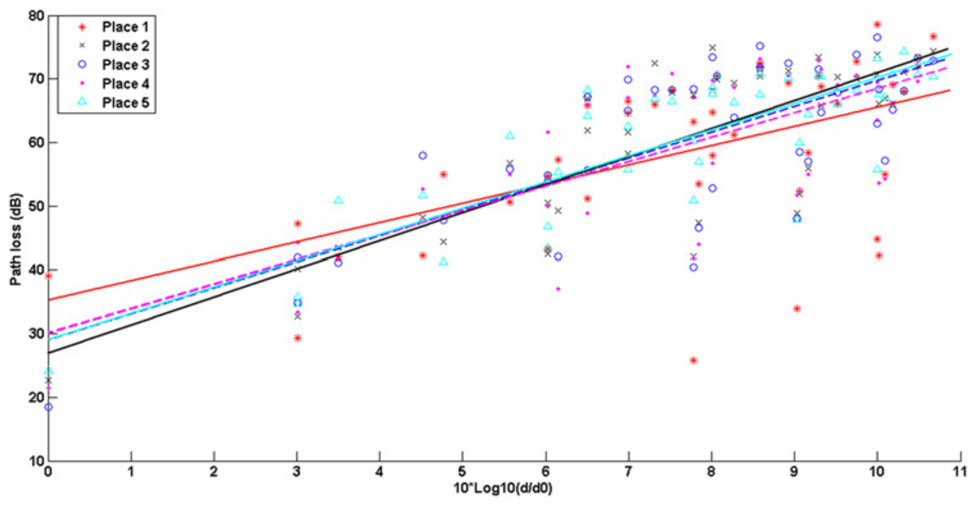

Fig. 8 *Path loss at different positions in the mandatory high band*

Table 2 Variation of path loss with surrounding environment

Ch. No.	Path loss parameters									
	Place 1		Place 2		Place 3		Place 4		Place 5	
	n	$Pl(d_0)$	n	$Pl(d_0)$	n	$Pl(d_0)$	n	$Pl(d_0)$	n	$Pl(d_0)$
0	1.8	36	2.6	37	3.0	33	3.3	32	2.9	34
1	**2.6**	**37**	**3.2**	**36**	**3.3**	**34**	**3.2**	**35**	**3.1**	**33**
2	2.7	36	3.4	33	3.4	32	3.5	34	3.1	32
3	3.1	33	4.0	28	4.0	29	3.6	30	3.1	33
4	2.9	36	4.4	28	4.1	29	3.6	32	3.8	29
5	3.0	35	4.4	28	4.1	29	3.6	32	4.1	28
6	**3.0**	**35**	**4.4**	**27**	**4.1**	**29**	**3.8**	**30**	**4.1**	**29**
7	3.2	34	4.5	26	4.2	28	3.9	30	3.9	31
8	3.3	34	4.6	28	4.2	30	4.1	30	3.9	32
9	3.1	38	4.5	29	4.0	33	4.1	32	3.9	33
10	2.2	44	4.5	29	3.7	33	4.1	31	3.3	37

The parameters of the lognormal distribution is determined for all channels and reported. It is found that the mean of the lognormal distribution is zero in all observation while the standard deviations vary with the body size and channel conditions. Table 3 provides the detail variation of standard deviation of shadow fading for different channels. Table 4 provides the variation of standard deviations at different places in the room. From the observation, it is found that in most of the channels the standard deviations of shadow fading decreases in NLOS than in LOS conditions. High value of standard deviation is found on the thin person. Variations of standard deviations are also observed for the different places in the room.

Table 3 Variation of standard deviations of shadow fading for different channels

Ch. No.	Thin		Normal		Fat	
	LOS	NLOS	LOS	NLOS	LOS	NLOS
0	11.41	5.96	7.40	7.13	7.55	5.88
1	**8.93**	**5.83**	**6.86**	**7.08**	**8.01**	**5.66**
2	10.11	7.06	7.66	6.07	8.43	6.49
3	11.14	7.56	8.30	6.10	8.30	6.53
4	10.79	7.56	8.09	5.34	8.61	6.21
5	10.59	7.72	7.92	5.93	8.88	6.39
6	**10.50**	**8.28**	**7.90**	**6.26**	**8.88**	**6.76**
7	10.38	8.22	8.18	6.76	8.92	6.71
8	10.32	8.21	8.47	7.13	9.16	6.38
9	10.01	8.19	8.44	7.18	9.36	6.16
10	10.61	7.76	9.27	6.69	9.94	5.96

Table 4 Variation of standard deviations of path loss at different place

Ch. No.	Place 1	Place 2	Place 3	Place 4	Place 5
0	13.98	6.16	7.42	5.56	6.47
1	**9.25**	**4.46**	**4.97**	**4.75**	**5.13**
2	11.12	6.21	5.69	4.40	6.26
3	12.28	6.58	6.01	6.99	7.55
4	11.67	6.07	6.45	7.89	6.88
5	11.32	7.29	7.83	8.55	6.49
6	**11.16**	**7.86**	**8.59**	**9.18**	**6.76**
7	10.75	8.09	8.53	9.82	7.39
8	10.57	8.20	8.91	9.64	7.23
9	10.93	8.37	9.04	9.92	6.46
10	12.10	8.33	9.32	10.22	6.63

4. Conclusion: This Letter has experimentally determined the path loss of on-body UWB channels for different frequency bands defined in IEEE 802.15.6 standard. To the best of our knowledge, no one has analysed the channels in the frequency bands as defined in the IEEE 802.15.6 standard. The signals transmitted from the transmit antenna is significantly affected by the channel. Thus, to recover the signal at receiver it is necessary to undo the effect of channel on the transmitted signal. The mathematical model of the channel is utmost prerequisite to remove the effect of channel from the received signals. Path loss is one of the important characteristics of wireless channel. The system designers for WBAN communication require the detail knowledge of the channel for efficient realisation of the system. They require the channel information for investigation of the performance of different transmission schemes as well as for the development of efficient algorithms for WBAN communication. In detail analysis of UWB on-body channels provide necessary information of channels as required for researchers involved in WBAN. Variations of path loss model parameters in the frequency bands of IEEE 802.15.6 standard are closely analysed and reported for both LOS and NLOS channel conditions. Variation of path loss parameters with the size of human body for both LOS and NLOS channel conditions are analysed and reported. Variation of model parameters with the surrounding environment is also observed. These reported values of the model parameters will be useful for researchers and system designers involved in UWB WBAN system designing for the development of efficient and reliable wireless healthcare system.

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