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Characterization of dynamic wireless body area network channels during walking



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Abstract

In this work, finite-difference time-domain was used for the investigation of dynamic wireless body area network channel characteristics during walking, thus accounting for dynamic aspects and body postures. This involves the study of on-body, off-body, and body-to-body communication in an empty environment, at the center frequency of 2.45 GHz. The channels were investigated in terms of fade variation and their corresponding amplitude distributions. For on-body channels, the fade variation was found to be periodic, with larger fade variations for the channels involving the nodes at the hand and thigh. For off-body and body-to-body channels, channels with the absence of line of sight experienced constructive and destructive interference as the distance between the end nodes changes, resulting in larger fade variations. For the amplitude distribution of the channels, a multivariate normal distribution was considered. The distribution has the capability of modeling channels jointly which makes it easier for network analysis and was considered because of the significant correlation between the channels. The resulting estimated multivariate distributions fit well with the simulated data, for on-body, off-body, and body-to-body channels.

Keywords: Fading channels, On-body communication, Off-body communication, Body-to-body communication, Wireless body area network

1 Introduction

In recent years, there has been substantial research on wireless body area networks (WBANs) due to their potential applications in areas involving monitoring and transmission of human physiological data, such as health monitoring and sports activities. The communication could involve the transmission between nodes mounted on the human body realizing an on-body network, between an on-body network and a node away from the human body (external node) acting as an access point realizing an off-body network [1], and between two on-body networks realizing a body-to-body network. These kinds of networks require a low-power communication approach due to their need for long battery life and the close proximity of body surface nodes to human tissue. In addition to this challenge, the networks are subjected to varying signal shadowing caused by relative human body orientation between the communicating nodes which vary with the human body movement. These challenges make

a study and modeling of WBAN channel characteristics important [2].

Most of the existing studies on on-body, off-body, and body-to-body channels are based on measurements [3–5]. For on-body channels, measurements were conducted in [3] at four locations using seven receivers and a transmitter attached on the body. Autocorrelation and cross-correlation functions were reported, and the data collected were used to develop models for fading in various on-body links. Similar studies were conducted in [6] in the frequency range of 3–5 GHz and in [7] for ultrawideband 3.1–10.6 GHz. In [8], the effect of antenna polarization with respect to the body surface was examined, while in [9], the comparison for three locations of the hub on the human was conducted.

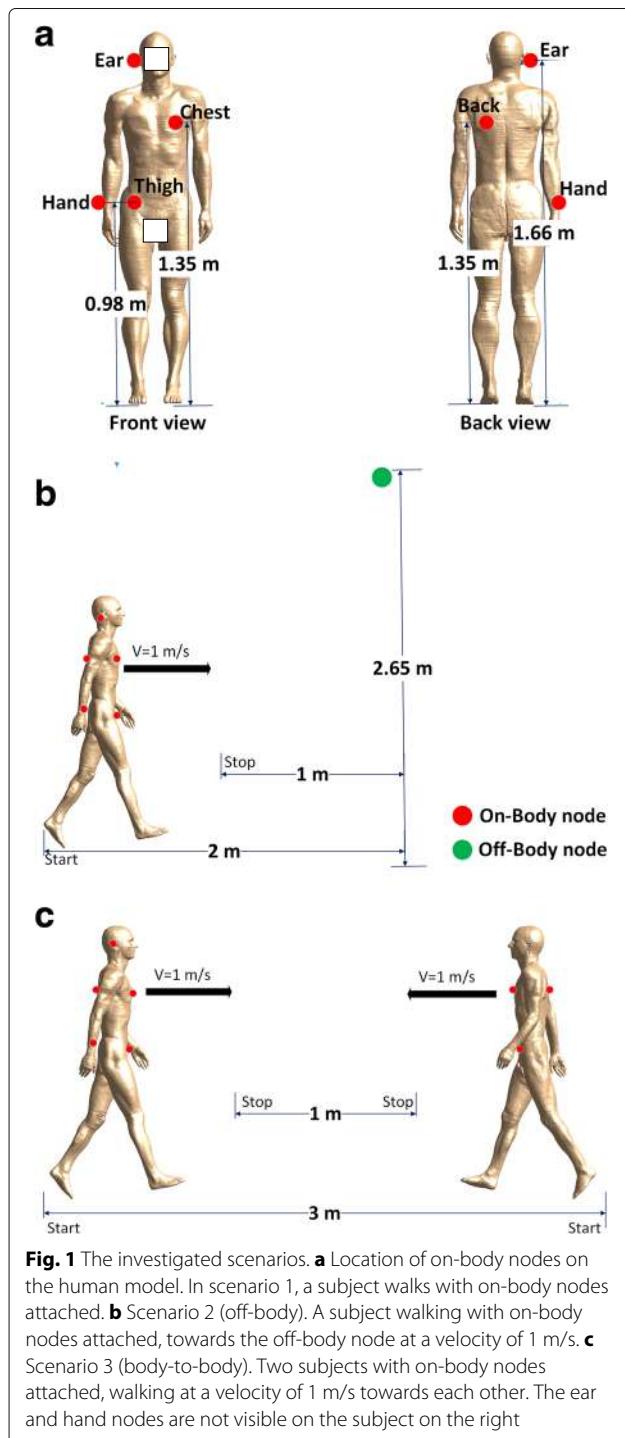
For off-body channels, path loss was modeled in [4] from the measurement conducted in an anechoic chamber, while in [2], the measurements were conducted in an indoor environment. The lognormal distribution proved to be a good fit in describing normalized signal amplitude in both. As in [8], the impact of antenna polarization on off-body channel characteristics was studied in [10], and the importance of off-body diversity gain for various off-

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body channels was investigated in [11]. Further in [12], measurement conducted using multiple-input-multiple-output antennas showed improvement on the reliability of the off-body channels. A methodology for determining the optimal positions of these antennas independent of the frequency was presented in [13].

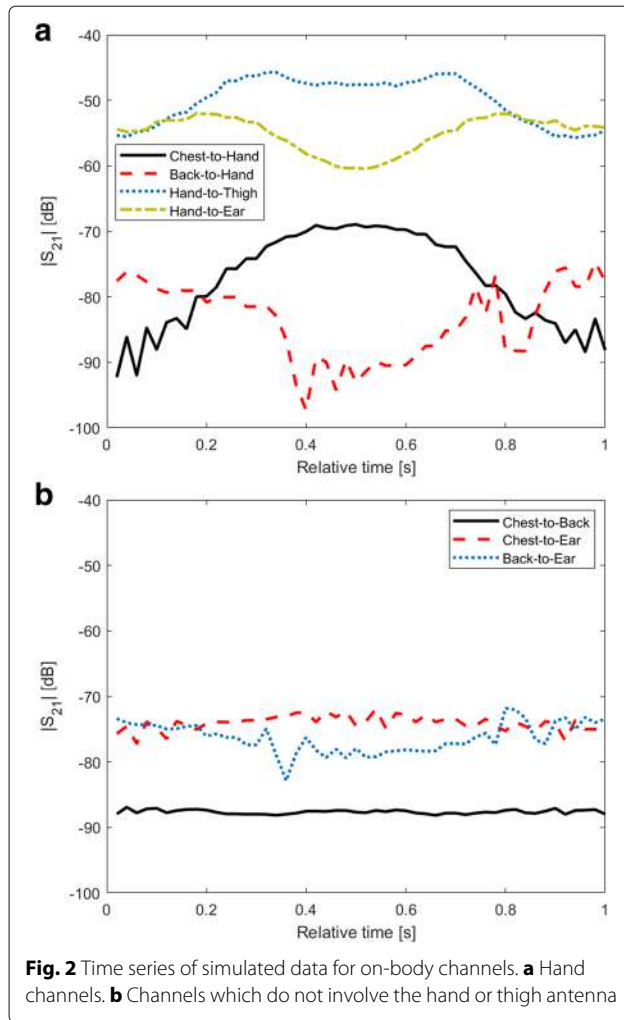


For body-to-body channels, a study in [5] investigated the impact of users' body rotation, tilting, walking in the line of sight (LOS), and non-line-of-sight conditions on the outdoor body-to-body channels. A similar study in an indoor environment was conducted in [14, 15] and at the ultrawideband frequency of 2–8 GHz in [16]. The studies highlighted how the movement affected the channel dynamic properties. This was confirmed by the study in [17] which was conducted in both indoor and outdoor environments to obtain the mean path loss and the standard deviation for different body motion scenarios and antenna placements. As in [12], a diversity combining scheme was investigated in [18] and has shown some promising results.

Since the aforementioned models are applicable for a particular measurement setup, other researchers have tried to use physical models instead [19, 20]. These models are based on calculation of time-varying shadowing effects of human body movement and the addition of multipath component using statistical distribution depending on the location. Another approach is the use of numerical simulations such as finite-difference time-domain (FDTD) [21–24]. In [24], a walking phantom created by animation software is used for simulating the time-varying on-body communication channel in which mean path loss was investigated. A similar study was conducted in [23] to represent in addition the delay properties of the channels, and a study focusing on ultrawideband was conducted in [22]. The studies which apply FDTD have so far been limited to static on-body network channels, using a homogeneous phantom [21, 24], with low time resolution [22]. This does not cover the dynamic behavior from the off-body and body-to-body channels, which require a high time resolution, and the use of heterogeneous phantom to be more realistic.

Table 1 Simulation parameters for on-body, off-body, and body-to-body scenarios

Parameter	Value
Software	Sim4Life, Poser
Human model	Duke Model (height 1.77 m, weight 70.2 kg) [25]
Walking model	Thalman model [28]
Antenna	Dipole
Frequency	2.45 GHz
Antenna separation	5 mm
Sampling rate	50 Hz
On-body node locations	Right ear, left chest, right thigh, right hand, left back
Off-body node location	2.65 m high
Walking velocity	1 m/s



The novelties of this study are as follows:

- The on-body, off-body, and body-to-body dynamic channels are investigated together in the same conditions so that a more complete picture of the overall network can be observed and compared.
- The study makes use of heterogeneous phantom and uses time resolution of 50 frames per second to increase the accuracy of the data obtained.
- The channel gain is separated into path loss and antenna gain; this cannot be achieved through measurements since the body is within the near field of the antenna.
- The study investigates the correlation between the channels and the application of multivariate normal distributions in the modeling of WBAN channels. This could enable the modeling of a network of multiple channels jointly, instead of using separate models for separate channels

The rest of this paper is organized as follows: Section 2 describes the methodology used in configuration and data analysis, Section 3 discusses the obtained FDTD simulation results, and Section 4 concludes the paper.

2 Methodology

This section describes the scenarios used to analyze different aspects of on-body, off-body, and body-to-body communication channels. The surrounding environment was not included in the simulations, so that the effect of the body on the radio channels can be obtained independent to the other factors. It also describes the method to analyze the results.

2.1 Scenarios

Employing FDTD, a heterogeneous human model of height 1.77 m and weight 70.2 kg (Duke Model) [25]

Table 2 Average channel gain and standard deviation of on-body channels

Number	Channel name	Propagation		TX antenna		RX antenna		Overall	
		Mean [dB]	STD [dB]	Mean [dB]	STD [dB]	Mean [dB]	STD [dB]	Mean [dB]	STD [dB]
1	Chest-to-back	−29.97	0.31	−28.17	0	−29.49	0	−87.63	0.31
2	Chest-to-hand	−37.31	6.62	−23.93	3.38	−13.80	2.61	−75.04	7.11
3	Chest-to-thigh	−28.36	2.01	−20.96	0	−19.12	1.62	−68.44	1.88
4	Chest-to-ear	−34.70	1.14	−19.61	0	−19.69	0	−74.00	1.14
5	Back-to-hand	−42.27	4.24	−25.19	3.05	−14.42	4.40	−81.88	5.89
6	Back-to-thigh	−38.67	7.30	−30.51	0	−27.59	1.17	−96.77	6.66
7	Back-to-ear	−43.43	2.29	−20.95	0	−11.66	0	−76.03	2.29
8	Hand-to-thigh	−20.38	4.01	−15.34	3.57	−13.57	2.24	−49.30	3.54
9	Hand-to-ear	−28.77	3.41	−12.04	1.17	−13.89	1.78	−54.69	2.70
10	Thigh-to-ear	−35.01	3.36	−22.01	2.59	−19.31	0	−76.34	4.92

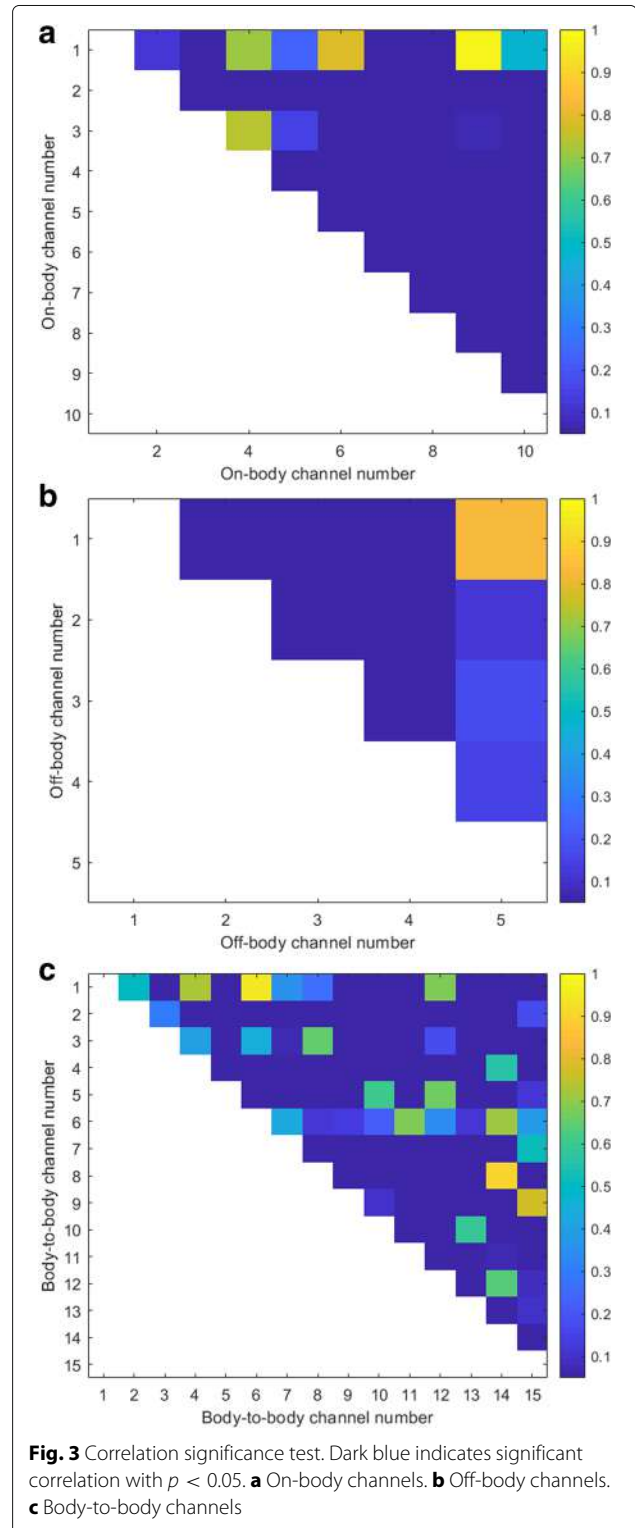
was used to represent a male adult human body. A half wavelength antenna (dipole) with a resonance frequency of 2.45 GHz was used as a radiating element for a single tone signal at the same frequency. This frequency was chosen to fit with the Wi-Fi technology that is often present in the indoor environment. The antenna was positioned 5 mm away parallel to the body to reduce the effect of the body on the radiation pattern of the antenna [26]. This separation is small enough for realistic applications. The antenna type and configuration were the same for all simulation scenarios. We simulated 50 frames of Duke walking 1 m per 1 s (velocity 1 m/s), in order to grasp not only the slow fading caused by shadowing but also the fast fading effects caused by body reflection, diffraction, and scattering involved in these dynamic channels [27]. The orientation of the body parts in these frames was estimated using the Thalmann model [28] and was applied to the phantom using Poser software [29]. For each frame, software capable of conducting FDTD calculations (Sim4Life) was set to calculate for each antenna, radiation pattern, and the gain at their current location. Due to the close proximity of the antenna to the human body, the radiation pattern and hence the gain are not similar to those of free space. Further, the software was set to calculate S_{21} parameter between all the nodes available on a given scenario [30]. During calculation, a grid of 2 mm was used on the phantom which is equivalent to $\lambda/60$ at the 2.45-GHz center frequency. This makes the limitations imposed by discretization of the round surface of the phantom negligible. Three scenarios were considered as shown in Fig. 1.

- Scenario 1 (on-body), where the subject walks with on-body nodes attached (Fig. 1a)
- Scenario 2 (off-body), where the subject walks towards an off-body node (Fig. 1b)
- Scenario 3 (body-to-body), where two subjects walk towards each other (Fig. 1c)

The same wearable antenna placements (Fig. 1a) were considered in all three simulated scenarios. Table 1 summarizes the parameters used in the FDTD simulations of the given scenarios.

For the on-body scenario, on-body nodes were placed at five different locations on the human body (Fig. 1a). The node positions were chosen with regard to possible medical and non-medical applications. For example, the node on the ear emulates hearing aid instrument, the node on the thigh represents a possible location for a smartphone, the hand represents a fitness tracker, etc. [31]. In addition to this, the node at the back is added as a possible space diversity node for off-body communication where human body shadowing could be significant [18]. This represents the on-body part of the network.

For the off-body scenario, an off-body node located at a height of 2.65 m was considered in addition to the on-body nodes (Fig. 1b). The location of the off-body node at such height represents Wi-Fi routers, commonly placed



on the ceiling in an indoor environment. The simulation starts at a horizontal distance of 2 m between the subject and the off-body node to capture the effect of being in close proximity to such an elevated antenna.

For the body-to-body scenario, two identical subjects (Duke) with identical on-body nodes were used for the simulations (Fig. 1c). The subjects were set to walk towards each other, starting from a distance of 3 to 1 m representing one walking circle for each. The study in this close proximity is important not only for typical body-to-body network applications [15], but also for the study of inter-on-body network interference [32] and inter-on-body network cooperation [33].

2.2 Data analysis

A total of 30 S_{21} parameters were obtained from the simulations, in which 10 were for on-body channels, 5 for off-body, and 15 for body-to-body channels. The parameters were then used to give insight on channel fading variations with time and distance. The parameters were also used to analyze the correlation of different channels and the use of multivariate normal distribution in describing the channel amplitudes.

2.2.1 Fading variation

The amount of fading a specific WBAN channel experiences depends on the location of its two end nodes on the human body, and the fading variation depends on relative movements of the body parts on which these nodes are located. The close proximity of the antennas to the body affects the overall radiation of the signal [26], and the movements of body parts may also lead to a periodic change of the direction of maximum radiation and hence the gain in the direction of communication [34]. In addition, radio wave propagation is significantly attenuated by human body tissue, and hence, penetration through the body is negligible. The movement of body parts may also cause periodic shadowing to the channel. The S_{21} parameter can be expressed in terms of antenna gain, and the propagation losses as

$$S_{21}[\text{dB}] = P_L[\text{dB}] + G_{TX}[\text{dBi}] + G_{RX}[\text{dBi}] \quad (1)$$

where P_L is the propagation loss and G_{TX} and G_{RX} are the transmitting and receiving antenna gains in the direction of communication, taking into consideration the proximity to the human body. With no cables involved in the simulation, S_{21} parameter can be interpreted as the overall channel gain as it is the ratio between the received signal at the receiver port and the transmitted signal at the transmitter port.

2.2.2 Amplitude distribution

One of the approaches of modeling potential correlated channels is by using multivariate normal distribution given by [35]

$$f(x, \mu, \Sigma) = \frac{1}{\sqrt{|\Sigma|(2\pi)^N}} \exp \left\{ -\frac{1}{2}(x - \mu)\Sigma^{-1}(x - \mu)' \right\} \quad (2)$$

where N is the number of channels being modeled together, μ is $1 \times N$ matrix containing the channels' means, and Σ is the $N \times N$ covariance matrix. Multivariate normal distributions are relatively easy to work with especially in a network with multiple channels. However, this is only applicable when the channels to be considered show a significant correlation which is indicated by the large correlation coefficient and can be confirmed with low p values (< 0.05). Pearson's method was used to find the linear correlation coefficient between the channels, and their corresponding p values were calculated using Student's t distribution [36]. Further, the estimated distribution was compared with the simulated data using two-sample Kolmogorov-Smirnov test (KS test) at 0.05 significant level to quantify the goodness of the fit [37].

3 Results and discussions

In this section, the results obtained from the simulations described in Section 2 are presented. The results for each scenario are presented separately, and when appropriate,

Table 3 Covariance matrix Σ for on-body channels ($\times 10^{-9}$)

0.0022	− 0.0394	− 0.03907	0.0020	0.0117	0.0007	0.0213	− 0.9190	0.0029	0.0156
− 0.0394	13.7279	3.5024	2.0961	− 4.4469	1.1376	− 3.9243	120.5754	− 47.5976	8.5976
− 0.03907	3.5024	5.6366	0.0917	− 0.7241	0.2386	− 1.2142	50.1142	− 9.4664	1.9884
0.0020	2.0961	0.0917	0.6442	− 0.7345	0.1656	− 0.6702	19.79063	− 6.4854	0.9994
0.0117	− 4.4469	− 0.7241	− 0.7345	2.1490	− 0.36736	1.0777	− 38.8186	14.2770	− 2.6643
0.0007	1.1376	0.2386	0.1656	− 0.3674	0.1231	− 0.3030	7.0338	− 5.1940	0.8827
0.0213	− 3.9243	− 1.2142	− 0.6702	1.0777	− 0.3030	1.6979	− 38.4941	12.8211	− 2.1676
− 0.9190	120.5754	50.1142	19.7906	− 38.8186	7.0338	− 38.4941	1525.4063	− 258.5792	44.2089
0.0029	− 47.5976	− 9.4664	− 6.4854	14.2770	− 5.1940	12.8211	− 258.5792	251.42130	− 40.0852
0.01562	8.5976	1.9884	0.9994	− 2.6643	0.8827	− 2.1676	44.2089	− 40.0852	10.0612

they are compared. The channels are described by their antenna location, for example, a channel between a ceiling node and a hand node is called ceiling-to-hand.

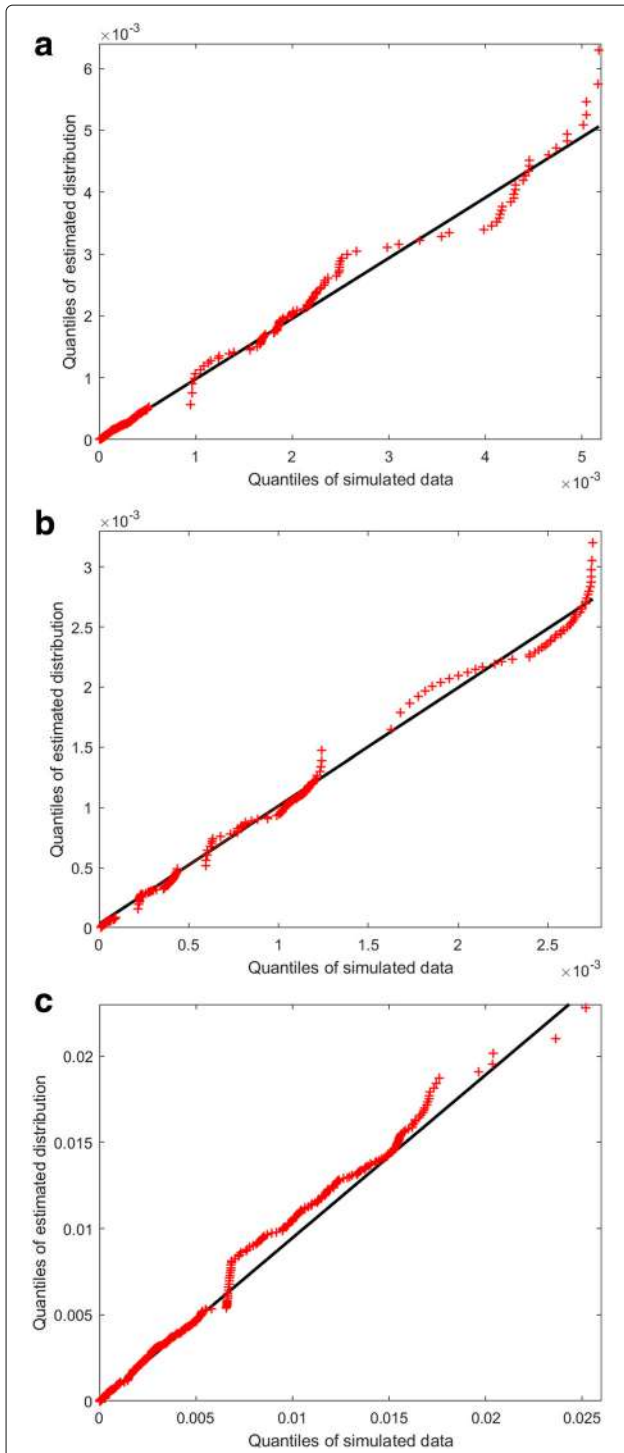


Fig. 4 Quantile-quantile plot of estimated multivariate normal distribution and the simulated data. **a** On-body channels. **b** Off-body channels. **c** Body-to-body channels

3.1 On-body channels

3.1.1 Fade variation

The results of the fade variation for the considered on-body channels are summarized in Fig. 2 and Table 2. As expected, the time series (Fig. 2) show a larger variation for the channels involving the nodes located at the hand and the thigh, than for the other channels. This is related to variation in shadowing, as these body parts move from one location to the other during walking. The largest variation of channel gain is obtained on the chest-to-hand channel (7.11 dB), as the hand moves from the shadowed region to the LOS. The variations are contributed by both, propagation loss and antenna gain. The channel that is least effected by movement of body parts during walking is the chest-to-back channel as confirmed by the lowest standard deviation (STD) of 0.31 dB. The largest average channel gain is obtained for the hand-to-thigh channel (-49.3 dB). The channel has the shortest distance

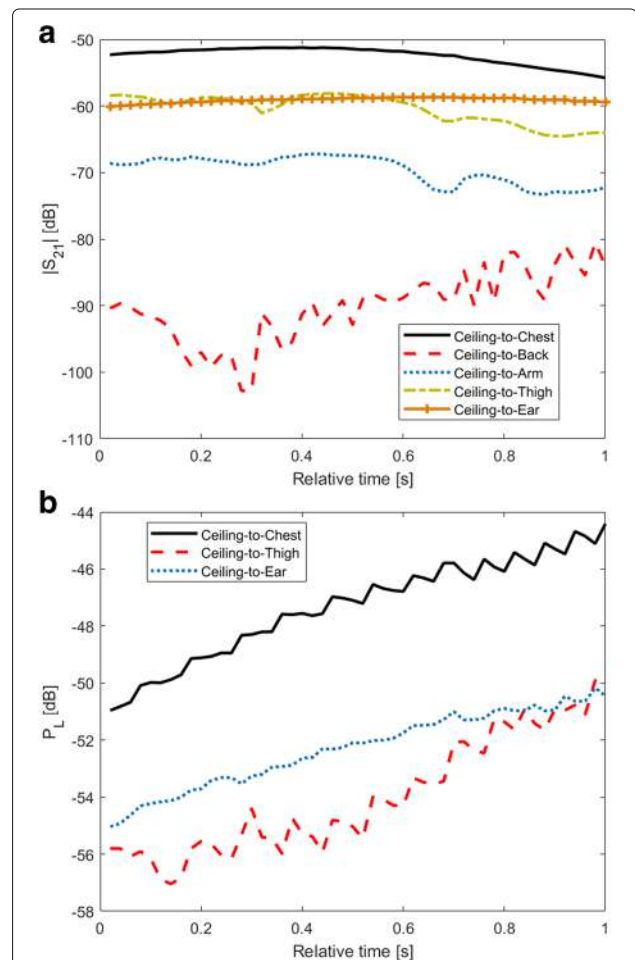


Fig. 5 Time series of simulated data for off-body channels. **a** Overall channel gain. **b** Propagation gain

Table 4 Average channel gain and standard deviation of off-body channels

Number	Channel name	Propagation		TX antenna		RX antenna		Overall	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD
		[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	Ceiling-to-chest	− 47.65	1.78	− 1.89	1.30	− 2.79	1.53	− 52.33	1.32
2	Ceiling-to-back	− 54.15	3.89	− 1.10	0.96	− 33.42	4.00	− 88.67	5.37
3	Ceiling-to-hand	− 60.84	0.82	− 2.65	1.16	− 5.90	1.10	− 69.39	2.31
4	Ceiling-to-thigh	− 54.69	2.07	− 3.25	1.47	− 2.29	2.76	− 60.24	2.17
5	Ceiling-to-ear	− 52.38	1.34	− 0.22	0.85	− 6.49	0.29	− 59.09	0.37

between the end nodes and least body shadowing as confirmed by the propagation loss (− 15.89 dB). The smallest average channel gain is obtained for the back-to-thigh channel (− 96.77 dB) contributed by small propagation loss and antenna gain.

3.1.2 Amplitude distribution

To confirm the use of a multivariate normal distribution in the estimation of the amplitude distribution, the channels have to be tested for correlation significance. Figure 3a shows the p values of the considered on-body channels, with 80% of the channels having $p < 0.05$, indicating a significant correlation between them. Since the channels show significant correlations, a multivariate normal distribution given by (2) can be used to estimate the amplitude distribution. The estimated covariance matrix is given in Table 3. To evaluate the goodness of the fit, a quantile-quantile plot of the estimated multivariate normal distribution of all 10 on-body channels against the simulation results is shown in Fig. 4a. The plot approximately coincides with the identity line, meaning that the estimated distribution is a good fit of the simulated data. The KS test confirms that the two datasets are from the same distribution with asymptotic $p = 0.2178$ and test statistic $ks2stat = 0.0468$.

3.2 Off-body channels

3.2.1 Fade variation

The results of the fade variation for the considered off-body channels are summarized in Fig. 5 and Table 4. The results show overall stable channels with exception from the ceiling-to-back channel (Fig. 5a). This is because in the absence of LOS, the resulting power received is a summation of reflected and diffracted fields, resulting in constructive and destructive interference as the subjects move from one location to another. We also notice the overall increase in the channel gain with time as back node moves out of the shadow region as the subject gets closer to the off-body node. This is not the

case for the other channels as they are affected by the change in elevation angle and hence the antenna gain in the direction of communication. There is, however, an overall decrease in propagation loss for these channels (ceiling-to-chest, ceiling-to-thigh, ceiling-to-ear) as the subject gets closer to the off-body node as shown in Fig. 5b.

3.2.2 Amplitude distribution

Similar to the on-body channels, the off-body channels were tested for correlation significance so that a multivariate normal distribution could be used to estimate the amplitude distribution of the channels. Figure 3b shows the p values of the considered off-body channels, with 60% of the channels having $p < 0.05$, indicating a significant correlation between them. The resulting estimated multivariate distribution's quantile-quantile plot with estimated covariance matrix given Table 5 shows a good fit with simulated data (Fig. 4b). The KS test confirms that the two datasets are from the same distribution with asymptotic $p = 0.5982$ and test statistic $ks2stat = 0.0481$.

3.3 Body-to-body channels

3.3.1 Fade variation

The results of the fade variation for the considered body-to-body channels are summarized in Table 6. Similar to the off-body channels, the body-to-body channels involving the node located at the back have shown the largest fade variations due to the absence of LOS

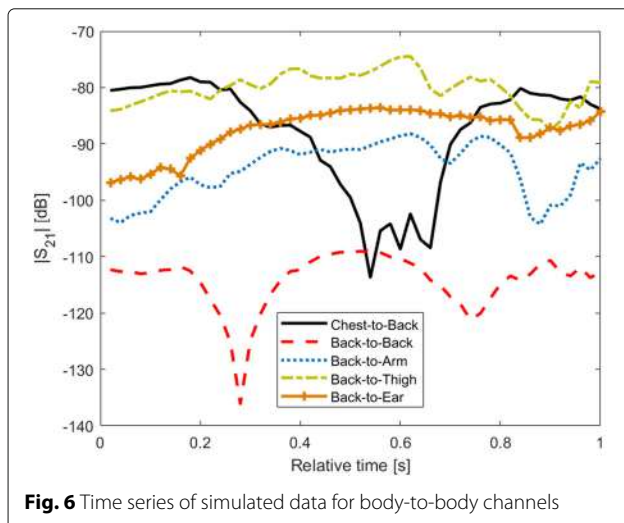
Table 5 Covariance matrix Σ for off-body channels ($\times 10^{-9}$)

113.6780	− 5.8442	22.4157	66.2266	0.4873
− 5.8442	0.4581	− 1.1750	− 3.4201	0.2269
22.4157	− 1.1750	5.9168	15.9113	− 0.7007
66.2266	− 3.4201	15.9113	49.2340	− 2.1518
0.4873	0.2269	− 0.7007	− 2.1518	2.1860

Table 6 Average channel gain and standard deviation of body-to-body channels

Number	Channel name	Propagation		TX antenna		RX antenna		Overall	
		Mean [dB]	STD [dB]	Mean [dB]	STD [dB]	Mean [dB]	STD [dB]	Mean [dB]	STD [dB]
1	Chest-to-chest	−45.70	4.05	3.30	0.19	3.30	0.19	−39.09	3.7
2	Chest-to-back	−57.03	9.76	3.37	0.11	−30.69	0.19	−84.35	9.82
3	Chest-to-hand	−46.84	4.21	3.06	0.21	−6.08	0.92	−49.86	3.57
4	Chest-to-thigh	−45.09	2.58	2.67	0.64	4.36	1.99	−38.06	2.02
5	Chest-to-ear	−44.94	2.32	2.79	0.60	−5.07	0.50	−47.22	1.66
6	Back-to-back	−51.77	5.02	−30.74	0.13	−30.74	0.13	−113.26	4.98
7	Back-to-hand	−55.84	5.63	−31.52	0.82	−5.94	0.76	−93.30	4.83
8	Back-to-thigh	−49.91	2.57	−34.21	1.31	4.51	1.77	−79.60	2.98
9	Back-to-ear	−53.22	3.85	−28.72	0.36	−4.92	0.28	−86.85	4.04
10	Hand-to-hand	−46.35	1.89	−8.16	1.88	−8.16	1.88	−62.68	2.93
11	Hand-to-thigh	−47.28	3.47	−7.73	1.80	4.28	1.58	−50.73	2.40
12	Hand-to-ear	−49.28	3.35	−6.79	1.52	−8.32	1.80	−64.39	2.57
13	Thigh-to-thigh	−47.12	3.85	4.56	1.69	4.56	1.69	−39.33	2.36
14	Thigh-to-ear	−48.72	3.11	3.52	2.63	−7.74	2.15	−52.93	1.83
15	Ear-to-ear	−50.54	4.65	−6.26	0.82	−6.26	0.82	−63.06	3.44

as indicated by their standard deviation. The channels also have the lowest average channel gain for the same reason. Figure 6 shows the time series of the channels involving the nodes located at the back. The effect of constructive and destructive interference can be seen clearly especially for the chest-to-back and back-to-back channels. On the other hand, the channels which have constant LOS (chest-to-chest, chest-to-thigh, and thigh-to-thigh) have the largest average channel gain.

**Fig. 6** Time series of simulated data for body-to-body channels

3.3.2 Amplitude distribution

The p values of the considered body-to-body channels are shown in Fig. 3c. The results show that 68% of the channels have $p < 0.05$, indicating a significant correlation between the channels; hence, multivariate normal distribution could be used in the estimation of the amplitude distribution of the channels. The resulting estimated multivariate normal distribution's quantile-quantile plot with covariance matrix given in Table 7 is shown in Fig. 4c. The plot approximately coincides with the identity line, meaning the distribution is a good fit of the simulated data. The KS test confirms that the two datasets are from the same distribution with asymptotic $p = 0.9037$ and test statistic $ks2stat = 0.0206$.

3.4 Comparison of channels

The fade variations for on-body channels have shown to depend on the periodic movement of the body part in which the channel nodes are attached. Channels such as chest-to-hand had the largest variation due to the movement of the hand from the shadowed region to the LOS, while chest-to-back channel (on-body) has the least. This is not the case, for off-body and body-to-body channels in which the largest fade variations are shown by those channels with the absence of LOS instead. The ceiling-to-back and chest-to-back channels have the largest fade variations for off-body and body-to-body scenarios respectively. This is because these channels are dominated by constructive and destructive interference

Table 7 Covariance matrix Σ for body-to-body channels ($\times 10^{-9}$)

23993	— 17981	5757.3	— 703.41	1391.2	— 0.0356	6.5306	— 26.735	30.134	— 468.17	1210.4	49.177	11182	— 1693.0	992.49
— 17981	1.4274	— 7.2651	— 86.469	— 21.296	— 0.0119	— 0.2928	— 0.9383	— 0.5358	— 2.7282	— 20.0514	— 3.4622	— 75.720	5.5570	1.8840
5757.3	— 7.2651	1610.6	435.12	425.48	0.1167	3.2503	— 2.8037	9.8418	— 93.996	420.35	42.274	2892.4	— 383.19	234.14
— 703.41	— 86.469	435.12	7944.8	1791.8	0.9558	21.264	78.906	38.252	219.77	1233.2	186.30	5715.6	— 99.747	— 319.98
1391.1	— 21.296	425.48	1791.8	612.31	0.2425	4.4915	14.6965	10.934	— 11.068	228.72	8.2676	2082.0	— 174.32	— 44.460
— 0.0356	— 0.0119	0.1167	0.9558	0.2425	0.0007	0.0009	0.0064	0.0029	— 0.0284	— 0.0407	0.0198	0.6476	— 0.0193	— 0.0269
6.5306	— 0.2928	3.2503	21.264	4.4915	0.0009	0.0979	0.2825	0.1338	0.8845	5.8413	0.9724	20.483	— 1.1909	— 0.2368
— 26.735	— 0.9383	— 2.8037	78.906	14.696	0.0064	0.2825	1.1716	0.3680	3.2113	13.220	2.5442	48.205	— 0.2621	— 3.4321
30.134	— 0.5358	9.8418	38.252	10.934	0.0029	0.1338	0.3680	0.2620	0.7181	9.3956	1.2007	44.2433	— 3.5498	— 0.1764
— 468.17	— 2.7282	— 93.996	219.77	— 11.068	— 0.0284	0.8845	3.2113	0.7181	37.283	94.594	22.835	— 51.286	38.947	— 15.834
1210.4	— 20.051	420.35	1233.2	228.72	— 0.0407	5.8413	13.220	9.3956	94.594	642.92	113.61	1562.0	— 89.772	54.165
49.177	— 3.4622	42.274	186.30	8.2676	0.0198	0.9724	2.5442	1.2007	22.835	113.61	28.623	162.44	5.0584	10.517
11182	— 75.720	2892.4	5715.6	2082.0	0.6476	20.483	48.205	44.243	— 51.286	1562.0	62.442	11781	— 872.03	208.94
— 1693.0	5.5570	— 383.19	— 99.747	— 174.32	— 0.0193	— 1.1909	— 0.2621	— 3.5498	38.9469	— 89.7723	5.05838	— 872.03	183.56	— 54.062
992.49	1.8840	234.14	— 319.98	— 44.460	— 0.0269	— 0.2368	— 3.4321	— 0.1764	— 15.834	54.165	10.517	208.94	— 54.062	64.984

between the reflected and diffracted fields, which vary significantly with distance. For the case of the average channel gain, larger values have been seen in channels with LOS and relatively short distance for on-body (hand-to-thigh), off-body (ceiling-to-chest), and body-to-body (chest-to-thigh).

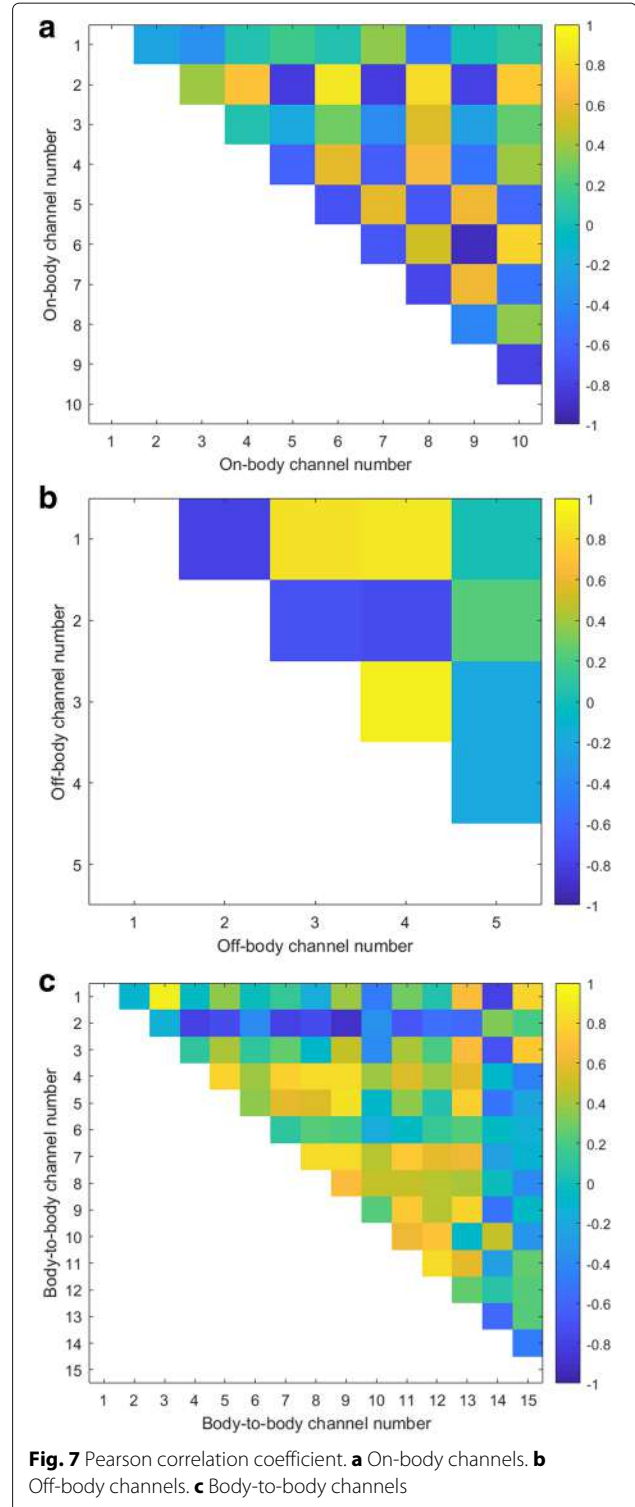
The channels for all scenarios showed a significant correlation with $p < 0.05$ for 80% of on-body channels, 60% of off-body channels, and 68% of body-to-body channels. This justified the use of multivariate normal distribution in the estimation of the amplitude distribution of the channels. The resulting estimate of amplitude distribution showed a good fit with the simulated data with quantile-quantile plots coinciding with the identity line for all the scenarios.

The antenna placements favorable for off-body and body-to-body communications are those that have the least fading and least fade variations. The chest node appears to be more favorable for the off-body communication due to its low and stable fade values (Fig. 5a). However, this is only applicable in the LOS situation when the subject is facing the off-body node. When the subject orientation changes as in the case of a subject moving away from the off-body node, the back node could be the better option. The best practice will then be to alternate between the chest and back node depending on the subject orientation. This can be confirmed by the negative linear correlation between the two channels as shown in Fig. 7a. A similar approach can be taken to exploit spatial diversity from other channels with negative linear correlation in Fig. 7. For the on-body communications, we also notice that the channels involving the back node experience the most fading (Table 2). This implies that in a star topology network, the back node is not a feasible option as the center node.

4 Conclusion

In this work, FDTD was used in the investigation of dynamic WBAN channel characteristics during walking. More specifically, the channels considered were 10 on-body, 5 off-body, and 15 body-to-body channels. The channels were investigated in terms of fade variation and their corresponding amplitude distributions. For on-body channels, the fade variation was found to be periodic, with a larger fade variation shown by the channels involving the nodes at the hand and thigh. Off-body and body-to-body channels with the absence of LOS experienced constructive and destructive interference as the distance between the end node changed. This resulted in larger fade variation than the channels involving the nodes at the hand and thigh. For the amplitude distribution of the channels, the multivariate normal distribution was considered. The distribution was considered after the channels show significant correlation between each other. The resulting

estimated multivariate distributions fit well the simulated data, for on-body, off-body, and body-to-body channels. This will reduce the complexity of performance analysis of the network.



Abbreviations

FDTD: Finite-difference time-domain; LOS: Line of sight; STD: Standard deviation; WBAN: Wireless body area network

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Availability of data and materials

The dataset(s) supporting the conclusions of this article are available in the figshare repository https://figshare.com/articles/Characterization_of_Dynamic_Wireless_Body_Area_Network_Channels_During_Walking_zip/6226949.

Authors' contributions

MM and WJ identified the channel to be modeled. MM conducted the simulations with GV, analyzed the data with ET, and wrote the manuscript. WJ supported and supervised the research. WJ, GV, ET, and MC proofread the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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