Characterization of Off-Body Area Network Channels During Walking

Marshed Mohamed, Wout Joseph, Günter Vermeeren, Emmeric Tanghe, and Michael Cheffena

Abstract—In this work, the off-body area network channel characteristics during walking were investigated using finite-difference time-domain. The channels were investigated in terms of fade variation and the correlation between different channels. Larger fade variations were experienced by the channel with the absence of line-of-sight, due to constructive and destructive interference as the distance between the end nodes changes. The channels showed significant correlation and hence a multivariate normal distribution was considered. The distribution has the capability of modeling channels jointly which make it easier for network analysis. The resulting estimated multivariate distributions fit well with the simulated data.

Index Terms—Fading channels, On-body communication, Off-body communication, Body-to-body communication, Wireless body area network

I. INTRODUCTION

In recent years, there has been substantial research on wireless body area networks (WBAN) due to their potential applications in areas involving monitoring and transmission of human physiological data. The communication could involve the transmission between nodes mounted on the human body and a node away from the human body (external node) acting as an access point realizing an off-body network [1]. This kind of network is subjected to varying signal shadowing caused by human body movement which varies the relative human body orientation between the communicating nodes.

Most of the existing studies on off-body channels are based on measurements [2]–[6]. Path loss models were obtained in [2] and [3] from the measurement conducted in an anechoic chamber and an indoor environment respectively. The lognormal distribution proved to be a good fit in describing normalized signal amplitude in both. Measurement conducted in [4] using multiple-input-multiple-output antennas showed improvement on the reliability of the off-body channels and was investigated further in [5]. A methodology for determining the optimal positions of these antennas independent of the frequency was presented in [6].

Since the aforementioned models are applicable for a particular measurement setup, other researchers have tried to use numerical simulations such as finite-difference time-domain

(FDTD) [7]–[10]. In [10], time-varying on-body communication channel simulations were used to investigate the mean path loss. The simulations used a walking phantom created by animation software and utilized FDTD to calculate the results. A similar study was conducted in [9] to represent in addition the delay properties of the channels, and a study focusing on ultrawideband was conducted in [8]. The studies that apply FDTD have so far been limited to static on-body network channels, using a homogeneous phantom [7], [10], with low time resolution [8]. This does not cover the dynamic behavior from the off-body channels, which require a high time resolution, and the use of heterogeneous phantom to be more realistic.

In this study, a heterogeneous phantom and time resolution of 50 frames per second were used to increase the accuracy of the data obtained. In addition to that, the channel gain was separated into path loss and antenna gain, this cannot be achieved through measurements since the body is within the near field of the antenna. Further, The study investigates the correlation between the channels and the application of multivariate normal distributions in the modeling of the amplitude distribution. 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 II describes the methodology used in configuration and data analysis, Section III discusses the obtained FDTD simulation results, and Section IV concludes the paper.

II. METHODOLOGY

A. Scenarios

In the simulation environment, a male adult human body was represented by a heterogeneous human model of height 1.77 m, weight of 70.2 kg (Duke Model) [11]. To fit with Wi-Fi technology often present in the indoor environment, a half wavelength antenna (dipole) located at a height of 2.65 meters with a resonance frequency of 2.45 GHz was used as an off-body node (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. To reduce the effect of the body on the radiation pattern, the on-body antennas were positioned 5 mm away [12] from the body at five locations (Fig. 1a). The node positions were chosen with regards to possible applications such as hearing aid instrument, smartphone, fitness tracker etc. [13]. Fifty frames of Duke walking at a velocity of 1 m/s were used, in order to grasp not only the slow fading caused by shadowing but also the
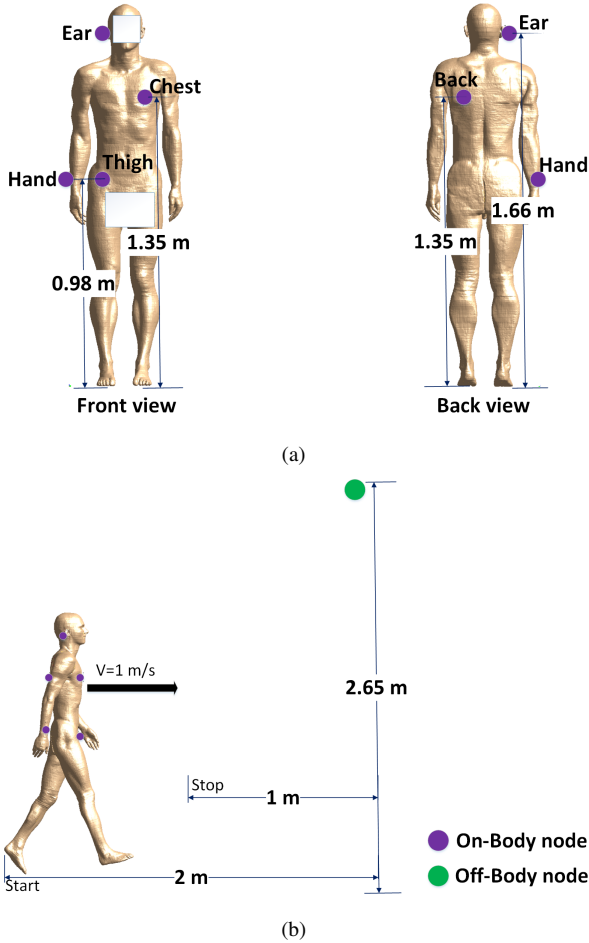
Fig. 1. The investigated scenario. (a) Location of on-body nodes on the human model. (b) A subject walking with on-body nodes attached, towards the off-body node at a velocity of 1 m/s.

fast fading effects caused by body reflection, diffraction and scattering [14]. The orientation of the body parts in these frames were estimated using the Thalmann Model [15] and were applied to the phantom using Poser software [16].

For each frame, the radiation pattern and the gain of each antenna at their current location were calculated using software capable of conducting FDTD calculations (Sim4Life). The radiation pattern and hence the gain is not similar to that of free space due to the close proximity of the antenna to the human body. Further, the software was set to calculate S_{21} parameter between all the nodes available [17]. To minimize the limitations imposed by discretization of the round surface of the phantom, a grid of 2 mm was used on the phantom which is larger than $\lambda/10$ at the 2.45 GHz center frequency. The simulation starts at a horizontal distance of 2 meters between the subject and the off-body node to capture the effect of being in close proximity to such an elevated antenna.

B. Data Analysis

1) Fade Variation: The amount of fading and the fade variation a specific WBAN channel experiences depends on the location of its two end nodes on the human body, and on the relative movements of the body parts on which these nodes are located respectively. The close proximity of the antennas to the body affects the overall radiation of the signal [12], and as the radio wave propagation is significantly attenuated by human body tissue, transmission through the body is negligible. The movements of body parts may also lead to periodic shadowing to the channel, and a periodic change of the direction of maximum radiation of the antenna, and hence the gain in the direction of communication [18]. 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, 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.

2) Channel Correlation and Amplitude Distribution: The Pearson's method was used to find the linear correlation coefficient between the channels, and their corresponding p values were calculated using a Student's t distribution. For the channels with significant correlation indicated by the large correlation coefficient and confirmed with low p values ($<$ 0.05), multivariate normal distribution can be used to model the amplitude distribution. Multivariate normal distributions are relatively easy to work with especially in a network with multiple channels and are given by [19]

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

where N is the number of channels being modeled together, μ is $1 \times N$ matrix containing the channels' means, and $\mathbf{\Sigma}$ is the $N \times N$ co-variance matrix [20]. 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 [21].

III. RESULTS AND DISCUSSIONS

1) Fade Variation: The results of the fade variation are summarized in Table I and Fig. 2. The results show overall stable channels with exception from the Ceiling-to-Back channel Fig. 2a. Due to the absence of LOS in this channel; the resulting power received is a summation of diffracted and reflected fields, resulting in constructive and destructive interference as the subject moves from one location to another. Further, as the subject gets closer to the off-body node, the back node moves out of the shadow region resulting in the overall increase in the channel gain with time. 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. 2b.

TABLE I
AVERAGE CHANNEL GAIN AND STD OF OFF-BODY CHANNELS.

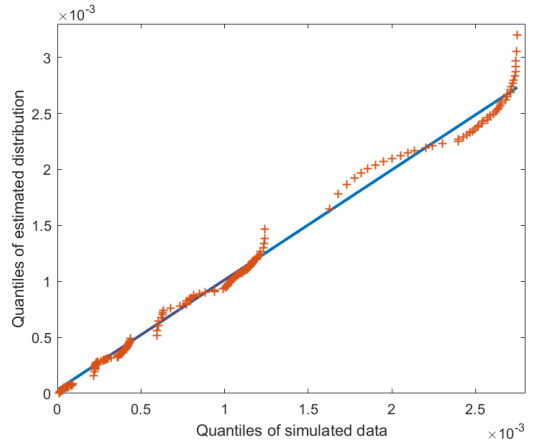| #	Channel name	Propagation		TX Antenna		RX Antenna		Overall	
		Mean [dB]	STD [dB]	Mean [dB]	STD [dB]	Mean [dB]	STD [dB]	Mean [dB]	STD [dB]
1	Ceiling-to-Chest	-47.65	1.78	-1.89	1.30	-2.79	1.53	-52.33	1.32
2	Ceiling-to-Back	-54.15	3.89	-1.10	0.96	-33.42	4.00	-88.67	5.37
3	Ceiling-to-Hand	-60.84	0.82	-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
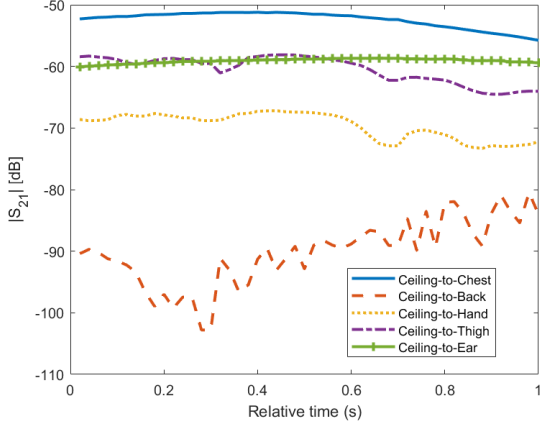
(a)
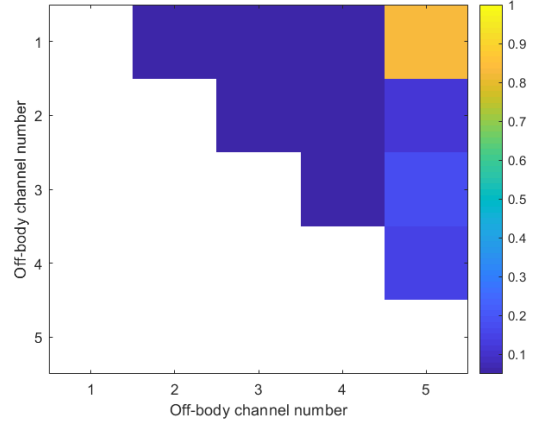
(a)
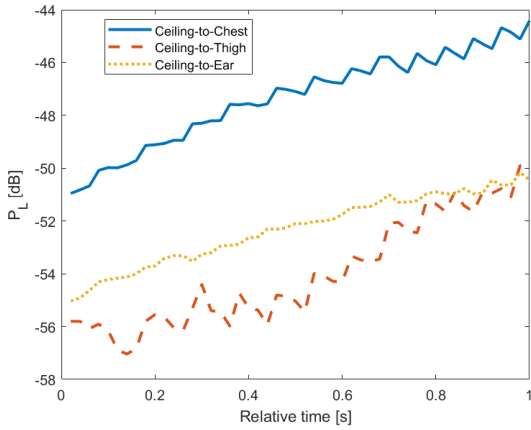
(b)

(b)

Fig. 2. Time series of simulated data for off-body channels. (a) Overall channel gain. (b) Propagation gain.

Fig. 3. (a) Correlation significance test. Dark blue indicates significant correlation with $p < 0.05$. (b) Quantile-Quantile plot of estimated multivariate normal distribution and the simulated data.

2) Channel Correlation and Amplitude Distribution: The channels correlation significance test results are summarized in Fig 3(a). The figure shows that 60% of the channels have $p < 0.05$, indicating a significant correlation between them. Multivariate normal distribution of Σ given in Table II and μ which can be obtained from Table I was used to describe the amplitude distribution. Figure 3(b) shows a good fit between the resulting estimated distribution and the simulated data quantile-quantile plot. The KS test confirm that the two datasets are from the same distribution with asymptotic

$p = 0.5982$ and test statistic $ks2stat = 0.0481$

Considering the scenario where the subject is facing the off-body node, the Chest node appears to be more favorable for the off-body communication due to its low and stable fade values Fig 2(a). However, 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 exploit spatial diversity by alternate between the Chest and Back node depending on the

TABLE II
COVARIANCE MATRIX Σ FOR OFF-BODY CHANNELS ($\times 10^{-9}$).

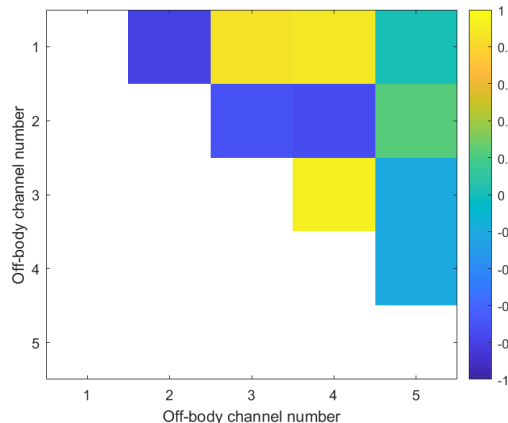|				
113.6780	−5.8442	22.4157	66.2266	0.4873
−5.8442	0.4581	−1.1750	−3.4201	0.2269
22.4157	−1.1750	5.9168	15.9113	−0.7007
66.2266	−3.4201	15.9113	49.2340	−2.1518
0.4873	0.2269	−0.7007	−2.1518	2.1860

Fig. 4. Pearson correlation coefficient.

subject orientation. This can be confirmed by the negative linear correlation between the two channels as shown in Fig 4.

IV. CONCLUSION

In this work, FDTD was used in the investigation of dynamic off-body channel characteristics during walking. The channels were investigated in terms of fade variation, and the correlation between the channels. Due to the absence of LOS the Ceiling-to-Back channel 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. The channels show significant correlation between each other and hence the multivariate normal distribution was considered in modeling of amplitude distribution. The resulting estimated distribution fit well the simulated data. This will reduce the complexity of performance analysis of the network.

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