Physical-Statistical Channel Model for Off-body Area Network

Marshed Mohamed, Michael Cheffena, Arild Moldsvor, and Fernando P. Fontan

***Abstract*—In this letter, a physical-statistical based channel model for off-body wireless communications is presented. The model utilizes a dynamic human walking model, which provides detailed description of the movement of the different body parts. The received signal is composed of a direct component, which might be subject to shadowing by the body parts, and a multipath component due to reflections from the environmental scatterers. The uniform theory of diffraction (UTD) is utilized to accurately calculate the time-varying shadowing and scattering effects of the direct signal due to the moving of body parts. A Rayleigh distribution is used to represent the multipath fading effects by the scatterers around the human body. The model is validated in terms of first and second order statistics using 2.36 GHz measurement data, showing good agreement.**

***Index Terms*—Time-varying channels, indoor propagation, fading channels, wireless body area network, off-body communication.**

I. Introduction

IN recent years there has been substantial research on wireless body area network (WBAN) due to its potential applications in health monitoring, sports activities, and any other application which requires monitoring and transmission of human physiological data. The communication could involve among others the transmission between nodes mounted on the human body (body surface node) and a node away from the human body (external node) acting as an access point [1]. This kind of communication is known as off-body communications, and is subjected to periodic signal shadowing caused by the human body movement, between the body surface node and the external node. Due to the close proximity of body surface nodes, and their need for a long battery life, WBAN requires a low-power communication approach. This demands a close understanding of the wireless channel characteristics [2].

There have been several studies on improvement of the performance of an off-body communication system. For example, in [3] diversity gain for various off-body channels was investigated and its importance in off-body communication was noted. Measurement conducted in [4] showed that using multiple-input, multiple output antennas drastically improves the reliability of the off-body link. A methodology for determining the optimal positions of these antennas, independent of frequency or communication standard used, was presented in [5].

The performance improvement methods presented in for example, [3-5], rely on good understanding of the propagation channel characteristics. An empirical characterization of off-body wireless channels is presented in [6]. The measurements were conducted in an anechoic chamber, and Lognormal and Ricean distributions were used to model the path-loss. In [7], similar studies were conducted in an indoor environment where Lognormal distribution proved to be a good fit in describing the normalized signal amplitude. Further studies were conducted in [8] in which also the impact of antenna polarization on channel characteristics was investigated. Nakagami distribution was used to describe the fading component.

Unlike the models in [6-8], which are purely empirically based and applicable only in the environments similar to the measurement site; we propose a more accurate physical-statistical based channel model for off-body communications. Generally, physical-statistical models are more accurate than merely empirical models as they rely on electromagnetic based methods for calculating the needed model parameters. They are also more effective for simulating large scenarios compared to purely physical models [9].

II. The Physical-Statistical Off-body Channel Model

The considered propagation scenarios are shown in Fig. 1. In both scenarios, the transmitter is on the right wrist of the subject's body walking on the spot. The two scenarios are differentiated by orientation and motion of the transmitter (Tx) relative to the receiver (Rx). To obtain the locations of the body parts during movements, a human walking model

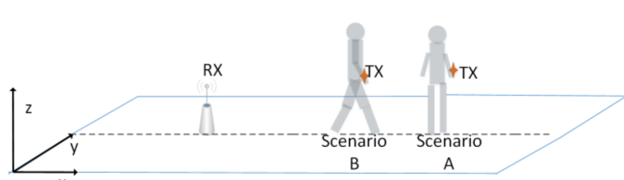

Fig. 1. Considered propagation scenarios where a person walks: A) with direction of motion perpendicular to the receiver. B) direction of motion parallel to the receiver.

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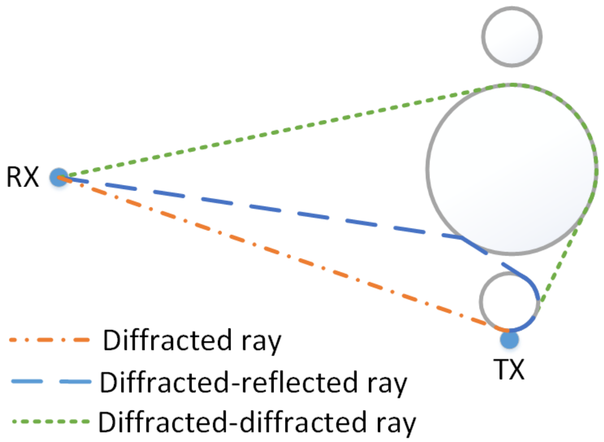

Fig. 2. Ray tracing of three cylinders. Small circles represent arms, and the large circle represents the trunk. For clarity, only one ray from each type is shown in the figure. Left arm is shadowed by the trunk from the transmitter at current position.

described in [10] is used. In the model, the human body is represented by 12 dielectric cylindrical volumes of different radii except for the head that is represented by a sphere. Due to their canonical shapes, the uniform theory of diffraction (UTD) will be used to calculate, by electromagnetic computation (physically), the time-varying signal contributions from the human body. UTD can also account for the creeping waves which cannot be predicted with geometrical optics and Kirchhoff diffraction equation [9, 11]. The environmental contributions to the total received signal causes multipath fading, and will be described statistically using a Rayleigh distribution.

A. Contribution from the Human Body

Based on our propagation scenario shown in Fig. 1, the most significant signal contributions from the human body come from the two arms and the trunk. Considering the three cylinders representing the two arms and a trunk as shown in Fig. 2, three types of rays will exist depending on the relative position between the cylinders and the receiver. From the right arm where the transmitter is positioned, there will be diffracted rays. These rays can only exist if the trunk is not blocking their path to the receiver. From the trunk there will be diffracted-reflected rays which only exist when the laws of reflection are satisfied, and diffracted-diffracted rays, see Fig. 2. Like the trunk, the left arm will have similar rays, but will only exist when the trunk is not blocking the left arm.

The diffracted field can be expressed as [12, 13]

$$E_d(Rx) = C.H_{\parallel\perp}.e^{-jkx}.\frac{e^{-jks_d}}{s_d} \tag{1}$$

where s_d is the distance between the detachment point and the receiver, and x is the distance along the surface of the cylinder between the transmitter location and the detachment point, C is a constant associated with the transmission field power, and $H_{\parallel\perp}$ is intermediate function depending on hard and soft Fock radiation functions. The diffracted-reflected field can be expressed as in [11]

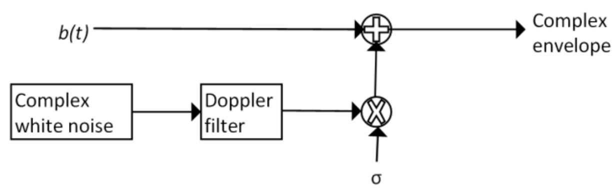

Fig. 3. Channel simulator for off-body communication. The parameter σ is the standard deviation of the multipath component and *b(t)* is the time varying contribution from the human body, Section IIA.

$$E_{dr}(Rx) = \sqrt{\frac{\rho_1^r.\rho_2^r}{(\rho_1^r + s_r)(\rho_2^r + s_r)}}R_{\parallel\perp}.E_d(Q_R).e^{-jks_r} \tag{2}$$

where s_r is the distance between the reflection point and the receiver, ρ_1^r and ρ_2^r are the radii of curvature of the reflected field, Q_R is the reflection point, $E_d(Q_R)$ is the diffracted field given by (1), and $R_{\parallel\perp}$ is the polarization dependent reflection coefficient as given in [11]. The total diffracted-diffracted field can be expressed as

$$E_{dd}(Rx) = \sqrt{\frac{\rho_2^d}{s_d(\rho_2^d + s_d)}}.T_{\parallel\perp}.\sqrt{\frac{d\eta(Q_1)}{d\eta(Q_2)}}E_d(Q_1)e^{-jks_d} \tag{3}$$

Here ρ_2^d is the second radius of curvature of the diffracted field, Q_1 and Q_2 are the attachment and detachment points, respectively, $T_{\parallel\perp}$ is the polarization dependent diffraction coefficient, and $\sqrt{d\eta(Q_1)/d\eta(Q_2)}$ is the conservation of energy flux in the surface ray strip from the attachment to the detachment point [11]. The summation of all these fields makes up the human contribution $b(t)$ on the overall received signal, Fig. 3.

B. Contributions from the environment

The reflection of the signal from objects around the human body results in multipath fading effects which is described statistically using a Rayleigh distribution. The movement of the transmitter as well as the movements of people in the environment create time-varying channel conditions. Characterizing the Doppler spectra is thus important for the determination of the variance of the off-body wireless channel. The Doppler spectrum associated with this kind of movement is given by [14]

$$S(f) = \frac{1}{f^2 + e} \tag{6}$$

where e is a model constant of a value 0.094.

C. The Overall Simulation Model

The proposed physical-statistical channel model for simulating the off-body wireless channel is shown in Fig. 3. In the model, a complex white Gaussian process with zero mean and unity standard deviation is passed through a Doppler filter given in equation (6) for spectrum shaping. The resulting complex series is multiplied by the standard deviation, σ, to

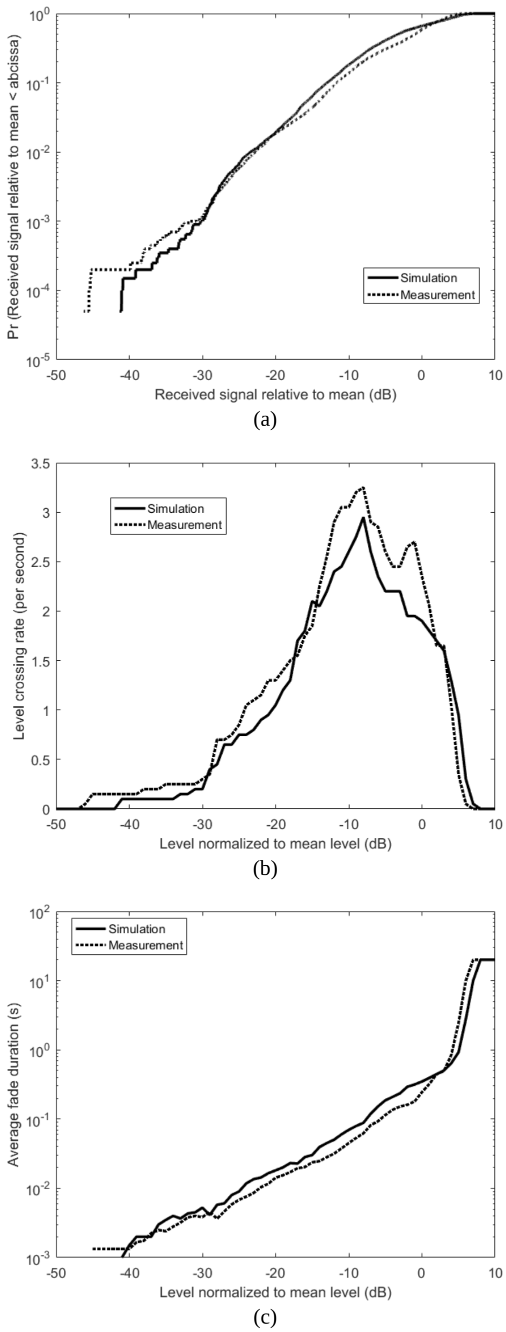

Fig. 4. Scenario A. Comparison between simulation and measurement data statistics. (a) Cumulative distribution function. (b) Level crossing rate. (c) Average fade duration.

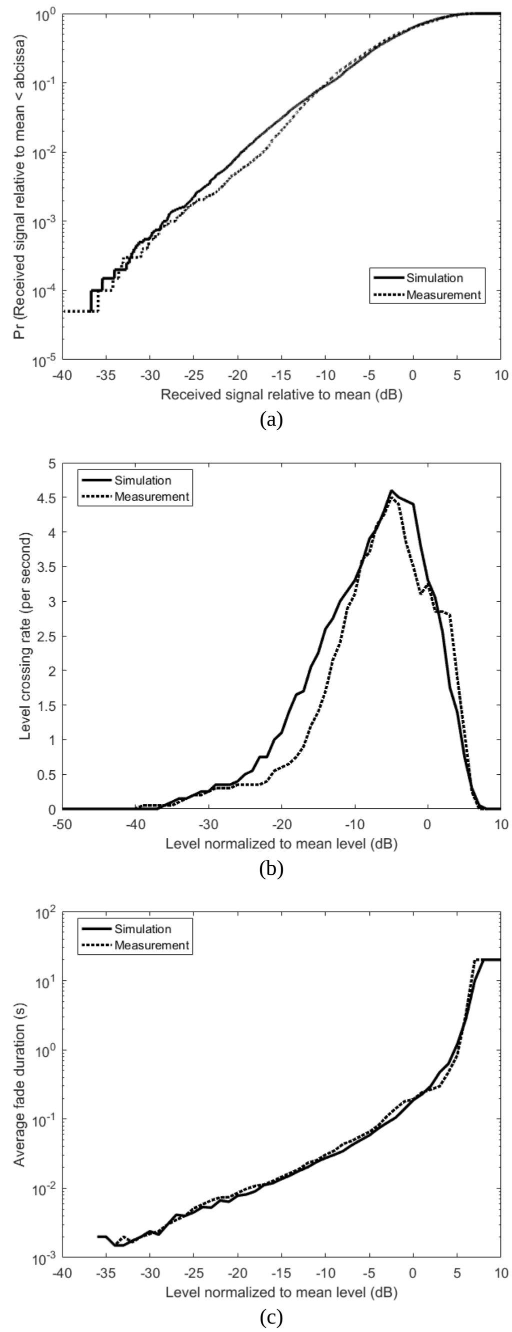

Fig. 5. Scenario B. Comparison between simulation and measurement data statistics. (a) Cumulative distribution function. (b) Level crossing rate. (c) Average fade duration.

represent the multipath contributions from the environmental scatterers. Then, the position dependent contributions from the human body $b(t)$, as described in Section II-A are added. The movement and position of the body worn transmitter is determined using the human walking model presented in [10].

III. Experimental Data

Publicly available experimental data collected by the National ICT Australia [2] is used for validating the developed channel model. For off-body measurements, a commercial wearable antenna was strapped to the right wrist of a 181.5 cm / 78 kg male test subject and used as a transmitting antenna. Due to large movement of the arm during walking, the location is ideal for testing the performance of the prosed model under high signal dynamic conditions. The antenna was worn such that the E-plane of the antenna was perpendicular to the floor of the environment. The receive antenna was placed on an aluminum tripod 2 meters away from the test subject. Both the transmitting and receiving antenna were omnidirectional and were considered as part of the channel. A

Table 1.Simulation parameters

Parameter	Value
Frequency (f)	2.36 GHz
Relative permittivity of human skin (μ_r)	38.0630 - 10.5847i
Relative velocity (v_r)	1.6 m/s
Length of the upper and lower arms (l_a)	0.30 m
Radius of the arms (r_a)	0.04 m
Radius of the trunk (r_t)	0.20 m
σ of scenario A (σ_A)	0.0032
σ of scenario B (σ_B)	0.37

vector signal analyzer (VSA) was used to transmit a tone of 2.36 GHz and measure the received signal. The received signal amplitude was recorded for every 1 millisecond over a period of 20s. The measurements were taken while the subject walked on a treadmill with the receiver on his left side in scenario A, and the receiver behind him in scenario B as shown in Fig. 1. See [2] for more information on the measurement set-up.

IV. Model Validation and Discussions

Two different scenarios (shown in Fig. 1) are considered for validating the model developed in Section II. The resulting simulation data were then compared with the measurement data collected in [2]. The simulation parameters are shown in Table 1 where μ_r is obtained from [15], σ_A and $\sigma_B$were selected such that the simulations results fits the measured data, and the remaining parameter were obtained from the experimental setup [2]. Fig. 4a and 5a, show good agreements between the measured and modelled cumulative distribution functions (CDFs) of the received signal for the two scenarios shown in Fig. 1. To validate the model further, the time varying properties of the signal were compared by observing their level crossing rates and average fade duration for the two scenarios, see Fig. 4b, 4c, 5b and 5c. These second order statistics quantify how often the signal crosses a certain threshold, and how long it stays below the threshold. Good agreement between the developed model simulation results and the measurement results is observed.

The agreement of both first and second order statistics with the measured data illustrates the accuracy of the proposed channel model. The model proposed is not limited to the location of transmitter on the arm, but can be adjusted to suite other node locations, considering their movement in relation to the human body is known. This gives an advantage over empirical models in which measurement results of one node in a given environment may not be similar or applicable to another node location or another environment.

V. Conclusion

A physical-statistical based channel model for off-body wireless communications was developed. In this method, the detailed description of the movement of the different body parts were obtained from a dynamic human walking model. The received signal was composed of a direct component subjected to time-varying shadowing, reflection, and diffraction effects in accordance with the dynamic movement of the body parts, and a multipath component due to reflection from environmental scatterers. The human walking model together with UTD was used to calculate time-varying contributions from the body parts, and the multipath components from the environment were represented by a Rayleigh distribution. The developed model was validated in terms of first and second order statistics utilizing 2.36 GHz measurement data for two different propagation scenarios. The simulations showed good agreement with the measured data.

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