A Review of Channel Modelling for Wireless Body Area Network in Wireless Medical Communications

Attaphongse Taparugssanagorn, *Member, IEEE*, Alberto Rabbachin, *Member, IEEE*, Matti Hämäläinen, *Member, IEEE*, Jani Saloranta, and Jari Iinatti, *Senior Member, IEEE*

Centre for Wireless Communications, University of Oulu, Finland

***Abstract*— In the Wireless Body Area Network (WBAN), radio propagations from devices that are close to or inside the human body are complex and distinctive comparing to the other environments since the human body has a complex shape consisting of different tissues. Therefore, the channel models are different from the ones in the other environments. We present a literature survey on channel characterizations and modelling for WBAN. The interesting common result is that the propagation wave is diffracting around the human body rather than passing through it. The path loss is very high especially when the receive antenna is placed on the different side from the transmit antenna. The lognormal distribution turns to be the best fit for the small-scale fading rather than the traditional Rayleigh and Ricean distributions in the other environments. Moreover, the high correlation between delay bins is observed. In addition to the literature survey, we propose a procedure including the measurement campaigns and the channel characterizations to obtain the channel models with fulfilling what they are missing.**

I. Introduction

Future communication systems are driven by the concept of being connected anywhere at anytime. This is not limited to even in medical healthcare area. Wireless medical communications [1]-[4] assisting people's work and replacing wires in a hospital are the applying wireless communications in medical heathcare. One example is wireless medical telemetry [5]-[11] which is the remote monitoring of a patient's health through radio technology. This gives patients greater mobility and increased comfort by freeing them from the need to be connected to hospital equipments that would otherwise be required to monitor their condition. This improves in quality of patient care and the efficiency of hospital administration capabilities. Moreover, wireless medical telemetry also serves the goal of reducing healthcare costs because it permits the remote monitoring of several patients simultaneously. The development of this technology will lead to a Wireless Body Area Network (WBAN) [12]-[16], where smart wireless medical sensors measuring, for example, electrocardiogram (ECG), non-invasive blood pressure and the blood oxygen saturation placed in (implantable) and around (wearable or placed close to) the body can communicate with the outside world using wireless networks and provide medical information. The information can be forwarded to a physician, real-time.

The average power consumption of the radio in the sensor nodes must be reduced below 100μW [12]. Today's low power radios such as Bluetooth and Zigbee [13] cannot meet this stringent requirement and new innovative solutions must be found. Ultra-Wideband (UWB) communication is believed to have strong advantages which are promising for WBAN applications [17]-[20]. UWB communication is a low-power high data rate technology with large bandwidth signals that provides robustness to jamming and has low probability of interception [18]-[19]. UWB low transmit power requirements, which are mainly used in low data rate networks with low duty cycles, allow longer battery life for body worn units [21]. Moreover, UWB can be used to monitor vital parameter as respiration and heart-rate [21], [22]. In addition, UWB offers good penetrating properties that could be applied to imaging in medical applications [22]. These are ones of the main reasons for UWB being a potential candidate for WBAN. In order to design and develop a competent and reliable system suitable for WBAN, a knowledge of a radio propagation channel as well as a simple and generic channel model are inevitably required. In the last few years, there have been investigations on UWB indoor and outdoor radio propagation modelling and characterization [19], [20], [23]-[35]. In the WBAN, radio propagations from devices that are close to or inside the human body are complex and distinctive comparing to the other environments since the human body has a complex shape consisting of different tissues with their own permittivity and conductivity. Therefore, the channel models for WBAN are different from the ones in the other environments.

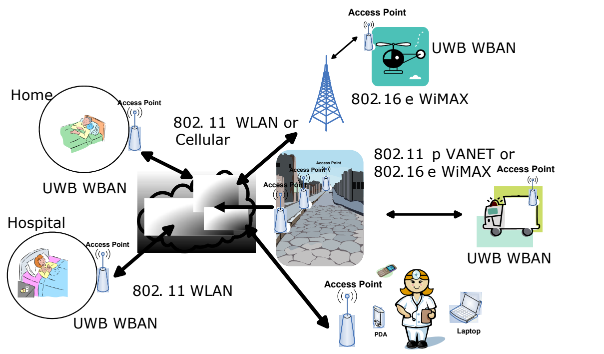

Fig. 1. The overview of a remote medical system with WBAN.

We propose a system architecture of a remote medical

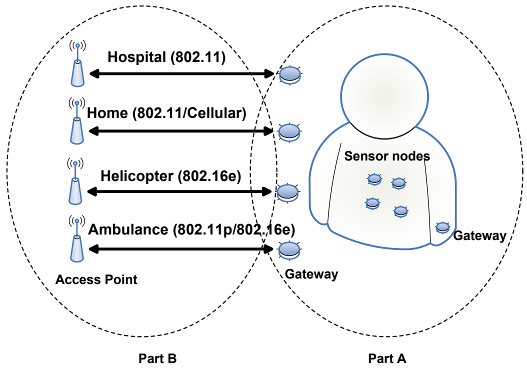

Fig. 2. The channel links in wireless medical communications: (A) the WBAN channels, the channels from the sensor nodes on/in the body to the gateway, (B) the channel between the gateway and the access point nodes.

system with WBAN as described in Fig. 1. The range of WBAN covers the sensor nodes on/in the body and the access point. Four different scenarios, in a hospital, at home, in an ambulance van and a helicopter, are shown in Fig. 1. The communications between an access point to the backbone network are dependent of the use scenarios. From the hospital to the backbone, IEEE802.11 WLAN can be employed. Besides WLAN, a traditional cellular can also be used in the home case. IEEE802.11 p Vehicular Ad hoc Networks (VANET) [36] or 802.16e Worldwide Interoperability for Microwave Access (WIMAX) [37] is proposed for the ambulance van case. For the ambulance helicopter, 802.16e WIMAX is a good candidate.

In this paper, we review the research works on the channel characterizations and modelling for WBAN in particular for an indoor environment as it emulates a hospital or a home. At the end, we propose a procedure to obtain the channel models for WBAN. The channel models are based on the extracted channel parameters from the measurements.

II. Channel Model in Wireless Medical Communications

Due to the fact that the main scatterers are in the nearfield of the antenna, the channel models for WBAN in wireless medical communications are definitely different from the existing generic indoor and outdoor channel models. As depicted in Fig. 2, the channel links in wireless medical communications can be divided into two main links, i.e., the part A (WBAN part): the channels among the sensor nodes and the channels from the sensor nodes on/in the body to the gateway, which can be either on the wall of the hospital room or on the body in the case when the patients walk outside the building (can be a wristwatch or in a bag), and the part B: the channel between the gateway and the access point. There have been some studies on the channels among the sensor nodes on the human body based on the Remcom finite difference time domain (FDTD) based simulation [38], [39] or/and the measurements [39]-[46]. Nevertheless, more investigations on various scenarios and methods must be pursued. Only few papers have reported the measurements for the channels from the sensor nodes to the gateway [47], [48].

A. FDTD Based Simulation

The FDTD based simulation [51]-[53] was used to model electromagnetic field propagation around the human body. An anatomical and a theoretical model of a body was provided by the visual Human project of the National Library of Medicine [52]. This FDTD technique attempts to solve Maxwell's equations by using finite difference approximations to the spatial and temporal derivatives found in the equations. It has the ability to model electromagnetic propagation in very complex geometric configurations albeit with a large computational requirements, despite the fact that it is conceptually simple and relatively easy to implement [51], [53]. With this, a simplified inhomogeneous human model can be simulated with specific organs and tissues and the electromagnetic wave propagation around the body is then simulated [38], [39]. Nonetheless, the simulation is limited to simple scenarios that do not include the impact of a surrounding indoor environment and the impact of antennas worn on the body.

B. Measurement Campaigns

Most of the existing measurements are performed in the frequency domain method since it has a good dynamic and it is easy to calibrate due to only one required equipment [40]-[46], [54]. In the frequency domain measurement applying frequency sweep technique, a vector network analyzer is used to measure the S21 parameter between two antennas placed at various positions on a human body, and complex channel transfer functions are obtained. The time domain responses can be obtained using Inverse Fast Fourier Transform (IFFT). There are, however, some drawbacks such as long duration of the measurements, non stationary measurements are impossible, and high distance measurements require long RF cable.

In the time domain measurement [55], very short pulses are generated. The output signals are directly in time domain. Two instruments are used (trigged using a cable). Drawbacks are, for instance, limited measurement dynamics and impossibility for narrowband measurements.

In [40], the wideband channel characteristics of the in-body channels from 10 MHz to 10 GHz are analyzed. The frequency domain measurements are conducted inside the pig body. The experimental results show the frequency dependent path loss. At the high frequency band, the attenuation is severe. The frequency domain channel model using Zero-pole parameters is proposed and it has an excellent fit to the measured channel. The effects on the human body surface to the propagation channel are investigated in [38], [39], [42]-[44]. The frequency band used was 2-6 GHz, which includes both the Industrial Scientific and Medical (ISM) frequency bands at 2.4 and 5 GHz as well as a significant portion of the UWB mask alloted by the FCC [50]. [47] presents the measurements in a hospital room. The channel characteristics are investigated and both time domain and frequency domain models are implemented.

However, they do not take the effect of the human body close to the antennas into account. In [48] the measurements are conducted in an office environment in both line-of-sight (LOS) and non line-of-sight (NLOS) scenarios. The transmit antenna is fixed near the wall and the receive antenna is attached on the human body by changing the position. The antenna pattern of back side is significantly decreased by shadowing of the body. One cluster channel model is proposed according to the measured channel impulse response.

III. Channel Characterizations and Modelling

This section describes the general channel properties that are useful for system design. The statistical parameters and the analysis of the existing results are presented.

A. Path-Loss Model

Due to the very wide frequency band of a UWB channel (>500 MHz), the path loss is a function of frequency as well as of distance and can be expressed by a product of the terms [32], [56]

$$PL(f,d) = PL(f)\,PL(d)\,. \tag{1}$$

The frequency dependence of the pathloss is given as [56]

$$\sqrt{PL(f)} \propto f^{-\kappa}, \tag{2}$$

where κ denotes the frequency dependence factor determined by the geometric configurations of the objects. The distance dependence of the pathloss in dB is written as [32]

$$PL(d) = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \tag{3}$$

where d_0 is the reference distance, PL_0 is the pathloss at the reference distance, n is the pathloss exponent ($n = 2$ for free space), and X_σ is a shadowing (large-scale) fading defined as the variation of the local mean around the pathloss, which is a Gaussian-distributed random variable with zero mean and standard deviation σ in dB. The average path loss can be directly calculated from the measured channel transfer functions as [32]

$$PL(d) = 10\log_{10}\left[\frac{1}{MN}\sum_{j=1}^{M}\sum_{i=1}^{N}\left|H_j^d(f_i)\right|^2\right], \tag{4}$$

where H_j^d denotes the jth channel transfer function at a frequency f_i in a distance d, M is the number of channel transfer functions for the distance d, and N is the number of frequency components in the channel transfer function.

The most common aspect from [38], [39], [42]-[44] indicates that only little energy is inside the body. Instead, the propagating wave is diffracting around the human body rather than passing through it. Unsurprisingly, the path loss increases with respect to the distance and the path loss exponent around the human body n between 5 and 7.4 is much higher than the one in free space ($n = 2$). However, the exponent along the front of the human body is around 3 [42], [44]. [42] also points out that the choice of separation between the antennas

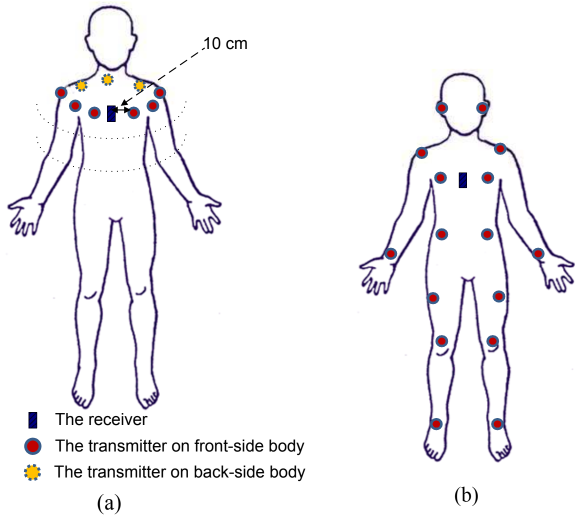

Fig. 3. Measurement locations for channel part A (between the sensor nodes on/in the body and the gateway): (a) around the body (b) along the same side of the body for standing position.

for d_0 affects the results of path loss due to antenna mismatch. It indicates that a body-aware antenna design could improve system performance. Only slightly increase in the path loss with increasing frequency is found out in [39], [44].

B. Small-Scale Fading

The small-scale fading or the amplitude distribution measured near the body is founded out to be also different from the other environments. Since there are only a small number of multi-path components from the diffraction around the body, the lognormal distribution shows a much better fit rather than the traditional Rayleigh and Ricean models [34], [39], [44]. Moreover, [39] found out that there is a significant correlation between delay bins. This can be explained by the physical phenomenon that when the transmitter is very close to receiver meaning very short path length, the multi-path components have overlapping path trajectories. Besides the first so-called cluster due to the diffraction of the propagation waves, the second cluster due to the ground reflections is also observed. This reflection becomes dominant when the receiver is placed on a different side of the body than the transmitter. Furthermore, only weak correlation between the bins of the first and the second cluster is noticed. This means that they are statistically independent. However, the two cluster behavior, which is weak for data communications, is not a real situation. In a real situation, there is also the reflections from the scatterers in the surrounding environment [43], [44]. This energy from the extra multipaths increasing diversity gain can be exploited by the receiver to improve system performance.

IV. Proposed Procedure

We now propose a procedure to obtain the channel models for WBAN. The measurements are conducted applying the frequency domainan method using an HP Agilent 8720ES,

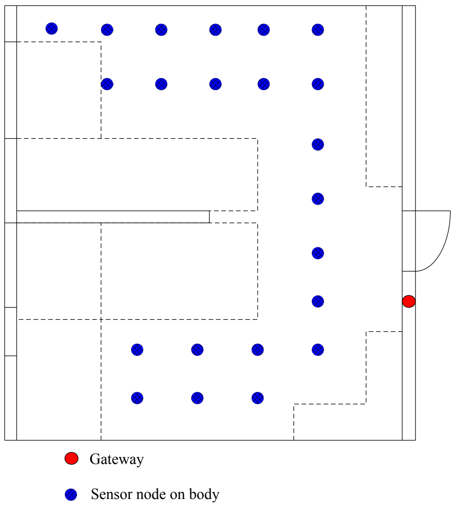

Fig. 4. The measurement locations for channel between the gateway and the person with the sensor node.

vector network analyzer (VNA), two BroadSpec^{TM} antennas [57] via the coaxial cables and a control computer with LabView^{TM} 7 software. The measurements are carried out in the frequency band of 3.0-11.0 GHz, which covers both the Industrial Scientific and Medical (ISM) frequency bands as well as the main of the frequency bands of the UWB mask allotted by the FCC. The antennas are attached to the clothes of the person wearing them.

As described before, the radio channels are composed of the part A or the WBAN part and the part B. For the part A, the measurements in an anechoic chamber are first carried out as a reference in order to account for deterministic channel characteristics due to the human body and find out the optimal positions of the sensors on the body. Then, we focus on indoor environments such as a hospital room or a home where patients are rehabilitating. The measurements are performed for both standing and sleeping positions. Moreover, the posing of arm movement according to the realistic scenario is taken into account.

At this point we consider the body surface to body surface channel. In the future, we can also include the implant to implant (in-body) channel and the implant to body surface (implant to wearable sensor nodes or gateway) channel. Fig. 3 depicts the measurement locations for channel between two sensor nodes including around and along the body. The measurements around the body are taken at three levels of the torso, i.e., the chest, the midtorso, and the abdomen levels as illustrated in Fig. 3(a). Fig 3(b) shows the positions along the body, i.e., the ears, the shoulders, the chest, the abdomen, the wrists, the thighs, the knees, and the ankles.

The channel between the body surface and the gateway is also taken into account. The positions of the gateway and the person with sensor node are shown in Fig. 4.

Finally, the radio channel for WBAN is modelled according to the extracted channel parameters described before from the measurements. A possible model considering a real situation, i.e., including also the reflections from the scatterers in the surrounding environment can be a superposition of a correlated Lognormal and a modified Saleh-Valenzuela (SV) models, which correspond to the diffraction around the body [44] and the reflections from the surrounding environment [23], respectively.

V. Summary

This paper reviewed the research works on the channel characterizations and modelling for WBAN in particular for an indoor environment as it emulates an hospital or home environments. In a WBAN, radio propagations from devices that are close to or inside the human body are complex and distinctive comparing to the other environments since the human body has a complex shape consisting of different tissues. Therefore, the channel models are different from the ones in the other environments. The interesting common result was that the propagating wave is diffracting around the human body rather than passing through it. The path loss is very high especially when the receive antenna is placed on the different side than the transmit antenna. The lognormal distribution turns to be the best fit for the small-scale fading rather than the traditional Rayleigh and Ricean distributions in the other environments. Moreover, the high correlation between bins was observed. In addition to the literature survey, we proposed a procedure including the measurement campaigns and the channel characterizations to obtain the channel models.

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