Different experimental WBAN channel models and IEEE802.15.6 models: comparison and effects

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Abstract— **In this paper, a summary of the IEEE802.15.6 wireless body area network (WBAN) radio channel models is given and the models are compared to the corresponding results obtained from the measurements carried out at the Oulu University hospital, Oulu, Finland. CWC has done a set of experimental UWB on-body channel modeling independently of the measurements that are behind the IEEE model. Being statistically more reliable, CWC's results correspond with the models presented by the IEEE806.15.6 task group. Different scenarios for the WBAN link setups have been considered in both campaigns.**

Keywords- hospital;on-body; in-body; impulse response

I. INTRODUCTION

Nowadays, most of the human's medical measurements are carried out using devices which are connected using wires between sensors and measuring devices. In addition, in consumer applications such as MP3 players, earphone is mainly connected to player with wire. Every music listening runner knows that wires of a player militate against running experience. Therefore, it would be pleasant to get rid of wires of music player. Circumstances are similar in health care. Wireless sensors would make nursing easier by removing offending wires. Simultaneously it would introduce an automatic patient docking so that when a patient is moved from one unit to another, attached measuring tags are automatically connected to new monitoring devices. More applications of wireless body area network (WBAN) can be found, e.g., from [1].

A ballpark division of WBAN scenarios can be done to implantable and wearable cases. The situation where a sensor locates inside a human, or animal body, is called implantable. Likewise, a wearable sensor is attached on body. As it is evident, the communication links between a sensor and a medical monitoring device are totally different in these two cases. In implantable situation, characteristics of a radio propagation channel are mainly defined by tissues of a body, whereas, a radio signal of wearable WBAN is propagated through air. Hence, physical layer (PHY) solutions, antenna and propagation characteristics for implantable and wearable WBANs differ greatly from each others. Nevertheless, both need to consider tissue protection measured by specific absorption rate, i.e., a rate at which energy is absorbed by a tissue when exposed to a radio frequency electromagnetic field. [2] Therefore, only very low power radios can be considered to be deployed in WBAN. Ultra wideband (UWB) technique, for example, offers solution for wearable WBAN by providing inherently low power spectrum density, high capacity of transmission and accurate ranging.

In the final report of the channel modeling subgroup of the IEEE 802.15 task group 4a, the channel models for energy-efficient wireless personal area networks (WPAN), e.g., sensor networks was provided [3]. The channel model for UWB WBAN was developed as a spin-off. The model was derived via finite difference time domain (FDTD) simulations with the bandwidth of 2 GHz. The simulations indicated that no energy is penetrating through a body but diffracting around a body and reflecting from extremities. The measurements were carried out to confirm the model. It was revealed that scattering is not uncorrelated for systems where both transmitter and receiver are placed on the same side of a body [3]. The measurements also indicated that there are always two clusters of multipath components (MPC), i.e., an initial wave diffracting around a body and a reflection from the surroundings. [3] Later on, a bunch of measurement campaigns has been carried out all over the world to model WBAN channel more accurately. CWC has been done several measurement campaigns at the Oulu University hospital focusing on the UWB band. A nice survey of existing WBAN models can be found, e.g., from [4].

In 2007, the IEEE 802.15 task group 6 (TG6) was established to develop communication standard optimized for low power devices and operation both in-body and on-body [5]. The channel modeling subgroup released the final channel model for WBAN in April 2009 [6].

In this paper, we study differences between IEEE 802.15.6 and CWC's channel model, and their possible impact on on-body communication. The paper is organized as follows: Section II introduces procedure of WBAN channel modeling. IEEE 802.15.6 and CWC channel models are presented in Section III. It also describes difference between them and what kind of impact these differences might have to performance of a wireless communication system. The paper is concluded in Section IV.

II. WBAN CHANNEL MODELING

A. Common measurement setup

Measurements for both IEEE802.15.6 TG's and CWC's experiments were based on similar kind of setups where radio channel's frequency response was measured. Vector network analyzer (VNA) is utilized to measure S_{21}-parameter which corresponds to a channel transfer function. Fig. 1 illustrates the measurement setup. In this case, VNA is controlled by a computer with LabVIEW software. The recorded S_{21}-parameter is measured and stored for post-processing.

Post-processing is started by windowing the measured frequency domain channel responses to improve its dynamic range in time domain. The windowed channel responses are transformed into the time domain through inverse discrete Fourier transform (IDFT) resulting to channel impulse responses (IR). [7, 8]

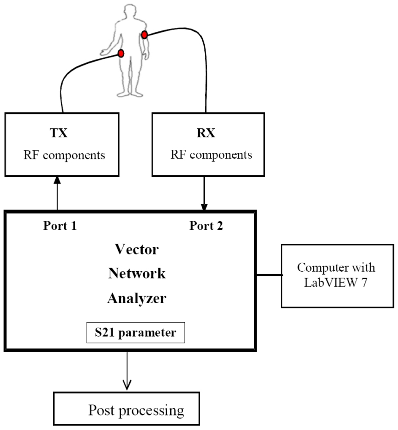

Figure 1. Frequency domain measurement using a vector network analyzer.

B. Pathloss model

Pathloss model is used to define power falloff relative to the distance. Path gain PL at a frequency f in decibels is defined as [7]

$$PL(f) = 10 \cdot \log_{10}|H(f)|^2, \tag{1}$$

where $H(f)$ denotes to measured S_{21} at a frequency f. A pathloss $L_{\text{path}}(d)$ at a distance d in is given by [7]

$$L_{\text{path}}(d) = PL_0 + 10 \cdot \gamma\log_{10}(d) + S \quad [\text{dB}], \tag{2}$$

where S is the log-normal shadowing term with zero mean and standard deviation of σ_S. The intercept point PL_0 and pathloss exponent γ are derived by a least square fitting the measured average pathloss over the frequency range. The average pathloss l_{path} at a distance d adopted by IEEE802.15.6 is [7]

$$l_{\text{path}}(d) = -10 \cdot \log_{10}\left\{\frac{1}{N_F}\sum_{m=1}^{N_F} PL(f(m))\right\} \ [\text{dB}], \tag{3}$$

where N_F is the total number of measured samples over the frequency range and $f(m)$ is the frequency corresponding to m^{th} sample. The procedure to generate pathloss model is included in detail in [9].

The current CWC WBAN model does not support path loss information. It describes only the multipath propagation statistics. When calculating the link distances, distances around the perimeter of the body instead of through the body should be taken into account due to the propagation mechanism around the body.

C. Power delay profile

Pathloss model alone is not enough to describe WBAN radio channel accurate enough. In wideband and UWB communications, different multipath components can be distinguished very accurately. Due to very wide frequency band, highly frequency selective channels are present, and therefore, dedicated power delay profile (PDP) models are needed. The PDP is characterized by MPCs having gain a_l, propagation delays τ_l and associated phase shifts θ_l, where l is the MPC index. Hence, the complex low-pass channel impulse response $h(t)$ is represented by

$$h(t) = \sum_{l=0}^{L-1} a_l \exp(j\theta_l)\,\delta(t - \tau_l), \tag{4}$$

where L indicates to the total number of MPCs, $\delta(\cdot)$ is the Dirac's delta function and t is the time. [10, 11]

As other narrowband and wideband radio channel models, WBAN channel models are used in WBAN communication link performance studies. For simulations, channel realizations are generated as illustrated in Fig. 2 [12]. At first, amplitudes of a random vector $\boldsymbol{X}$, where each component having a certain distribution derived from measurement data, is generated. The amplitude vector of the channel is obtained by scaling $\boldsymbol{X}$ with a channel profile derived from experimental data. Finally, a complex channel vector $\boldsymbol{h}$ is generated by introducing uniformly distributed phase for each channel component. [12]

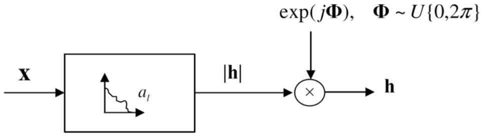

Figure 2. Block diagram of a fixed tapped delay line channel model generator.

III. WBAN CHANNEL MODELS

This section discusses the IEEE 802.15.6 and CWC channel models. It also introduces differences between them and what impact these differences might have on simulation results. The frequency bands covered by TG6 are presented in Table I [6]. From the listed bands, both TG6 and CWC models cover the on-body channels between 3.1 – 10.6 GHz. Due to the common region, this paper is focused only on the channel models within that band.

TABLE I. LIST OF IEEE802.15.6 FREQUENCY BANDS

Description	**Frequency band**
Implant	402 – 405 MHz
On-body	13.5 MHz
On-body	5 – 50 MHz (HBC)
On-body	400 MHz
On-body	600 MHz
On-body	900 MHz
On-body	2.4 GHz
On-body	3.1 – 10.6 GHz

A. IEEE 802.15.6 Channel Models

The WBAN channel models defined by TG6 cover both implant and on-body scenarios [6]. Implanted devices are operating within the frequency range of 402 – 405 MHz, whereas communication in other frequency bands is on-body including 2.4 GHz ISM and 3.1 – 10.6 GHz UWB bands. The following scenarios are included; implant to implant (CM1), implant to body surface (CM2), implant to external (CM2), body surface to body surface (CM3) and body surface to external (CM4).

1) On-body channel models

In the UWB band, scenarios CM3 and CM4 are included providing pathloss and PDP models. PDP models for CM3 and CM4 are assumed as single cluster models with Rician K-factor describing the amplitude distributions of taps. For both scenarios, amplitude variations fitted well to log-normal distribution with zero-mean and standard deviation σ. In CM3, the path amplitude a_l is modeled by exponential decaying factor Γ with Rician factor γ_0 in dB as

$$10 \cdot \log_{10}|a_l|^2 = \begin{cases} 0, & l = 0 \\ \gamma_0 + 10 \cdot \log_{10}\left(\exp\left(-\frac{\tau_l}{\Gamma}\right)\right) + S, & l \neq 0 \end{cases} \quad (5)$$

where S is a stochastic term having the log-normal distribution with zero-mean and standard deviation σ_S. Respectively, the path amplitude for CM4 is given by

$$|a_l|^2 = \exp\left(-\frac{\tau_l}{\Gamma} - k[1 - \delta(l)]\right)\beta, \quad (6)$$

where k is a term including effects of K-factor and β is log-normally distributed stochastic term with zero-mean and standard deviation σ_β. The path arrival time with a path arrival rate λ and the number of arrival paths L having the average of $\bar{L}$ are modeled by Poisson distributions given by

$$p(\tau_l|\tau_{l-1}) = \lambda\exp\left(-\lambda(\tau_l - \tau_{l-1})\right) \quad (7)$$

and

$$p(L) = \frac{\bar{L}^L \exp\,(\bar{L})}{L!}, \quad (8)$$

respectively. Finally, the amplitude phase is modeled by uniform distribution over [0, 2π).

Quasi-static channel model is also included in the final report of IEEE 802.15.6 channel modeling subcommittee [6]. On-body measurements were carried out in an anechoic chamber with center frequency of 4.5 GHz and bandwidth of 120 MHz to model the fading effect due to movements of a human body. Log-normal distribution for path amplitude seems to fit best when an object is motionless or having only minor motion. When an object has larger movement, path amplitudes fit well to Weibull distribution.

2) In-body channel models

The channel models for implant to implant and implant to on-body are also crucial for WBAN applications. In the near future, we are going to see more clever devices that are installed inside a body. Apparatuses such as intelligent joints and corresponding implants can inform their condition automatically, or by request. The radio signal propagation inside a body varies from the one in free space due to the different electrical behaviors of different body tissues. In addition, the change in the relative permittivity ε_r has an impact on speed of light inside a body. All these need to be taken into account, for example, in antenna design, where free space assumptions are not valid anymore.

In [7], there are discussion and path loss models for in-body propagation at 400 MHz frequency band. However, the presented results are based only on FDTD simulations. The existing results do not give information on radio channels for in-body communication in UWB frequency band either. On the other hand, experimental radio channel models for implant communication based on real human measurements are very challenging research topic.

B. CWC's UWB WBAN Channel Models

The channel models of CWC are focused on on-body WBAN within the UWB band. From wide set of measurements, the PDP models for on-body UWB WBAN have been derived [8, 12–15]. In [8], the WBAN measurements were carried out with several volunteers including both males and females having different ages. In addition, one of the persons had a titanium alloy aortic valve implant. The measurement setups were the following: laying in bed, standing, pseudo-dynamic walking and pseudo-dynamic eating.

The measurements expressed that a metallic implant that has been installed close to skin has significant impact on channel impulse response. Despite of being under skin, the metal in the implant changes the electrical properties around its neighborhood, which can then be seen from the MPC profile as shown in Figure 3. Similar variation to the impulse response is affected by clothes. For example, jacket or brassiere that includes metal will change the shape of the IR. Another issue that has an impact on the close body propagation is the age and gender of a human. The relative permittivity is again changed due the different fluid and fat concentrations, and this change can be seen from the channel impulse responses.

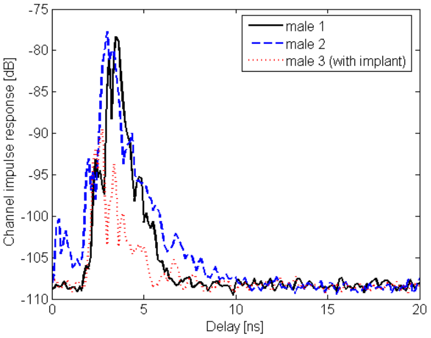

Figure 3. Channel impulse responses measured in a chest level. One person has an implant.

The measurement results from real hospital environment are summarized in [12, 13]. Measurements environments included regular hospital ward room, hospital corridor and surgery room. The on-body and body-to-external links were measured. Two situations, where a patient is either lying down or standing, were considered. The UWB WBAN channel model was extracted from the measurement data yielding to the double cluster model where rapidly decaying 1^{st} cluster responds the effect of a human body and 2^{nd} cluster having a multiple sub-clusters is caused by the reflections from surroundings. Hence, path amplitude decaying is modeled as [12]

$$10 \cdot \log_{10}|a_l| = \begin{cases} 0, & l = 0 \\ \gamma_{01} + 10 \cdot \log_{10}\left(\exp\left(-\frac{\tau_l}{\Gamma_1}\right)\right), & 1 \le l \le l_1, \\ \sum_{m=1}^{M} \gamma_{02m} + 10 \cdot \log_{10}\left(\exp\left(-\frac{\tau_l}{\Gamma_{2m}}\right)\right), & l_2 \le l \le L-1, \end{cases} \tag{11}$$

where M is the number of sub-clusters within the 2^{nd} cluster, l_1 and l_2 are the number of MPCs in 1^{st} and 2^{nd} cluster, respectively. The amplitude variation is modeled by the log-normal distribution with zero-mean and standard deviation σ_χ. The path arrival times for both clusters are defined as in (7) having a separate path arrival rates. The total number of arrival paths is modeled by Poisson distribution according to (8).

The results from pseudo-dynamic measurements covering walking and arm movement are presented in [13–15]. Pseudo-dynamic movement models were used to model walking and eating cycles. Pseudo-dynamic assumptions were based on the fact that during the recording period, the channel should be stable due to the frequency domain measurement approach. It was concluded that the Weibull distribution is the most appropriate distribution for path amplitude in the pseudo-dynamic cases, whereas the log-normal distribution is better one in static cases.

In addition, CWC has carried out channel measurement campaign at the Oulu University hospital where antennas were not attached on a body [16]. In these measurements, a link between sensor nodes and a medical monitoring device was considered.

C. Comparison

In the both models, similar measurement setups were applied, even having the same antennas (SkyCross SMT-3TO10M-A). Through the all measurements, antennas were separated from body with dielectric material. In the CWC model, the measurements were carried out in the real hospital environments, whereas simulated hospital environments were applied in the measurement campaign of the IEEE. The different environments and positions of the channel models for on-body (B2B) and body-to-external (B2E) links are summarized in Table II.

TABLE II. STATIC IEEE AND CWC CHANNEL MODELS

CHANNEL MODEL		POSITION	ENVIRONMENT
B2B	IEEE	LYING DOWN	SIMULATED HOSPITAL WARD ROOM
	CWC	LYING DOWN	HOSPITAL WARD AND SURGERY ROOMS
		STANDING	HOSPITAL ROOM WARD AND CORRIDOR
B2E	IEEE	STANDING	OFFICE ROOM
	CWC	LYING DOWN	HOSPITAL WARD AND SURGERY ROOMS
		STANDING	HOSPITAL WARD ROOM AND CORRIDOR

1) On-body channel models

In the scenario of on-body, the transmitter position was fixed, whereas receiver position was changed around the body. In each position, 100 channel responses were recorded. The measured results were averaged over the different receiver positions. [8, 12] The IEEE model includes measurements results averaged over 11 positions. [7]. In the measurements of IEEE, only 10 snapshots were recorded at each position. This raises a concern about statistical reliability. However, a total of 110 snapshots were taken over a human body.

Both approaches independently ended up to log-normal amplitude distribution. The IEEE model makes use of the single cluster model, whereas double cluster model is applied in the CWC's model. The examples of generated channel impulse responses of both models are depicted in Figure 4.

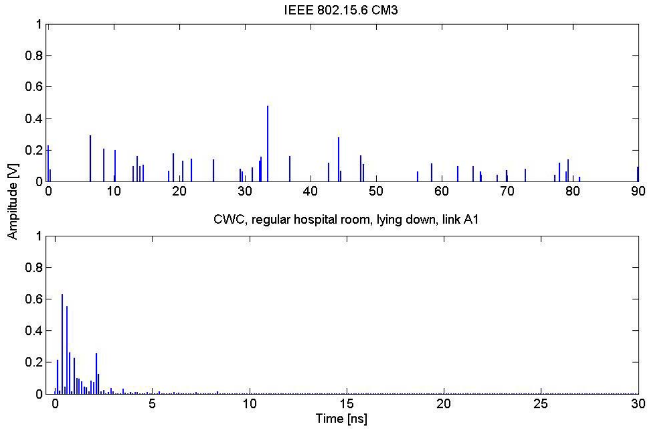

Figure 4. Generated channel realizations of IEEE 802.15.6 CM3 and CWC models.

2) Body-to-external channel models

In the body-to-external scenario, a transmitter is located meters away from the receiver on the human body. The IEEE measurement campaign was carried out in the office room surrounded by metal walls and windows, and was furnished by desks, chairs and PC monitors. Four different receiver positions were considered, i.e., the receive antenna was aligned to transmit antenna at 0, 90, 180 or 270 degrees to model various human directions. The measurement campaign of CWC was carried out at the real hospital environment. Different body directions were considered and measurement results were averaged over several body directions.

In Figure 5, the generated impulse responses are illustrated for instance. In IEEE CM4 model, there is a very long excess delay that can be explained by the metal walls of the office room [7]. The body direction of 0 degree is coming out as a strong line-of-sight component. The effect of a human body and surrounding is seen as double cluster impulse response in the lower figure.

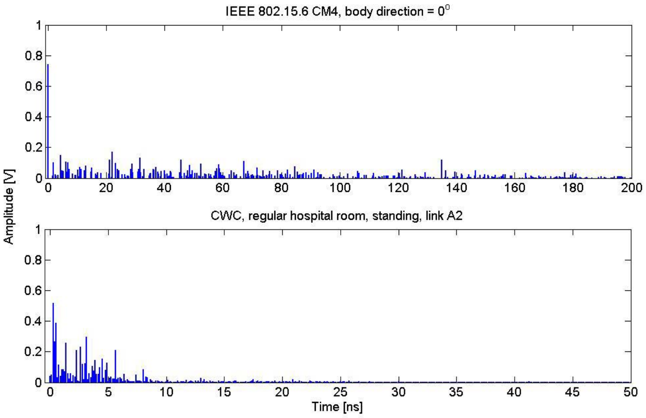

Figure 5. Generated channel realizations of IEEE 802.15.6 CM4 and CWC models.

3) *Pseudo-dynamic channel models*

A real-time channel sounder was applied to capture dynamic channel behavior due to the movement of a human body in the IEEE measurements. The transmit signal having the center frequency of 4.5 GHz and the bandwidth of 120 MHz was used. The CWC measurements included the whole UWB band, but having pseudo-dynamic motion model due to limitations of frequency domain measurement approach. Despite of the different measurement approach, both concluded that the path amplitude is log-normal distributed in static or low motion scenarios and Weibull distributed with increasing movement.

IV. FUTURE WORK

Due to the very low power spectral density the UWB signal has, it is potential radio interface for medical WBAN communication. One of the key issues in close body communication is that transmission does not cause any harm to human tissues.

The radio channel measurements carried out by CWC for WBAN application were focused on only UWB band. Currently the results cover the whole FCC band. In the future, the possibility to focus only on global UWB band within 6 – 8.5 GHz is a reasonable assumption. In addition, to make the models more generic, the influence of the antennas used in the measurement should be removed from the results.

Our future work consists of WBAN link performance simulations where the channel models are used.

V. CONCLUSION

Based on independent experimental radio channel modeling campaigns, the results obtained by CWC at the real hospital environments correspond with the finding presented in IEEE802.15.6 sub-task group for WBAN on-body channels. In addition, the channel models of CWC are more precise and cover hospital environment more widely than the IEEE models within the UWB band. Both approaches ended up similar path amplitude distributions. The delay spreads of the channel models are diverse instead. Due to the double cluster model of CWC, more MPCs have to be taken into account. The path amplitudes of the 2nd cluster are remarkable, whereas, amplitudes of late MPCs of IEEE CM4 are negligible. The situation is the other way around in the on-body models; the path amplitudes of late MPCs are significant in the case of IEEE CM3.

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