A Dynamic Channel Model of UWB-WBAN for Some Medical Applications

Attaphongse Taparugssanagorn*,†, Bin Zhen‡, Raffaello Tesi*, Matti Hämäläinen*, Jari Iinatti*, and Ryuji Kohno*,†
*Centre for Wireless Communications, University of Oulu, Oulu, Finland
†Center of Medical Information & Communication Technology, Yokohama National University, Yokohama, Japan
‡National Institute of Information and Communications Technology (NICT), Yokosuka, Japan

***Abstract*—In hospitals patients and other medical facilities have various levels of mobility, e.g., walking, wheelchairing, eating, etc. There is also growing evidence that for most medical conditions having patients move or walk, as much as they can tolerate, will improve their health. With keeping this in mind, not only static wireless body area network (WBAN) radio channels usually investigated, but also dynamic scenarios due to the effect of body motion must be considered. The contribution of the work described in this paper is to expand the knowledge of the ultra-wideband (UWB) channel in the frequency range of 3.1-10 GHz in close proximity of a dynamic human body. Based on experimental measurements a two-state alternating Weibull renewal process is modelled for the dynamic fade characteristics of the channel. The model can then be used to better design communication network protocols for WBANs.**

I. Introduction

Using wireless communications in medical care has been experiencing continuous developments and improvements during recent years. In this type of application a patient's health can be remotely monitored through the use of radio technology. As a result of this technology patients have more comfort and mobility since the number of medical devices and cumbersome wirings that are physically connected to patients is minimized. The ultra-wideband (UWB) frequency band has been much interested for wireless body area networks (WBANs) due to its particular characteristics [1]. For instance, the monitoring of human vitals and movements requires a relatively low data rate which in the case of UWB translates into very small transmitting power requirements, i.e., longer battery life. This is a very desirable feature for devices that are going to be close to the body and meant to be used for extended periods of time. It is natural to expect that the channel characteristics in WBAN scenarios are different from the ones in typical environments, i.e., indoor or outdoor [2, 3] due to the effect of the human body with its complex shape and different tissues, each with a different permittivity [3].

The channel models for on-body WBANs have been initially developed by IEEE 802.15 task group 4a [3] as a spin-off of the channel models for energy efficient wireless personal area network (WPAN). In Nov. 2007, IEEE wireless body area networks TG6 was established in order to develop communication standard optimized for low power devices and operation both in-body and on-body. And recently in April 2009, the channel modeling subgroup has released the final channel model for WBAN [4]. UWB measurements around the human body have been carried out by various researchers in the meanwhile [5-6]. However, dynamic scenarios due to body motions, which most likely take place in medical care fields, have not been covered in those studies and have rarely been investigated [7-9]. The channel characteristics are altered time-variantly since the link distance changes when arm moves, body will block the LOS link, and the antenna polarization mismatch due to the misalignment of the transmit (Tx) and receive (Rx) antennas [8]. The radio channel fade, caused by the body motions, leads to transmission errors. The hypothesis radio channel without memory cannot be retained for a real radio communication channel because of this dependence between the probability of error at a given moment and the state of the error sequence at the preceding moments. In [9], the real-time measurements at 4.5 GHz with a bandwidth of 120 MHz were taken for investigating the dynamic feature due to body motions. A three-state Fritchman model was proposed to describe the two-good-state and one-bad-state characteristics of such dynamic channels.

In this paper, experimental studies under dynamic conditions, namely, body movements in scenarios covering the entire UWB frequency band were taken. Instead of analyzing only the peak as in [9], three strongest peaks capturing most of the energy of the channel were taken into account. A two-state alternating Weibull renewal process was found to excellently fit the observation.

II. Channel Measurement Setup and Scenarios

The channel measurement system is the same as in [8] and consists of an HP Agilent 8720ES, a vector network analyzer (VNA), SkyCross SMT-3TO10M-A antennas, 5-m long SUCOFLEX® RF cables with 7.96 dB loss and a control computer with LabVIEW™ 7 software.

The measurements were taken corresponding to realistic scenarios in a regular hospital room with the size of 6.3 m×7.2 m×2.5 m in the Oulu university hospital as shown in Fig. 2 in [8]. We defined two measured radio links, A1 and A2. For the radio link A1, the Rx antenna was at the middle front of the torso and the Tx antenna was placed on the left wrist. These locations are comfortable for most patients and

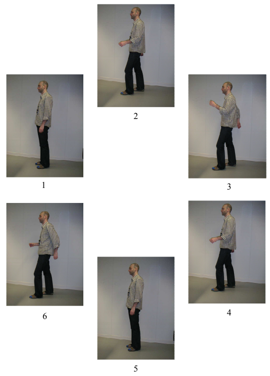

Fig. 1. Positions of a walking cycle.

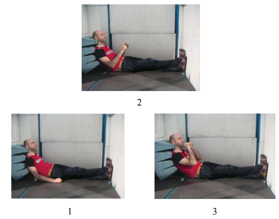

Fig. 2. Arm positions in a half eating cycle.

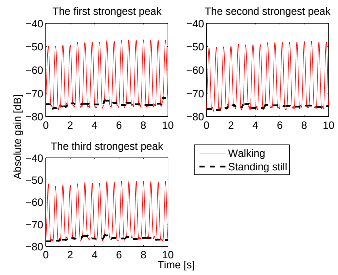

Fig. 3. Comparison of the amplitudes of the three strongest peaks for the channel link A1 in the walking and standing cases.

they are potential places for antennas/transceivers connected to electrocardiogram (ECG) sensors and a pulse oximeter. For the radio link A2, the subject was 2-m away from and facing toward the Rx antenna placed on a 2-m high pole and the Tx antenna was on the left wrist of the subject.

The measurements correspond to usual situations of patients in the regular hospital room, i.e., walking, lying, as well as eating while lying. A pseudo-dynamic measurement method was applied, where each position in a walking cycle in Fig. 1 was kept still for the whole measurement period (e.g. 100 snapshots or realizations per position), and was modified according to the walking cycle. This is because processing a single frequency domain measurement in the 3.1-10 GHz band takes several seconds, a real-time measurement of the radio channel fluctuations due to body motions is not feasible. A pseudo-dynamic measurement emulates the situation when the subject is eating while lying down as shown in Fig. 2 was also taken. Based on an actual measurement, a walking cycle or an eating cycle lasts 0.6 s assuming an equal time interval between consecutive positions, i.e., 0.1 s. To be able to study the dynamic features, the measurements were extended from an walking or an eating cycle til 10 s walk or eating. In addition, an interpolation was done in order to obtain 0.1 ms sampling interval as [9] has.

III. Results and Analysis

A. Path Gain

The measured S_{21}-parameters or channel transfer functions are converted to the time domain, i.e., channel impulse responses (IR) using an inverse fast Fourier transform (IFFT). A Hamming windowing is used to reduce sidelobes. As explained in [8], the characteristics of on-body WBAN channels including body motions are altered time-variantly since the link distance changes when arm moves, body will block the LOS link, and the antenna polarization mismatch due to the misalignment of the transmit (Tx) and receive (Rx) antennas. In this paper dynamic features of path fading process, which is important for system designs, are taken into account. In practice, only a subset of total resolved multipath components is important and is used for designing a UWB Rake receiver, e.g., partial Rake (PRake) collecting only the first L paths and selective Rake (SRake) collecting only the first K strongest paths. The average energy captures of the only first strongest path, the two strongest paths and the three strongest paths for the channel link A1 in the walking cases are 52.32%, 73.52%, and 81.55%, respectively. Therefore, only three strongest peaks capture most of the energy of the channel and are considered in our study. The comparison of the gain of the three strongest peaks of the impulse response for the channel link A1 in the walking and standing cases are shown in Fig. 3. The averaged path gain in the standing still case is also plotted as a reference and its mean is later set to be a threshold level.

B. Statistic Analysis

Due to the limit of space, only the results for the channel link A1 in the walking case are presented as examples. Fig. 4 compares the amplitude distributions of the three strongest peaks and the distribution best fitting the static and pseudo-dynamic channels. A least squares parameter estimation is applied for distribution fitting. We can see that the amplitudes are log-normally distributed in the static case with the following corresponding mean μ and standard deviation σ: (-71.96, 2.18), (-74.09, 1.99), and (-75.825, 1.95) for the first strongest peak, the second strongest peak, and the third strongest peak, respectively. The Weibull distribution, of which the probability density function (PDF) given by

$$f\left(x\,|a,b\right) = ba^{-b}x^{b-1}\exp\left(-\left(x/a\right)^{b}\right) \qquad (1)$$

with the corresponding scale a and shape parameters b, is the best one for characterizing the probabilistic nature of the amplitudes in the dynamic situations. The corresponding scale and shape parameters (a, b) for the first strongest peak, the second strongest peak, and the third strongest peak in the

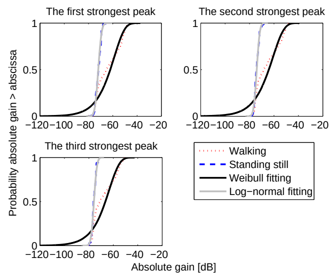

Fig. 4. Comparison of CDFs of the amplitude distributions of the three strongest peaks and the distribution fittings for the channel link A1 in the walking and standing cases.

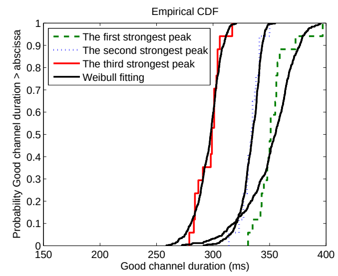

Fig. 6. Comparison of CDFs of the good channel durations of the three strongest peaks and the distribution fittings for the channel link A1 in the walking and standing cases.

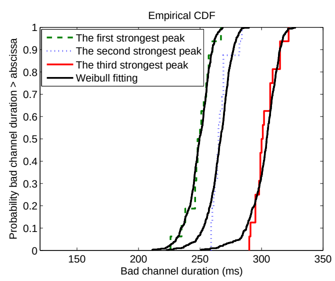

Fig. 5. Comparison of CDFs of the bad channel durations of the three strongest peaks and the distribution fittings for the channel link A1 in the walking and standing cases.

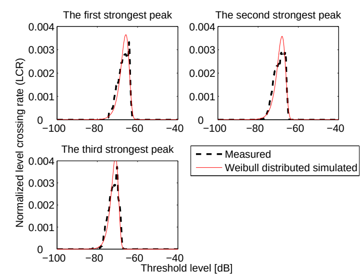

Fig. 7. Comparison of the normalized average LCR of the three strongest peaks of the impulse response for the channel link A1 in the walking and standing cases and the Weibull distributed simulated samples.

walking case are (1.28×10^{-6}, 0.49), (8.20×10^{-7}, 0.47), and (4.61×10^{-7}, 0.50), respectively.

The fade or bad channel duration determining how long the amplitude lies below a given threshold level chosen from the mean amplitude of the first peak in the standing case (-72 dB) is shown in Fig. 5. This helps to determine the most likely number of signaling bits that may be lost during a fade. On the other hand, the non-fade or good channel duration determining how long the amplitude lies above a given threshold level is shown in Fig. 6. The average fade duration (AFD) and the average good channel duration for all scenarios are summarized in Table I. A Weibull distribution with the corresponding scale parameter a and shape parameter b expressed in (1) well fits the measured distribution of both bad channel and good channel durations. The fitting parameters for all scenarios are summarized in Table II. The given threshold level is chosen in such a way that a good channel is guaranteed to have longer duration than a bad channel for the first peak. However, changing the threshold does not affect the distribution type, but only the parameters a and b.

Level crossing rate (LCR) at any threshold level is defined as the expected rate at which the signal envelope crosses that level in positive (or negative) going direction. Fig. 7 shows the average normalized LCRs in positive as a function of threshold level for the first peak, the second peak, and the third peak, which are all found to be 0.0007 (absolute values are 18.64, 18.91, and 17.87, respectively) at the threshold level (-72 dB). The signal crosses the threshold for each 0.53 s, 0.52 s, and 0.56 s of observation time. Provision of 8 dB extra margin increases this to 5 s, which clarifies the favorable slow fading. The LCRs of the Weibull distributed samples with the corresponding scale parameters and corresponding shape parameters show similarity to the empirical ones. The received signal experience periods insufficient signal strength or fading interval during which the bit error rate is close to one half and the receiver may not function reliably. These are useful in predicting the burst of errors without doing the end-to-end system simulation and in the design of the error control codes, interleaver.

C. *Two-State Alternating Weibull Renewal Process Model*

A model representing specific details of the measured dynamic fade characteristics is proposed. As we can see in Fig. 6, a Weibull distribution well fits the measured distribution for both bad channel and good channel durations. In addition, only one state in each channel type is sufficient to describe such a narrow distribution. In other words, there is no big difference of durations in each channel state. In this case, the well-known two-state Markov or the simplified Gilbert model cannot be used since the durations of both bad channel and good channel do not follow a geometric distribution. Therefore, we propose a two-state alternating Weibull renewal process, where in one state good channel duration and in the other state bad channel duration are generated, as shown in Fig. 8. The model represents an alternating renewal process meaning that the probability of producing a bad channel duration is independent of the previous bad channel duration and is also independent of the previous good

TABLE I
STATISTICAL PARAMETERS FOR THE DYNAMIC CHANNELS

Measurement scenario	Average duration (ms)		Level crossing rate
	Bad Channel (first, second, third peaks)	Good Channel (first, second, third peaks)	(first, second, third peaks)
Channel link A1: walking	248.94, 266.63, 302.82	352.83, 333.42, 296.53	18.64, 18.91, 17.87
lying and eating	147.95, 189.45, 191.47	355.74, 144.74, 307.95	10.18, 10.22, 8.22
Channel link A2: walking	112.27, 62.41, 23.50	185.70, 289.18, 346.01	12.69, 12.68, 11.70
lying and eating	173.88, 179.69, 207.64	428.57, 340.11, 313.53	13.09, 11.40, 10.03

TABLE II
PARAMETERS OF TWO-STATE ALTERNATING WEIBULL RENEWAL PROCESS MODEL

Measurement scenario	Weibull scale parameter a and shape parameter b	
	$F_{\mathrm{bd}}(x\,\|a,b)$ (first, second, third peaks)	$F_{\mathrm{gd}}(x\,\|a,b)$ (first, second, third peaks)
Channel link A1: walking	(a = 0.25, 0.27, 0.31), (b = 29.56, 32.03, 33.32)	(a = 0.36, 0.34, 0.30), (b = 19.57, 44.77, 32.37)
lying and eating	(a = 0.40, 0.16, 0.34), (b = 3.57, 2.14, 1.72)	(a = 0.16, 0.21, 0.21), (b = 3.03, 1.62, 1.49)
Channel link A2: walking	(a = 0.20, 0.33, 0.346), (b = 4.30, 1.75, 101.00)	(a = 0.12, 0.07, 0.03), (b = 8.33, 2.79, 56.38)
lying and eating	(a = 0.18, 0.20, 0.23), (b = 12.74, 2.42, 4.54)	(a = 0.44, 0.37, 0.35), (b = 21.95, 4.72, 3.72)

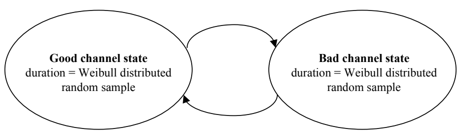

Fig. 8. A two-state alternating Weibull renewal process.

channel. Each state has its own Weibull distribution functions $F_{\mathrm{gd}}(x\,|a,b)$ and $F_{\mathrm{bd}}(x\,|a,b)$ for the good state and the bad state, respectively, where their corresponding parameters are summarized in Table II. At any given time the channel can be either in the good state or in the bad state. A variable of interest is the probability $p(t)$ that the channel is in a good state at time t or usually called "a renewal function". $p(t)$ is given by

$$p(t) = 1 - F_{\mathrm{gd}}(t\,|a,b) + \int_0^t p(t-x)dH(x), \qquad (2)$$

where $H(x)$ is the convolution of $F_{\mathrm{gd}}(x\,|a,b)$ and $F_{\mathrm{bd}}(x\,|a,b)$ and given by

$$H(x) = F_{\mathrm{gd}}(x\,|a,b) * F_{\mathrm{bd}}(x\,|a,b)\,. \qquad (3)$$

Since $H(x)$ in (3) is not available in a closed-form solution, an approximation can be done by the saddlepoint method [10]. The probability that the channel is in a bad channel state is $1 - p(t)$.

IV. CONCLUSIONS

We have studied the dynamic characteristics of UWB WBAN radio channel due to the body motions. Since a real-time measurement of the radio channel fluctuations due to the body motions is not technically feasible over a frequency band of several GHz, a pseudo-dynamic method was applied. Three strongest peaks capturing most of the energy of the channel were taken into account in the study. The dynamic features of path fading process, e.g., the good and bad channel durations as well as the LCR, which were important for a cross layer design, was statistically analyzed. Finally, a two-state alternating Weibull renewal process was found to excellently fit the observation. The model can provide good usability and high accuracy with low complexity.

REFERENCES

[1] S. Gezici and Z. Sahinoglu, "Theoretical Limits for Estimation of Vital Signal Parameters Using Impulse Radio UWB," *IEEE Communications Society subject matter experts for publication in the ICC 2007 proceedings*, 2007.

[2] S. S. Ghassemzadeh and V. Tarokh, "The Ultra-Wideband Indoor Path Loss Model," Tech. Rep. P802.15 02/277r1SG3a, AT&T Labs, Florham Park, NJ, USA (IEEE P802.15 SG3a contribution, June 2002).

[3] A. Molisch *et al*, "A Comprehensive Standardized Model for Ultrawideband Propagation Channels," *IEEE Trans. Antennas and Propagation*, vol. 54, no. 11, Nov. 2006.

[4] K. Y. Yazdandoost, "Channel Model for Body Area Networks (BAN)," IEEE 802.15-08-033-09, 2008.

[5] A. Fort, C. Desset, J. Ryckaert, P. De Doncker, L. Van Biesen, and P. Wambacq, "Characterization of the Ultra Wideband Body Area Propagation Channel," in *Proc. International Conference ICU*, pp. 22-27, 2006.

[6] A. Taparugssanagorn, C. Pomalaza-Ráez, A. Isola, R. Tesi, M. Hämäläinen, and J. Iinatti, "UWB Channel for Wireless Body Area Networks in a Hospital Environment," in *Proc. Wireless Personal Multimedia Communications (WPMC)*, Sep. 2009.

[7] D. Miniutti *et al*, "Dynamic Narrowband Channel Measurements around 2.4 GHz for Body Area Networks," IEEE P802.15-08-0033-00-0006, 2008.

[8] A. Taparugssanagorn, C. Pomalaza-Ráez, R. Tesi, M. Hämäläinen, and J. Iinatti, "Effect of Body Motion and the Type of Antenna on the Measured UWB Channel Characteristics in Medical Applications of Wireless Body Area Networks," in *IEEE International Conference on Ultra-Wideband (ICUWB)*, Sep. 2009.

[9] B. Zhen, M. Kim, J. I. Takada and R. Kohno, "Characterization and Modeling of Dynamic On-body Propagation," in *ICST Conference on Pervasive Computing Technologies for Healthcare*, 6 p, April, 2009.

[10] C.-H. Jun and S.-H. Lee, "Variables Sampling Plans for Weibull Distributed Lifetimes under Sudden Death Testing," in *IEEE Trans. on Reliability*, vol. 55, no. 1, March 2006.