Impact of Difference in WBAN Channel Models on UWB System Performance

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Abstract—**In this paper, the performances of two singleband ultra wideband (UWB) systems, i.e., direct sequence UWB (DS-UWB) and UWB frequency modulation (UWB-FM) are studied in two different channel models to reveal an impact of a channel model on the system's performance. The applied channel models are the experimental wireless body area network (WBAN) channel model developed at the Centre for Wireless Communications (CWC), Finland, and the IEEE 802.15.6 channel model. The simulation results indicate that the choice of the WBAN channel model applied in the simulations has a major impact on the performance of UWB-FM, whereas it is not such a crucial in the case of DS-UWB.**

Keywords–DS-UWB; medical; UWB-FM

I. INTRODUCTION

In April 2009, the channel modeling subcommittee of the IEEE 802.15 task group 6 (TG6) released the wireless body area network (WBAN) channel models for in-body and on-body communications to evaluate performances of different physical layer proposals [1]. Several frequency ranges were covered including, e.g., ultra wideband (UWB) from 3.1 GHz to 10.6 GHz and 2.4 GHz industrial, scientific and medical (ISM) band. Along with the IEEE 802.15.6, the WBAN channel measurement campaigns have been carried by the Centre for Wireless Communications (CWC), Finland. The CWC's channel models are focused on the on-body UWB WBAN channels [2]. Despite the independent measurement campaigns, both approaches ended up similar kind of UWB channel models. Nevertheless, dissimilarities exist among the channel models leading to the possible difference in the system performance. These similarities and differences are discussed in Section II.

In this paper, the impact of the different channel models on a UWB system performance is studied by using two different single band UWB physical layer approaches, i.e., direct sequence UWB (DS-UWB) and UWB frequency modulation (UWB-FM). The paper is organized as follows: the studied systems followed by an introduction of the applied channel models are discussed in Section II. A software simulator is introduced in Section III. Section IV presents simulation parameters for both systems, whereas the next section gives and discusses the simulation results. The paper is concluded in Section VI.

II. SYSTEM MODELS

This section gives a brief introduction to DS-UWB and UWB-FM followed by a short discussion on the applied channel models.

A. DS-UWB

In this impulse radio concept, ultra wide spectrum is generated by using very short pulses. A data bit is spread over multiple pulses by applying a pseudorandom code to achieve a processing gain due to pulse repetition. [3]

In DS-UWB, the Gaussian monocycle, or its higher order derivatives, is typically used as a pulse waveform [3]. The center frequency and bandwidth of a signal are modified by adjusting the pulse length and the degree of derivative. When the UWB band from 3.1 GHz to 10.6 GHz is available, this is a nice way to design a proper pulse. Problems are encountered when an available spectrum is reduced, e.g., the UWB band of 6.0–8.5 GHz allocated by the European Union (EU) [4]. It becomes troublesome to find the Gaussian pulse fitting to this spectrum without filtering. A simple way to design a proper pulse for a desired frequency range is introduced in [5]. Since it is based on the eigenvalue decomposition of an impulse response corresponding to a desired spectrum mask, a pulse waveform is called as an eigenpulse. This approach gives an easy way to match a signal spectrum with a frequency allocation defined by a local regulatory body.

At a receiver, rake reception is utilized to combine different signal components propagated through a multipath channel. In optimal manner, all multipath components (MPC) are collected and combined by an all-rake receiver. Since there may be hundreds of MPCs in a UWB channel, the all-rake receiver is too complex and impossible to implement. Partial-rake (p-rake) by collecting N first MPCs is less complex, and thus being more feasible for low-complexity WBAN receivers. Maximum ratio combining (MRC) is the optimal combining technique by coherently adding up selected MPCs, whereas non-coherent square law combining (SLC) sums the squared envelopes of the selected MPCs. [3]

B. UWB-FM

In simple UWB-FM technique, information is spread over a UWB band by applying a double frequency modulation (FM) [6]. A constant-envelope UWB signal is created by a low-modulation index digital frequency shift keying (FSK) followed by a high-modulation index analog FM. A received signal is demodulated by applying the delay-line FM demodulator followed by, e.g., a phase-locked loop. In the FM demodulator, the received signal is delayed by [6]

$$\tau = \frac{N_d}{4f_c}, \quad N_d = 1,3,5, \ldots \tag{1}$$

where f_c is the carrier frequency. The useful RF bandwidth of the FM demodulator (B_{DEMOD}) is defined by N_d and the carrier frequency as follows [6]

$$B_{DEMOD} = \frac{2}{N_d} f_c. \tag{2}$$

It is important that N_d is selected correctly since wrongly chosen value of N_d leads to the suboptimal operating bandwidth of the FM demodulator, and hence performance degradation.

C. WBAN channel models

The performances of the studied systems are examined by applying two different WBAN channel models. This section gives a gentle description of the channel models. The more detailed discussion on the channel models and their differences can be found from [7].

1) IEEE 802.15.6

The WBAN channel models defined by the IEEE 802.15.6 cover both in-body and on-body scenarios [1]. The channel models for the UWB band of 3.1–10.6 GHz include on-body (CM3) and body-to-external (CM4) cases. The channel measurements were done in a simulated ward and office room to model the on-body and body-to-external UWB channels, respectively. Generated channel impulse responses of CM3 and CM4 with the body direction of 0 degree, i.e., the orientation of a receive antenna is in line with a transmit antenna are illustrated in the upper graphs in Figure 1 and Figure 2, respectively. In the IEEE on-body channel model, several positions were averaged including non line-of-sight (NLOS) channels yielding to disperse channel realizations. The office room was surrounded by metal walls leading to the large delay spread of the channel impulse response as illustrated in Figure 2. The on-body and body-to-external channels are modeled as single cluster models with the log-normal amplitude distribution.

2) CWC's models

The CWC's WBAN channel models within the UWB band are based on the measurement campaigns in the real hospital environments at the Oulu University hospital. A ward, a surgery room and a hospital corridor were included. On-body and body-to-external links were measured while a patient being either sleeping or standing position. From the measurement data, double cluster channel models with the log-normal amplitude distribution were extracted. [2]

In the lower graphs in Figure 1 and Figure 2, generated channel impulse responses for on-body and body-to-external links are depicted, respectively. On-body channel measurements of the CWC included only the link from a wrist to a chest, and thus having shorter delay spread than corresponding IEEE channel model.

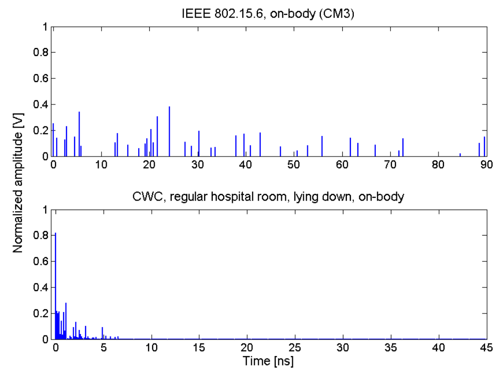

Figure 1. Generated on-body channel impulse responses.

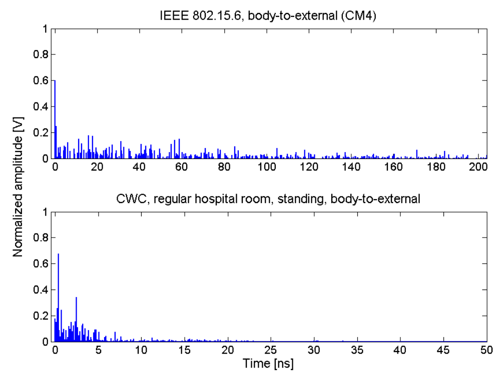

Figure 2. Generated body-to-external channel impulse responses.

D. Applications

The high resolution electrocardiography (ECG) makes it possible to measure and record late potentials of the QRS complex which are microvolt-level waveforms [8]. The QRS complex is a recording of a single heart beat and it corresponds to the depolarization of the ventricles [9, 10]. Ventricular tachycardia is a fast heart rhythm originating in one of the ventricles of a heart. This may be a life-threatening arrhythmia since it may lead to a ventricular arrhythmia and sudden death. By using the high resolution ECG presented in [8], the microvolt-level waveforms of the QRS complex can be measured. When the sampling frequency of 20 kHz and the sample size of 24 bits are applied, it yields to the information rate of 480 kbps per channel. Hence, the total information rate is 5.76 Mbps in the standard 12-lead ECG measurement procedure. These data rates are used in simulations.

III. PHY LAYER SIMULATOR

In order to study performances of different singleband UWB PHY layer approaches in the introduced WBAN channels, a software simulator was developed in MATLAB®.

The first step is to generate the random binary data bits $b[k] \in \{0, 1\}$. The k^{th} data bit is then transformed to the antipodal representation $d[k] \in \{-1, 1\}$. For UWB-FM, $d[k]$ is applied to adjust a frequency of a FSK modulated signal.

DS-UWB is implemented by using an N_c-length spreading code $c_p \in \{-1, 1\}$. According to c_p, two antipodal pulse waveforms are applied, i.e., eigenpulses $h_{p,1}(t)$ and $h_{p,-1}(t)$ corresponding to the chips '1' and '–1', respectively, and are given by

$$h_{p,-1}(t) = -h_{p,1}(t) = h_p(t)c_p. \tag{3}$$

The transmitted signal $s(t)$ for DS-UWB with binary pulse amplitude modulation (BPAM) is defined as

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{j=1}^{N_c} h_p(t - kT_b - jT_c)\left(c_p\right)_j d[k], \tag{4}$$

where t is time, T_b refers to the bit time and T_c is the chip length [3]. When on-off keying (OOK) is utilized, $d[k]$ is replaced by $b[k]$, i.e., nothing is transmitted in the case of bit '0'. Energy of pulse corresponding to the chip '1' is doubled to maintain average pulse energy constant. Frequency modulation is applied to spread the FSK modulated signal to a desired RF range in the case of UWB-FM. For both systems, the average energy of the transmitted signal is normalized to one.

The signal propagates through the multipath channel $h(t)$ defined as

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l), \tag{5}$$

where L is the number of MPCs, α_l refers to the attenuation factor of the l^{th} MPC and $\delta(\cdot)$ denotes the Dirac delta function. The channel energy is normalized to one, i.e., $\sum_{l=0}^{L-1} \alpha_l^2 = 1$. The received signal $r(t)$ is constructed from the multipath propagated signal and the additive white Gaussian noise (AWGN) $n(t)$ having the variance σ_n^2, and thus the received signal is

$$r(t) = s(t) * h(t) + n(t), \tag{6}$$

where $*$ denotes the convolution operation.

At a receiver, p-rake with either MRC or SLC is utilized in the case of coherent or non-coherent DS-UWB, respectively. For UWB-FM, the delay-line FM demodulator followed by the FSK demodulator presented in [11, pp. 63] is applied. The block diagram of the simulator is depicted in Figure 3.

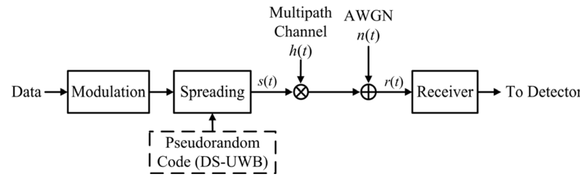

Figure 3. Block diagram of the simulator.

For DS-UWB with MRC, the signal-to-noise power ratio (SNR) at the output of the p-rake receiver ($SNR_{p\text{-}rake}$) can be evaluated as

$$SNR_{\text{p-rake}} = \frac{E_b\left(\sum_{l=0}^{N_f-1} \mu_l \alpha_l\right)^2}{\sigma_n^2 \sum_{l=0}^{N_f-1} \mu_l^2}, \tag{7}$$

where E_b is the bit energy, N_f is the number of rake fingers, l is the index of the MPC and μ is the MRC weighting factor. For UWB-FM, the FM demodulator acts as a nonlinear SNR converter. The subcarrier SNR (SNR_{SUB}) is expressed as

$$SNR_{\text{SUB}} = \frac{B_{\text{RF}}}{B_{\text{SUB}}} SNR_{\text{RF}}^2 \left(\frac{1}{1 + 4SNR_{\text{RF}}}\right), \tag{8}$$

where B_{RF} is the RF bandwidth, B_{SUB} is the subcarrier bandwidth and SNR_{RF} refers to SNR at the receiver input [6].

The theoretical results in the AWGN channel and results presented in [6] were applied to verify functionality of the UWB PHY layer simulator. For each simulation case, 2000 channel realizations are generated. A simulation is running until 100 bit errors have occurred or 10^7 bits have transmitted.

IV. Simulation Parameters

The baseline for the study is that both systems occupy the same frequency band, i.e., the 6.0–8.5 GHz UWB band defined by the EU [4]. The spectra of the studied systems are depicted in Figure 4. In on-body communication, the link between two on-body sensors having the information rate (R_b) of 480 kbps is considered. This simulates the situation where a measuring sensor node transmits data to a gateway, both being attached on a body. Data is transmitted from an on-body gateway to an external medical monitoring device with R_b = 5.76 Mbps in the other scenario. According to the information rates, the parameters for both systems are fixed. The pulse length of DS-UWB is set to 1.5 ns, and thereby the processing gains are around 21 dB and 31 dB for 5.76 Mbps and 480 kbps, respectively. In UWB-FM, the frequency deviation is equal to the information rate, and hence the modulation index for FSK is one.

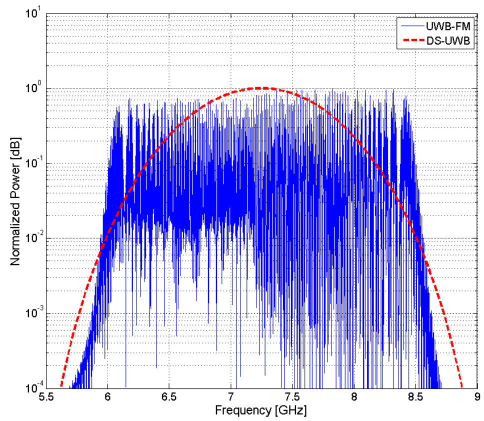

Figure 4. Spectra of the studied systems.

The receiver of DS-UWB applies N_f-finger p-rake receiver with MRC or SLC in the case of coherent or non-coherent DS-UWB, respectively. The modulation scheme for MRC is binary pulse amplitude modulation (BPAM) and on-off keying (OOK) for SLC, respectively. BPAM is not applied for SLC, since the polarity of the data bit is needed in the decision. Nothing is transmitted in the case of bit "0" in OOK, and therefore the pulse power of OOK is twofold compared to BPAM to maintain the same average transmitted power. The bit energy-to-noise power spectral density ratio (E_b/N_0) of DS-UWB is defined at the input of the receiver. The simulation parameters for DS-UWB are tabulated in Table I.

TABLE I. PARAMETERS FOR DS-UWB SIMULATIONS

Parameter	Value
Pulse length (T_p) [ns]	1.5
Pulse type	Eigenpulse
Modulation method	BPAM, OOK
Processing gain (PG_{dB}) [dB]	20.63, 31.43
Combining technique	MRC, SLC
Rake receiver	p-rake
Number of fingers (N_f)	1,3,10,15
Center frequency [GHz]	7.25
-20 dB bandwidth (B_{-20dB}) [GHz]	2.5

In the case of UWB-FM, the carrier frequency is fixed to 7.25 GHz and the RF bandwidth is varied to study the dependence of performance on the RF bandwidth. In Table II, the simulation parameters for UWB-FM are summarized. For UWB-FM, E_b/N_0 is defined in the decision. Therefore, there is a penalty factor for DS-UWB, because all available MPCs are not exploited.

TABLE II. PARAMETERS FOR UWB-FM SIMULATIONS

Parameter	Value
RF bandwidth (B_{RF}) [GHz]	2.5, 2.0, 1.5, 1.0, 0.5
Carrier frequency (f_c) [GHz]	7.25
Modulation index of FSK (β_{FSK})	1

Both systems are studied under the on-body UWB WBAN channels defined by the IEEE 802.15.6 and CWC [1, 2]. The both models include several different environments, positions and links. The scenarios of the channel models equated with each other as much as possible are selected under study. The characteristics of the chosen scenarios are given in Table III. When the IEEE CM4 is applied, the body direction of 0 degree is considered.

TABLE III. STUDIED SCENARIOS

Channel model	Measurement environment	Position	Link	R_b [Mbps]	Acro-nym
IEEE	Simulated ward	Lying down	On-body	0.48	IEEE1
	Office room	Standing	Body-to-external	5.76	IEEE2
CWC	Ward	Lying down	On-body	0.48	CWC1
	Ward	Standing	Body-to-external	5.76	CWC2

V. SIMULATION RESULTS

In Figure 5, the performance of DS-UWB having R_b = 480 kbps in the IEEE1 and CWC1 channels is depicted. Remarkable difference in the performance is in evidence when coherent DS-UWB is considered. The performance of 1-finger MRC saturates in the CWC1 channel, whereas the CWC1 channel provides better performance for 3-finger MRC than the IEEE1 channel. This indicates that there is a very weak 1st MPC in the CWC1 channel leading to weak performance. When more energy is collected by using more rake fingers, the performance improves significantly. Non-coherent DS-UWB needs at least 10 fingers to work in both channels. Although non-coherent DS-UWB applies more fingers than coherent DS-UWB to attain reasonable BER level, it does not outperform MRC because more noise is integrated at a receiver due to increased number of rake fingers.

The performance of UWB-FM with R_b = 480 kbps in the IEEE1 and CWC1 channels is illustrated in Figure 6. In the IEEE1 channel, the performance of UWB-FM saturates with all the studied bandwidths. The reason is that the IEEE1 channel is sparse and has long delay spread contrary to the CWC1 channel.

Figure 7 and Figure 8 represent the results of the performance simulations of DS-UWB and UWB-FM, respectively, having R_b = 5.76 Mbps in the IEEE2 and CWC2 channels. The results are very similar to the findings from the IEEE1 and CWC1 channels. MRC with three rake fingers has better performance in the CWC2 channel than the IEEE2 channel, and UWB-FM suffers from the long delay spread of the IEEE2 channel.

The results of the DS-UWB simulations indicate that 1st MPC of the CWC1 and CWC2 channels are weak leading to the performance saturation. When the number of rake fingers is increased, the performance of DS-UWB in the CWC1 and CWC2 channels is better than in the IEEE1 and IEEE2 channels. In the case of UWB-FM, the performance difference between the CWC and IEEE channel models is significant.

VI. CONCLUSION

The performances of two singleband UWB systems, i.e., DS-UWB and UWB-FM were studied in two different WBAN channel models. Two scenarios were included by considering the on-body and body-to-external links having the data rates of 480 kbps and 5.76 Mbps, respectively.

The IEEE on-body channel model is more generic than the CWC channel model by averaging different receiver locations on a body. However, the measurement campaigns, which from the on-body and body-to-external models were extracted, were carried out at the simulated hospital environments, and thus the IEEE models are not as realistic as the CWC models in that sense. The weakness of the CWC on-body model is that only one link from a wrist to a chest was measured. Hence, the representation of the on-body channel is not as realistic as the IEEE channel model.

The simulation results indicated that the choice of the channel model applied in simulations plays a crucial role in the system's performance. This was shown to be very true for UWB-FM which performance saturates in the IEEE channel models, whereas good results were obtained by using the CWC channel models.

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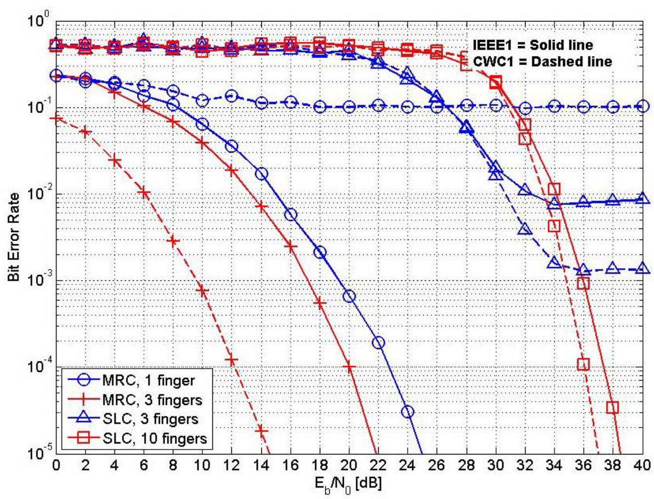

Figure 5. Performance of DS-UWB with R_b = 480 kbps.

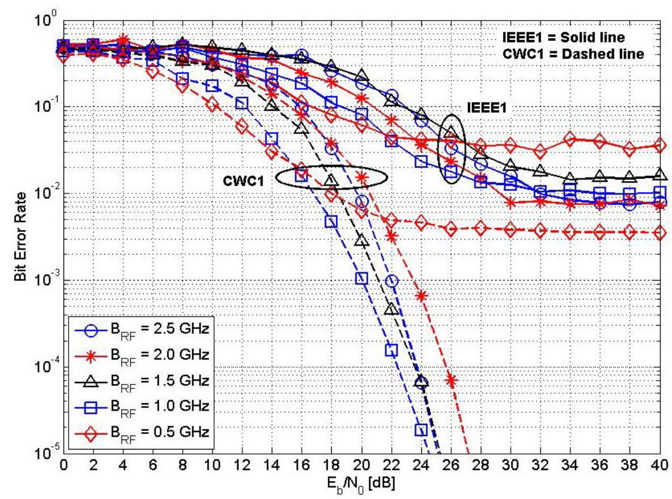

Figure 6. Performance of UWB-FM with R_b = 480 kbps.

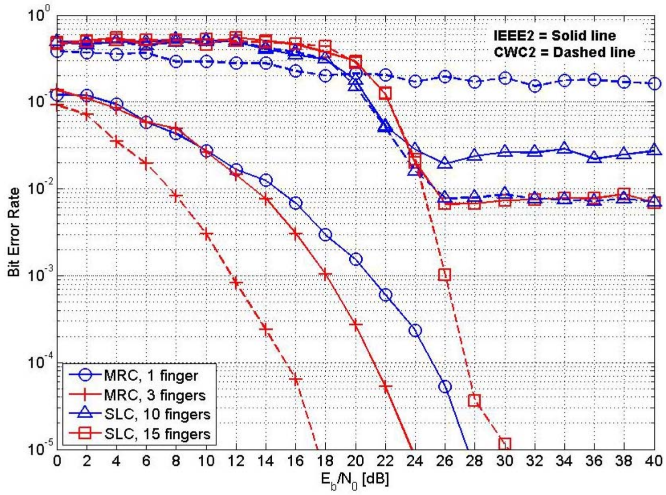

Figure 7. Performance of DS-UWB with R_b = 5.76 Mbps.

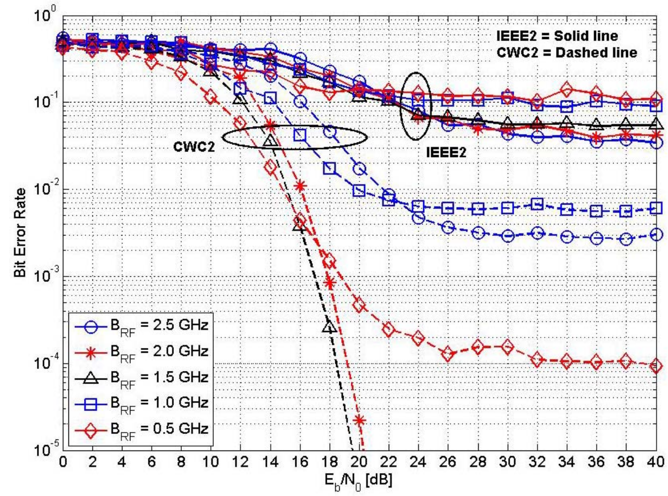

Figure 8. Performance of UWB-FM with R_b = 5.76 Mbps.