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Performance Assessment of IR-UWB Body Area Network (BAN) based on IEEE 802.15.6 Standard

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***Abstract*—Performance of impulse radio-based ultra-wideband (IR-UWB) communications in wireless body area networks are investigated using the dedicated IEEE 802.15.6 standard. An IR-UWB transceiver system is implemented for both on-off keying and differential binary phase-shift keying modulations. Bit error rates are determined from measurements for different on-body links with different data rates. It is shown that that using a 25 dB-gain LNA at the receiver, reaching an uncoded BER of 10^{-3} was not possible for some links operating at higher data rates. Power and energy consumption issues are then addressed and results in terms of required pJ/bit to achieve a certain quality of communication are given and discussed.**

***Index Terms*—Body area network, IEEE 802.15.6, impulse radio, ultra-wideband, energy consumption.**

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) technology can be used at a very low energy level for short-range, high data rate wireless communication. In recent years, an important UWB application is wireless body area network (WBAN), which consists in communications for healthcare, medical monitoring, and entertainment. To meet the requirements of WBAN, the architecture of IEEE 802.15.6 standard offers one common MAC layer with three PHY layers, including narrowband (NB) PHY, UWB PHY, and human body communication (HBC) PHY. In UWB PHY, the impulse radio ultra-wideband (IR-UWB) is a strong candidate for WBAN [1]. Thus, the performance of on-body IR-UWB communications based on the IEEE 802.15.6 PHY definition is investigated in this paper by means of uncoded bit error rate (BER). Furthermore, power and energy consumption issues are also addressed.

Section II describes the studied system model while section III shows measurement settings and results. Finally, section IV concludes the paper.

II. SYSTEM MODEL

Two operation modes are defined in the UWB part of IEEE 802.15.6 standard, the default mode and the high quality of service (QoS) mode. In the default mode, IR-UWB is defined as mandatory PHY with on-off keying (OOK) modulation. In the high QoS mode, IR-UWB is also mandatory with differential binary phase-shift keying (DBPSK) modulation. Thus, both OOK and DBPSK schemes are considered in this paper. One bit rate is defined as mandatory, namely 0.4875 Mbps. In addition to this bit rate, two higher bit rates, 1.95 Mbps and 7.8 Mbps, are implemented. One channel is defined as mandatory for the low band whose central frequency is 3993.6 MHz with 499.2 MHz bandwidth, which will be considered throughout the paper. This channel is compliant with indoor and outdoor regulation of most countries.

The system model is simulated with Matlab and then implemented in the test bench. The model includes transmitter and receiver communicating pairs. The overall scheme includes a transmitter sending bit sequences modulated with bursts of pulses and a receiver receiving the signal that has propagated through the channel. Real channels for different links on the human body are used in measurement.

A. Transmitter for OOK and DBPSK

The OOK modulation strategy assigns b information bits from an alphabet of size $M = 2^b$ with a coded-pulse sequence of length $2b$ from a code set alphabet of the same size [2]. The mandatory symbol mapper is set with $b = 1$, which corresponds to $M = 2$. Then the pulse shaping shall place a pulse waveform when the input bit is 1. Thus, the transmitting signal is given by

$$x(t) = \sum_{n=0}^{2b-1} d_n^m w(t - nT_{sym}/2 - mbT_{sym} - h^{2bm+n}T_w) \tag{1}$$

where d_n^m is the n^{th} codeword over the m^{th} transmitting symbol, T_{sym} is the symbol time, h^j is a time hopping sequence and $w(t)$ is the pulse waveform with pulse duration T_w. The chirp pulse shape with 500 MHz bandwidth is used.

The DPSK modulation is differentially encoded such that the transmitting symbols are given by

$$c_m = c_{m-1}\exp(j\varphi_m) \tag{2}$$

where c_m represents the m^{th} differentially encoded symbol, $m = 0, 1, \ldots, N-1$ and $c_{-1} = 1$. Such symbol carries either one bit of information (DBPSK) or two bits of information (DQPSK). In this paper, only DBPSK is taken into

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consideration.

After the generation of DBPSK symbols, the pulse shaping shall place a pulse waveform according to the UWB symbol structure. Then the transmitting signal is given by

$$x(t)=\sum_{m=0}^{N-1} c_m w(t-mT_{sym}-h^{(m)}T_w) \tag{3}$$

where c_m is the m-th transmitting symbol and $h^{(m)}$ is a time hopping sequence. There is no mandatory pulse shape in this standard. During the study, both chirp and short pulses burst have been tested and found to give similar results. So only short pulse-based results are presented in the following.

B. Description of Receivers

The receiver for OOK modulation is based on energy detection (ED) and its decision variable is expressed as [4]

$$w_n^{(m)}=\int_q^{q+Tw} r(t)^2\,dt \tag{4}$$

where $r(t)$ is the received waveform. q corresponds to the start position of the n^{th} codeword in the m^{th} symbol which is equal to $nT_{sym}/2 + mT_{sym} + h^{2m+n}T_w$. The decision on the m^{th} received bit is based on the comparison between the decision variables $w^{(m)}$. During one symbol time duration, if the integrated energy in the first received time slot is larger than in the second working slot, the received bit is zero. Otherwise it is one.

The receiver for DBPSK modulation is based on cross correlation. The decision variable is the cross correlation value of two adjacent pulses. It uses the previous received pulse burst to check the phase change without using locally generated signal sequence as reference. The decision variable can be presented as

$$v^{(m)}=\int_p^{p+Tw} r_m(t)r_{m-1}(t)\,dt \tag{5}$$

where p corresponds the start position of the m^{th} symbol which is equal to $mT_{sym}+h^{(m)}T_w$. If the decision variable is larger than zero, the received bit is detected as zero, otherwise it is one.

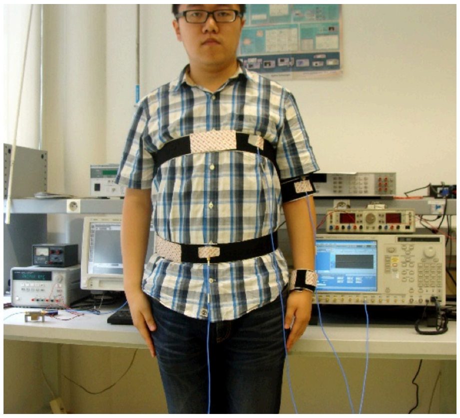


Fig. 1. On-body measurement experiment.

III. MEASUREMENT

A. Measurement Setting

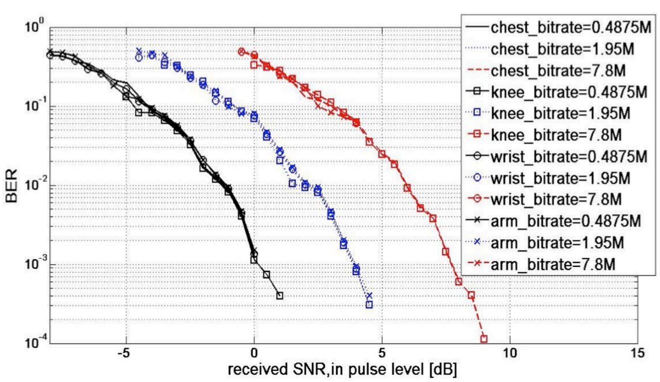
To assess the performance of on-body communications in real indoor propagation environment, measurements are conducted in a 7.5m x 9.5m laboratory room furnished with tables, chairs, computers, and other office equipment. The measurement system consists in an arbitrary waveform generator (Tektronix AWG7122B), a digital oscilloscope (Agilent DSO91204A), a low noise amplifier (LNA: Transcom TA010-180-30-15), and a control computer with Matlab.

The transmitted waveform is generated by Matlab and sent to the AWG. The AWG is used for waveform generation with a sampling rate of 12 GSa/s and an output power of -18 dBm. Transmitting antennas are then fed with a 2-meter long coaxial cable. The transmitted signal has a 3.99 GHz central carrier frequency.

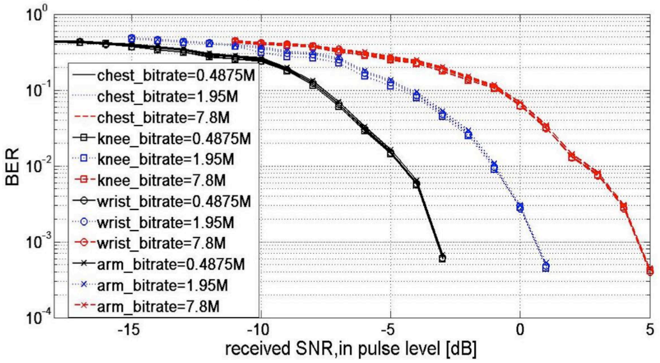
The received signal at RX antenna position is amplified by the LNA connected to a 3 dB attenuator in order to provide a 25 dB gain at 4 GHz with a noise figure worse than 6 dB. Compared with available LNAs suitable for UWB BAN applications [3], this performance seems reasonable. The noise power at the receiver is about -50.6 dBm for the 500 MHz channel. Then the amplified signal is directly sampled using the scope with a sampling rate of 12 GSa/s and sent to the computer. The signal stored in the computer is firstly filtered by an ideal 5th order Chebyshev bandpass filter with 500 MHz bandwidth and then synchronized by correlation with the original transmitted signal waveform. Finally receiver models are used to perform demodulation according to the considered modulation scheme (OOK or DBPSK). For each link, one measurement cycle tests 10^5 bits and is repeated about 50 times. Results are then averaged in order to calculate the BER.

The body area network under study consists in a set of nodes, which is supposed to monitor health-related parameters, like heart rate, blood pressure, temperature, movements… To meet these application requirements, four nodes are deployed in chest, upper arm, wrist and knee with a hub on the waist [4]. Consequently, four links are investigated, between the waist and the other nodes. During the study, the subject under test stands up and remains in a relatively still position.

Wideband monopole antennas (Skycross SMT-3TO10M) are used for both transmission and reception. These antennas are quasi-omnidirectional with 3.1-10.6 GHz bandwidth and about 0 dBi gain at 4 GHz. They are directly attached on the body by a belt about 3-5 mm above the skin. The radiated polarization is consequently mainly tangential to the body. Although this polarization suffers from higher path-losses compared to the orthogonal one, this antenna orientation is the most practical from user's perspectives. The TX antenna is located at the waist whereas the RX antenna is successively located on the different node locations. Like in previous studies [5,6], the interference from the cables was found to be negligible. A picture of the set-up is shown in Fig. 1 where TX and RX antenna locations are visible (except the knee location). The subject under test is an adult, male, whose height is 1.80 meters and weight is 81 kg.

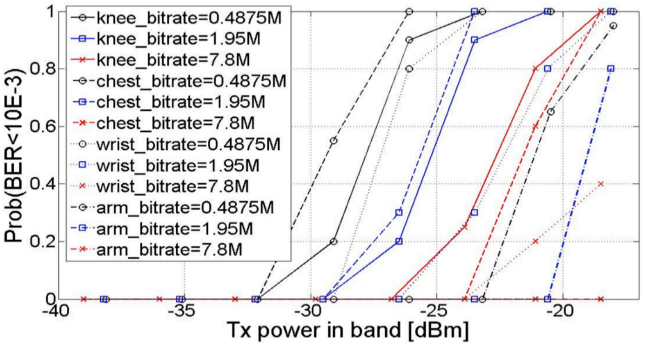


(a) OOK modulation

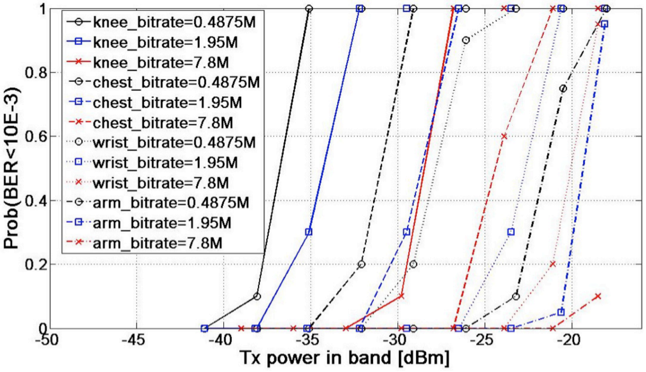


(b) DBPSK modulation

Fig. 2. Measurement performance: BER versus received SNR.



(a) OOK modulation



(b) DBPSK modulation

Fig. 3. Performance of detection capability for different links.

B. Performance Analysis

The performance of on-body communication is firstly evaluated in terms of uncoded BER versus received SNR in pulse level. Fig. 2a and Fig. 2b show measurement results for different links and bit rates for OOK and DBPSK modulation respectively. When comparing BER performances between OOK and DBPSK, it is noted that DBPSK outperforms OOK by approximately 3 dB, which is consistent with theoretical calculation [7]. The lowest data rate is presented in black curve with circle marks. For the next blue curve with square marks and red curve with cross marks, the data rate is four times higher compared to the previous one, and this decreases by approximately 4 dB the performance in between each data rate.

The probability that the BER is less than 10^{-3} for different links and bit rates is investigated for different TX power values. TX power is varied using different combinations of attenuators at AWG's output. In that way, the full dynamic of generated signals is maintained. Results are shown in Fig. 3a for OOK modulation and in Fig. 3b for DBPSK. For each link, the lower bit rate needs lower transmitted power than higher bit rate to reach a given probability. It is therefore possible to use lower power consumption to realize a robust communication. The wrist link and arm link work worse because antennas are attached on the side of body and no direct propagation path exists (non light-of-sight conditions). The knee link has the best performance and outperforms the chest link which suffers slightly from belly shadowing. While comparing results from Fig. 3a and Fig. 3b, one has to take into account that because of the time duration required to perform all the measurements, OOK and DBPSK performance have been measured over two consecutive days. Consequently, antenna positions and subject's body orientation could not be kept strictly unchanged. Indeed, knee and chest performances are more similar in the OOK scenario than in the DBPSK scenario. Slight changed in the antenna positions, which would have more or less emphasized the belly shadowing, could explain this. Due to the limitation of the AWG, the transmitted power in band can only reach -18 dBm whereas the regulation limit is -15 dBm for a 500 MHz band. So there is a 3 dB room to improve these results, of course at the expense of higher power consumption. However, it is noticeable that achieving BER < 10^{-3} will be difficult for highest bit rates (considering a 25 dB gain LNA).

While it is clear from Fig. 3 that using lower bit rates leads to using lower TX power, it does not necessary mean lower energy consumption. The duty cycle to transmit a given data must also be taken into account. In BAN, each sensor having a limited battery size, energy aspects become a critical issue. The TX power should naturally be high enough to reach a given SNR but the energy consumption should be kept as low as possible at the same time. That is why the different bit rates are now investigated in terms of TX energy consumption. Taking into account performance of IR-UWB transmitters

TABLE I
ENERGY PER BIT OF TX

(OOK/DBPSK)	0.4875Mbps	1.95Mbps	7.8Mbps
Chest link	91.1pJ/48.9pJ	54.6pJ/25.0pJ	45.3pJ/20.2pJ
Knee link	114.8pJ/12.8pJ	57.2pJ/6.43pJ	40.4pJ/5.70pJ
Wrist link	162pJ/128pJ	169pJ/101pJ	NA/40.3pJ
Arm link	776pJ/691pJ	NA/194pJ	NA/NA

available in the literature [8]-[9], a total efficiency of 4% for the transmitter is considered.

Table I shows the minimum TX energy per bit required at the transmitter to reach a 90% probability that BER is less than 10^{-3}. Results are given for the three investigated bit rates and for both modulation schemes. Although results are given for all links, it is to be noted that reaching 90% probability that BER $< 10^{-3}$ was not possible for some bit rates for wrist and arm links in OOK scenarios, and for arm link in DBPSK scenarios. Overall, it can be observed that OOK modulation needs more energy than DBPSK to achieve the same performance. So from a transmitter point of view, DBPSK outperforms OOK. However, if both TX and RX were to be considered, conclusions could be different since DBPSK needs to sample received signals, which is energy consuming. Nevertheless, if the receiver is a central unit (presumed larger and more powerful, like smartphone-type), using DBPSK modulation could be an interesting option in order to keep node's complexity as low as possible while the receiver's digital processing is performed into the central unit. Table I also shows the great heterogeneity in the results. In fact, the lowest energy per bit is achieved at 5.70 pJ/bit for the knee link with the highest bit rate and DBPSK modulation whereas the highest energy is 776 pJ/bit with the lowest bit rate and OOK modulation. So a factor of 136 exists between these links. Consequently, designing a unique versatile solution for transmitters appears to be a non-easy task and an optimization depending on the type of link may have to be conducted.

IV. CONCLUSION

In this paper, we have presented measurement results using a transceiver system following the IEEE 802.15.6 IR-UWB PHY definition with OOK and DBPSK modulations. Performance is compared for different links with different bit rates. For each link, lower bit rates need lower transmitted power than higher ones to reach a given BER value. However, higher bit rates remain more energy efficient even if it is more difficult to reach an acceptable probability for the BER to be less than 10^{-3} for instance. In fact, considering UWB density power regulation and specific propagation issues related to the human body (NLOS conditions, body absorption…), achieving robust on-body communications appears to be rather challenging. In particular, it has been shown that over 25 dB gain LNAs are required even for quasi-still positions of the human body. This fact consequently raises the issue of energy consumption in IR-UWB BANs for mid/long term applications, especially if small sensors, with limited room for the battery, are considered. Furthermore, as perspectives of this study, additional experimentations are required in order to investigate the effect of the subject's mobility on the performance and on the energy consumption. Also, different subjects (male/female/child) with various morphologies (small, tall, etc.) need also to be considered in order to draw more global conclusions.

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