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Performance of UWB Impulse Radio With Planar Monopoles Over On-Human-Body Propagation Channel for Wireless Body Area Networks

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Abstract—Ultrawideband (UWB) is a promising technology for wireless body area networks (WBANs). This paper studied the impacts of 3.1–10.6 GHz on-human-body UWB channel on the impulse radio WBAN system. A performance evaluation method is presented for the realistic UWB WBAN systems, which observes the waveform distortion along the signal path. The measurement and characterization of the 3.1–10.6 GHz on-human-body UWB channel are devised to generate the radiographs of path loss and delay spread for the first time. The performance of the UWB impulse radio WBAN transceiver in terms of bit error rate (BER) is evaluated based on the waveform distortion and on-human-body channel measurement, which shows the human body effect is more significant than the environment effect, especially when the propagation channel contains no line-of-sight path. Various candidate pulse shapes and modulation schemes for UWB WBAN are studied and their performances with the measured WBAN channel are evaluated and compared.

Index Terms—Bit-error rate (BER), body area network (BAN), impulse radio (IR), modulation, on-human-body channel, pulse shape, radio propagation, ultrawideband (UWB).

I. INTRODUCTION

A BODY AREA network (BAN) is a network with its nodes placed close to the body on or in everyday clothing [1]. A WBAN employs wireless technology to realize the connectivity among nodes [2], which is proposed for a wide range of lifestyle and medical applications. The emerging UWB impulse radio (IR) is a promising technology for WBAN due to its low power and wideband characteristics [3]–[5]. According to the FCC regulations that approved the use of UWB in USA, the mean transmit power of these devices must not exceed -41 dBm/MHz from 3.1 to 10.6 GHz [6]. Simultaneously, the wideband nature of the UWB technology permits a fine time resolution. It is particularly beneficial to biomedical applications, e.g., health monitoring, human body probing, real-time diagnosis, etc. [7], [8], which basically require low transmit power together with fine time-resolution. All of these features make UWB an ideal candidate for WBAN applications.

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Since the WBAN devices are attached and operate around the human body, the human body effect becomes a crucial part of radio propagation channel. Measurements and characterization of the on-human-body channel are essential for the investigation. Furthermore, the impacts of on-human-body channel on the performance of the overall WBAN transceiver are highly demanded in the WBAN system design and implementation.

The UWB antenna and channel characterization considering human body effects were conducted for wireless personal area network (WPAN) applications [9]–[11]. The effect of the body on UWB signal propagation was measured for one antenna placed on the body and the other antenna kept away from the body. There are only a few papers that report channel measurements and modeling with both transmit and receive antennas placed on the body for WBAN applications [12]–[22]. Review of these studies shows that no measurement and modeling that cover the whole UWB band from 3.1 to 10.6 GHz has been made. Also, the reported channels were all sparsely sounded on a few pre-defined points. The important statistical characteristics of the channels had to be extracted from the limited number of samples or FDTD simulations.

The impact of on-human-body channel on the overall UWB impulse radio WBAN system is not clear. As the operation band covers several gigahertz range, the frequency selective fading of the channel leads to a comprehensive effects on the overall WBAN system. There is very few paper dealing with this kind of issues currently.

This paper presents the study of on-human-body UWB channels for WBAN applications, which contains two part of works: the characterization of the channel itself, and the impact of the on-human-body channel on the whole UWB impulse radio WBAN system.

Section II discusses a UWB impulse radio WBAN system with various candidate monocycle pulse shapes and modulation schemes. A realistic system BER evaluation method based on waveform distortion analysis is studied. Section III presents the measurement and characterization of on-human-body channel for the spatial domain. Based on the method discussed in Section II and the measurement results obtained in Section III, the overall UWB impulse radio WBAN system performance with on-human-body channel is evaluated, the result is summarized and discussed in Section IV. Section V concludes the study of on-human-body UWB channel presented in this paper.

II. UWB IMPULSE RADIO WBAN

UWB impulse radio is basically a time-domain method employing discrete monocycle pulses for data transmission. There-

Fig. 1. Flowchart for analyzing waveform distortion and system performance considering on-human-body WBAN channels. In this case, the separation of channel and antennas is not practical, transfer function $G(f)$ is the comprehensive effect including transmit antenna, on-human-body channel and receive antenna.

fore, the pulse shape and modulation scheme affects the system performance directly. For binary modulation, there are three widely proposed schemes: pulse position modulation (PPM) [3], phase-shift keying (PSK) and on-off keying (OOK) [23]. The binary antipodals (bi-phase) PSK and OOK are actually also special cases of pulse amplitude modulation (PAM). As stated in [20], the OOK can be very robust for UWB WBAN system. All of these three schemes require correlation-based demodulation, where the received monocycle is multiplied by the template monocycle and then integrated for a binary decision. If the pulse shape is not distorted by the channel, BER performance of BPSK and OOK will keep independent to the pulse shape employed. BER of PPM is always dependent to the pulse shape, thus pulse shape design is necessary for PPM [24].

However, the received pulse shape is inevitably distorted by the varied frequency responses of realistic UWB system. As there is 7.5-GHz bandwidth for UWB operation, it is not possible to maintain a flat frequency response. The frequency selective fading leads directly to waveform distortion. As a result, BER performance of these UWB modulations will be degraded and depend on the received (and thus transmitted) pulse shapes. In a WBAN scenario, the most crucial part along the signal path that results in waveform distortion is the on-human-body channel, in which fluctuation of wideband channel characteristics is inherently decided by physics.

To obtain the received waveform in a real WBAN scenario, it is convenient to use frequency domain method as the specifications and measurements of real components are normally given in the frequency domain. The analysis methodology is shown in Fig. 1. The transmitted pulse shape is firstly converted to frequency domain by Fourier transform, thus effects of on-human-body channel modeled by transfer function $G(f)$ can be used to calculate received waveform in frequency domain, the received time-domain signal can be obtained by inverse Fourier transform. Note that separation of WBAN channel and antennas is not possible in this kind of scenarios, so the transfer function $G(f)$ is the comprehensive effect including transmit antenna, on-human-body channel and receive antenna. The performance of overall UWB WBAN system can be evaluated in terms of BER with the received waveform.

Fig. 2. Waveform of Gaussian second derivative (Scholtz's pulse) in the time domain. The amplitude of the waveform is normalized to 1 V. The duration is about 0.37 ns and -10 dB bandwidth is about 7 GHz.

As the BER analysis is deterministic, it is desirable to find the most typical and representative channel characteristics for the evaluation. Various modulation schemes and pulse shapes transmitted need to be compared under the given representative WBAN channels.

The impulse radio WBAN with three transmitted pulse shapes are evaluated: Gaussian first-order derivative, Gaussian second-order derivative and rectangular pulse. The Gaussian derivatives are proposed in terms of their ultrawideband power spectrum density. In particular, Gaussian second-order derivative, as used by Scholtz and colleagues, achieves best BER performance in ideal case where perfect synchronization is assumed and only AWGN channel is considered [24]. The Gaussian derivative pulse can be represented as

$$w(t) = A \left[1 - 4\pi \left(\frac{t}{\tau} \right)^2 \right] \exp \left[-2\pi \left(\frac{t}{\tau} \right)^2 \right] \quad (1)$$

where τ is the time constant which controls the pulse duration and resultant bandwidth. Fig. 2 shows the waveform of a Gaussian derivative whose duration in the time domain is about 0.37 ns and -10 dB bandwidth in the frequency domain is about 7 GHz.

The rectangular pulse is easy to realize in terms of hardware complexity and power consumption, the latter is a basic requirement for battery-powered WBAN devices.

In this paper, Binary PPM, PSK, and OOK modulations are compared. From the viewpoint of communication theory, OOK is always 3-dB less power efficient than binary PSK. But OOK demodulation can be very simple in hardware [20], the received waveform can be used also as the template monocycle for demodulation, thus, OOK demodulation becomes a process of energy detection. The BER to be obtained for OOK in this paper is based on energy detection, where the BER result does not depend on the received waveform.

III. MEASUREMENT AND CHARACTERIZATION OF UWB ON-HUMAN-BODY CHANNEL

Radio propagation channel measurement and characterization have always been recognized as having an important part to play in the development of complex wireless networks. This is particularly true for UWB radio [11], [25]–[27].

Fig. 3. The antenna used in the measurement of on-human-body channel. It is made in silver on a 0.8-mm thick substrate with $\epsilon_r = 5.9$.

The channel measurements were devised to generate the radiographs of path loss and delay spread for the first time. The channel parameters as path loss and delay spread are extracted and the statistical distributions of the channel variations are determined from the radiographs. Considering that a human body has a finite size, we conducted channel measurements on and in close proximity to the body at a much higher spatial resolution. The sampling distance was set to be 2 cm, which is shorter than the minimum wavelength within the frequency range [12]. We believe that these measurements represent the most extensive set of publicly reported measurements taken to characterize on-human-body UWB radio channel.

A. Description of Measurements

The measurements were carried out using a 40-GHz HP ES-8510 network analyzer. The antennas used in the measurements were two planar monopoles [28]–[30]. The shape and geometry of the antennas are shown in Fig. 3. The antennas are made in silver on a $\epsilon_r = 5.9$ substrate. Fig. 4 shows the measured antenna return loss on and off the human body. As shown, the antenna return loss is above -10 dB from 3.1 to 3.5 GHz and is below -10 dB from 3.5 to 10.6 GHz for the off-body case. The antenna return loss is improved to below -10 dB for the on-body case over the entire UWB band. This is due to the lossy nature of the body. Fig. 5 shows the measured antenna far-field radiation patterns for both E- and H-planes at the UWB central frequency 6.85 GHz. It is seen that the antenna has an omnidirectional radiation pattern in the E-plane and an ∞ shaped radiation pattern in the H-plane. It is known that the antenna radiation patterns will change when it is placed on the body [18], [20], [21], [31]. Unfortunately, the change cannot be measured with our testing facilities. The WBAN device in the real scenario suffers also from the unstable antenna radiations, as a result, such effects can not be ignored in the measurement.

The setup can measure the transfer function of the channel. The amplitude loss and phase shift of each frequency component caused by the channel is recorded. With 4.6875 MHz

Fig. 4. The antenna and its measured return loss. The antenna return loss is improved to below -10 dB for the on-body cases over the entire UWB band due to the lossy nature of the body.

steps, 1601 frequency points were recorded over the frequency range of 3.1–10.6 GHz. That is, a multipath with a time delay up to 213 ns can be detected, which is suitable for indoor environments [32]. The time domain resolution corresponds to the ability to resolve two closely spaced responses. For UWB channel sounding, the time domain resolution is important and critical due to narrow pulses, consequently, a minimum window is desirable [27]. Using the minimum window, one can find the time domain resolution to be 133 ps.

The measurements were conducted in both anechoic chamber and a staff lounge room. The latter is a typical indoor environment with size of $8 \times 8 \times 4$ m. The main rationale of choosing the staff lounge room and the anechoic chamber was to investigate the influence of the environment and to expose the impact of the human body on the UWB signal propagation.

The measurements were made on or in close proximity to each body. During the measurements, the person under test was to stand straight and upright at a fixed location and the transmit antenna was placed on the right upper arm near the shoulder. The transmit antenna placed there because a longer path and a better human safety are offered. Fig. 6 shows the defined points to generate the radiographs of path loss and delay spread. The receive antenna was placed to each point to collect the data. The horizontal step of these points is 8 cm and the vertical step is 2 cm. Note that not all the Rx points are placed on the body, a cylindrical distribution of test points are performed, with the perimeter of 1 m to make most test points in trunk placed on the body.

The measured result is severely related to the orientation of antennas. In this measurement campaign, the plates of both transmit and receive antennas were placed in parallel to the nearest skin of human body. This is because that WBAN devices need to be wearable in most scenarios, the space between paralleled antenna and skin is around 0.5–1 cm. The transmit antenna was fixed on clothes of right upper arm. At the point of measurement, the receive antenna was carefully rotated within the parallel plane to the body to minimize polarization loss with

Fig. 5. The antenna measured radiation patterns at 6.85 GHz. It has an omnidirectional radiation pattern in the E-plane (the YZ plane) and an ∞ shaped radiation pattern in the H-plane (the XZ plane). (a) E-plane (the YZ plane). (b) H-plane (the XZ plane).

respect to the transmit antenna. In real scenarios, further link degradation may be observed.

B. Statistical Parameters of the Channel

A total of 2930 frequency transfer functions were recorded of which 2730 were recorded in the staff lounge room and 200 in the anechoic chamber. Each frequency transfer function consists of 1601 frequency points.

Fig. 7 plots the transfer function measured at test point A in both anechoic chamber and staff lounge room. The loss is

Fig. 6. Location of test points around human body. All test points form a cylinder with a 1-m perimeter.

relatively small in the staff lounge room due to the reflection paths by the environment, this is particularly clear at frequencies lower than 6 GHz. However, the fluctuations will certainly affect the system performance.

The path loss in decibel can be directly calculated from the measured transfer function of the channel as [11]

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

$H_j^d(f_i)$ denotes the j^{th} transfer function of the channel at a frequency f_i at a distance d . M is the number of transfer functions for the spatial distance d , and N is the number of frequency components in the transfer function of the channel [12], [14]. The average path loss can be expressed as

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

where PL_0 is the path loss at the close-in reference distance d_0 , n is the path loss exponent, and X_σ is the shadowing fading in

Fig. 7. Transfer functions at test point A in Fig. 6 in anechoic chamber and staff lounge room. The phase is unwrapped. The loss is relatively small and amplitude fluctuations is high in the staff lounge room due to environment reflections. (a) Magnitude. (b) Phase.

dB. We set d_0 to be 1 m for better comparison with available results and find the values for PL_0 , n , and X_σ from (2).

Fig. 8 shows the radiograph of channel path loss on and in close proximity to the body in an unfolded format. Note the ground level is at 0.2 m and the position of Tx antenna is (0, 1.2 m). The radiograph is generated from (2) based on the channel transfer functions measured in the staff lounge room. It clearly shows the qualitative information on the channel. From Fig. 8, the line-of-sight (LOS) region is located at the top two corners in the radiograph, which is mainly the side of the body near the transmit antenna. The non line-of-sight (NLOS) region is located from the top to bottom middle part of the radiograph, which is mainly the other side of the body away from the transmit antenna.

The radiograph also contains quantitative information on the channel. The channel path loss model parameters such as PL_0 , n , and X_σ defined in (3) can be extracted from it by performing a least square fit computation. Table I shows the extracted PL_0 and n values for various routes. It is known that the shadow fading X_σ is lognormally distributed around a mean of 0 dB for mobile and personal propagation channels. However, our extracted mean that varies from 0 to 0.9 dB and the standard deviation from 3.5 to 8 dB suggest that the shadow fading of UWB on-human-body propagation channel be likely not to be lognormally distributed. The measured results agree well with the models in a minimum range of 0.1–1 m. Path loss exponents given in [12] are 4.1 and 2.7 for the horizontal and vertical routes, respectively. They are quite closed to the results

Fig. 8. The radiograph of channel path loss on and in close proximity to the body. The unit of path loss is dB. The result is obtained by the measurements in staff lounge room. The position of Tx antenna is (0, 1.2 m).

TABLE I
EXTRACTED PL_0 AND n FROM RADIOGRAPH.

Routes	Front Side		Back Side	
	PL_0 (dB)	n	PL_0 (dB)	n
Vertical	-82	2.6	-82	2.9
Horizontal	-101	3.7	-93	2.8
Diagonal	-86	2.2	-84	2.7

here that are 3.7 and 2.6. Note that the larger path loss exponent for the horizontal route indicates more severe diffractions around the human body. The horizontal route can be considered as the most difficult propagation path for the WBAN channel.

The rms delay spread τ_{rms} can be calculated from channel impulse responses, which are obtained by inverse Fourier transform from the transfer functions. The root mean square delay spread τ_{rms} is the square root of the second central moment of the power delay profile and expressed as

$$\tau_{\text{rms}} = \sqrt{\frac{\sum_{k=1}^K \tau_k^2 h(p, \tau_k)}{\sum_{k=1}^K h(p, \tau_k)} - \left(\frac{\sum_{k=1}^K \tau_k h(p, \tau_k)}{\sum_{k=1}^K h(p, \tau_k)} \right)^2} \quad (4)$$

where $h(p, \tau_k)$ is the power delay profile obtained from measurement point p and scaled such that the first wave arrives at $\tau = 0$ in the profile. It is clear that strong echoes with long delays contribute significantly to τ_{rms} .

Fig. 9 shows the radiograph of channel rms delay spread on and in close proximity to the body in an unfolded format. The radiograph is generated from the transfer functions measured in the staff lounge room. Note that in the calculation, the threshold level of the signal should be carefully considered. Usually, the threshold level is set to be 30 dB down from the peak in the studies of radio propagation channels for cellular radio or wireless local area network applications. Here another approach is adopted. We consider a time interval from 0 to 100 ns to calculate $\bar{\tau}$ and τ_{rms} . This is because echoes from obstacles fade away after this time for WBAN applications.

Fig. 9. The radiograph of channel rms delay spread on and in close proximity to the body. The unit of rms delay spread is ns. The result is obtained by the measurements in staff lounge room. The position of Tx antenna is (0, 1.2 m).

The radiograph of channel rms delay spread contains both qualitative and quantitative channel information. As can be seen, the rms delay spread τ_{rms} is larger in the NLOS region and smaller in the LOS region. Since the rms delay spread values were not normally distributed, it was necessary to employ non-parametric statistical analysis. The statistics of the rms delay spread were compiled. The maximum value of the rms delay spread is 12 ns. The rms delay spread values are less than 6 ns 50% of the time and less than 9 ns 90% of the time. It is a very important parameter since the performance of wireless communications systems operating in multipath environments is very sensitive to the values of rms delay spread.

IV. UWB WBAN PERFORMANCE OVER ON-HUMAN-BODY CHANNEL

Based on the analysis in Section II, numerical simulation can be employed to evaluate the performance of the UWB WBAN over on-human-body channels.

The transfer functions of on-human-body channel are obtained from previous measurement. Only a few cases out of the 2930 transfer functions need to be selected to demonstrate the impact of on-human-body channel. According to the radiograph shown in Figs. 8 and 9, three representative cases are selected according to their path loss and rms delay spread characteristics.

- 1) The LOS component is dominant, the path loss and τ_{rms} are small, which occurs along or near right arm where the transmitting antenna is placed. The transfer function is obtained from point A in Fig. 6 (right side near hand).
- 2) Both LOS and NLOS components exist and they are comparable. The path loss and τ_{rms} are near average. This occurs at the front and back of the trunk. The transfer function is obtained from point B in Fig. 6 (front side near heart).
- 3) The NLOS component is dominant, the path loss and τ_{rms} are large. This occurs at the opposite (left) side of the body. The transfer function is obtained from point C in Fig. 6 (left side below hand).

The above three cases of on-human-body channel are evaluated in both anechoic chamber and staff lounge room. This highlights the impact of human body in different environments.

Fig. 10. BER performance of the UWB impulse radio WBAN over on-human-body channels in anechoic chamber and staff lounge room. Various monocyple pulse shapes and modulation schemes are presented and compared. (a) Point A in anechoic chamber. (b) Point A in staff lounge room. (c) Point B in anechoic chamber. (d) Point B in staff lounge room. (e) Point C in anechoic chamber. (f) Point C in staff lounge room.

The simulation setting and parameters used are the same as described in Section II. As rms delay spread values are less than 6 ns 50% of the time, 6 ns window in time domain is selected for monocyple duration, corresponding to a maximum data rate (chip rate) of 167 Mbps. Note that a more rigorous criteria of 9 ns (90% of the time) may be adopted for certain applications.

Fig. 10 shows the BER performance of the UWB impulse radio WBAN system over on-human-body channels in both anechoic chamber and staff lounge room. Various transmitted pulse shapes and modulation schemes described in Section II are presented. For better distinction and comparison, these BER results are categorized by their channel scenarios. It is clear that the BER performance is more sensitive to its position on human body (A, B, and C) than to the environment (anechoic chamber and staff lounge room), which indicates that the impact of human body is more significant than that of the environment.

Note that in Fig. 10, the E_b represents the bit energy of received waveform rather than transmitted waveform. This actually normalized the energy of received waveform and neglected the absolute value of path loss. The intention of using received bit energy E_b is to expose the unique impacts of human body on the WBAN radio propagation. Otherwise, the path loss dominates the channel characteristics, and the impact of human body

is less distinctive. It is predicted in this case that BER of OOK (energy detection) will be independent to the pulse shape distortion as well as the channel environment if path loss is not considered. This is shown clearly in Fig. 10.

The BER at each point in anechoic chamber and staff lounge room indicates the impacts of on-human-body channel on the overall UWB WBAN system. A clear trend is, the more propagation path involving body, the worse performance of the WBAN. From point A to point C, the LOS component decreases, more and more radio propagation relies on the human body. As a result, more and more performance degradation is observed in the whole WBAN system. The indoor propagation channel further degrades the BER comparing with result obtained for anechoic chamber.

It is notable that BER at point C is very poor even in the anechoic chamber where the indoor multipath is eliminated. Clearly, this is resultant from the human-body effects. At point C, the rms delay spread is approaching 10 ns. However, 6 ns window is selected as the monocycle duration. There is strong intersymbol interference that results in destructive BER degradation.

Review of these results shows PPM is very sensitive to the rms delay spread than PSK and OOK. It can be explained from its time-shift nature, which needs a longer chip time and thus higher probability of intersymbol interference. PSK is a slightly better choice than PPM in most cases, especially when higher rms delay spread presents (e.g., at point B). The energy detection method of OOK is less sensitive to the channel environment, and can be the most power-efficient way under very high rms delay spread (e.g., at point C). But OOK is less superior when the LOS components dominate the channel.

The efficiency of modulation scheme also depends on the pulse shape. It seems that the result is case by case, there is not a pulse shape in certain modulation that can perform best for different channel environments. However, if OOK is employed, rectangular pulse should be selected for its advantages in hardware implementation.

V. CONCLUSION

In this paper, we studied the ultrawideband on-human-body channel for wireless body area networks, including the characterization of the on-human-body UWB channel and its impact on the UWB WBAN system performance in terms of bit-error rate. The channel characterization was based on the measurement in indoor and anechoic chamber environments. The radiographs of path loss and delay spread were generated for the first time, which contain both qualitative and quantitative channel information. The results show that the path loss exponent was around $2.7 \sim 3.7$ and the maximum value of the rms delay spread was 12 ns. The rms delay spread values were less than 6 ns 50% of the time and less than 9 ns 90% of the time. The impact of on-human-body channel on the overall UWB WBAN system was analyzed through the waveform distortion. Regarding the overall system performance, the result shows that the human body effect is more significant than the environment effect, especially when the propagation channel contains no LOS path. Various candidate monocycle pulse shapes and

modulation schemes were compared, showing that PPM is very sensitive to rms delay spread and OOK is less sensitive to channel environments. The most suitable pulse shape depends on the modulation schemes employed and should be studied case by case.

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