

Towards sparse characterisation of on-body ultra-wideband wireless channels

Xiaodong Yang¹ ✉, Aifeng Ren¹, Zhiya Zhang¹, Masood Ur Rehman², Qammer Hussain Abbasi³, Akram Alomainy⁴

¹School of Electronic Engineering, Xidian University, Shaanxi, Xi'an 710071, People's Republic of China

²Centre for Wireless Research, University of Bedfordshire, Luton, LU1 3JU, UK

³Department of Electrical and Computer Engineering, Texas A&M University at Qatar, Doha 22880, Qatar

⁴School of Electronic Engineering and Computer Science, Queen Mary College University of London, E1 4NS, UK

✉ E-mail: xiao_dong_yang@hotmail.com

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With the aim of reducing cost and power consumption of the receiving terminal, compressive sensing (CS) framework is applied to on-body ultra-wideband (UWB) channel estimation. It is demonstrated in this Letter that the sparse on-body UWB channel impulse response recovered by the CS framework fits the original sparse channel well; thus, on-body channel estimation can be achieved using low-speed sampling devices.

1. Introduction: Body-centric wireless communications (BCWC) will be a focal point for future communications from an end-to-end user's perspective [1]. Ultra-wideband (UWB) communication is a low-power, high-data-rate technology with large bandwidth signals that provide robustness to jamming and have a low probability of detection [2]. For BCWC, long battery life is necessary; therefore, UWB, which has low power transmission characteristics, is a good candidate for BCWC. An understanding of the radio propagation environment is critical for designing UWB transceivers. Therefore, UWB channel modelling, which plays a key role in understanding the propagation environment [3–5], has caused extensive concern. For BCWC, a UWB radio channel is typically measured in two ways: frequency domain using a frequency sweep technique and time domain using a narrowband pulse [6]. Both of these methods have their specific advantages and disadvantages; however, the issue regarding channel estimation for BCWC has been focused on intensively and extensively. For frequency domain technique, high-end vector network analyser (VNA) is necessary to guarantee measurement accuracy and range. On the other hand, in the time domain UWB system, a high-rate analogue-to-digital converter (ADC), which is very expensive and power consuming, is an important device for ensuring the normal running of systems. All these factors drive researchers to further study the UWB channel estimation technique for BCWC.

For on-body UWB communications, it has been demonstrated that most of the energy is received via the direct path, with some multipath reflections at a later time [7–9]; this indicates that the delay spread is very large and the number of paths is small. Such kind of propagation characteristic provides us the prerequisite for estimating the UWB on-body channel using the new approach since the channel has the property of sparsity. By solving the l_1 -regularised problem presented in [10], the impulse response of the channel can be obtained. The solving process is based on the compressive sensing (CS) framework originally proposed by Candes *et al.* [11]. With the success of sparse UWB channel estimation for on-body scenario, the cost of measurement is significantly reduced; thus, the UWB channel measurement idea for BCWC is further updated.

The paper is organised as follows. Section 2 gives a brief introduction of CS; Section 3 accomplishes the sparse UWB on-body channel estimation using the CS framework; Section 4 draws some conclusions from the study.

2. Basics of CS framework: Generally, to recover a signal, the sampling rate must be twice the maximum frequency present in the signal [12]. Candes *et al.* [11] pioneered a new theory of sampling; under his theory, Shannon's theorem was surpassed and proven that it does not apply in all cases. In this section, CS is briefly introduced according to his framework. Suppose discrete time signal $x \in R^{N \times 1}$ can be expressed using an orthonormal basis $\Psi = [\psi_1, \psi_2, \dots, \psi_N]$, which can be written as

$$x = \sum_{i=1}^N \psi_i \theta_i \quad (1)$$

where θ is a vector with many zero components. Writing it using matrix notation, we obtain

$$x = \Psi \theta \quad (2)$$

The precondition for applying compressive sampling reconstruction process is that the signal x should be sparse for the basis Ψ .

Suppose the sparsity of the vector is K ($K \ll N$), the signal x can also be written as

$$x = \sum_{k=1}^K \psi_{i_k} \theta_{i_k} \quad (3)$$

where θ_{i_k} are coefficients. According to Candes' theory, the sampling rate can be reduced to sub-Nyquist rate. For signal x , we can find its M linear measurements

$$s = \Phi x, \quad \Phi \in R^{M \times N} \quad (4)$$

Here, each line of Φ can be seen as a sensor, and by multiplying it with the signal, a part of information of the signal is collected. With M measurements and Φ , we can reconstruct the original signal. In short, the basic framework of the compressive sampling is

$$s = \Phi x = \Phi \Psi \theta \quad (5)$$

where Φ is an $M \times N$ measurement matrix ($M \ll N$), Ψ is an $N \times N$ matrix, θ is a vector with K non-zero components in the basis Ψ and s is the measurement signal. The near-perfect reconstruction is

based on the strict l_1 optimisation problem presented in the following equation:

$$\min_{\theta^* \in R^M} \|\theta^*\|_{l_1} \quad \text{s.t.} \quad s = \Phi\Psi\theta^* \quad (6)$$

Kim *et al.* [10] developed an interior-point l_1 reconstruction algorithm; in this Letter, we used the algorithm presented in [10] to recover the signal.

3. Sparse on-body UWB channel estimation using CS framework:

In recent years, some works have been done on the system-level modelling for UWB BCWC [8, 13]; in [8], the authors tried to investigate the effects of on-body channels on UWB systems using different pulse modulation techniques. On the basis of the idea shown in [8], the novel on-body UWB channel estimation approach is actually an inverse problem. We try to explore the way of predicting UWB BCWC channels without performing experimental measurement campaigns. It is noted that a prerequisite for applying the CS framework is that the impulse response of the BCWC UWB channel is sparse. On the basis of the literature review, UWB channels for on-body scenario meet the sparse characteristics. For on-body UWB communications, it has been demonstrated that most of the energy is received via the direct path, with some multipath reflections at a later time [7–9]; this indicates that the delay spread is very large and the number of paths is quite small. Such kind of propagation characteristics lead to the sparsity of the impulse response of the channel, which is essential for the on-body UWB channel characterisation. The objective of this work is to recover the sparse impulse response of the on-body UWB channel by applying the similarity between the communication process and the CS framework.

At the transmitting terminal of the UWB system, the signal is composed of a pulse sequence. The duration for each pulse is very short; the mathematical expression for the transmitting signal is [14]

$$s(t) = d(t) \otimes p(t) \quad t \in [0, T_s] \quad (7)$$

where T_s is the transmitting interval, $p(t)$ is the monopulse and $d(t)$ is the pulse excitation. The excitation signal can be modelled as $d(t) = \sum_{i=1}^N d_i \delta(t - \tau_i)$, and $\{d_i, \tau_i\}$ represents the magnitude and phase of the i th pulse, respectively. We decompose the problem of sparse on-body UWB channel estimation into two parts: without on-body channel and with on-body channel. In the first part, it is assumed that the channel is ideal.

3.1. Part 1: Binary sequence reconstruction using compressive sampling UWB system without considering radio channels: In [15], acquiring and reconstructing signals can be achieved by

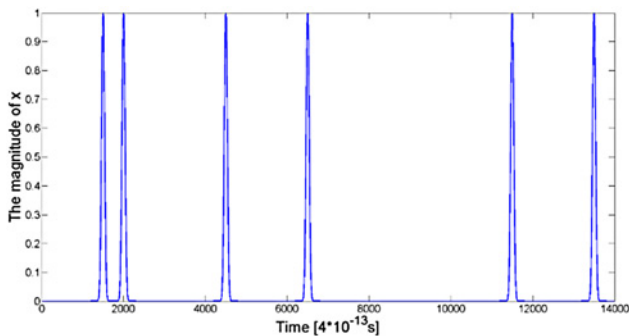


Figure 1 Random sparse signal for the CS framework

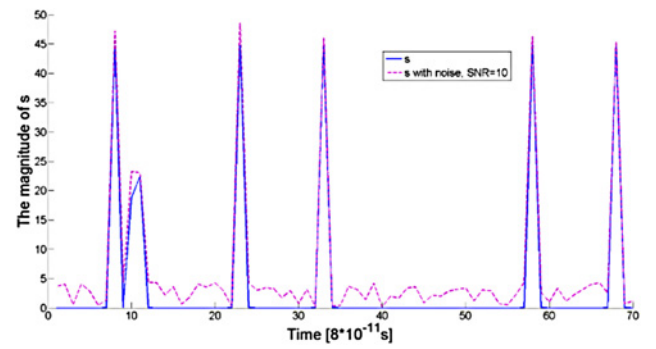


Figure 2 Output of ADC

using a fixed finite impulse response (FIR) filter-based system; it is found that the FIR filter-based system can be modelled as a CS framework. By considering the convolution operation and the FIR filter in the UWB system, the problem can also be likened to a basic CS framework.

Considering an FIR filter h with length B , we use x to denote the signal, which is about to enter the filter and s to denote the signal after the ADC. It is noted that the symbols used here consist of the symbols presented in Section 2. In mathematics, FIR filter and ADC are modelled as the convolution between h and x :

$$s = h \times x \quad (8)$$

Comparing (8) with (4), we can obtain the measurement matrix Φ . In addition, (8) should be associated with (5) to match the basic CS framework; therefore, x is decomposed into the product of an orthonormal basis Ψ and sparse vector θ . In the system, θ is a random sparse binary sequence while Ψ is a Gauss wave sequence. Figs. 1–3 present the basic variables in the CS framework. In Fig. 1, sparsity-inspired random signal is given, which also represents variable x in the basic CS framework. The frequency for the binary sequence is 5 GHz; therefore the interval between two Gaussian pulses is $\Delta T = 2 \times 10^{-10}$ s. On the other hand, the minimal time interval used in the simulation is set to $\Delta T/500$ to achieve the discretisation of successive time. In addition, the width of the Gauss wave is $\sigma = \Delta T/10$. Fig. 2 shows the output signal of ADC in the UWB communication system. However, one should note that the time interval has changed to 4×10^{-8} s, which corresponds to the period of low-speed sampling. It is noted that the magnitudes are accumulated; this is due to the integral effect for every UWB communication. In Fig. 3, l_1 reconstruction algorithm was used to reconstruct the transmitted binary sequences; it can be seen that the recovered signals match the original signals very well, demonstrating the effectiveness of the reconstruction.

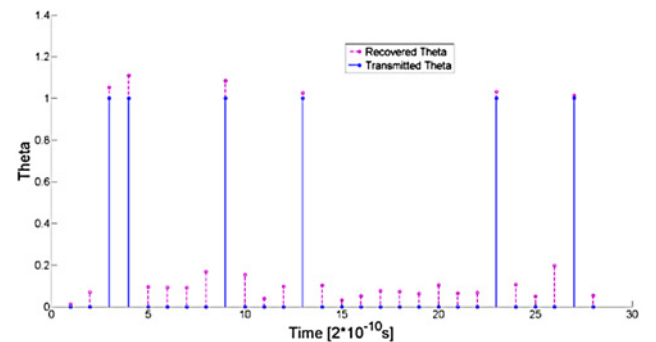


Figure 3 Comparison between transmitted binary sequences and recovered ones

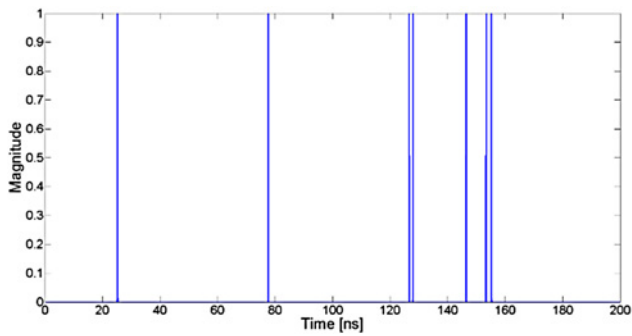


Figure 4 Random binary information

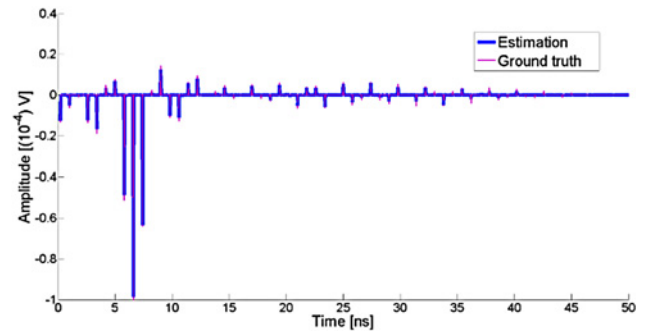


Figure 7 Comparison between the real sparse body-surface IR and the recovered sparse body-surface IR

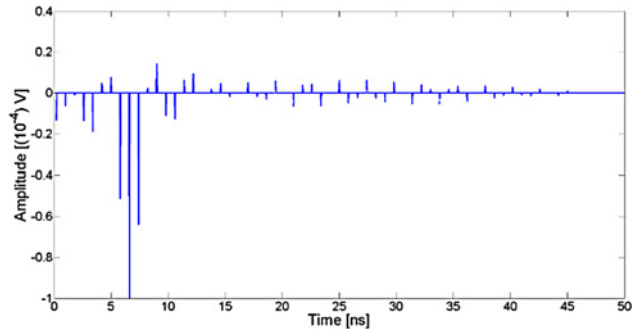


Figure 5 Sparse body-surface UWB channel impulse response

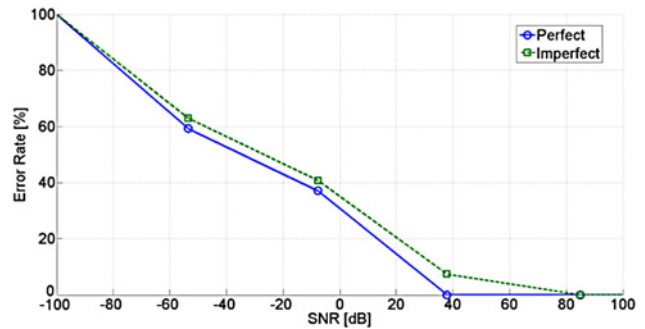


Figure 8 Comparison of signal-to-noise ratio for perfect and imperfect on-body UWB channels

3.2. Part 2: Body-surface UWB sparse IR reconstruction considering channel effect: Figs. 4–7 present the IR reconstruction process for on-body UWB channel. It is clear in Fig. 7 that the recovered sparse on-body IR is very close to the original sparse IR, demonstrating the feasibility of sparse on-body IR reconstruction using the CS framework. To obtain the typical on-body impulse response, tapered slot antennas (TSAs) were used [16]. The antenna has good performance (e.g. VSWR, radiation pattern, gain etc.) over the whole UWB range and has been demonstrated to be a very good electromagnetic transceiver for on-body wireless communications. The frequency domain measurement technique was used in the whole measurement process. Two TSAs were connected to a Hewlett Packard 8720ES VNA first; then, they were fixed to the body surface to measure the on-body frequency domain transmission response. The frequency range during the measurement is 3–10 GHz [7]. Then, by adopting inverse discrete Fourier transform, the UWB on-body channel impulse response can be obtained. It should be noted that in the transform process, the sampling rate is 1601 and the sampling time is 50 ps. The measurement took place in the

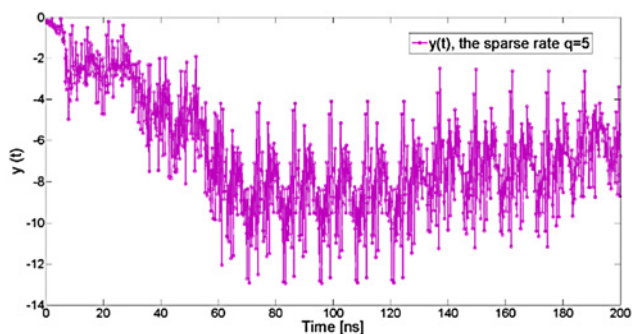


Figure 6 Signals at the receiving terminal

wireless sensor laboratory at Queen Mary, University of London. The laboratory is analogous to the typical wireless body area networks propagation environment. When compared with the free space IR, it is normal to see the distortion in the on-body IR. Such kind of distortion is mainly due to the absorption and reflection by the human body. It is noted in Fig. 8 that the error rate of perfect on-body UWB channel estimation and imperfect channel estimation are similar; it is worth noting that, for imperfect channel, the error rate becomes 0 when the SNR is more than 80 dB.

4. Conclusion: In this Letter, sparse UWB on-body channel impulse response estimation was achieved using the CS framework which has been found very attractive in many other research fields [17–20]. This channel estimation approach is of important significance to BCWC [21]. Users are sensitive to the prime cost and power consumption of terminal devices (e.g. cell phone, tablet etc.); these problems can be safely solved via using low-speed sampling devices at the receiving terminals. Once these low-speed sampling devices are used, it is necessary to apply the CS framework to the channel estimation module [22, 23]. It should be noted that the channel estimation approach presented in this Letter can be extended to other propagation environments as well.

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