

ADAPTIVE CHANNEL ESTIMATION FOR SPARSE ULTRA WIDEBAND
SYSTEMS

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ADAPTIVE CHANNEL ESTIMATION FOR SPARSE ULTRA WIDEBAND
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In memory of my brother, Enoch (1976-2013)
and dedicated to my parents.

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ABSTRACT

Increased research in ultra wideband (UWB) systems in the last two decades has established it as a technology for high-speed, short-range applications. UWB also offers low power consumption, immunity to multipath fading, increased security, and low interference in multipath environments. Unfortunately, it is a great challenge to obtain accurate channel state information at the receiver side of UWB systems, especially in time-varying applications. Consequently, this research deals with the design of an adaptive channel estimation algorithm for sparse UWB systems. Using measurement data, this thesis considers the estimation of a long sparse multipath channel in a mobile UWB system. Recent advances in Compressive Sensing (CS) applications in signal processing make CS to be a legitimate candidate for processing sparse signals. Among the broad application areas of CS is channel estimation. Based on the objectives of the research, the contributions of this thesis are in three parts. Firstly, channel measurements usually provide accurate Channel Impulse Response (CIR), which helps to accurately model any channel behaviour. Thus, this thesis provides channel measurements in various mobile line-of-sight scenarios to precisely measure the efficacy of the proposed channel estimation algorithm. Secondly, traditional channel estimation algorithms like the Least Mean Square (LMS) and Normalised LMS (NLMS) algorithms do not consider the structural information of the channel. In addition, CS-based LMS and NLMS algorithms do not consider the use of the channel sparsity to control the algorithm performance. Therefore, this thesis also proposes a number of Sparseness-Controlled (SC) LMS and NLMS algorithms for estimating sparse UWB channels. Lastly, the thesis presents an analysis of the performance of the proposed estimators in terms of the Mean Square Error (MSE), steady-state excess MSE, convergence speed, robustness, and computational complexity. Simulation results show that unlike traditional algorithms, the proposed estimators perform better to improve the estimation of the CIR of sparse UWB channels. Even though, for all the scenarios considered, compared to the SC- l_0 -Norm NLMS (SC-L0-NLMS) algorithm, the SC-reweighted zero-attracting NLMS (SC-RZA-NLMS) algorithm provides excellent performance, the SC-ZA-NLMS algorithm is less computationally complex than both and it performs in close proximity to both at higher SNR. For the sparse channel, when SNR is 30 dB, the SC-ZA-NLMS algorithm converges faster with better MSE of -38.2391 dB compared to the SC-RZA-LMS algorithm, which converges at -33.9805 dB. Therefore, the SC-ZA-NLMS algorithm is the most suitable for accurately estimating the sparse UWB channel.

ABSTRAK

Peningkatan penyelidikan dalam sistem jalur lebar ultra (UWB) dalam dua dekad sebelum ini telah menetapkan ia sebagai satu teknologi untuk aplikasi berkelajuan tinggi, jarak dekat. UWB juga menawarkan penggunaan kuasa yang rendah, imuniti kepada pemudaran pelbagai arah, keselamatan dipertingkatkan dan gangguan dalam persekitaran pelbagai arah yang rendah. Malangnya, ia adalah satu cabaran besar untuk mendapatkan maklumat keadaan saluran yang tepat di bahagian penerima sistem UWB, terutamanya dalam aplikasi masa yang berbeza-beza. Maka, penyelidikan ini berkaitan dengan reka bentuk suatu algoritma anggaran saluran mudah suai untuk sistem UWB jarang. Menggunakan data pengukuran, tesis ini menganggap anggaran saluran pelbagai arah jarang yang panjang dalam sistem UWB mudah alih. Kemajuan terkini dalam aplikasi Mampatan Penderiaan (CS) pemrosesan isyarat menjadikan CS menjadi calon yang sah bagi pemrosesan isyarat jarang. Antara bidang aplikasi CS yang meluas adalah anggaran saluran. Berdasarkan objektif kajian, sumbangan tesis ini berada dalam tiga bahagian. Pertama, pengukuran saluran biasanya menyediakan Saluran Tindak Balas Denyut (CIR) tepat, yang membantu untuk model dengan tepat mana-mana tingkah laku saluran. Oleh itu, tesis ini menyediakan pengukuran saluran dalam pelbagai senario garis nampak mudah alih yang membantu mengukur keberkesanan algoritma anggaran saluran yang dicadangkan dengan tepat. Kedua, algoritma anggaran saluran tradisional seperti algoritma Min Kuasa Dua Terkecil (LMS) dan LMS Ternormal (NLMS) tidak mempertimbangkan maklumat struktur saluran. Selain itu, CS berasaskan algoritma LMS dan NLMS tidak mempertimbangkan penggunaan jarang saluran untuk mengawal prestasi algoritma. Oleh yang demikian, tesis ini juga mencadangkan beberapa Kawalan Kejarangan (SC) algoritma LMS dan NLMS untuk menganggar saluran UWB jarang. Akhir sekali, tesis ini membentangkan analisis prestasi penganggar yang dicadangkan dari segi Ralat Min Kuasa Dua (MSE), keadaan seimbang berlebihan MSE, kelajuan penumpuan, keteguhan, dan kekompleksan pengkomputeran. Keputusan simulasi menunjukkan bahawa tidak seperti algoritma tradisional, penganggar yang dicadangkan melaksanakan lebih baik untuk meningkatkan anggaran CIR jarang saluran UWB. Walaupun, untuk semua senario yang dipertimbangkan, berbanding dengan algoritma SC- I_0 -norma NLMS (SC-L0-NLMS), algoritma SC-pemberat semula penarikan-sifar NLMS (SC-RZA-NLMS) yang menyediakan prestasi yang sangat baik, algoritma SC-ZA-NLMS yang kurang kompleks pengkomputeran daripada kedua-duanya dan dilaksanakan berdekatan dengan kedua-duanya pada SNR yang tinggi. Untuk saluran yang jarang, apabila SNR ialah 30 dB, algoritma SC-ZA-NLMS menumpu lebih cepat dengan MSE lebih baik iaitu -38.2391 dB berbanding dengan algoritma SC-RZA-LMS, yang menumpu pada -33.9805 dB. Oleh itu, algoritma SC-ZA-NLMS adalah yang paling tepat untuk menganggar saluran UWB jarang.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The use of ultra wideband (UWB) technology in transceiver design for wireless communications systems in recent years is because of the high data transmission rates [1], [2] it offers. In addition, UWB offers immunity to multipath fading, increased security, low interference, and low power consumption in multipath environments. Most of the UWB system designs have focused on stationary transceivers because the UWB wireless channel changes rapidly with change in transceiver position or scatters position. Thus, limiting transceiver movement helps simplify system design. Nevertheless, mobile applications, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) propagation scenarios, can also take advantage of the very high-data rate capabilities of UWB. The Infostation [3]–[7], which is an example of V2I propagation scenario, is one of such applications where UWB has potential. The design of UWB transceivers for such mobile scenarios with rapid time-varying channel portends more complex design approach.

In order to achieve efficient wireless communication, the mobile UWB transceiver system will employ channel estimation (CE) methods to help implement equalisation and diversity techniques at Rake receivers [8]. The performance of the employed CE algorithm highly depends on not only the wireless channel, but also on the appropriateness of the channel model used [9]. Hence, information about the channel behaviour is very important in the channel estimator design in particular, and transceiver design in the broad sense.

In general, CE methods may be either non-adaptive or adaptive. Fundamentally, non-adaptive methods depend so much on the prior knowledge of the statistics of the channel in which they will be deployed [10]. However, such channel statistics are not readily available in the case of UWB channels, given the very random nature of the channel, which worsens in mobile scenarios [11]–[15]. A natural option is to consider the adaptive methods, which inherently do not require prior knowledge of the channel statistics [16]. Unfortunately, in most cases, adaptive CE algorithms also suffer from poor convergence rates and tracking especially in mobile application.

Therefore, there is the need to develop adaptive CE (ACE) algorithms with high convergence rate, good tracking, and ability to estimate both dense and sparse channels with a high degree of accuracy.

1.2 Problem Statement

The performance of any wireless system is critically dependent on the availability of accurate channel estimate [17]. Typically, the UWB channel is either “sparse” or “dense”, depending on the measured bandwidth and the considered environment [14], which makes estimating the channel coefficients a challenge. The use of adaptive algorithms will serve well in estimating such channels.

Unfortunately, in using existing adaptive algorithms, like the least mean square (LMS) and recursive least square (RLS) algorithms and their respective variants, the issue of convergence, tracking, and implementation complexity arise. Finding mathematical and signal processing approach to solving the convergence, tracking, and complexity issues in ACE for UWB application is a crucial task in the development of mobile UWB transceivers. Fortunately, it is possible to exploit the dense/sparse nature of the UWB channel using compressive sensing (CS) techniques to improve on the convergence speed of the selected adaptive algorithm.

This research focuses on the design of an ACE algorithm for sparse UWB systems. It will consider using sparse penalties that will keep the estimator’s

complexity low and therefore, converge with minimal of iterations. This implies that the number of operations, i.e., multiplications, divisions, and additions/subtractions, required to make a complete iteration should be minimal. Moreover, the algorithm needs to be robust in different channel conditions, i.e., small disturbances with small energy, resulting from either internal or external effect on the adaptive filter, should result in only small estimation errors.

1.3 Objectives

The aim of this research is to develop a CE algorithm for mobile UWB systems using adaptive system identification approach. To achieve this aim, the following objectives are addressed:

- To create a dataset of channel impulse response that represents sets of real UWB channel coefficients in a typical communication system for indoor and outdoor environments.
- To create an adaptive channel estimation algorithm that is robust in mobile UWB communication channels, and exhibits low cost function when compared with results of the channel measurement dataset.
- To evaluate the performance of the proposed adaptive algorithm in terms of its computational complexity.

1.4 Scope of Work

The scope of this research is limited to the mathematical formulation, algorithm development, and implementation of the overall adaptive approach on software platform. The data set used for the simulation of the developed adaptive method is from time-domain UWB channel measurements in different line-of-sight (LOS) mobile scenarios using Time Domain Corporation's PulsON[®] 410 Ranging and Communications Module (P410 RCM). This channel-sounding device transmits at a

bandwidth of 2.2 GHz over the frequency range of 3.1-5.3 GHz and a centre frequency of 4.3 GHz. These UWB channel measurements are conducted in three different environments at the Universiti Teknologi Malaysia, Skudai campus. Each measurement mimics a different mobile scenario. The measurements are conducted in both indoor and outdoor environments. The indoor measurement mimics a classroom environment whereas the outdoor measurements are done in both roadway and recreational park environments.

1.5 Contributions

The main contribution of this research is the development of a robust adaptive channel estimation algorithm for sparse UWB channels. The proposed algorithm exploits the channel sparsity to enhance performance of the LMS and NLMS algorithms and uses same to control the selection of the regulation parameter in the sparse penalty. CIR from UWB channel measurements are used to test the viability of the algorithms. The channel measurements are also used to understand the behaviour of the UWB channel. These time-domain UWB channel measurements are done in three unique UWB channel scenarios, namely, outdoor roadway, outdoor recreational park, and indoor multimedia information access environments. From the channel measurements, a dataset of the acquired CIR is created.

The results of the UWB channel measurements show that the measured CIR varies from slightly dense to highly sparse channel response. Because of this, CS-based channel estimators are proposed. More precisely, variants of LMS and NLMS algorithms are used since LMS-based algorithms have shown to be robust in most environments. Unfortunately, selection of an optimal regulation parameter for the sparse penalty is difficult. Thus, the need to provide a means of selection this parameter. The resulting LMS-based algorithms (i.e., SC-ZA-LMS, SC-RZA-LMS, and SC-L0-LMS) and NLMS-based algorithms (i.e., SC-ZA-NLMS, SC-RZA-NLMS, and SC-L0-NLMS) take into account the sparseness measure of the UWB channel via a modified sparse penalty function.

Finally, a detailed performance analysis of the proposed sparseness-controlled algorithms shows that they outperform the LMS and NLMS algorithms in terms of convergence speed and tracking ability. Though computationally complex than the LMS and NLMS algorithms, simulation results show superior performance in both dense and sparse channels. The results also show that taking the computational complexity of the algorithms into consideration, the SC-ZA-NLMS algorithm is the best candidate for estimating both dense and sparse UWB channels.

1.6 Thesis Outline

The remainder of the thesis is organised as follows. The second chapter presents the literature review. Firstly, an overview of UWB communication systems is presented with emphasis on the impulse radio UWB (IR-UWB) and multiband orthogonal frequency division multiplexing (MB-OFDM) UWB systems. The chapter also discusses a comprehensive review of reported UWB channel measurements in the literature. The fundamental aspect of UWB channel estimation techniques is also presented in this chapter. Previous works on ACE and non-ACE algorithms for UWB systems are discussed as well. The chapter ends with a discussion of the compressive sensing approach for UWB channel estimation and a presentation on sparse channel estimation algorithms.

Chapter 3 provides a comprehensive discussion on the methods used in this work. This includes a presentation on the measurement setup, the steps for the algorithm development, simulations and verifications, and finally an analysis of the performance of the proposed algorithm. The chapter also discusses the measurement setup used in the channel measurements; this encompasses a description of the testbed, transmitter/receiver specifications, and a discussion of channel, i.e., measurement environment. Lastly, the channel estimation modelling procedure is given.

In Chapter 4, a detailed outlook of the UWB channel measurements conducted is presented. General measurement principles for UWB channel measurements are also discussed in this chapter. The chapter also covers the description of the

measurement environments, procedures used, and the post-processing. Finally, it ends with a time dispersion analysis of the measurement data.

Chapter 5 details the algorithm development. It introduces the UWB signal model. Finally, some sparsity constraint algorithms suitable for UWB channel estimation are also presented in this chapter.

Chapter 6 presents a performance analysis as well as the simulations and discussions of the algorithms. The presented performance analysis includes the convergence performance, steady-state mean square error (MSE) analysis, convergence analysis, robustness analysis, and computational complexity analysis. Computer simulations are finally used to verify these performance analysis results.

Finally, Chapter 7 presents the general conclusions of this research work and recommendations for future works. It also highlights the proposed algorithm, its significance, and some significant results.

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