ARTIFACT PATHS REMOVAL ALGORITHM FOR ULTRA-WIDEBAND CHANNELS

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To my father and mother; my source of inspiration
To my brother; best friend and supporter
To my sister in law and lovely nephew (Amir)

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ABSTRACT

Ultra-wideband (UWB) is a promising technology for achieving high data rate communications. When UWB channel measurements are conducted, channel impulse responses (CIRs) are extracted from measured UWB waveforms using CLEAN deconvolution algorithm. However, artifact paths that represent unreal received multipath components (MPCs) are generated during this process. These artifact paths are registered as part of the measured CIRs representing a reflected signal from a scatterer. In reality, these paths do not represent a real scattering environment and this affects accurate channel modeling. Therefore, removal of the artifact paths is important to conserve better and have a more real scattering environment. In this work, an algorithm was developed to remove artifact paths from measured CIRs. The algorithm development was achieved based on the concept of geometric elliptical modeling applied to wideband channels, where the effective path in each ellipse is utilized to represent the channel response of the ellipse. Several UWB channel measurements were conducted to obtain the measured UWB waveforms. In addition, the characteristics of the UWB channels were analyzed in terms of CIRs properties and their stationarity regions. The algorithm performance was evaluated by comparing the single-template CLEAN CIRs with the CIRs result from the application of the developed algorithm on single-template CLEAN CIRs. Results showed that the developed algorithm can successfully remove the artifact paths. Besides that, an enhancement in the received power was achieved. For a specific measured channel, the received power enhancement obtained was more than 5%. The algorithm is beneficial for enhancing accuracy of CIRs extracted from a single-template CLEAN algorithm. Consequently, more accurate channel characteristics are gained leading to improved channel modelling and different parameter extractions.

ABSTRAK

Jalur lebar ultra (UWB) adalah teknologi yang menjanjikan pencapaian kadar data komunikasi yang tinggi. Apabila ukuran saluran UWB dijalankan, tindak balas saluran denyut (CIRs) diekstrak dari bentuk gelombang UWB yang diukur menggunakan algoritma penyahkonvolusi CLEAN. Walau bagaimanapun, laluan artifak yang mewakili komponen pelbagai arah (MPCs) diterima tidak dihasilkan dengan betul semasa proses ini. Laluan artifak ini berdaftar sebagai sebahagian daripada CIRs diukur mewakili isyarat terpantul dari penyelerak. Secara realiti, laluan ini tidak mewakili persekitaran berselerak yang sebenar dan ini memberi kesan kepada model saluran yang tepat. Oleh itu, penyingkiran laluan artifak adalah penting untuk penjimatan lebih baik dan persekitaran serakan lebih nyata. Dalam kerja ini, algoritma dibentuk untuk membuang laluan artifak dari CIRs diukur. Pembentukan algoritma yang telah dicapai berdasarkan konsep pemodelan geometri elips digunakan untuk saluran jalur lebar di mana laluan yang berkesan dalam setiap elips digunakan untuk mewakili tindak balas saluran elips. Beberapa ukuran saluran UWB telah dijalankan untuk mendapatkan bentuk gelombang UWB diukur. Di samping itu, ciri-ciri saluran UWB telah dianalisa dari segi sifat-sifat CIRs dan kawasan kepegunan. Prestasi algoritma dinilai menerusi perbandingan antara CIRs CLEAN templat tunggal dengan yang terhasil daripada penggunaan algoritma dibentuk atas CIRs. Keputusan menunjukkan bahawa algoritma dibentuk berjaya mengeluarkan laluan artifak. Selain itu, penambahbaikan dalam kuasa yang diterima juga dicapai. Misalnya, untuk saluran diukur tertentu, lebih dari 5% daripada peningkatan kuasa diterima telah diperolehi. Algoritma yang dibentuk adalah bermanfaat untuk meningkatkan ketepatan CIRs diekstrak daripada algoritma CLEAN templat tunggal. Oleh yang demikian, ciri-ciri saluran yang lebih tepat diperolehi, membawa kepada pemodelan saluran lebih tepat dan pengekstrakan parameter yang berbeza.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AoA	-	Angle of arrival
AoE	-	Angle of elevation
APR	-	Artifact paths removal
BW	-	Bandwidth
CAPR	-	Complete artifact paths removal
CAT	-	Channel analysis tool
CIR	-	Channel impulse response
DARPA	-	Defense Advanced Research Projects
DSO	-	Digital signal oscilloscope
FCC	-	Federal Communications Commission
GEV	-	Generalized Extreme Value
GoF	-	Goodness of fit
GPS	-	Global Positioning System
I2V	-	Infrastructure to vehicle
IEEE	-	Institute of Electrical and Electronics Engineers
IO	-	Interlacing object
ITU	-	International Telecommunication Union
ITU-R	-	International Telecommunication Union

Radiocommunication Sector

K-S - Kolmogorov - Smirnov

LOS - Line of sight

MIMO - Multiple-input multiple-output

MPC - Multipath component

NB - Narrow-band

P410 - PulsON 410

PDF - Probability distribution function

PDP - Power delay profile

PN - Pseudo-noise

Rx - Receiver

SMA - SubMiniature version A

SR - Stationarity region

ToA - Time of arrival

ToAR - Time of Arrival Reconstruction

Tx - Transmitter

USB - Universal Serial Bus

UWB - Ultra-wideband

VNA - Vector network analyzer

WB - Wide-band

WCC - Wireless Communication Centre

WPAN - Wireless Personal Area Network

WSN	-	Wireless Sensor Network

LIST OF SYMBOLS

B_f	-	Fractional or relative bandwidth
f_H	-	Higher frequency
f_L	-	Lower frequency
a	-	Channel gain
a_k	-	Channel gain of path k
τ	-	Delay time
$h(\tau)$	-	Time-invariant channel impulse response
δ	-	Dirac function
k	-	MPC index
K	-	Maximum number of MPCs in a channel snapshot
$\chi_k(\tau)$	-	Distorted UWB pulse
$\otimes$	-	Convolution operator
f_c	-	Center frequency
$\tau_{\max}$	-	Maximum value of excess delay
$H(f)$	-	Time-invariant channel transfer function
$s(t)$	-	Transmitted waveform
$y(t)$	-	Received waveform

$h(t)$ - Channel impulse response of an arbitrary waveform

r - Correlation process

$r_{ss}(t)$ - Auto-correlation

$r_{sy}(t)$ - Cross-correlation

τ_1 - Runtime of path 1

d_1 - Traveling distance of path 1

τ_2 - Runtime of path 2

d_2 - Traveling distance of path 2

c - Signal propagation speed

τ_d - Duration between the arrival of two UWB pulses

τ_k - Delay time of path k

$h(t_n, \tau)$ - Time –varying channel impulse response

n - Channel snapshot index

N - Maximum number of measured channel snapshots

$\Delta\tau$ - Ellipse width

$h\left(t_n, \tau_k\right)$ - Channel response for path k in channel snapshot n

t - Time variation index

$\mathbf{nz}$ - Vector of nonzero elements

SI - Sparsity index

SI_n - Sparsity index of nth channel snapshot

$P(t_n, \tau)$ - Power delay profile

C - Correlation coefficient

ρ - Correlation coefficient between two PDPs

$\mathrm{cov}(\mathrm{x}, \mathrm{y})$ - Covariance

σ - Standard deviation of random variable X

σ - Standard deviation of random variable Y

c_{TH} - Correlation threshold value

λ - Exponential distribution continuous inverse scale parameter

α - Weibull distribution shape parameter

β - Weibull distribution scale parameter

ψ - GEV distribution shape parameter

σ - GEV distribution scale parameter

μ - GEV distribution location parameter

$\mathrm{h}_{\mathrm{LOS}}$ - Channel response of the LOS path

$\mathbf{h}_{\mathrm{CLN}}$ - Channel snapshot vector from the measured CIR

H_{CLN} - CIR of Single-template CLEAN

H_{APR} - CIR after using APR algorithm

H_{CAPR} - CIR after using CAPR algorithm

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The wireless communications field represents a big engineering success in the recent two to three decades. The success is not considered from the scientific view only, but from the economic and impact on society as well. Many companies that were not known transferred to be a giant household due to their work on the wireless communications systems. In addition, several countries are depending on the wireless communications industry as a main dominant part in their economical budget. By observing the communications of information in history, wireless communications show its oldest form. It started simply through shouts or jungle drums that were an innovative way of communications before civilization eras in order to transmit the information wirelessly. No cable or wiring was used for this purpose. Smoke signals were an example of a line of sight (LOS) communication that conveys a certain message to the receiving partner. However, the wireless communication, as we know, started with the basis of electromagnetic signals transmission led by Maxwell and Hertz [1].

The first publicized wireless communication was successfully conducted by Marconi in 1898. The demonstration was achieved in the English Channel from a boat to the Isle of Wight. The great achievement of Marconi led him to be recognized as the inventor of the modern wireless communications. Nobel prize was awarded to him in 1909 due to this achievement [1]. It is noted that some talks advertise that Tesla was the first successful person in achieving the first wireless communications system by demonstrating the transmission of the information through electromagnetic waves, but the stronger public relations of Maroni led him to be regarded as the inventor of the wireless communications system [1]. The utilization of radio communications (one direction) spread out throughout the whole world in the following years. A wide network of transmission of information wirelessly was available by the late 1930s.

Wireless communications advanced by the following decades, as the necessity for having a high data rate communication was available for the transmission of audio and video signals. In this case, the idea of using signals of high bandwidth in the wireless communication systems started, where ultra-wideband (UWB) signals were a proposed option for this requirement, and the pioneering contribution in the field of UWB communications was achieved by Bennett and Ross in 1978 [2] and Harmuth in 1981 [3]. A huge frequency band can be made from the UWB system that it ranges from 3.1 – 10.6 GHz [4]. This high bandwidth leads to high data rate communication according to what Shannon illustrated in his work [5].

In order to have a successful communication system, there are several parameters that need to be studied and modeled accurately. One of these parameters is the wireless channel. Indeed, the performance of the wireless communication system depends on the propagation condition between two entities that are the transmitter (Tx) and the receiver (Rx) where the channel represents the medium between them [6]. As the propagation channel is an important part in any communication system where it represents the environment in which the signal travels from the Tx to the Rx, understanding the behavior of the communication system channel is needed. The transmitting and receiving devices need to make an agreement with the channel characteristics where the devices are operated to provide the ultimate outcome. As a result, a prerequisite part of the UWB system design is the understanding of the UWB propagation channel.

As the signal is transmitted through the channel to the receiving side, several scatterers are available which comprise the scattering environment of the particular channel. The scatterers represent the interlacing objects (IOs) available in the channel between the transmitting and the receiving sides. Due to the availability of the different scatterers in the channel, multipath components are generated due to the reflection, diffraction or scattering of the propagated signal with the available scatterers.

Knowing the scattering environment is important for accurate channel modeling and characterization. As the number of multi-paths can be approximated to be the same number of scatterers (considering a single scattering case), determining the real number of scatterers is crucial for knowing a particular channel behavior. Based on that, determining the accurate channel behavior in terms of its scattering environment is needed for accurate communication system design. This can be achieved for different communication channels, where UWB channel is part of them.

As the case of any communication system, the wireless channel (or simply referred as the channel) is a main part in determining the performance limit of wireless communication systems [7]. This case is applicable in any practical case, where the testing, design and improvement of the system depends on understanding the channel that signals propagate through. In order to achieve this purpose, channel measurements are needed in order to study its effect on the propagated signals.

Channel measurements are valuable in studying different channel characteristics. The channel impulse response (CIR) is extracted from the received measured waveform obtained during the channel measurement campaign. From the CIR, different channel parameters are extracted representing the different characteristics such as power, delay spread, and frequency dispersion. The obtained parameters from the measurements are beneficial in studying and modeling the channel small scale and large scale characteristics.

In the case of UWB channel measurements, CLEAN algorithm is used in order to extract the CIRs from the measured UWB waveforms. In CLEAN, the data are processed by comparing the measurement information (dirty map) with *a priori* information (template). Then the resulted CIRs , representing the clean map, are reconstructed based on cancelling the detected similarities [8]. However, the extracted CIRs usually contain artifact paths. These artifact paths are registered as channel response values representing a reflected signal from a scatterer. In reality, these paths do not represent a real scattering environment and this affects accurate channel behavior [8], [9]. Therefore, removing the artifact paths is important to conserve better and more realistic scattering environment which results in more accurate channel characterization and modeling.

In the literature, some approaches are available in developing the CLEAN algorithm through the removal of the artifact paths and getting better scattering environment. The approaches focused on using multi-template CLEAN algorithm instead of the single-template one. In the multi-template CLEAN, the deconvolution between the received waveform and the template is done with several UWB template waveforms instead of a single one in the single-template case. These cases are seen in [8], [10], [11]. The proposed template waveforms are extracted from channel measurements in particular environments. If the CIRs need to be extracted for other measurement environments, the template waveform should be found from that specific environment. The template that is not proper for the deconvolution process may decrease the algorithm performance [12]. In this case, developing an approach that enhances the obtained outcome of the single-template CLEAN algorithm is beneficial for the general utilization in any environment with the same original undistorted template waveform.

1.2 Problem Statement

UWB channel measurement is conducted in order to study the channel behavior in a particular environment. The CIRs are extracted from the measured UWB waveforms through the utilization of the CLEAN algorithm. The method is based on a deconvolution process between the received UWB waveforms and a template waveform. The resulted CIRs contain artifact paths that do not represent real multipath components (MPCs) and are generated during the deconvolution process. Therefore, removing these artifact paths is needed to get more accurate scattering environment and, as a result, more accurate channel is observed. Previous researches focused on the idea of using multi-template CLEAN to decrease the effect of artifact paths.

However, this method contains the challenges of the need of getting the UWB template waveforms from the measured environments [8], [10]–[12]. In addition, if the selected template accuracy is low, the extracted CIRs accuracy will decrease [12].

In order to address the main research problem given above, answers to several questions need to be provided as a prerequisite.

1. What is the importance and the aim of this study?
2. What is the theoretical framework that can be used to develop an algorithm to remove such artifact paths?
3. How to do the UWB channel measurements, and what are the measurement techniques and devices that can be used?
4. How to validate the research?
5. What are the consequences of the application of the algorithm on the channel behavior?

1.3 Research Aim and Objectives

The aim of this study is to obtain accurate channel behavior based on cleaning the measured UWB CIRs from any artifact paths. The results in removing artifact paths are important for modeling specific statistics [13] where accurate number of paths is crucial. Extracting more accurate CIRs that represent the real scattering environment results in better channel characterization and modeling. In the final outcome, better UWB communication system performance is achieved.

In the purpose of providing the possible solutions to the presented problem statement, the objectives of this research are as follows:

- To measure and study the UWB channel through conducting outdoor and indoor measurement campaigns.

- To extract measured CIRs using the single-template CLEAN algorithm.

- To develop an algorithm to remove the artifact paths in addition to analyzing and evaluating the performance of the proposed algorithm.

1.4 Scope of Research

The scope of this research can be seen in the following points:

- The algorithm is developed based on the theory of elliptical modeling where the wideband channel comprised of several delay taps.

- The algorithm is used after the CIRs extraction by the single-template CLEAN algorithm.

- UWB channel measurements are based on Time-Domain technique.

- The equipment used in the measurements is PulsON 410 which is a UWB radio transceiver.

- The frequency range of the UWB measurement is 3.1 – 5.3 GHz.

- The transmitted UWB pulse bandwidth is 2.2 GHz, and the center frequency is 4.3 GHz.

- The transmission power from PulsON 410 is -14.3 dBm.

- Channel measurements are based on single-input single-output (SISO) scheme, where two antennas are used in the measurement, one at the transmitting side and the other at the receiving side.

- MATLAB$^{®}$ software is used for simulation results and analysis.

- The UWB channel measurements are conducted in outdoor and indoor environments.

- The conducted measurements have LOS communication.

1.5 Research Contributions

This research contributes to the huge field of UWB communications in terms of the UWB channel part. The contribution goes to provide more accurate CIRs through clearing the measured CIRs (single-template CLEAN CIRs) from any artifact paths generated due to the utilization of the single-template CLEAN algorithm. The contributions of this thesis are shown in the following subsections

1.5.1 Removal of the Artifact Paths from the Measured CIRs

The main contribution of this thesis is the development of an algorithm that removes the artifact paths from the measured CIRs. The algorithm represents an enhancement to the CLEAN algorithm and will be run after getting the CIRs by CLEAN. Thus, it can be used to structure the data after the CLEAN algorithm and get CIRs which are more practical and more likely to be empty from artifact (or phantom) paths.

Two main phases have been developed in this algorithm: Firstly, the development of the algorithm based on the theory of the elliptical modeling has been programmed. In this stage, the removal of the artifact paths is the main purpose of this algorithm. Secondly, In order to restore accurate time of arrivals (ToAs) of the received paths, phase 2 has been added, where another algorithm is developed for this purpose. Based on that, the real channel values with their accurate ToAs have been preserved and any path that does not agree with the elliptical modeling theory has been removed. Notice that the paths removal does not affect the real channel behavior as this removal agrees with practical cases stated in the literature.

1.5.2 Sparse Indoor and Outdoor UWB Channel Measurements

In order to understand and study the behavior of the UWB channel, several measurements have been conducted. The measured data enhances the knowledge of the channel and is needed for the development of the algorithms. The measurements were conducted in outdoor and indoor environments in order to have full insight on the difference in the measured CIRs that is caused due to the measurement environment.

1.5.3 Stationarity Regions for UWB Channels

The stationarity regions of the UWB channel have been extracted based on the correlation between the power delay profiles (PDPs) of the measured channel snapshots (one channel snapshot represents one measured UWB pulse with its received multi-paths). The regions are studied based on the conducted measurement of the mobile run scheme and the statistical analysis has been achieved. The knowledge of the stationarity regions assists in defining the distance steps where the channel has significance variation.

1.5.4 Channel Sparsity Determination using the Sparsity Index

The sparsity index has been defined as the number of non-zero elements in the channel snapshots registered during the measurements. The analysis of the sparsity of each channel is done by focusing on this parameter. In addition, it has been used in order to calculate the received power of the channel in this type of sparsity behavior.

1.6 Thesis Outline

The thesis consists of six chapters. The outline of the remaining chapters is presented in this section.

In Chapter 2, the literature review of the work is illustrated. It starts from the explanation on the theory of the UWB communication. The UWB channel is then illustrated in terms of the theory. The different channel measurement techniques are elaborated along with the theory of the CLEAN algorithm and the CIR extraction. Finally, the chapter goes to the related works in this field.

In Chapter 3, the methodology that has been used to achieve the research objectives is described. The chapter starts with the method of conducting channel measurements in terms of the used equipment and the selected environment. Then the method of algorithm development is presented.

In Chapter 4, the measurement campaigns that have been conducted in this research are elaborated. Studying the channel behavior in detail has been achieved in terms of the effect of the different measurement environments. In order to understand the UWB channel characteristics in terms of the measured CIRs in the measurement environments, indoor and outdoor measurements are conducted. The chapter contains also the sparsity analysis of the UWB channel. The sparsity index is defined and used for this purpose. More details about the organization of this chapter and the reason for its sections hierarchy is shown in the Introduction section of the chapter.

In Chapter 5, the results of the developed algorithm is presented. A comparison is shown between the results of the developed algorithm with the results of the single-template CLEAN algorithm. In addition, the effect of applying the developed algorithm on single-template CLEAN CIRs is shown in terms of the received power and the number of received paths.

In Chapter 6, the conclusion of the conducted research is contained, where the main points of the research are restated in addition to elaborating the research findings. An illustration of the objectives achievements has been included. The limitations and challenges that are encountered in this research are presented. Finally, main points of the future work that can be conducted based on the lessons that are learned and understood from the research shown in this thesis have been included.

enhanced the power extracted from the CIRs, which is good for better Signal to Noise (SNR) values. The number of received paths shows the spread of the channel, where this research made enhancement in decreasing the number of paths due to the removal of any possible artifact paths. In this regard, other metrics can be evaluated in the future, such as the RMS delay spread to check how the difference of the number of paths affected this metric, the possible decrement of the RMS delay spread will be beneficial in getting better coherence bandwidth values, where the two metrics are inversely proportional.

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