Low-complexity schemes for UWB localization over indoor wireless channels

Chen, Wei

2008

Chen, W. (2008). Low-complexity schemes for UWB localization over indoor wireless channels. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/41845>

<https://doi.org/10.32657/10356/41845>

Low-Complexity Schemes for UWB Localization over Indoor Wireless Channels

CHEN WEI

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Master of Engineering

2008

Acknowledgments

I would like to express my heartfelt gratitude and appreciation to my advisor, Assoc. Prof. Erry Gunawan, for his valuable supervision and encouragement throughout the course of the project. Without his guidance and support, this thesis would not have been possible.

Table of Contents

Acknowledgments	i
Summary	vii
List of Abbreviations and Symbols	ix
1 Introduction	1
1.1 Motivation	1
1.2 Objectives	3
1.3 Major Contributions of the Thesis	3
1.4 Explanation of Important Terms in the Thesis	4
1.5 Organization of the Thesis	5
2 Overview of UWB Systems	7
2.1 UWB Systems	7
2.2 Three Major Means for the Realization of UWB Signals	10
2.2.1 Single Band Time Hopping UWB Systems	10
2.2.2 Direct Sequence UWB Systems	10
2.2.3 Multiband-Orthogonal Frequency-Division Multiplexing UWB Sys- tems	11

2.3	Ranging and Localization	12
2.3.1	Application Scenarios	12
2.3.2	Algorithms for Ranging	13
2.3.3	Algorithms for Localization	14
2.4	Indoor Wireless Channels	14
2.5	The UWB system in This Thesis	15
3	Techniques for the UWB localization	17
3.1	Techniques for the ToA Estimation in the TH-BPSK UWB system	18
3.1.1	Threshold Based Schemes	18
3.1.2	Statistics Based Schemes	20
3.1.3	Subspace Based Schemes	21
3.1.4	Transformation Based Schemes	22
3.1.5	Spatial Correlation Schemes	22
3.1.6	Recently Published Ranging Schemes	23
3.1.7	Performance Bound of ToA Estimations	23
3.2	Techniques for the AoA Estimation in the TH-BPSK UWB system	24
3.3	Localization Schemes using Estimated ToAs	25
3.3.1	Localization using Available Estimated ToAs Equally	25
3.3.2	NLoS Channels Detection/Differentiation	25
3.3.3	NLoS Error Mitigation	29
3.4	Distributed Techniques	31
3.5	Tracking Techniques	32
4	An Improved Direct Path Detection Scheme for UWB Indoor Ranging	33

TABLE OF CONTENTS

v

4.1	Background	33
4.2	Joint Amplitude and Energy Detection for ToA Estimation	34
4.3	Simulation results	38
4.4	Comparison with the MUSIC Algorithm	44
4.5	Conclusion	48
5	A DP/NDP-APs Distinguishing Algorithm for UWB localization Schemes over Stationary Indoor Wireless Channels	49
5.1	Background	49
5.2	Distinguishing the DP-APs and the NDP-APs	52
5.3	The APL distribution of the FDP	56
5.4	Numerical results	61
5.5	Conclusion	72
6	The Performance Evaluation of the Combined Proposed Schemes	75
6.1	Conclusion	81
7	Conclusion and Recommendations	83
7.1	Conclusions	83
7.2	Recommendations for Further Research	84

Summary

This research focuses on low complexity schemes for ultra wideband (UWB) localization applications over indoor wireless channels.

The existing low complexity ranging algorithms detect the direct path (DP) by obtaining the leading edge of the correlation of the received signal and the local template or the energy within a short observation window, which crosses a certain specified threshold. These schemes, however, have common weaknesses that their performance is sensitive to the threshold setting. In this thesis, we propose an improved direct path detection scheme in indoor wireless channels. According to the power-delay profile of the impulse response of indoor wireless channels, several paths of the received signal may be closely spaced together as a cluster. It indicates that even if the DP signal is relatively weak, we can expect considerable energy will be received in the next several nanoseconds. Hence a double-threshold DP detection scheme of the amplitude and the energy of a relatively long observation window nearby will increase the robustness of the DP detection performance. The settings of the threshold values will be studied by simulations.

To improve the accuracy of locating a mobile subscriber (MS) in the common office environment, a new algorithm is also proposed to distinguish between the direct path-anchor points (DP-APs) and the not-direct path-anchor points (NDP-APs). In wireless communication systems over mobile outdoor wireless channels, the DP-APs and the NDP-APs are distinguished by measuring the standard deviation of the estimated channel parameters. That technique may not work properly for the indoor wireless channel, where the channel may remain static and no deviation can be observed for a relatively long time when nothing is moving in the local area.

There are many published papers focus on the NLoS detection/identification techniques. In the localization algorithm based on the NLoS detection/identification techniques, all the ranging estimates obtained from NLoS channels are considered biased. However, for the UWB system over indoor wireless non-line-of-sight channels, the DPs may only be partially blocked and still can be correctly detected when the channel noise is relatively weak. Also, in realistic applications, there usually are not enough APs with the LoS channel to the MS for the localization. Hence it is important to distinguish those correct ranging estimates obtained from NLoS channels and use them for the localization. The proposed scheme distinguishes between the DP-APs and the NDP-APs by testing the additional energy losses during propagation of the FDPs on the APs. And only those APs whose FDPs are more likely to be the DPs to the MS are considered for the localization. Simulation and a set of measurements in a modern office are carried out to verify the performance of the proposed localization scheme. Simulation and measurement results show that the proposed scheme is promising for localization using UWB systems in the common office environment.

List of Abbreviations and Symbols

Abbreviations

ADC	A/D converter
AoA	angle of arrival
APL	additional power loss
APs	anchor points
AWGN	additive white Gaussian noise
BPSK	binary phase-shift keying
CIR	channel impulse response
CRLB	Cramer-Rao lower bound

DAA	detect and avoid
DS	Direct sequence
EFA	early false alarm
FCC	Federal Communications Commission
FDPs	first detected paths
GML	global maximum likelihood
GPS	global positioning system
ISI	inter-symbol interference
LoS	line-of-sight
MB-OFDM	multiband-orthogonal frequency-division multiplexing
MF	match filter
MIC	Ministry of Internal Affairs and Communications
MMR	maximum to minimum energy sample ratio

List of Abbreviations and Symbols

xi

MPCs	multipath components
MS	mobile subscriber
NLoS	non-line-of-sight
PDFs	probability density functions
PDP	power delay profile
PPM	pulse position modulation
PSD	power spectral density
PWTC	Positioning and Wireless Technology Center
RF	radio frequency
RMS	root mean square
SNR	signal-noise ratio
TDoA	time difference of arrival
TH	time hopping
ToA	time of arrival

UWB ultra wideband

WLAN wireless local area networks

WPAN wireless personal area networks

Symbols

$(\cdot)^H$ the complex transpose transform

$(\cdot)^T$ the transpose transform

b_i $b_i \in \{-1, +1\}$ are the bi-polar modulated data

B_f the fractional bandwidth

$(B_x(i); B_y(i))$ the approximation of the CRLB of the i th location estimate

c the propagation speed of light in the free space

$\mathbf{C}$ the matrix that characterizes the spatial and spectral information of the signal

d the number of channel response samples before the LoS

	path
D_i	the distance between the transmitter and the i th AP
$E\{\cdot\}$	the expectation
F	the matrix constructed by frequency vectors
f_H	the higher -10 dB frequency
f_L	the lower -10 dB frequency
$g(t)$	the pulse shape normalized to give unit power
$\mathbf{g}_0$	the template vector
$\mathbf{g}(\tau)$	the delayed template vector
G_r	the gain of the AP antennas
G_t	the gain of the mobile subscriber
$h(t)$	a given channel realization
h_0	the gain of the channel impulse response sample corresponding to the LoS path

h_i	the gain of the i th channel impulse response sample
$\mathbf{h}_i$	a series of measurements of h_i
$\mathbf{h}$	the discrete channel impulse response vector
$\mathbf{I}$	the identity matrix
L	the channel length
L_{array}	the number of antenna in the array
L_w	the length of the observation window for the energy threshold
$m_R(i)$	the reflection index of the i th materia
$m_T(i)$	the refraction index of the i th materia
M	is the number of the blockage materials
$n(t)$	the channel noise
N	the number of anchor points
$P(\cdot)$	the probability density function
$Pr(\cdot)$	the probability

$\Pr_c$	the probability of correct detection
P_{APL}	the additional power loss
P_{1m}	the free-space power loss at 1 meter distance
P_{rw}	the power of the received signal
P_{tw}	the power of the transmitted signal
$\mathcal{Q}(\cdot)$	the Q-function
$r(t)$	the received waveform
$\mathbf{R}$	the covariance matrix
$R(\mathbf{m}_R(i), \boldsymbol{\theta}_R(i))$	the reflection power coefficients of the i th reflection
$s(t)$	the transmitted UWB waveform
$\sup(\cdot)$	the peak value
$\mathbf{S}$	the code matrix constructed by the TH code
T_f	the pulse repetition period

$T(\mathbf{m}_T(i), \boldsymbol{\theta}_T(i))$	the refraction power coefficient of the i th refraction
$\mathbf{v}$	a normalized delay vector
$(x_i; y_i)$	coordinates of positions
α_i	the normalized scale factor of the i th base station
Δt	the minimum resolution time
κ	the kurtosis of the channel
$\mu_{ h(t) }$	the mean of $ h(t) $
$\boldsymbol{\phi}$	the array phase vector
ρ_1	the predetermined amplitude threshold
ρ_2	the predetermined energy threshold
$\rho_e(i)$	the threshold offset of the i th threshold
σ^2	the variance
σ_e	the standard deviation of delay estimation

$\sigma_{ h(t) }$	the standard deviation of $ h(t) $
τ	time delay
τ_m	the mean excess delay spread of the channel
τ_{rms}	the root mean square delay spread of the channel
θ	the angle of arrival
θ_R	the reflection angle vector
θ_T	the refraction angle vector
ϑ	the unbiased estimator of positions
ω	the normalized AWGN vector
χ	a Chi-Squared Distribution number
$(\xi_x(i); \xi_y(i))$	the i th ($i = 1, 2, \dots, N$) estimate's normalized residual

Chapter 1

Introduction

1.1 Motivation

The ultra wideband (UWB) system has drawn considerable attention among researchers because of its attractive features such as high data transmission rate and high-resolution localization over indoor wireless channels [1]. It is considered as one of the most promising technologies for short-range wireless applications and ad-hoc networking applications. The advantages of UWB technology are important even to cellular operators, as UWB technology may play a key role in the future 4G network solution by providing enhancement and add-on functionality [2].

The Federal Communications Commission (FCC) of the United States approved the intentional emission of UWB signals contained within specified emission masks in 2002. The flexibility provided by the emission masks greatly raised the interest of deploying UWB technology in high data rate communication. For those low-rate, location-enabled UWB applications, standardization is given by the IEEE 802.15.4a Task Group. The main interest is in providing communications with high-precision ranging and localization, low-power emission and consumption, as well as low cost [3].

Applications such as location-sensitive billing and fraud detection would require high

accuracy. As a result, many research has been focused on the accuracy study which can be divided into three areas: 1) the algorithms of channel parameters estimation, such as angle of arrival (AoA) estimation, time of arrival (ToA) estimation, or time difference of arrival (TDoA) estimation over the indoor wireless channel [4, 5, 6]; 2) localization algorithms and approaches to calculate the location of a mobile subscriber (MS) from the channel parameter estimates on the anchor points (APs) [7, 8]; 3) performance analysis and evaluation methods for those algorithms [9].

Major sources of error in indoor wireless channels include relatively weak signal of the direct path (DP), multipath propagation and non-line of sight (NLoS) propagation [10].

The main problem of ranging in the indoor wireless channel is that the indoor wireless channel is a dense multipath channel and the DP signal may be weaker than the non-direct paths signal mainly due to two reasons; the DP signal becomes weak because of the obstruction of the DP and non-direct path signals become strong because of several unresolvable rays adding constructively [11, 12]. An optimum threshold needs to be set at the AP to maximize the probability of correct detection of the DP in the delay estimation [13]. Because the DP could be weak due to the above mentioned reasons, the detection performance of the existing single-threshold algorithm is sensitive to the threshold value, which should be predetermined according to the received signal power and the estimated characteristics of the noise.

The localization error caused by the ranging errors can be mitigated using multiple APs in the radio localization algorithms. Multiple APs localization algorithms have well been studied in narrow-band systems over outdoor wireless channels. The study shows that the non-direct path error is still recognized as a critical issue for localization, which is caused by the APs whose first detected paths (FDPs) are not the DPs to the MS [14]. When using the popular least squares method, the non-direct path error can be reduced by increasing the number of the APs. But increasing the number of the APs may cause other problems, such as overload in cellular network, synchronization difficulty, computational inefficiency, etc.

Let the direct path-anchor points (DP-APs) denote those APs whose FDPs correspond to the DPs from the MS and hence can give correct ranging estimations. And let the

not-direct path-anchor points (NDP-APs) denote those APs whose FDPs correspond to pure noise/interference or non-direct paths. For outdoor wireless channels, research work shows that the DP-APs and the NDP-APs can be distinguished by measuring the standard deviations of the estimated channel parameters and hence the above mentioned problem is solved [15]. However the technique may not work properly for the indoor wireless channel, where the channel may remain static and no deviation can be observed for a relatively long time.

Steps must be taken to mitigate these impairments to improve the localization accuracy.

1.2 Objectives

This thesis has two objectives. One is to improve the ranging performance by taking the cluster effect into consideration to increase the accuracy of the DP detection. The other is to improve the localization performance by developing an efficient algorithm to reduce the error introduced by the NDP-APs. The performance of the proposed algorithms will be evaluated by simulations.

1.3 Major Contributions of the Thesis

The performance of the existing single-threshold DP detection algorithms drops significantly when the threshold value is not set properly [13]. In order to improve the robustness of the performance, an improved DP detection algorithm is proposed by exploiting the statistical characteristics of the indoor wireless channel. In the proposed algorithm, the amplitude of the potential signal path and the energy of the observation window are compared to two thresholds respectively for the DP detection. The threshold settings and the performance of the proposed algorithm are studied by simulations.

A new algorithm is also proposed for distinguishing between the DP-APs and the NDP-APs in the indoor office environment by testing the additional energy losses during propagation of the FDPs on the APs. A set of measurement results was performed in

a common office environment. The measurement statistics and the simulation statistics show the same trend as what we expected. It can be very useful for UWB localization applications in modern office environment.

1.4 Explanation of Important Terms in the Thesis

Since there are a lot of differences between the outdoor wireless channels for the narrow-band signals and the indoor wireless channels for the UWB signals, some terms used in this thesis need to be clarified.

LoS channels	radio channels where there is visual line of sight between the transmitting antenna and the receiving antenna
NLoS channels	radio channels where there is no visual line of sight between the transmitting antenna and the receiving antenna regardless whether the UWB signal can penetrate the blockage on the visual line of sight or not. Therefore, in NLoS channels, direct path signals (the definition is given below) may exist at the AP because the UWB signal may be able to penetrate the blockage on the line-of-sight path.
direct path	the signal path where the UWB signals propagate along the line of sight between the transmitting antenna and the receiving antenna regardless whether there are blockages or not on this path. Because of the UWB signals' ability of blockage penetration, direct path signals may be only partially blocked and still can be correctly detected in NLoS channels. In [16, 17], algorithms are used to estimate the ToA from the NLoS channel. We use the term 'direct path' instead of 'LoS path' in this thesis to avoid the confusion.

direct path-APs	anchor points whose first detected paths correspond to the direct paths from the MS. Since direct paths may be correctly detected as the first detected paths in NLoS channels, the direct path-APs do not necessarily have a visual LoS, or LoS channel, to the MS.
not-direct path-APs	anchor points whose first detected paths correspond to pure noise/interference or non-direct paths.
signal path	At the receiver, if we recover a nonzero channel response sample at resolvable time instances from the received waveform, we declare that we find a signal path. If the gain of the channel response sample crosses a certain threshold, we call it a detectable path. Otherwise we call it a non-detectable path.
signal ray	: A ray is a physical path that the signal travels along.
signal cluster	A small group of signal rays or signal paths that arrives at the receiver within a short period of time due to signal reflections from different surfaces of the same object is called a cluster.

1.5 Organization of the Thesis

The organization of the remainder of the thesis is as follows. Chapter 2 provides the background material of the UWB system and the characterization of the indoor wireless channel. Firstly, the concept of UWB is explained followed by descriptions of the major UWB systems. The current development status of the UWB techniques and applications is introduced. The major characteristics of the indoor wireless channel are also listed in this chapter. Since wireless localization is based on channel parameter estimation, a detail discussion about estimation techniques in indoor wireless channels will be given in Chapter 3. Chapter 4 proposes an improved DP detection algorithm for ranging in UWB systems over indoor wireless channels. The desired threshold values are also studied in the same chapter. In Chapter 5, a technique for distinguishing DP/NDP-APs

is proposed to improve localization accuracy in the multiple APs localization system over indoor wireless channels. A set of measurement results performed in a modern office environment is also described in this chapter to justify the algorithm. The performance of the localization using the combination of the two proposed algorithms is evaluated and compared with the localization performance of the existing algorithms in Chapter 6. Finally, Chapter 7 provides some concluding remarks and future work for possible extension.

Chapter 2

Overview of UWB Systems

2.1 UWB Systems

The UWB radio is an emerging technology that has attracted a great deal of interest from academia and industry. An UWB signal is a signal whose bandwidth is large with respect to the carrier or center frequency of the spectrum. A measurement metric appropriate for UWB signals is the fractional bandwidth B_f , defined as [2]:

$$B_f = 2 \frac{f_H - f_L}{f_H + f_L} \quad (2.1)$$

where f_H and f_L are the higher and lower -10dB bandwidth, respectively. Originally, UWB signals have been generated by transmitting very short pulses as, for example, the pulse in Fig. 2.1.

The pulse duration usually is on the order of a few hundred picoseconds. This technique, known as impulse radio (IR), has been extensively used in radar applications. And the UWB term refers to waveforms that are characterized by an instantaneous fractional

Figure 2.1: The UWB pulse.

bandwidth B_f greater than about 0.20, while narrow-band signals are defined as signals with fractional bandwidth less than 0.01.

In 2002, the FCC of the United States approved the intentional emission of UWB signals contained within specified emission masks. It is defined that UWB transmitter is an intentional radiator that, at any point in time, has a fractional bandwidth $B_f > 0.20$ or has an absolute bandwidth $B \geq 500\text{MHz}$ regardless of the fractional bandwidth. The spectral mask is also given.

On 27th March 2006, Japan's Ministry of Internal Affairs and Communications (MIC) issued a preliminary approval for UWB emissions policy in Japan. The UWB unlicensed spectrum allocation consists of two bands, a lower band between 3.4 and 4.8GHz and an upper band between 7.25 and 10.25GHz for indoor devices only. For the lower band, implementations of interference mitigation techniques such as detect and avoid (DAA) mechanisms are required. This is to protect current and future services from potential interference as well as to ensure coexistence with incumbent systems and new services

Figure 2.2: The proposed UWB emission limits for indoor communications systems [18].

like WiMAX, 4G and digital broadcast. However, between 4.2 and 4.8GHz of the lower band, interference mitigation techniques can be waived until the end of December 2008. The emission limits for both bands are -41.3dBm/MHz , the same as those approved by the US FCC. Korea's Ministry of Information and Communication announced that the target UWB spectrum will be allocated from 3.1 to 4.8GHz for the low band and from 7.2 to 10.2GHz for the high band. For the low band, DAA mechanisms are mandatory in order to protect existing services. However, for 4.2 to 4.8GHz the DAA mechanisms can be exempted until June 2010. The usage of the target band will be allowed for both indoor and outdoor communication systems. Fig. 2.2 [18] shows the proposed UWB emission limits for indoor communications systems in the US, Europe, Japan, and Korea.

The spectral mask is designed to enable UWB technology to overlay with available services such as the global positioning systems (GPS) and the IEEE 802.11 wireless local area networks (WLAN). The flexibility provided by those regulations greatly raised the

interest of many large establishments in forming industry alliances such as WiMedia and the UWB Forum to deploy UWB technology.

UWB communications systems offer two advantages [18, 2]:

- i) High data rate transmission. Current UWB systems can support more than 500Mbps data transmission within 10m over the line-of-sight (LoS) channel.
- ii) High precision ranging. UWB systems have excellent time-domain resolution and can provide sub-centimeter resolution for ranging applications in the indoor environment.

2.2 Three Major Means for the Realization of UWB Signals

2.2.1 Single Band Time Hopping UWB Systems

In general single band time hopping (TH) UWB systems, one bit is transmitted over N frames. Each frame contains only one short pulse, which occupies the whole frequency band defined by the FCC. The duration of the frame is much larger than that of the pulse and the specific position of the pulse in the frame is decided by the chosen time hopping code. The common modulation methods for the single band TH UWB system are pulse position modulation (PPM) and binary phase-shift keying (BPSK) [19].

The single band TH UWB system is relatively easy to analyze. A lot of research work has been done based on them to study the system performance over the indoor wireless channel. It is also likely to be adopted in the low-rate, location-enabled applications.

2.2.2 Direct Sequence UWB Systems

Recently, the UWB concept has been extended to continuous carrier-based transmission techniques, provided that the occupied bandwidth of the transmitted signal is very large.

This produces a very high data rate, independently of the characteristics of the pulses [20].

Direct sequence (DS) spread spectrum is one of the spread spectrum forms, in which each transmission is modulated by a pseudo-random or specific binary sequence which serves to spread the waveform spectrum. Instead of transmitting bit per bit, such system will transmit a sequence for every bit.

In the DS-UWB system, the frequency band defined by the FCC is divided into the higher band and the lower band. UWB signals can be modulated to transmitting in one of the two bands or both. It supports up to 8 logical channels, which is known as picoNets.

2.2.3 Multiband-Orthogonal Frequency-Division Multiplexing UWB Systems

In the multiband-orthogonal frequency-division multiplexing (MB-OFDM) UWB system, the frequency band is divided into fourteen 528MHz bands. Information is transmitted using OFDM modulation on each sub-band. The OFDM carriers are efficiently generated using an 128-point IFFT/FFT. Information is coded across all bands in use to exploit frequency diversity and provide robustness against multi-path and interference. The fourteen sub-bands are grouped into 5 groups. Group A is mandatory, Groups B to E are optional. It supports up to 18 picoNets [21].

Both DS-UWB systems and MB-OFDM UWB systems are spectrally efficient. But comparing to the DS-UWB system, the MB-OFDM UWB system has some attractive advantages.

- i) The OFDM technology has an inherent robustness against narrow-band interference. Narrow-band interference will affect at most a couple of tones. Information from the affected tones can be erased and recovered via the forward error correction (FEC) codes.
- ii) The MB-OFDM UWB system uses cyclic prefix to preserve orthogonality between

sub-carriers, which allows the AP to capture multi-path energy more efficiently.

iii) The hardware of the MB-OFDM UWB system is relatively easy to design and realize.

Hence, the MB-OFDM UWB system is now the most favorite realization of the UWB technology for high data rate wireless transmission among the industries.

2.3 Ranging and Localization

2.3.1 Application Scenarios

Location awareness is one of the fundamental problems in tomorrow's wireless networks. In areas where there is a clear LoS to GPS satellites, GPS can provide a good estimate of the user's location on the earth. However, in indoor and dense urban environments a clear LoS to GPS satellites is typically unavailable, and accurate localization becomes a more challenging problem. It is possible for the UWB technology to provide highly accurate ranging in the indoor environments, owing to its inherent high delay resolution and ability to penetrate obstacles. Therefore, developing localization schemes for UWB systems over indoor wireless channels becomes more and more important. UWB localizers can provide various important add-on applications in the future such as [18]:

- i) Location sensitive billing. Accurate localization service in indoor and dense urban environments can enable a service provider to charge at different rates depending on whether the subscriber is at home, in the office, or on the road. It also enables a service provider to encourage desirable usage behavior by employing location price discrimination.
- ii) Personal location. Rescuers could find people in a variety of situations, including civilians in a burning building, injured skiers on the slopes, or hikers in a remote area.
- iii) Smart homes and offices. Home or office appliances with integrated UWB technology enable technologies that turn the desired appliances on or off, by knowing the location of both the appliance and the individual.

iv) Resource management. It could also be useful in the wireless system design and for the radio resource and the mobility management. With the ability to locate a wireless call, system planners could dramatically improve their ability to configure cells and wireless systems. Cells could be better positioned and tuned, and spectral efficiency improved. More effective resource management could be obtained through the allocation of channels based on the knowledge of the wireless caller's location. Moreover, a service provider who may have multiple agreements with personal computers, cellular, or satellite carriers could offer its customers the ability to choose a carrier that best suits their needs at any given time and location.

2.3.2 Algorithms for Ranging

The common techniques for ranging in wireless communication systems are the ToA estimation and the AoA estimation.

i) The ToA Estimation [16, 13]. After the AP detects the first arrived signal path, the distance information is extracted from the relative delay between the time of transmission and the ToA. This technique can be further classified into ToA one-way-ranging (ToA-OWR) and ToA two-way ranging (ToA-TWR). The former requires perfect synchronization between the transmitter and the AP, while the latter does not require synchronization between the transmitter and AP. Also the difference between ToAs in several APs is used to reconstruct a transmitter's position. It is called the TDoA estimation. This requires highly precise synchronization between the APs, but not precise synchronization between transmitter and APs.

ii) The AoA Estimation [5]. Distance between terminals is reconstructed from the angle between them; this technique requires adoption of expensive antenna arrays, and the results are highly sensitive to the multipath, NLoS propagations, and the array precision.

2.3.3 Algorithms for Localization

A popular method for computing the location of a MS is through the method of least squares. For example, in the ToA based localization scheme, the location is estimated by minimizing the sum of squares of a nonlinear cost function with the ToA estimation results from several APs. Assume that there are N APs, which are located at coordinates $(x_1; y_1), (x_2; y_2), \dots, (x_N; y_N)$, respectively. A MS transmits a waveform at time t_0 and the estimated ToAs from the N APs are $\hat{t}_1, \hat{t}_2, \dots, \hat{t}_N$. The estimated location of the MS will be given by

$$(\hat{x}_0; \hat{y}_0) = \operatorname{argmin} \sum_{i=1}^N f_i \quad (2.2)$$

where f_i is given by

$$f_i = \|(c(\hat{t}_i - t_0))^2 - (x_i - x_0)^2 - (y_i - y_0)^2\| \quad (2.3)$$

Here c denotes the propagation speed of light and $\|x\|$ denotes the absolute value of x .

2.4 Indoor Wireless Channels

The indoor wireless channel covers a wide variety of situations, ranging from residential or office buildings, hospitals to factories. It does not suffer from the environmental effects as do outdoor radio channels but the variation of building size, shape, structure, layout of rooms and, most importantly, the type of construction materials. Owing to reflection, refraction and scattering of radio waves by structures inside a building, the transmitted signal most often reaches the AP by a lot of paths, resulting in a phenomenon known as dense multipath.

Many propagation models have been developed to characterize indoor radio propagation

and one of the important models is Saleh and Valenzuela's [10]. They used their measurement results in a medium-size two-story office building, together with measurement results from other researchers, to develop a statistical model of the indoor radio channel for the simulation and analysis of various indoor communication schemes. The model was shown to fit the measurements and may be extended to other buildings by adjusting its parameters. The model assumes that the multipath components arrive in clusters. The received amplitude of each component is an independent Rayleigh random variable, with a variance that decays exponentially with propagation delay, as well as with time delays, within a cluster. The corresponding phase angles for each component are independent uniform random variables over $[0, 2\pi]$. The clusters and multipath components within a cluster form a Poisson-arrival process with different rates. The multipath components and the clusters have exponentially distributed inter-arrival times. The formation of the clusters is related to the building structure, while the multipath components within each cluster are formed by multiple reflection from the objects between the transmitter and the AP. The model has enough flexibility to permit reasonably accurate fitting of the measured channel responses and is successful for application in office environments.

The the IEEE 802.15.4a group's final report on the indoor wireless channel model for ranging and localization adopts those basic ideas of Saleh and Valenzuela's model and gives out several set of parameters for different kinds of indoor environments [22].

Note that although the signal paths recovered at the APs are useful for the ranging and the communication applications, they may only represent the distortion of individual pulses and do not have corresponding physical transmission paths.

2.5 The UWB system in This Thesis

In this thesis, the study focuses on the low-speed binary time-hopping single-band UWB system over indoor wireless channels for ranging and localization applications. It is assumed that the transmitted waveform is constructed by a short pulse that fits the FCC mask in the frequency domain. The second Gaussian derivative pulse windowed to 1ns duration is used as the transmitted pulse in this thesis but no specific pulse shape

is required for the proposed algorithms. At the receiver, it is assumed that the channel impulse response can be recovered from the received waveform using the stored pulse shape as the template. The IEEE 802.15.4a multipath model is applied to generate the channel impulse response.

Chapter 3

Techniques for the UWB localization

Notice that this thesis focuses on low complexity schemes. We make this choice because of the following reason. Since the UWB system has a high center frequency and very low power spectral density, each of the APs covers a relatively small area. Full coverage needs a large number of APs and hence the cost of one AP should be as low as possible, which limits its computational power and the memory for data storage. On the other hand, the AP should sample the received waveform at very high speed to recover the information. Normally a signal frame will be sampled more than 1000 times [2]. Hence the less data we need for the decision, the less computational load and processing delay we have. Because of those information that we introduced in Chapter 2 and this chapter, we focus on threshold-based ToA estimation schemes using the single-band TH-BPSK UWB system over the indoor wireless channel in this thesis.

In this chapter, we will describe the techniques for the ToA estimation in a TH-BPSK UWB system. Among the many techniques for the ToA estimation in the TH-BPSK UWB system, Chapter 4 will focus on a threshold based technique for its relative simplicity. Other ranging and localization techniques in UWB systems are also introduced

in this chapter.

3.1 Techniques for the ToA Estimation in the TH-BPSK UWB system

3.1.1 Threshold Based Schemes

ToA estimation techniques have been fully studied in the outdoor wireless channel [23, 24]. In the outdoor wireless channel, the first signal path arriving at the AP, which would be considered as the DP by ranging algorithms, usually is the strongest path. Since the ranging problem turns into finding the strongest signal path, no threshold would be needed. In some outdoor wireless channels where the DP is not the strongest path, it can be detected by full search method based on the maximum likelihood or the minimum mean square error criteria [25], because outdoor wireless channels are sparse and the computation load of such a search is relatively light.

However, for the indoor wireless channel, the DP is relatively weak in a lot of cases and the multipath is so dense that there are usually hundreds of signal paths, which make the computational load of the full search method based on the maximum likelihood criteria very heavy. Hence, in the conventional scheme, the potential signal paths are examined one by one. A predetermined amplitude or energy threshold is set and compared with a potential signal path's amplitude or energy. The first path that crosses the threshold, or the FDP, will be set as the estimated DP [16, 13]. The estimated signal propagation time will be the time difference between the time when the signal is transmitted and the arrival time of the FDP.

In [26], an improved threshold based scheme is introduced as the second stage of the proposed acquisition scheme. It includes two steps:

- 1) Compare all the potential signal paths' amplitudes in the search region to a threshold. Those potential signal paths whose amplitudes cross the threshold proceed to the next

step.

2) For every potential signal path that proceeds to this step, the time difference between itself and its closest survivor potential signal path is calculated. If the time difference exceeds a predefined constant, then that potential signal path is eliminated. After all potential signal paths are tested, the earliest surviving path is declared as the DP. This step is based on the clustered nature of the indoor wireless channel. Since multipaths occur in clusters, an isolated survivor potential signal path is most likely an early false alarm (EFA).

Since the bandwidth of single-band UWB signals is very large, the Nyquist rate sampling becomes impractical in some applications. Hence motivating lower complexity and yet accurate ranging techniques using symbol rate sampling is proposed in [27]. In [27], symbol rate energy samples that are obtained after a square-law device are compared with a normalized threshold to estimate the ToA. The threshold selection approach is based on the minimum and maximum values of the energy samples.

For timing or synchronization purpose, the dirty template approach [28, 29] and the compressed sensing (CS) approach [30] are proposed. In [29], “dirty templates” are extracted from the received waveform and used for timing acquisition by cross correlation, which exhibits a unique maximum at the correct timing. In [30], received UWB signals are approximated by a linear combination of a few atoms from a pre-defined dictionary, which will be used for CS reconstruction of the channel.

The ToA estimation performances of three transceiver types, energy detection, stored reference/template and transmitted reference/template, are examined in [31]. The simulation results in [31] show that with the threshold based algorithm, the ToA estimation performance using energy detection is close to the ToA estimation performance using transmitted reference and no conclusion can be drawn on the ToA estimation performances between using energy detection and using stored reference.

3.1.2 Statistics Based Schemes

The estimation of the ToA for a DP is equivalent to locating the first signal path in the received waveform, which is a piecewise stationary process characterized by different characteristics before and after the first signal path [32]. Based on this assumption, the DP detection is equivalent to segmentation of non-stationary processes with abrupt changes [33].

UWB signals can be modeled as temporally correlated processes (correlation arising from the transmitted waveform) with an exponential decaying power delay profile (PDP) with decaying constant equal to the root mean square delay spread of the channel impulse response (CIR). Hence the problem turns into estimation of the FDP, h_0 , from a series of measurements $[\mathbf{h}_{-d}, \mathbf{h}_{-d+1}, \dots, \mathbf{h}_{-1}, \mathbf{h}_0, \mathbf{h}_1, \dots, \mathbf{h}_{L-1}]$ by the optimal classification rule derived from the Neyman-Pearson criterion [34] extended to multiple hypotheses. Here L is the length of the channel. The null hypothesis H_0 indicates the absence of any change, which means that no signal from the desired user is received. The hypothesis H_j indicates the hypothesis that the DP of the desired user's signal is at the j th element of the measurements vector. In the hypothesis H_j , the measurements $\mathbf{h}_i, i \in [-d, j-1]$ and $\mathbf{h}_i, i \in [j, L-1]$ will have different covariance matrices, which are denoted by $\mathbf{R}_0$ and $\mathbf{R}_1$, respectively. The hypotheses H_0 and H_j can be expressed as [32]:

$$H_0 \quad \rightarrow \mathbf{h}_i \sim \mathcal{N}(0, \mathbf{R}_0), i \in [-d, L-1] \quad (3.1)$$

$$H_j \quad \rightarrow \begin{cases} \mathbf{h}_i \sim \mathcal{N}(0, \mathbf{R}_0), i \in [-d, j-1] \\ \mathbf{h}_i \sim \mathcal{N}(0, \mathbf{R}_1), i \in [j, L-1] \end{cases} \quad (3.2)$$

The optimal estimator for the DP is given by

$$\hat{h}_0 = \operatorname{argmax}_{\mathbf{h}_j, j \in [-d, L-1]} \{\Upsilon(j)\} \quad (3.3)$$

where $\Upsilon(j)$ is given by

$$\Upsilon(j) = \left(\frac{\Phi_B(j)}{\Phi_F(j)} \right)^{j/2} \frac{1}{\Phi_B(j)} \left(\frac{\Phi_B(j)}{\Phi_F(j)} + 1 \right)^{1-L/2} \quad (3.4)$$

Here the inner products $\Phi_B(j)$ and $\Phi_F(j)$ are given by

$$\Phi_B(j) = \mathbf{h}_j^T \mathbf{R}_0^{-1} \mathbf{h}_j \quad (3.5)$$

$$\Phi_F(j) = \mathbf{h}_j^T \mathbf{R}_1^{-1} \mathbf{h}_j \quad (3.6)$$

3.1.3 Subspace Based Schemes

Eigen-structure algorithms rely on the following properties of the covariance matrix $\mathbf{R}$ of the received waveform [35]:

- When no pair of signals is correlated and the additive Gaussian noise is white, the space spanned by its eigenvectors can be partitioned into two subspaces, namely, the signal subspace and the noise subspace. The K eigenvectors corresponding to the largest K eigenvalues span the signal subspace and the other $L - K$ eigenvalues span the noise subspace, where K is the number of the signal sources and L is the dimension of the correlation matrix $\mathbf{R}$.
- The steering vectors corresponding to the signal sources are orthogonal to the noise subspace.

In principle, the eigenstructure-based methods search for channel parameters, such as ToA, following the rules that the steering vectors associated with these parameters are

orthogonal to the noise subspace or are contained in the signal subspace. In [36, 37], the subspace technique is applied to the UWB system.

As in [37], for TH-PPM UWB systems, the ToA estimation can be obtained by finding a normalized delay vector $\mathbf{v}$ that can minimize the evaluation function as follows:

$$\hat{\mathbf{v}} = \underset{\|\mathbf{v}\|=1}{\operatorname{argmin}} \sum_{j=0}^1 \mathbf{v}^H \mathbf{S}_j^H \mathbf{R}^{-P} \mathbf{S}_j \mathbf{v} \quad (3.7)$$

where $\mathbf{S}$ is constructed by the TH code and $\mathbf{R}$ is the covariance matrix of the received signal.

In [38], the eigenstructure-based multiple signal classification (MUSIC) approach is applied to the ToA estimation in frequency domain.

3.1.4 Transformation Based Schemes

In [39], the tunnel diode is used to transform the received UWB pulse into another form whereby the level difference between the desired pulse and the noise is increased. Hence, this transformation results in a better performance in a leading-edge pulse detection scheme.

However, the above mentioned scheme fails in the presence of a dominant jammer. To solve the problem, an improved transformation based scheme is proposed in [40]. In the improved scheme, an envelope detector is added to resist dominant jammer and recover the performance.

3.1.5 Spatial Correlation Schemes

A cluster can be defined as an accumulation of multipath components (MPCs) arriving with almost the same ToA [10]. Hence, those impulse signals probably will be detected

simultaneously at adjacent array points. In [41], the ToA is estimated by analyzing the spatial correlation of multipath signals captured by a 7×7 antenna array. The spatial correlation values of each delay bin are calculated using the power-delay profile of the adjacent antennas. Those delay bins that are associated with high correlation values will be declared as the ToA of the MPCs and the smallest ToA will be declared as the ToA of the DP.

3.1.6 Recently Published Ranging Schemes

In [4], a two-step ToA estimation scheme is proposed for UWB ranging systems. Firstly, the channel is divided into blocks of unit length and a threshold is set to detect the energy block where the DP belongs, or called the DP block. The threshold is chosen using the maximum to minimum energy sample ratio (MMR), which was proposed to be the metric for dynamic setting of the normalized threshold in [42]. Then, the DP will be located in the DP block by the match filter (MF) based coherent algorithms.

3.1.7 Performance Bound of ToA Estimations

The performance bound of the ToA estimation in UWB system is discussed in [43, 44]. In [43], the Cramer-Rao lower bounds for maximum likelihood (ML) channel gain and ToA estimation in an UWB system are derived. And in [44], the Ziv-Zakai bound [45] and the Weiss-Weinstein bound [46] are applied to a two-sensor receiver for better prediction of the ToA estimation performance than the Cramer-Rao lower bounds.

Those performance bounds are based on the ML criteria and cannot closely predict the ToA estimation performance of the threshold based algorithms, which are biased with predetermined threshold values.

3.2 Techniques for the AoA Estimation in the TH-BPSK UWB system

In [5], an AoA estimation scheme using digital channelization receiver architecture is proposed. In this scheme, the array output at the AP is split into multiple frequency channels and down-convert each channel into much lower frequency to allow the use of the low sampling rate A/D converter (ADC). The AoA estimation is obtained by forming a direction finding function using the spectral information as follows

$$\hat{\theta} = \operatorname{argmin}_{\theta \in [-\pi/2, \pi/2]} |P_C^\perp C \mathbf{1}_{L_{array} \times 1}| \quad (3.8)$$

where L_{array} is the number of antennas in the array, $\mathbf{1}_{L_{array} \times 1}$ is a column vector of all elements equal to 1 and the orthogonal projection matrix $P_C^\perp$ is given by

$$P_C^\perp = I - C(CC^H)^{-1}C^H \quad (3.9)$$

Here, I is the identity matrix, $(\cdot)^H$ denotes the complex transpose matrix and C is a unique matrix that characterizes the spatial and spectral information of the signal, which is given by

$$C = \operatorname{diag}\{\phi\}F \quad (3.10)$$

where ϕ is the array phase vector and F is constructed by the frequency vectors.

3.3 Localization Schemes using Estimated ToAs

3.3.1 Localization using Available Estimated ToAs Equally

In typical indoor wireless localization systems, the MS's location would be determined using the estimated ToAs from the available APs around. For example, in the least squares localization scheme, the location is estimated by minimizing the sum of squares of a nonlinear cost function with the ToA estimation results from the available APs. The least squares scheme works very well if all APs have LoS channels to the MS. If part of the APs only have NLoS channels to the MS, the localization error of the least squares scheme, which is caused by the NLoS ranging errors, can be reduced by increasing the number of the APs [47]. However, in practical indoor localization applications, only a few APs may be available to the MS and a major part of the available APs may be NLoS APs. Hence, the least squares scheme that equally uses the estimated ToAs from all available APs need to be improved.

Two consecutive steps can be utilized to deal with NLoS situations [48]. The first step is NLoS detection that differentiates the NLoS APs from the LoS APs using the received waveform. If this step has been succeeded, the second step is NLoS mitigation that tries to use the estimated ToAs from NLoS APs to assist the position estimation.

3.3.2 NLoS Channels Detection/Differentiation

If we can obtain many subsequent range estimates over an indoor wireless channel, the running variance estimator can be used to detect NLoS channels [49]. The running variance estimator computes the variance of the subsequent range estimates and compares it to a certain threshold. The channel is a LoS channel if the variance is below the threshold and is a NLoS channel if otherwise.

A similar algorithm, called the residual test, is proposed in [50]. It can simultaneously determine the number of LoS BSs and identify them in the localization applications with many subsequent MS's location estimates. The residual test computes the square of the

normalized residuals of all the range estimates and the i th ($i = 1, 2, \dots, N$) estimate's normalized residual can be expressed as

$$\xi_x^2(i) = \frac{[\hat{x}(i) - \hat{x}(N)]^2}{B_x(i)}, \quad (3.11)$$

$$\xi_y^2(i) = \frac{[\hat{y}(i) - \hat{y}(N)]^2}{B_y(i)}, \quad (3.12)$$

where $(\hat{x}(i), \hat{y}(i))$ is the i th location estimate and the approximation of the CRLB of the i th location estimate $B_x(i)$ and $B_y(i)$ can be expressed as

$$B_x(i) = \sum \frac{[\hat{x}(i) - \hat{x}(N)]^2}{\sigma^2([\hat{x}(i) - \hat{x}(N)]^2 + [\hat{y}(i) - \hat{y}(N)]^2)}, \quad (3.13)$$

$$B_y(i) = \frac{[\hat{y}(i) - \hat{y}(N)]^2}{\sigma^2([\hat{x}(i) - \hat{x}(N)]^2 + [\hat{y}(i) - \hat{y}(N)]^2)}, \quad (3.14)$$

where σ^2 is the variance of the measurement noise. The decision of the NLoS identification is made by testing how many normalized residuals are over a certain threshold.

This kind of algorithm would not work properly when the MS is moving and the channel changes significantly during the observation time, for example, crossing a door and entering another room. In this case, testing the change of SNR [49] may help to identify the NLoS channels because a sudden decrease of SNR could indicate the movement from a LOS into an NLOS condition, and vice versa.

However, the above methods would not work over the channels where neither the MS

nor anything nearby is moving and hence the same variance will be observed for both LoS and NLoS channels. Also utilizing subsequent range estimates or time series will cause latency.

When subsequent range estimates or time series are not available, the identification can be made by examining the received channel impulse response. Previous study can be found in [7, 51, 52]. The main idea is to differentiate the NLoS channels with the distribution of parameters that are extracted from the channel profile.

In [7], the authors propose a NLoS channel identification technique based on the multi-path channel statistics such as the kurtosis, the mean excess delay spread and the root mean square (RMS) delay spread.

The kurtosis is defined as a measure of whether the data are peaked or flat relative to a normal distribution; i.e., data sets with high kurtosis tend to have a distinct peak near the mean, decline rather rapidly, and have heavy tails, while data sets with low kurtosis tend to have a flat top near the mean rather than a sharp peak [53]. The kurtosis is given by the following expression

$$\kappa = \frac{E[(|h(t)| - \mu_{|h(t)|})^4]}{E[(|h(t)| - \mu_{|h(t)|})^2]^2} = \frac{E[(|h(t)| - \mu_{|h(t)|})^4]}{\sigma_{|h(t)|}^4} \quad (3.15)$$

where $E(\cdot)$ denotes the expectation, $|\cdot|$ denotes the absolute value, $h(t)$ represents a given channel realization, $\mu_{|h(t)|}$ and $\sigma_{|h(t)|}$ are the mean and standard deviation of $|h(t)|$, respectively.

The mean excess delay spread is defined as

$$\tau_m = \frac{\int_{-\infty}^{\infty} t |h(t)|^2 dt}{\int_{-\infty}^{\infty} |h(t)|^2 dt} \quad (3.16)$$

The root mean square delay spread is defined as

$$\tau_{rms} = \frac{\int_{-\infty}^{\infty} (t - \tau_m)^2 |h(t)|^2 dt}{\int_{-\infty}^{\infty} |h(t)|^2 dt} \quad (3.17)$$

The simulation results using the IEEE 802. 15. 4a multipath model show that the above mentioned channel statistics' probability density functions (PDFs) of the LoS channels are considerably different from those PDFs of the NLoS channels. Hence, the NLoS channels identification, can be performed by the joint channel statistics likelihood ratio test as follows [7]

$$J(\kappa, \tau_m, \tau_{rms}) \underset{H_1}{\overset{H_0}{\geq}} 1 \quad (3.18)$$

where the hypothesis H_0 denotes that the current channel is a LoS channel, the hypothesis H_1 denotes that the current channel is a NLoS channel and $J(\kappa, \tau_m, \tau_{rms})$ is given by

$$J(\kappa, \tau_m, \tau_{rms}) = \frac{P_{LoS}^{kurt}(\kappa)}{P_{NLoS}^{kurt}(\kappa)} \times \frac{P_{LoS}^{med}(\tau_m)}{P_{NLoS}^{med}(\tau_m)} \times \frac{P_{LoS}^{rms-ds}(\tau_{rms})}{P_{NLoS}^{rms-ds}(\tau_{rms})} \quad (3.19)$$

Here, $P_{LoS}^{kurt}(\kappa)$, $P_{NLoS}^{kurt}(\kappa)$, $P_{LoS}^{med}(\tau_m)$, $P_{NLoS}^{med}(\tau_m)$, $P_{LoS}^{rms-ds}(\tau_{rms})$ and $P_{NLoS}^{rms-ds}(\tau_{rms})$ are the PDFs of the kurtosis, the mean excess delay spread, and the RMS delay spread corresponding to the LoS and the NLoS channels, respectively.

In [52], a NLoS detection algorithm using the joint distribution of the channel mean excess delay and the channel total power is proposed. Simulation results show that the detection performance of the joint distribution test is better than that of testing the channel mean excess delay or the channel total power individually.

In [51], the NLoS detection algorithm based on the received pulse shape is also discussed.

In these NLoS channel identification algorithms, all the ranging estimates obtained from NLoS channels are considered biased and will introduce errors to the localization results. However, for the UWB system over indoor wireless NLoS channels, the DPs may only be partially blocked and still can be correctly detected. In [16, 17], schemes are used to estimate the ToA from the NLoS channel. Hence it is important to distinguish those potentially correct ranging estimates obtained from NLoS channels and use them for the localization.

3.3.3 NLoS Error Mitigation

Mitigation with Characteristics/Distribution of the NLoS Ranging Errors

The characteristics/distribution of the NLoS ranging errors can be used to mitigate the NLoS ranging errors and improve the localization accuracy.

In [8], a novel computationally efficient linear-programming (LP) approach is proposed under the following assumptions of UWB ToA-based range estimation: 1) The range bias errors in NLoS conditions are always positive and significantly larger in magnitude than the range-measurement errors in LoS conditions. 2) The LoS range estimates are already distinguished from the NLoS range estimates by the channel identification. With those assumptions, the NLoS range estimates are used to constrain the feasible region and hence increase the localization accuracy without introducing NLoS ranging errors in [8].

In [54], a prior knowledge of the ranging statistics with a cooperative maximization of the global likelihood among the network is proposed to reduce the error on the localization. The probability distribution of the ranging errors in the models [55] is used to design the range estimator under the global maximum likelihood criteria.

In [56], two NLoS mitigation algorithms are proposed based on how much a priori knowledge of the NLoS error is available. An NLoS state estimation (NSE) algorithm can be used if some prior information on NLoS errors is available from the empirical database; in the case where we do not have any knowledge about NLoS, an improved residual

algorithm can be applied to detect a small number of NLoS BSs.

Mitigation with Geometry Information

Another NLoS mitigation method is based on a priori mapping of characteristic properties at specific locations. In [57], a geo-regioning method is proposed to achieve rough localization in rich multipath environment. The regioning algorithm is based on the a priori knowledge of the average power delay profiles of the different regions. The measurement results show that the knowledge of the average power delay profiles of the different regions is sufficient to perform the regioning decision with reasonable reliability.

In [58], a NLoS mitigation method is proposed for urban environments. The method is based on an optimization of a set of nonlinear equations with the fact that in urban areas the buildings are usually organized in blocks, which adds useful constraints on the NLoS optimization problem.

Mitigation with Time Series Filtering

The constrained optimization procedure or the time series filtering method can be utilized to mitigate NLoS errors with the characteristic differences between the two channel state, LoS and NLoS. The time series filtering method, e. g. the Kalman filter, can also be applied to tracking applications to identify the NLoS channels and mitigate the NLoS errors.

In [59], a localization scheme is proposed using only three BSs. The NLoS error is mitigated by computing normalized scale factors or weights that adjust the NLoS-corrupted range measurements to near their LoS values. The normalized scale factors α_i ($i=1,2,3$) for the three BSs are defined as

$$\alpha_i = \hat{D}_i / D_i \quad (3.20)$$

where D_i is the correct distance between the MS and the i th BS. And the constraints on the α_i include:

- i) $0 < \alpha_i \leq 1$ because the NLoS error is a large positive bias.
- ii) The trigonometric relationships between D_i and the distances between the i th and j th BSs l_{ij}
- iii) If we use the location of the i th BS as the center and $\hat{D}_i$ as the radius to draw three circles, the correct location of the MS should fall into the overlapping area. And hence, the estimation error of the ranges are bounded.

The cost function to be minimized with these constraints is taken to be the sum of the square of the distances from the MS location to the points of intersection of the range circles closest to it. If NLoS identification is possible, at least for the serving BS, this information can be used to reduce the complexity of the algorithm and obtain more accurate positioning.

3.4 Distributed Techniques

Since the ad-hoc network draws more and more attention as the flexible and low-cost solution to the indoor communication and localization, many distributed localization schemes for UWB ad-hoc networks are proposed [60, 61]. The distributed localization schemes enable blind APs to compute their own locations. The major reason to choose the distributed localization schemes is that the ad-hoc network is usually lacking fixed infrastructure or extra resources. The distributed localization schemes firstly can share the load onto the whole network, while preserving reasonable computational complexity in each node. Secondly, distributed schemes usually have better scalability, flexibility, and potential reactivity to timely changes. Finally, they avoid the relay of information in multi-hop scenarios.

3.5 Tracking Techniques

When the MS is moving, the tracking techniques are needed in the ranging and the localization schemes to provide continuous and consistent location estimation.

In [62], the Kalman filter technique is applied to the NLoS channel identification and mobile positioning and tracking in UWB systems. It is shown that the UWB localization scheme with the Kalman filter technique can effectively respond to the NLoS/LoS changes in the indoor environment and improve the localization accuracy.

In [63], a grid-based Bayesian approach is proposed to jointly track the sequence of the positions and the sight conditions of the MS. This method is based on the assumption that both the position and the sight condition of the MS are Markov chains whose state is hidden in the received signals. The observations used for the localization are obtained from the power-delay profile of the received signals. As in UWB systems, the use of the whole power-delay profile allows to reach higher localization accuracy.

Chapter 4

An Improved Direct Path Detection Scheme for UWB Indoor Ranging

4.1 Background

The performance of the DP detection, or the ToA estimation, determines the ranging accuracy. ToA estimation techniques in the outdoor wireless channel have been well developed and analyzed [23, 24]. Most of them are based on the assumptions that the multipath channel is sparse and the DP (if not fully blocked) is the strongest path. And hence, the ranging problem turns into finding the strongest signal path. But those ToA estimation techniques designed for the outdoor wireless channel would not work properly in the NLoS indoor wireless channel, which represents the major part of the applications in the modern office environment.

The main problem of ranging in the NLoS indoor wireless channel is that the indoor

34 An Improved Direct Path Detection Scheme for UWB Indoor Ranging

wireless channel is a dense multipath channel and the DP signal may be weaker than the non-direct path signals mainly due to two reasons; the DP becomes weak because of the obstruction of the DP and the non-direct path signals become strong because of several unresolvable rays adding constructively [11, 12]. An optimum threshold needs to be set at the AP to maximize the probability of correct detection of the DP. Previous work on the DP detection using a set of indoor wireless channel measurements can be found in [16] where a predetermined amplitude threshold is set at the AP. After the discrete channel response is recovered from the received waveform, the first channel response sample whose amplitude cross the threshold, or the FDP, will be declared as the DP.

It was noted that the algorithm in [16] considers only one path at a time during the detection. Because the DP could be weak, the detection performance of the algorithm in [16] is sensitive to the threshold value, which should be predetermined according to the received signal power and the estimated characteristics of the noise. In [13] and [17], the threshold setting is investigated and the false alarm probability is given, but the above mentioned problem remains unsolved. Therefore, it is necessary to look for other methods to increase the robustness of the DP detection.

In this chapter, an improved detection algorithm is presented, which considers the clustering effect and the dense multipath properties of the indoor wireless channels. The performance of the proposed algorithm is evaluated by comparing it with the performance of the existing single-amplitude-threshold algorithm in [4] and the performance of the MUSIC algorithm. The settings of the threshold values and the energy window length for the proposed algorithm are investigated by simulations.

4.2 Joint Amplitude and Energy Detection for ToA Estimation

For the simplicity of the analysis, consider a single user BPSK UWB system and each bit is transmitted by one pulse. The received waveform at the AP can be expressed as

[64]

$$r(t) = \sum_{i=0}^{L-1} h_i s(t - i\Delta t) + n(t) \quad (4.1)$$

where h_i is the gain of the i -th channel response sample, which can be positive or negative. Δt is the minimum resolution time, L is the length of the channel and $n(t)$ is modelled as additive white Gaussian noise (AWGN) with a variance equal to σ^2 . Here, the multipath delay is assumed to be an integer multiple of the minimum resolution time Δt to simplify analysis. The transmitted UWB waveform can be defined as

$$s(t) = \sqrt{P_{tw}} \sum_j b_j g(t - jT_f) \quad (4.2)$$

where T_f is the pulse repetition period, $g(t)$ is the pulse shape normalized to give unit power, $b_j \in \{-1, +1\}$ are j th the bi-polar modulated data and P_w is the peak transmitted power of the system. The channel does not necessarily have a multipath arrival at each resolvable time instant, since the path arrival times are modelled as a double Poisson process [10]. This is accounted for by setting $h_i = 0$ for all i where there is no arrival at the resolvable time instant $i\Delta t$. In a low data rate UWB system, the pulse repetition period T_f is longer than the largest channel delay τ_{L-1} . Hence, there is no inter-symbol interference (ISI). In this chapter, we assume that we know the reference time at the AP, which is the time when the transmitter starts to transmit the signal.

Let $\mathbf{h} = [h_0, h_1, \dots, h_{L-1}]$ be the channel response sample vector with h_0 be the true channel response sample corresponding to the DP. Let $\hat{\mathbf{h}}$ be the estimated discrete channel response that has been recovered from the received waveform starting from the reference time using the global maximum likelihood (GML) algorithm [16], which can be expressed as

$$\hat{\mathbf{h}} = [\hat{h}_{-d}, \hat{h}_{-d+1}, \dots, \hat{h}_{-1}, \hat{h}_0, \hat{h}_1, \dots, \hat{h}_{L-1}]. \quad (4.3)$$

Here d , the number of estimated channel response samples before $\hat{h}_0$, can be expressed

36 An Improved Direct Path Detection Scheme for UWB Indoor Ranging

as

$$d = \lfloor D/(c\Delta t) \rfloor \quad (4.4)$$

where D is the distance between the transmitter and the AP, whose positions are both fixed at the time of measurement, c is the speed of light and $\lfloor \cdot \rfloor$ represents the integer part. For the existing single-amplitude-threshold DP detection algorithm in [16], the first channel response sample that is above the predetermined threshold ρ_1 will be declared as the sample corresponding to the DP. Hence if $\hat{h}_0$ is above the threshold ρ_1 and the preceding d channel response samples, $\hat{h}_{-d}, \hat{h}_{-d+1}, \dots, \hat{h}_{-1}$, are below the threshold, we can detect the DP correctly. The probability of correct detection of the existing single-amplitude-threshold DP detection algorithm with the threshold ρ_1 can be expressed as [16]

$$\Pr_c = \Pr(|\hat{h}_0| > \rho_1, |\hat{h}_{-d}| < \rho_1, |\hat{h}_{-d+1}| < \rho_1, \dots, |\hat{h}_{-1}| < \rho_1). \quad (4.5)$$

where $\Pr(\cdot)$ represents the probability. The estimation errors of channel response $\mathbf{h}_e$ can be expressed as

$$\mathbf{h}_e = \hat{\mathbf{h}} - [0, 0, \dots, 0, \mathbf{h}] = [\hat{h}_{-d}, \hat{h}_{-d+1}, \dots, \hat{h}_{-1}, \hat{h}_0 - h_0, \hat{h}_1 - h_1, \dots, \hat{h}_{L-1} - h_{L-1}]. \quad (4.6)$$

We model $\mathbf{h}_e$ as an AWGN vector with the same variance σ^2 as the channel noise. Hence (4.5) can be rewritten as

$$\Pr_c = \Pr(|\hat{h}_0| > \rho_1) [1 - 2\mathcal{Q}(\rho_1/\sigma)]^d \quad (4.7)$$

where $\mathcal{Q}(\cdot)$ is the Q-function [65]. Since the minimum resolvable delay Δt is usually less than 1ns, d , the number of estimated channel response samples before $\hat{h}_0$, could be in the order of tens or hundreds. Hence the performance of the existing single-amplitude-threshold algorithm is very sensitive to the threshold value or the variation of the signal power. In the following, we attempt to improve the existing single-amplitude-threshold

DP detection algorithm to be more robust.

In a typical indoor environment, the DP of the received signal will not be far away from the second path. This can be seen from the average ray arrival rate and the average cluster arrival rate in the multipath model adopted by IEEE 802.15 Study Group 4a [22]. For example the average cluster arrival rate and the average ray arrival rate for CM4 (the office NLoS environment) are 0.19 per nano-second and less than 2.09 per nano-second, respectively. Hence, we can expect that at the AP, considerable energy will be received right after the DP's arrival, which hardly happens to the noise only channel response samples in a single user UWB system. In multiuser UWB systems, the above statement would still be true if the TH code is long enough. Because of this unique characteristic of the indoor wireless channel, we propose to set another energy threshold ρ_2 at the AP to improve the performance of the DP detection. In the following, we will describe the proposed DP detection algorithm.

After the discrete channel response $\hat{\mathbf{h}}$ is recovered from the averaged received waveform, we declare the first channel response sample $\hat{h}_i$ that fulfills the following two rules as the channel response h_0 that corresponds to the DP:

- (1) Its amplitude $|\hat{h}_i|$ is above a predetermined threshold ρ_1 .
- (2) $[\hat{h}_i, \hat{h}_{i+1}, \dots, \hat{h}_{i+L_w-1}]$ is above another predetermined energy threshold ρ_2 as given in the following expression,

$$\sum_{j=i}^{i+L_w-1} \hat{h}_j^2 > \rho_2. \quad (4.8)$$

The probability of correct detection of the proposed DP detection algorithm with the thresholds ρ_1 and ρ_2 can be expressed as

$$\begin{aligned}
\Pr_c &= \Pr(|\hat{h}_0| > \rho_1, \sum_{i=0}^{L_w-1} \hat{h}_i^2 > \rho_2) \prod_{i=-d}^{-1} \left[\Pr(|\hat{h}_i| < \rho_1) + \Pr(|\hat{h}_i| > \rho_1, \sum_{j=i}^{i+L_w-1} \hat{h}_j^2 < \rho_2) \right] \\
&= \Pr(|\hat{h}_0| > \rho_1, \sum_{i=0}^{L_w-1} \hat{h}_i^2 > \rho_2) \prod_{i=-d}^{-L_w} \left[1 - 2\mathcal{Q}\left(\frac{\rho_1}{\sigma}\right) + 2\mathcal{Q}\left(\frac{\rho_1}{\sigma}\right) \Pr(\chi < \frac{\rho_2 - \hat{h}_i^2}{\sigma^2}) \right] \\
&\quad \times \prod_{i=-L_w+1}^{-1} \left[1 - 2\mathcal{Q}\left(\frac{\rho_1}{\sigma}\right) + 2\mathcal{Q}\left(\frac{\rho_1}{\sigma}\right) \Pr\left(\sum_{j=i+1}^{i+L_w-1} \hat{h}_j^2 < \rho_2 - \hat{h}_i^2\right) \right] \quad (4.9)
\end{aligned}$$

where χ is a Chi-Squared Distribution number with $L_w - 1$ degrees of freedom [65].

In the proposed algorithm, if one of the two thresholds is set at the optimum value, a small offset of the other threshold would not affect the ranging performance significantly. Hence, the proposed algorithm is more robust than the conventional single threshold algorithm. However, the IEEE 802.15.4a multipath model is very complex. To obtain the global maximum performance of the proposed two thresholds algorithm, against the length of the energy window and the two threshold values would depend on the amplitude distribution of each single channel impulse response which is very difficult to be approximated with a series of formulas. Hence simulations are performed to search for the optimum length of the energy window and the two threshold values.

4.3 Simulation results

We consider a single user BPSK TH-UWB system. The channel is generated based on the CM4 multipath model adopted by IEEE 802.15 Study Group 4a with the minimum resolvable delay of $\Delta t = 0.33\text{ns}$, in which the distance between the fixed transmitter and AP can be from 3 meters to 28 meters. Hence, d in (4.4) is uniformly distributed from 27 to 252 in the simulation. The second Gaussian derivative pulse windowed to 1ns duration is used as the transmitted pulse. The SNR is defined as the ratio of the power of the peak signal path to the noise variance and is fixed to 30dB [31, 44, 57] in the simulation. Each point of the simulation results is based on 1 million independent realizations of the IEEE 802.15.4a multipath model.

Figure 4.1: The probabilities of correct detection of the direct path for the proposed algorithm with different energy window length L_w over NLoS channels.

Figure 4.2: The standard deviation of delay estimation error for the proposed algorithm with different energy window length L_w over NLoS channels.

Define the average probability of correct detection of the DP and the average standard deviation of delay estimation error with threshold offsets $\rho_e(i)$ for the proposed algorithm as follows

$$\overline{\text{Pr}}_c(L_w) = \frac{\int_{\rho_2 - \rho_e(2)}^{\rho_2 + \rho_e(2)} \int_{\rho_1 - \rho_e(1)}^{\rho_1 + \rho_e(1)} \text{Pr}_c(L_w, \rho_1, \rho_2) d\rho_1 d\rho_2}{\int_{\rho_2 - \rho_e(2)}^{\rho_2 + \rho_e(2)} \int_{\rho_1 - \rho_e(1)}^{\rho_1 + \rho_e(1)} d\rho_1 d\rho_2}, \quad (4.10)$$

$$\overline{\sigma}_e(L_w) = \frac{\int_{\rho_2 - \rho_e(2)}^{\rho_2 + \rho_e(2)} \int_{\rho_1 - \rho_e(1)}^{\rho_1 + \rho_e(1)} \sigma_e(L_w, \rho_1, \rho_2) d\rho_1 d\rho_2}{\int_{\rho_2 - \rho_e(2)}^{\rho_2 + \rho_e(2)} \int_{\rho_1 - \rho_e(1)}^{\rho_1 + \rho_e(1)} d\rho_1 d\rho_2}. \quad (4.11)$$

Fig. 4.1 and Fig. 4.2 show the simulation results of the optimum performance and the average performance with $\rho_e(i)$ equals to 30 per cent of the optimum ρ_i for the proposed algorithm with different lengths of the energy window. For the optimum probability of correct detection of the DP, the threshold values $[\rho_1, \rho_2]$ for the energy window length $L_w = 2, 3, \dots, 10$ are $[0.1, 0.02]$, $[0.1, 0.025]$, $[0.1, 0.03]$, $[0.1, 0.035]$, $[0.1, 0.04]$, $[0.1, 0.04]$, $[0.1, 0.045]$, $[0.1, 0.05]$, $[0.1, 0.06]$, respectively. And for the standard deviation of delay estimation error, the threshold values $[\rho_1, \rho_2]$ for the energy window length $L_w = 2, 3, \dots, 10$ are $[0.08, 0.03]$, $[0.1, 0.035]$, $[0.1, 0.04]$, $[0.1, 0.045]$, $[0.1, 0.05]$, $[0.1, 0.055]$, $[0.1, 0.06]$, $[0.1, 0.06]$, $[0.1, 0.065]$, respectively. The results show that the optimum performance of the proposed algorithm varies relatively slow with different energy window length. It is also shown that $L_w = 4$ or 5 has the best robustness of estimation performance when the threshold offset exists. In the rest of the thesis, we choose $L_w = 5$ and $\rho_2 = 0.045$ for the proposed two-threshold algorithm.

Fig. 4.3 shows the analytical and the simulation results of the probability of correct detection of the DP versus the predetermined threshold value ρ_1 for the existing single-amplitude-threshold algorithm and the proposed algorithm with SNR equals to 30dB. Both the analytical and the simulation results show that the proposed algorithm has wider value range of ρ_1 for the desirable performance than the existing single-amplitude-threshold algorithm and hence is more robust. We can also see that the best performance that the proposed algorithm can achieve, which occurs at ρ_1 setting around 0.1 to 0.12, is

Figure 4.3: The probabilities of correct detection of the direct path for the proposed and the existing algorithm with different amplitude threshold value ρ_1 over NLoS channels.

Figure 4.4: The standard deviation of delay estimation error for the proposed and the existing algorithm with different amplitude threshold value ρ_1 over NLoS channels.

a bit better than that of the existing single-amplitude-threshold algorithm. The reason is that in order to avoid missing the DP when the DP's amplitude is lower than the threshold ρ_1 , we should make ρ_1 as low as possible. However, this will increase the probability of early false alarm caused by those amplitudes of the channel response samples correspond to noise contribution only, which are above the threshold ρ_1 . Setting the second energy threshold ρ_2 can decrease the probability of false alarm and allows us to use lower ρ_1 to obtain better performance.

Fig. 4.4 shows the analytical and the simulation results of the standard deviation of delay estimation error versus the predetermined threshold value ρ_1 for the existing single-amplitude-threshold algorithm and the proposed algorithm with SNR equals to 30dB. It shows that the proposed algorithm are less sensitive to the value of the threshold ρ_1 .

Note that when inter-symbol interference, narrow-band interference or multiuser interference exists and is not mitigated, the energy of the interference will add to the estimated channel response. And hence, there may not be considerable statistical difference between the period before and after the direct path of the current symbol arrival. In this case, both the conventional algorithm and the proposed algorithm will fail and cause large ranging errors.

4.4 Comparison with the MUSIC Algorithm

The MUSIC algorithm is a well-known technique for high resolution channel estimation. It is applied to UWB systems in [36, 37]. However, the channel length in UWB localization applications is usually tens of nanoseconds, corresponding to a few hundreds of samples. Hence, the computational load of the MUSIC algorithm is very heavy because of the eigenvalue decomposition or the inverse of the covariance matrix. In this simulation, we assume that the search area of the DP detection is narrowed down to 15-channel impulse samples by rough channel estimation. Each point of the simulation results are based on 10 thousands independent realizations of the multipath model CM4 adopted by IEEE 802.15 Study Group 4a. And the delay of the DP is uniformly distributed over [1, 15]. Independent fading following the Gaussian distribution is assumed for each

tap of the channel impulse response to fulfill the requirement of the MUSIC algorithm. The SNR is defined as the ratio of the power of the peak signal path to the noise variance and is fixed to 30dB in the simulation. For the existing single-threshold algorithm, the threshold is compared to the average energy instead of the amplitude of each tap of the channel impulse response over 10000 observations because of the fading. For the proposed algorithm, the thresholds are now compared to the average energy of the corresponding taps of the channel impulse response over 10000 observations. For the MUSIC algorithm, the power-of-R technique is used to estimate the noise subspace from the covariance matrix of the received waveform without knowing the exact rank of the signal subspace, which is the number of signal paths in the search area. The output spectrum of the MUSIC algorithm is normalized and then is compared to a threshold. The first output result crossing the threshold is declared as the output result that corresponds to the correct ToA of DP.

Figs. 4.5 and 4.6 show the probability of correct detection of DP and the standard deviation of delay estimation error for the existing algorithm, the proposed algorithm and the MUSIC algorithm. It is shown that under this simulation setting, the existing algorithm has the best optimum performance for both the probability of correct detection of DP and the standard deviation of delay estimation error. It is because the probability of EFA is significantly reduced in the short search area and the existing algorithm can use lower threshold to obtain better performance. Since the EFA problem is not as serious as in the full-length CM4 channels, the advantage of the proposed algorithm is weakened. And because the energy window length $L_w = 5$ and the energy threshold $\rho_2 = 0.045$ may not be the optimum value for this simulation setting, the performance of the proposed algorithm is a little worse than the existing algorithm. The simulation results show that the optimum performance of the MUSIC algorithm is worse than both the existing and the proposed algorithms. That is because when a signal path is relatively weak, the separation between the signal subspace and the noise subspace becomes difficult and the noise subspace estimation error will cause the delay estimation error. Note that the performance of the MUSIC algorithm is considerably less affected by the length of search area than the existing algorithm and the proposed algorithm do. Hence, if we apply the MUSIC algorithm to the full-length CM4 channels, the performance of the

Figure 4.5: The probabilities of correct detection of the direct path for the existing, the proposed and the MUSIC algorithm with different amplitude threshold value ρ_1 over NLoS channels.

Figure 4.6: The standard deviation of delay estimation error for the existing, the proposed and the MUSIC algorithm with different amplitude threshold value ρ_1 over NLoS channels.

MUSIC algorithm may remain the same as in Figs. 4.5 and 4.6, while the performance of the existing algorithm and the proposed algorithm degrade from the performance shown in Figs. 4.5 and 4.6 to the performance shown in Figs. 4.3 and 4.4. Comparing Figs. 4.3, 4.4, 4.5 and 4.6, it is found that the optimum probability of correct DP detection for the MUSIC algorithm will be a little better than those for the existing algorithm and the proposed algorithm if we use full-length CM4 channels. But in that case, the little improvement may not be worth the huge computational load of the MUSIC algorithm.

4.5 Conclusion

An improved DP detection algorithm has been proposed for ranging in the UWB system over the NLoS indoor wireless channel. The proposed algorithm considers the clustering effect and the dense multipath properties of the indoor wireless channels by setting another threshold to check the nearby energy of the possible DP. Simulation results based on the multipath model adopted by IEEE 802.15 Study Group 4a show that the proposed algorithm is less sensitive to the threshold value ρ_1 and has a little better optimum performance than the existing algorithm. The optimum performance of the proposed algorithm varies relatively slow with different energy window length. But if we take the threshold offsets into consideration, $L_w = 4$ or 5 should be chosen. It is also showed that reducing the length of the search area will enhance the performance for both the existing and the proposed algorithm. In the simulation with the length of the search area equals to 15, the optimum performance of the MUSIC algorithm is worse than those of the existing and the proposed algorithm.

Chapter 5

A DP/NDP-APs Distinguishing Algorithm for UWB localization Schemes over Stationary Indoor Wireless Channels

5.1 Background

In this thesis, the DP-APs denote those APs whose FDPs are DPs to the MS and hence can give correct ranging estimations. The NDP-APs denote those APs whose FDPs correspond to pure noise/interference, which will cause an early false alarm (EFA), or non-direct paths noted as miss-DP (MDP) errors.

Previous work on ranging in UWB system over indoor dense multipath channels can be found in [13, 16]. The ranging performance in [16] is obtained using a set of indoor

wireless channel measurements with an AP. It shows that relatively large ranging error occurs when the DP is heavily blocked and cannot be detected. This kind of errors can be mitigated using multiple APs radio localization schemes. Multiple APs radio localization schemes have been well studied in narrowband systems over outdoor wireless channels. The study shows that the non-direct path error is recognized as a critical issue for localization [14], which is caused by the NDP-APs. When using the popular least squares method, the localization error that is caused by the ranging errors can be reduced by increasing the number of the APs [47]. But increasing the number of APs may cause other problems, such as overload in cellular network, synchronization difficulty, computational inefficiency, etc. As a solution to the above problems, a DP/NDP-APs distinguishing algorithm was proposed. The measured standard deviation of the ToA or AoA at the APs was used to distinguish between APs whose FDPs correspond to the DP and those whose FDPs correspond to EFAs or non-direct paths [15]. The ToA or AoA of the non-direct path is known to have a significantly larger standard deviation than the standard deviation of the estimated ToA or AoA of the DP in cellular network.

However, localization in the indoor wireless channel is more complicated than in the outdoor wireless channel encountered in a cellular network. Sometimes the indoor wireless channel could be stationary. For example, a fireman (the target MS) is trapped in a burning building and cannot move; the APs are fixed and nothing is moving between or around the target MS and the APs. In that case, the standard deviation of the ToA or AoA will not be significant for both the DP and the non-direct path at the AP and the existing deviation based technique mentioned above will fail to distinguish between the DP-APs and the NDP-APs. Hence, the localization algorithm using the existing deviation based technique can only equally use the information from all the APs that involved in the multiple APs localization, which could cause considerable localization error in some undesirable environment. Also, when a relatively low threshold is accidentally used in the DP detection algorithm, the FDP at the AP may correspond to an EFA, which also cannot be distinguished from the DP by the existing deviation based technique and will cause localization error.

In the recently published work [7], a NLoS channel identification technique is proposed to solve the above mentioned problem. In the localization algorithm based on the NLoS

channel identification technique, all the ranging estimates obtained from NLoS channels are considered biased. However, for the UWB system over indoor wireless non-line-of-sight channels, the DPs may only be partially blocked and still can be correctly detected when the channel noise is relatively weak. In [16, 17], schemes are used to estimate the ToA from the NLoS channel. Also, in realistic applications, there usually are not enough APs with the LoS channel to the MS for the localization. Hence it is important to distinguish those potentially correct ranging estimates obtained from NLoS channels and use them for the localization.

In this chapter, we propose a DP/NDP-APs distinguishing algorithm for localization schemes in the UWB system over stationary indoor wireless channels, especially NLoS channels. In the proposed algorithm, we exploit the near free space loss characteristics of the DP. Firstly, we estimate the delay and the energy of the signal paths from the received waveforms using path detection schemes at the AP [16]. Then we compute the parameter called the additional power loss (APL) using the estimated delay and energy of the FDP for each AP, which do not require the channel to vary with time.

The proposed distinguishing algorithm can also be used for localization performance improvement in peer to peer UWB localization systems [66], which is currently being investigated as a promising solution for localization in the UWB system. And as in [8], if the reliable range estimates are already distinguished from the biased range estimates, the biased range estimates can be used to constrain the feasible region and hence increase the localization accuracy without introducing ranging errors.

In this thesis, we assume that the DP-APs do not necessarily have a clear LoS, or LoS channel, to the MS. Hence, distinguishing DP/NDP-APs is not equivalent to distinguishing LoS/NLoS channels and the proposed algorithm cannot be fairly compared with the localization algorithm using the NLoS channel identification technique. But to evaluate the performance of the proposed algorithm, the RMS algorithm, one of the NLoS channel identification technique, is studied in a localization simulation to compare with the proposed algorithm.

5.2 Distinguishing the DP-APs and the NDP-APs

The radio propagation can be approximated using a finite number of rays (paths) originated from the MS [35]. A ray, before arriving at an AP, may go through many reflections and refractions, which occur when the ray intersects with blockages (such as walls, doors, windows, etc.). The ray loses a certain amount of energy each time there is a reflection or refraction and during the propagation in between intersections the ray will experience the free-space propagation loss. Hence, after travelling l meters from the MS and undergoing a reflections and $b - a$ refractions, the power of the ray received at the AP can be expressed as [67]

$$P_{rw}(l, a, b) = P_{1m} l^{-2} \prod_{i=0}^a R(\mathbf{m}_R(i), \theta_R(i)) \prod_{j=0}^{b-a} T(\mathbf{m}_T(j), \theta_T(j)), \quad (5.1)$$

where $R(\mathbf{m}_R(i), \theta_R(i))$ and $T(\mathbf{m}_T(j), \theta_T(j))$ are the reflection power coefficient of the i th reflection and the refraction power coefficient of the j th refraction, respectively; $\mathbf{m}_R$ and $\mathbf{m}_T$ represent the materials' reflective indexes and refractive indexes of the blockages, respectively; and $\theta_R(i)$ and $\theta_T(j)$ are the reflection angle and the refraction angle of for the i th reflection and the j th refraction, respectively. If a ray does not go through any reflection and refraction, there is no energy loss except for free-space loss. This is accounted for by setting $R(\mathbf{m}_R(0), \theta_R(0))$ and $T(\mathbf{m}_T(0), \theta_T(0))$ to 1. P_{1m} is the free-space power loss at 1 meter distance, which can be expressed as

$$P_{1m} = G_t G_r \left(\frac{c}{4\pi f} \right)^2, \quad (5.2)$$

where G_t and G_r are the gains of the MS and the AP antennas, respectively, c is the speed of light in the free space, and f is the center frequency of the radio signal. Define

the APL as

$$\begin{aligned} P_{APL}(a, b|l) &= 10\log\left[\frac{P_{1m}l^{-2}}{P(l, a, b)}\right] \\ &= -10\sum_{i=0}^a \log[R(\mathbf{m}_R(i), \boldsymbol{\theta}_R(i))] - 10\sum_{j=0}^{b-a} \log[T(\mathbf{m}_T(j), \boldsymbol{\theta}_T(j))]. \end{aligned} \quad (5.3)$$

Because the direct rays do not undergo any reflections, the mean APL of the direct rays can be expressed as

$$E\{P_{APL}(b|D)\} = -10\sum_{b=0}^{\infty} P(b|D)bE\{\log T\}, \quad (5.4)$$

where D is the actual distance between the MS and the AP, $P(b|D)$ is the probability density function (PDF) for a ray that has undergone b intersections after travelling D meters and $E\{\log T\}$ is the average blockage refraction power coefficient among the different materials, which can be expressed as

$$E\{\log T\} = \sum_{i=1}^M Pr(m_i)E\{\log[T_i(\theta)]\}. \quad (5.5)$$

Here M is the number of the blockage materials, $Pr(m_i)$ is the probability of a signal blockage by the i th material and $E\{\log[T_i(\theta)]\}$ is the average refraction power coefficient of the i th material. The mean APL of the non-direct rays that travel $D + \Delta l$ meters can be expressed as

$$E\{P_{APL}(a, b|D+\Delta l)\} = -10\sum_{b=0}^{\infty} P(b|D+\Delta l)\sum_{a=0}^b Pr(a|b, D+\Delta l)[aE\{\log R\} + (b-a)E\{\log T\}], \quad (5.6)$$

where $Pr(a|b, D+\Delta l)$ is the probability of a ray that has undergone exactly a reflections and $b - a$ refractions after traveling $D + \Delta l$ meters, Δl is the excess distance of the non-direct rays and $E\{\log R\}$ is the average blockage reflection power coefficient, which

	The Average Refraction Power Coefficient	The Average Reflection Power Coefficient
Wallboard	0.6635	0.2166
Cloth Partition	0.4036	0.0838
Structure Wood	0.5385	0.1901
Wooden Door	0.4568	0.1882
Plywood	0.4770	0.2208
Glass	0.4765	0.3916
Styrofoam	0.9080	0.0570
Bricks	0.1439	0.3177
Concrete Block	0.0243	0.1997

Table 5.1: The average reflection power coefficients and the average refraction power coefficients of the nine common office blockage materials [68].

can be expressed as

$$E\{\log R\} = \sum_{i=1}^M Pr(m_i) E\{\log [R_i(\theta)]\}. \quad (5.7)$$

Here $E\{\log [R_i(\theta)]\}$ is the average reflection power coefficient of the i th material.

In [68], nine common signal blockages in the modern offices are measured and physical parameters of those materials at 5GHz is given. We assume both the reflection angle and the refraction angle are uniformly distributed over $[0, \pi/2)$ and calculate the average reflection coefficients and the average refraction coefficients using the basic physics formula, which are given in Table. 5.1. Considering that the modern offices usually have large rooms and soft partitions are used in the rooms, we can assume that the probability of a signal blockage by bricks or concrete block is much smaller than the probability of a signal blockage by any other materials given in Table. 5.1. From (5.5), (5.7) and Table. 5.1, we can show that

$$E\{\log T\} > E\{\log R\}. \quad (5.8)$$

Note that

$$\begin{aligned} \mathbb{E}\{P_{APL}(a, b|_{D+\Delta l})\} &> -10 \sum_{b=0}^{\infty} P(b|_{D+\Delta l}) \sum_{a=0}^b Pr(a|_{b, D+\Delta l}) b \mathbb{E}\{\log T\} \\ &= -10 \mathbb{E}\{\log T\} \mathbb{E}\{b|_{D+\Delta l}\}, \end{aligned} \quad (5.9)$$

where $\mathbb{E}\{b|_{D+\Delta l}\}$ denotes the average number of intersections that a ray has undergone after travelling $D + \Delta l$ meters. Because $\mathbb{E}\{b|_{D+\Delta l}\} > \mathbb{E}\{b|_D\}$, we obtain

$$\begin{aligned} \mathbb{E}\{P_{APL}(a, b|_{D+\Delta l})\} &> -10 \mathbb{E}\{\log T\} \mathbb{E}\{b|_{D+\Delta l}\} \\ &> -10 \mathbb{E}\{\log T\} \mathbb{E}\{b|_D\} \\ &= \mathbb{E}\{P_{APL}(b|_D)\}. \end{aligned} \quad (5.10)$$

Hence, we can expect the mean of the APL of the direct rays is much smaller than that of the non-direct rays and we can decide whether the FDP of each AP corresponds to the DP or the non-direct path by testing the estimated APL of the FDP, which can be expressed as

$$\hat{P}_{APL}(a, b|_l) = P_{1m} \frac{(c\hat{\tau}_0)^{-2}}{\hat{P}_0}, \quad (5.11)$$

where $\hat{P}_0$ and $\hat{\tau}_0$ are the estimated power and delay of the FDP, respectively. They can be obtained from the received waveform by using path detection schemes [16].

Assume there are redundant APs, for example, 3 APs are required for the 2-D location but there are M APs ($M > 3$) involved in the multiple APs localization. Based on the proposed distinguishing algorithm mentioned above, we could do the localization using the information only from those 3 APs that have small APLs, instead of using the information from all M APs. When brute force is used to find the estimated location that minimize the least square error, the computational load of the localization algorithm using the proposed distinguishing algorithm is roughly $3/M$ of the computational load of the localization algorithm using the conventional equally-using-all-APs algorithm. The computational efficiency of the localization algorithm with the proposed distinguishing

algorithm could be useful to develop a real time UWB localization system.

5.3 The APL distribution of the FDP

Define $\hat{P}'_{APL}$ as follows

$$\hat{P}'_{APL} = \frac{\hat{P}_{APL}}{P_{1m}} = \frac{(\hat{\tau}_0 c)^{-2}}{\hat{P}_0}. \quad (5.12)$$

In this section, we compare the distribution of the $\hat{P}'_{APL}$ for the FDP obtained from the simulation results and our measurements in a typical indoor office environment.

The measurements for the indoor office environment were performed at the Positioning and Wireless Technology Center (PWTC), which is located at the 4th floor of Research Techno Plaza in Nanyang Technological University, Singapore. PWTC is a typical modern office with width 27.3m, length 27.3m and height 2.8m. Its main area is soft partitioned and contains cupboards, metal cabinets, tables made of chipboard, plastic chairs, computers, etc. The main area is connected to other rooms directly or via very short corridors. There are some concrete or bricks structures constructed for lobbies or staircases and these areas protrude into the main area. Those structures can cause high attenuation to the DP and they are marked as heavily blocked area in Fig. 5.3. The environment is valuable for studying the effects of channel on the localization errors since various propagation scenarios are included. For all the 869 NLoS channel measurements, the location of the MS was the same and the AP was fixed at different spatial sample points, which were uniformly distributed along the linear routes $\mathbf{A}, \mathbf{B}, \dots, \mathbf{R}$, as shown in Fig. 5.3. The spacing between any two adjacent points of the same linear route is 0.2m, which is much larger than half wavelength to ensure independent sampling. The actual physical distance between the MS and AP positions are accurately measured for comparison. The pulse shown in Fig. 5.3 with power spectral density (PSD) conforming to the FCC regulation was the received pulse with the distance between the MS and AP equals to 2m. The minimum resolvable delay is set to 0.33ns as in the IEEE simulation program.

Figure 5.1: The environment of the measurements.

Figure 5.2: The pulse used in the measurements.

In this chapter, we recover the CIR from the received waveforms in the measurement using the generalized maximum likelihood algorithm [16] with a threshold for each channel profile. Different thresholds are set according to the peak path power and the noise level of the channel profiles to make the probability of the early false alarm sufficiently small. The average amplitude of the thresholds, which is normalized to the peak path amplitude of each channel profile, is 0.06. Each CR sample that crosses the threshold corresponds to a detectable signal path. We compute the APL of the FDP for each channel profile. Considering the system error, which may be caused by minimum resolvable delay and the unknown propagation delay in the LoS blockage structures, we decide the FDP of a channel profile corresponds to a DP when the range estimation error l_e is no larger than 0.1m, half of the spacing between two adjacent measurement points. Otherwise, the FDP corresponds to an EFA or a non-direct path.

For the simulation results presenting the APL distribution of the FDP corresponding to the DP and the EFA or the non-direct path, we use the 4a multipath model CM4 to generate 40000 independent channel response profiles, which corresponds to the NLoS indoor office environment. Since the 4a multipath model is suitable for the range between 3m and 28m, the delay of the DPs are set to be uniformly distributed between $3/c$ s and $28/c$ s. In this simulation, we assume the CR samples can be perfectly recovered from the received waveform using path detection schemes and no false alarm is considered. For a fair comparison with the measurement results, the minimum resolvable delay is set to 0.33ns. The thresholds, which are normalized to the peak path amplitude of each generated channel profile, is set to 0.06. Furthermore, the channel profiles generated by the 4a multipath model are normalized to have the same average peak signal path power as the channel profiles from the measurement.

For the simulation result presenting the APL distribution of the FDP corresponding to EFA, we recover the CIRs from the additive white Gaussian noise (AWGN) using the generalized maximum likelihood algorithm [16] with a threshold 0.06. The variance of the AWGN is set to 10^{-4} to have a peak SNR of 40dB, which is defined as the ratio for the power of the peak signal path to the noise power. The time length of the AWGN is uniformly distributed between $3/c$ s and $28/c$ s as the distribution for the delay of the DPs. If one of the CIRs that are recovered from the AWGN crosses the threshold, there

**A DP/NDP-APs Distinguishing Algorithm for UWB localization Schemes
over Stationary Indoor Wireless Channels**

60

Figure 5.3: The PDF of the $\hat{P}'_{APL}$ for the FDP.

will be an EFA and the APL of the first CR crossing the threshold will be computed and accounted for the APL distribution of the FDP corresponding to EFA. Otherwise, no APL will be accounted.

Fig. 5.3 shows the PDF of $\hat{P}'_{APL}$ of the FDP corresponding to the DP, the non-direct path and the EFA from the simulation results and the test based on our indoor office measurement. It shows that, as expected, the mean $\hat{P}'_{APL}$ of the FDP corresponding to the DP is significantly smaller than that of the FDP corresponding to non-direct path path for both the 4a multipath model and the stationary indoor office measured data. Fig. 5.3 also shows that the mean $\hat{P}'_{APL}$ of the FDP corresponding to the DP is significantly smaller than that of the FDP corresponding to EFA with a peak SNR 40dB. Note that the EFA is not the major problem in the UWB localization because the probability of the EFA can be reduced simply by raising the SNR or the threshold. Hence, we can decide whether the FDP of each AP corresponds to the DP or not by testing the estimated APL of the FDP. We note that the PDFs of $\hat{P}'_{APL}$ of the FDP

obtained from the 4a multipath model CM4 and the measurement are slightly different. The reason of the difference may be that we do not have enough space samples in the measurement because of the two heavily blocked areas in the measurements environment shown in Fig. 5.3.

5.4 Numerical results

We consider a single user BPSK TH-UWB system. The channel is generated based on the CM4 multipath model adopted by IEEE 802.15 Study Group 4a with the minimum resolvable delay of $\Delta t = 0.33\text{ns}$, in which the distance between the fixed transmitter and AP can be from 3 meters to 28 meters. Hence, d in (4.4) is uniformly distributed from 27 to 252 in the simulation. The second Gaussian derivative pulse windowed to 1ns duration is used as the transmitted pulse. The SNR is defined as the ratio of the power of the peak signal path to the noise variance and is fixed to 30dB in the simulation.

Firstly, we generate 1 million independent realizations of the IEEE 802.15.4a multipath model and do the DP detection using the existing single-amplitude-threshold algorithm for each one of them. Then three cases are examined as follows

1) Without the proposed APL algorithm. The ranging performance is calculated using all 1 million detection results. We refer to this case as 'all the channels' in the rest of this thesis.

2) Picking out 50 per cent channels/detection results using the proposed APL algorithm. We compute the APL for the detection result of each channel. And the ranging performance is calculated using only half of the 1 million detection results, whose APLs are among the smallest 50 per cent. We refer to this case as 'Channel Group 1' in the rest of this thesis.

3) Picking out 10 per cent channels/detection results using the proposed APL algorithm. We compute the APL for the detection result of each channel. And the ranging performance is calculated using only one tenth of the 1 million detection results, whose APLs are among the smallest 10 per cent. We refer to this case as 'Channel Group 2' in the

Figure 5.4: The probabilities of correct detection of the direct path for the proposed and the existing algorithm with different amplitude threshold ρ_1 over NLoS channels.

rest of this thesis.

Note that all the channels of Channel Group 2 are in Channel Group 1 and the channel groups may be different for different amplitude threshold value ρ_1 because of the different DP detection results.

Figs. 5.4 and 5.5 show the probability of correct detection of DP and the standard deviation of delay estimation error for all the channels, the Channel Group 1 and the Channel Group 2. All the performance curves show the same trend, that is with the increasing threshold value, the accuracy of the estimation is firstly improving because of the decreasing probability of EFA and then is degrading because of the increasing probability of MDP. As expected, the simulation results show that the DP detections

Figure 5.5: The standard deviation of delay estimation error for the proposed and the existing algorithm with different amplitude threshold ρ_1 over NLoS channels.

A DP/NDP-APs Distinguishing Algorithm for UWB localization Schemes
over Stationary Indoor Wireless Channels

64

Figure 5.6: The probabilities of DP detection error caused by the EFA and the MDP for the proposed and the existing algorithm with different amplitude threshold ρ_1 over NLoS channels.

made over Channel Group 2 have better performance than over all the channels or over Channel Group 1, which means that the DP detections with smaller APLs are statistically more accurate both on the probability of correct detection of DP and the standard deviation of delay estimation error. This is because when a NDP is declared as the DP in the estimation, it may have a large APL due to power loss in the reflections and the refractions; and also when a noise sample is declared as the DP, causing EFA error in the estimation, it may have a large APL due to the limited noise power. By eliminating those DP detections with relatively large APLs, the estimation error is decreased.

Figs. 5.6 and 5.7 show the probability of DP detection error and the standard deviation

Figure 5.7: The standard deviation of delay estimation error caused by the EFA and the MDP for the proposed and the existing algorithm with different amplitude threshold ρ_1 over NLoS channels.

of delay estimation error caused by the EFA and the MDP for all the channels, Channel Group 1 and Channel Group 2. The simulation results show that the major advantage of the proposed APL algorithm is suppressing the MDP errors. It is shown that for the errors caused by the MDP, the probability of error of Channel Group 2 is significantly less than that of all the channels and the standard deviation of delay estimation error of Channel Group 2 is 10dB less than that of all the channels when the threshold is relatively high. We note that when the threshold is relatively low, the probability of error and the standard deviation of delay estimation error caused by the MDP for Channel Group 1 and Channel Group 2 are higher than that for all the channels. This is because when the amplitude threshold is low, the EFA error is dominant in the DP detection and causes large APLs. Hence, channels that have MDP errors and relatively small APLs are more likely to be in Channel Groups 1 and 2 and the MDP error for Channel Groups 1 and 2 would be larger than that for all the channels. As the threshold value increases, the probability of correct DP detection rises quickly and many channels with correct DP detections fall into Channel Group 1 and Channel Group 2 because the correct DP detections tend to have smaller APLs than the EFA error cases and the MDP cases. Hence, the simulation results show that the MDP error for Channel Group 2 decreases while the MDP error for all the channels goes up due to the increasing threshold value. As the threshold value continually increases, more DPs may be missed in the detection and the probability of correct DP detection slowly degrades. Hence, the simulation results show that the MDP error for all the channels, Channel Group 1 and 2 increases.

To show the localization performance, we design a 2-D localization simulation. Three algorithm are tested.

- 1) The existing algorithm. Firstly, we do the DP detection/ranging using the existing single-amplitude-threshold algorithm. Then we equally use all the ranging results to perform localization with least square (LS) criteria.
- 2) The proposed APL algorithm. Firstly, we do the DP detection/ranging using the existing single-amplitude-threshold algorithm and compute APL for the estimation results. Then we choose three ranging results with the smallest APLs to perform localization with LS criteria.

3) The RMS algorithm. Firstly, we do the DP detection/ranging using the existing single-amplitude-threshold algorithm. Then we choose three ranging results that come from the channels with the smallest RMS to perform localization with LS criteria because the RMS of LoS channels is statistically smaller than the RMS of NLoS channels [7].

Assume 6 APs, which form a hexagon, are involved in the multiple APs localization with the fixed coordinates of $(14m, 0)$, $(-14m, 0)$, $(7m, 12.12m)$, $(-7m, 12.12m)$, $(7m, -12.12m)$ and $(-7m, -12.12m)$. The MS is placed randomly in the area where the distances to the 6 APs are all between 3m and 28m, which is the suitable range for the 4a multipath model. The noise is AWGN and the channel profiles between the MS and the APs are independently generated according to the IEEE 802.15.4a multipath model CM4 with the same 30dB peak SNR. Each point of the simulation results is based on 1 million independent realizations of the IEEE 802.15.4a multipath model.

Figs. 5.8 and 5.9 show the mean absolute error of the localization and the standard deviation of localization error for the existing, the proposed and the RMS algorithm over NLoS channels. The results show the optimum performance of the proposed APL algorithm is better than that of the existing algorithm but the improvement is not as much as in Fig. 5.5. This is because the existing algorithm uses all six ranging results to perform the LS localization while the proposed algorithm only uses the three ranging results with the smallest APLs. When the error of the redundant data is not significant, using more data in the LS localization will considerably improve the performance. Compared to the existing algorithm, the proposed algorithm achieves a little better performance with only half of the data. Hence the proposed algorithm can reduce the computing power requirement and the processing delay for anchor points without lowering the localization performance. As expected, the performance of the RMS algorithm is the worst in this simulation because the RMS criteria differentiate between the LoS channels and the NLoS channels and would not work properly in this case, as all channels are NLoS channels.

To study the localization performance of the proposed algorithm in the LoS environment and in the mixed LoS/NLoS environment, another two simulations are designed. One simulation uses 6 LoS channels generated by IEEE 802.15.4a multipath model CM3 and

Figure 5.8: The mean absolute error of the localization for the existing, the proposed and the RMS algorithm with different amplitude threshold value ρ_1 over NLoS channels.

Figure 5.9: The standard deviation of the localization error for the existing, the proposed and the RMS algorithm with different amplitude threshold value ρ_1 over NLoS channels.

Figure 5.10: The mean absolute error of the localization for the existing, the proposed and the RMS algorithm with different amplitude threshold value ρ_1 over LoS and mixed channels.

Figure 5.11: The standard deviation of the localization error for the existing, the proposed and the RMS algorithm with different amplitude threshold value ρ_1 over LoS and mixed channels.

the other simulation uses 3 LoS channels generated by IEEE 802.15.4a multipath model CM3 and 3 NLoS channels generated by IEEE 802.15.4a multipath model CM4. The rest of simulation settings are the same as the previous simulation.

Figs. 5.10 and 5.11 show the mean absolute error of the localization and the standard deviation of localization error for the existing, the proposed and the RMS algorithms over LoS and mixed channels. As expected, all algorithms perform better in LoS environment than in LoS/NLoS mixed environment. And comparing to Figs. 5.8 and 5.9, all algorithms perform better in LoS/NLoS mixed environment than in NLoS environment. Because the DP signals are statistically more powerful and more likely to cross the threshold in the LoS channels than in the NLoS channels, the advantage of the proposed APL algorithm on suppressing the MDP error is less significant. Hence the optimum mean absolute error of the localization for the existing algorithm is better than that for the proposed algorithm in LoS environment. But the proposed algorithm still outperform the existing algorithm a little in LoS/NLoS mixed environment because of its accuracy on ranging over NLoS channels as shown in Figs. 5.4 and 5.5. The simulation results show that the performance of the RMS algorithm is still not very good compared to the existing and the proposed algorithms. It may due to the complexity of the IEEE multipath model. The first sample of the channel impulse response generated by CM3 may be weak and cause estimation errors, which may be the result of the clustering effect of the indoor wireless channel. The RMS algorithm can differentiate the LoS channels from the NLoS channels but the estimation obtained from those LoS channels may not always be accurate and would degrade the performance.

5.5 Conclusion

A new DP/NDP-APs distinguishing algorithm for the localization algorithm in the UWB system is proposed. Based on the fact that the mean APL of the FDP corresponding to the DP is significantly smaller than that of the FDP corresponding to non-direct path and the EFA, we can distinguish the paths over stationary indoor wireless channels by testing the estimated APLs of the paths. The simulation results show that the proposed

algorithm outperforms the existing algorithm in the ranging and has considerable advantage on suppressing the MDP error over NLoS channels. The localization simulation results show that the proposed algorithm can do the localization with the least possible number of APs, which have the small APLs, and has less computational load and better localization performance than the localization algorithm using the conventional algorithm which uses all APs over NLoS channels. If there are no redundant AP, we still may improve the localization performance by putting a larger weightage on the AP that has smaller APL. It is also shown that the advantage of the proposed algorithm is less significant in LoS channels and hence the optimum mean absolute error of the localization for the existing algorithm is better than that for the proposed algorithm in LoS environment.

In this thesis, we assume that the DP-APs do not necessarily have a clear LoS, or LoS channel, to the MS. Hence, distinguishing DP/NDP-APs is not equivalent to distinguishing LoS/NLoS channels and the proposed algorithm cannot be fairly compared with the localization algorithm using the NLoS channel identification technique. Hence performance of the RMS algorithm is relatively poor in the simulation.

74 A DP/NDP-APs Distinguishing Algorithm for UWB localization Schemes
over Stationary Indoor Wireless Channels

Chapter 6

The Performance Evaluation of the Combined Proposed Schemes

In this chapter, we examine the performance of the combination of the two proposed schemes.

As in Chapter 5, We consider a single user BPSK TH-UWB system. The channel is generated based on the CM4 multipath model adopted by IEEE 802.15 Study Group 4a with the minimum resolvable delay of $\Delta t = 0.33\text{ns}$, in which the distance between the fixed transmitter and AP can be from 3 meters to 28 meters. Hence, d in (4.4) is uniformly distributed from 27 to 252 in the simulation. The second Gaussian derivative pulse windowed to 1ns duration is used as the transmitted pulse. The SNR is defined as the ratio of the power of the peak signal path to the noise variance and is fixed to 30dB in the simulation. Each point of the simulation results is based on 1 million independent realizations of the IEEE 802.15.4a multipath model. Four algorithms are tested in this ranging simulation.

- 1) The existing algorithm. Perform the ranging only with the amplitude threshold ρ_1 for all the channels.

- 2) The proposed two-threshold algorithm. Perform the ranging with the amplitude threshold ρ_1 and the energy threshold ρ_2 for all the channels. The length of the energy window $L_w = 5$ and $\rho_2 = 0.045$.
- 3) The proposed APL algorithm. First, perform the ranging only with the amplitude threshold ρ_1 for all the channels and compute APL for the estimation results. Then only consider the estimation results obtained from the channels whose APL is among the 10 per cent smallest APLs in all the channels. It is the same as the Channel Group 2 in Chapter 5.
- 4) The combination of the two proposed algorithms. Firstly, perform the ranging with the amplitude threshold ρ_1 and the energy threshold ρ_2 for all the channels. The length of the energy window $L_w = 5$ and $\rho_2 = 0.045$. Secondly, compute APLs for all the estimation results. Then only consider the estimation results obtained from the channels whose APL is among the 10 per cent smallest APLs in all the channels. It is the same as the Channel Group 2 in Chapter 5.

Fig. 6.1 and Fig. 6.2 show the probabilities of correct detection of the DP and the standard deviation of the delay estimation error for the four algorithms versus the threshold ρ_1 over CM4 channels. The performance of the first three algorithms are discussed in Chapter 4 and 5. The simulation results show that the combination of the two proposed algorithm has the best performance among the four algorithms. It is because comparing to the existing algorithm, the proposed two-threshold algorithm has advantage on suppressing the EFA errors as discussed in Chapter 4 and the proposed APL algorithm has advantage on suppressing the MDP errors as discussed in Chapter 5. Combining the two proposed algorithms adds up the advantages and significantly improve the estimation performance.

And then we do the localization simulation. The simulation setting are the same as the localization simulations in Chapter 5. Fig. 6.3 and Fig. 6.4 show the mean absolute localization error and the standard deviation of the localization error for the combined proposed algorithm and the existing algorithm versus the threshold ρ_1 over NLoS and LoS channels. Comparing Fig. 6.3 to Fig. 5.10, it is showed that although the existing algorithm still has the better optimum performance on the mean absolute localization

Figure 6.1: The probabilities of correct detection of the direct path for the four algorithms with different amplitude threshold value ρ_1 over NLoS channels.

Figure 6.2: The standard deviation of delay estimation error for the four algorithms with different amplitude threshold value ρ_1 over NLoS channels.

Figure 6.3: The mean absolute error of the localization for the existing and the combination of the two proposed algorithms with different amplitude threshold value ρ_1 over NLoS and LoS channels.

Figure 6.4: The standard deviation of the localization error for the existing and the combination of the two proposed algorithms with different amplitude threshold value ρ_1 over NLoS and LoS channels.

error over LoS channels, the performance difference on the mean absolute localization error between the existing and the combined algorithm is smaller than that between the existing and the proposed APL algorithm. Because the combination of the two proposed algorithms has better estimation performance than the existing algorithm over NLoS channels and has almost the same optimum performance as the existing algorithm with much flatter performance curves over LoS channels, the combination of the two proposed algorithms significantly improve the ranging and localization performance.

6.1 Conclusion

The combination of the two proposed algorithms adds up the advantages of the proposed two-threshold algorithm and the proposed APL algorithm and significantly improve the ranging and localization performance.

82 The Performance Evaluation of the Combined Proposed Schemes

Chapter 7

Conclusion and Recommendations

7.1 Conclusions

In this thesis, we have focused on developing low-complexity schemes for the UWB localization system over indoor wireless channels. Two schemes were proposed for increasing the robustness of ranging and reducing the localization error by mitigating the EFA and the MDP error.

Our work has been carried out in two aspects. Firstly, the robustness of the ranging performance in the indoor wireless channel is examined. Secondly, the mitigation of the non-direct path error in locating the MS from the channel parameter estimates is studied. Although most of the research work herein utilizes the UWB system model for analysis and simulation examples, the schemes we proposed can also be applied to other indoor localization systems without any difficulty.

From the first aspect of the study, we proposed an improved ToA estimation/DP detection algorithm to increase the robustness of the ranging performance against the threshold offsets. The existing way to estimate the ToA is through setting a proper threshold on the amplitude or the energy of the potential signal paths. However, if the threshold value is set below the optimum threshold value, the ranging performance of the existing

single-threshold scheme decreases significantly. To improve the robustness of the performance, a DP detection algorithm is proposed by exploiting the statistical characteristics of the indoor wireless channel. In the proposed algorithm, the amplitude of the potential signal path and the energy of the observation window are compared to two thresholds respectively for the DP detection. Simulation results show that the proposed algorithm is less sensitive to the threshold setting than the existing single-amplitude-threshold algorithm.

For the purpose of mitigating the NDP error in localization applications, a new algorithm is proposed for distinguishing between the DP-APs and the NDP-APs in the indoor office environment by testing the additional energy loss during propagation of the FDPs on the APs. To verify the proposed scheme, a set of measurement results was performed in a common office environment. The measurement statistics show that the APLs of the correct DP detections are statistically smaller than the APLs of the DP detections with the EFA or the MDP errors. The ranging simulation results show that the proposed algorithm outperforms the existing algorithm and has considerable advantage on suppressing the MDP error over NLoS channels.

The localization simulation results show that with only half of the data the proposed algorithm reaches better localization performance than the existing algorithm does over NLoS channels. It is also showed that the advantage of the proposed algorithm is less important in LoS channels and hence the optimum mean absolute error of the localization for the existing algorithm is better than that for the proposed algorithm in LoS environment. If there are no redundant AP, we still may improve the localization performance by putting a larger weightage on the AP that has smaller APL.

7.2 Recommendations for Further Research

Based on the techniques and schemes developed in this thesis, the scope of the current work may be further extended. In this thesis, we have assumed that no interference is present. But there may be all kinds of narrow-band interferences in realistic environment. Hence, the robustness of the proposed scheme in the indoor wireless channel with non-

AWGN and narrow-band interferences should be studied.

The dynamic threshold setting techniques, MMR and DMR, can be applied in our scheme to further improve the localization performance at the cost of complexity.

Recently published work shows that, if the reliable range estimates are already distinguished from the biased range estimates, the biased range estimates can be used to constrain the feasible region and hence increase the localization accuracy without introducing ranging errors. How to apply the above technique to the proposed localization scheme and improve the performance will be examined.

Author's Publications

- (1) W. Chen, E. Gunawan, K. C. Teh and L. C. Look, "Low-complexity schemes for UWB localization over indoor wireless channels," to be submitted

Bibliography

- [1] J. D. Taylor, *Introduction to Ultra Wideband Radar Systems*. Boca Raton, FL: CRC, 1995.
- [2] L. Yang and G. B. Giannakis, "Ultra-wideband communications: an idea whose time has come," *IEEE Signal Processing Magazine*, vol. 21, no. 6, pp. 26-54, Nov. 2004.
- [3] "Overview of ultra wideband radio technology," 2005. [Online]. Available: <http://www.ofta.gov.hk/en/ad-comm/tsac/ts-paper/ts2005p23.pdf>
- [4] S. Wu, Q. Zhang and N. Zhang, "A two-step TOA estimation method for IR-UWB ranging systems," in *Proc. CSNR*, pp. 302 - 310, May 2007.
- [5] J. P. Lie, C. M. See and B. P. Ng, "Ultra wideband direction finding using digital channelization receiver architecture," *IEEE Communications Letters*, vol. 10, no. 2, pp. 85 - 87, Feb. 2006.
- [6] M. Bocquet, C. Loyez, A. B. Delai, "Using enhanced-TDOA measurement for indoor positioning," *IEEE Microwave and Wireless Components Letters*, vol. 15, no. 10, pp. 612 - 614, Oct. 2005.
- [7] I. Guvenc, C. Chong and F. Watanabe, "NLOS identification and mitigation for UWB localization systems," in *Proc. IEEE WCNC*, pp. 1571 - 1576, Mar. 2007.
- [8] S. Venkatesh and R. M. Buehrer, "NLOS mitigation using linear programming in ultrawideband location-aware networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 5, pp. 3182 - 3198, Sep. 2007.

-
- [9] D. B. Jourdan, D. Dardari and M. Z. Win, "Position error bound for UWB localization in dense cluttered Environments," in *Proc. IEEE ICC*, vol. 8, pp. 3705 - 3710, Jun. 2006.
 - [10] A. Saleh and R. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE Journal on Selected Areas in Communications*, vol. 5, no. 2, pp. 128-137, Feb. 1987.
 - [11] J. M. Cramer, R. A. Scholtz, and M. Z. Win, "Evaluation of an ultra-wideband propagation channel," *IEEE Transactions on Antenna and Propagation*, vol. 50, no. 5, pp. 561-570, May 2002.
 - [12] J. Foerster, "The effects of multipath interference on the performance of UWB systems in an indoor wireless channel," in *Proc. IEEE VTC*, vol. 2, pp. 6-9, May 2001.
 - [13] D. Dardari and M. Z. Win, "Threshold-based time-of-arrival estimators in UWB dense multipath channels," in *Proc. IEEE ICC*, vol. 10, pp. 4723 - 4728, 2006.
 - [14] J. J. Caffery, Jr. and G. L. Stuber, "Overview of radiolocation in CDMA cellular systems," *IEEE Communication Magazine*, vol. 36, no. 4, pp. 38-45, Apr. 1998.
 - [15] M. Wylie and J. Holtzman, "The non-line of sight problem in mobile location estimation," in *Proc. IEEE ICUPC*, pp. 827-831, 1996.
 - [16] J. Y. Lee and R. A. Scholtz, "Ranging in a dense multipath environment using an UWB radio link," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 9, pp. 1677-1683, Dec. 2002.
 - [17] I. Guvenc and Z. Sahinoglu, "Threshold selection for UWB TOA estimation based on kurtosis analysis," *IEEE Communications Letters*, vol. 9, no. 12, pp. 1025 - 1027, Dec. 2005.
 - [18] C. Chong, F. Watanabe and H. Inamura, "Potential of UWB technology for the next generation wireless communications," in *Proc. IEEE SSTA*, pp. 422 - 429, Aug. 2006.
-

- [19] "Direct spread spectrum (DS) / time hopping (TH) UWB performances comparison in a multi-user Ad Hoc environment," 2005. [Online]. Available: <http://www.mics.ch/SumIntU04/MohamedMezzour.pdf>
- [20] S. S. Tan, A. Nallanathan and B. Kannan, "Performance of DS-UWB multiple-access systems with diversity reception in dense multipath environments," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 4, pp. 1269 - 1280, Jul. 2006.
- [21] S. A. Ghorashi, B. Allen, M. Ghavami and A. H. Aghvami, "An overview of MB-UWB OFDM," *IEE Seminar on Ultra Wideband Communications Technologies and System Design*, pp. 107 - 110, Jul. 2004.
- [22] "IEEE 802.15.4a final report," [Online]. Available: <ftp://ftp.802wirelessworld.com/11/04/>
- [23] E. S. Lohan, R. Hamila, A. Lakhzouri and M. Renfors, "Highly efficient techniques for mitigating the effects of multipath propagation in DS-CDMA delay estimation," *IEEE Transactions on Wireless Communication*, vol. 4, no. 1, pp. 149-162, Jan. 2005.
- [24] E. G. Strom, S. Parkvall, S. L. Miller and B. E. Ottersten, "Propagation delay estimation in asynchronous direct-sequence code-division multiple access systems," *IEEE Transactions on Communication*, vol. 44, no. 1, pp. 84-93, Jan. 1996.
- [25] S. Chowdhury, M. D. Zoltowski, and J. S. Goldstein, "Structured MMSE equalization for synchronous CDMA with sparse multipath channel," in *IEEE Proc. ICASSP.*, vol. 4, pp. 2113-2116, May 2001.
- [26] J. Ibrahim and R. M. Buehrer, "Two-stage acquisition for UWB in dense multipath," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 4, pp. 801 - 807, Apr. 2006.
- [27] I. Guvenc and Z. Sahinoglu, "Threshold-based TOA estimation for impulse radio UWB systems," in *Proc. IEEE ICU*, vol. 5, pp. 420 - 425, Sep. 2005.
- [28] L. Yang, "Timing PPM-UWB signals in Ad Hoc multiaccess," *IEEE Journal on Selected Areas in Communications*, vol. 24, pp. 794-800, Apr. 2006.

- [29] L. Yang and G. B. Giannakis, "Timing ultra-wideband signals with dirty templates," *IEEE Transactions on Communication*, vol. 53, pp. 1952-1963, Nov. 2005.
- [30] J. L. Paredes, G. R. Arce and Z. Wang, "Ultra-wideband compressed sensing channel estimation," *IEEE Journal of Selected Topics in Signal Processing*, vol. 1, pp.383-395, Oct. 2007.
- [31] I. Guvenc and Z. Sahinoglu, "TOA estimation with different IR-UWB transceiver types," in *Proc. IEEE ICU*, vol. 5, pp. 426 - 431, Sep. 2005.
- [32] C. Mazzucco, U. Spagnolini and G. Mulas, "A ranging technique for UWB indoor channel based on power delay profile analysis," in *Proc. IEEE VTC*, vol. 5, pp. 2595 - 2599, May 2004.
- [33] M.Niedzwiecki, *Identification of Time-varying Processer* . J.Wiley, June 2001.
- [34] J. V. Di Franco and W. L. Rubin, *Radar Detection*. Prentice Hall, Englewood Cliffs, N. J., 1968.
- [35] J. G. Proakis, *Digital Communication*. New York: McGraw-Hill, 1989.
- [36] C. Carbonelli, U. Mengali, and U. Mitra, "Synchronization and channel estimation for UWB signals," in *Proc. IEEE GLOBECOM*, vol. 2, pp. 1-5, Dec 2003.
- [37] P. Liu and Z. Xu, "POR-based channel estimation for UWB communications," *IEEE Transactions on Wireless Communication*, vol. 4, no. 6, pp. 2968 - 2982, Nov. 2005.
- [38] A. Chehri, P. Fortier and P. M. Tardif, "On the TOA estimation for UWB ranging in complex confined area," in *Proc. ISSSE*, pp. 533-536, Jul. 2007.
- [39] R. J. Fontana, "Experimental results from an ultra wideband precision geolocation system," in *Ultra-Wideband, Short-Pulse Electromagnetics*. New York: Kluwer, 2002, pp. 215-224.
- [40] J. P. Lie, C. M. See and B. P. Ng, "UWB ranging with high robustness against dominant jammer and multipath," *IEEE Microwave and Wireless Components Letters*, vol. 15, no. 12, pp. 907-909, Dec. 2005.

- [41] K. Makaratat, T. W. C. Brown and S. Stavrou, "Estimation of time of arrival of UWB multipath clusters through a spatial correlation technique", *Microwaves, Antennas and Propagation, IET*, vol. 1, no. 3, pp. 666 - 673, Jun. 2007.
- [42] S. Wu, Q. Zhang and N. Zhang, "MMR based threshold setting for TOA estimation of IR-UWB systems," Submitted to *IEEE Communications Letters*.
- [43] Y. Chen and N. C. Beaulieu, "CRLBs for NDA ML estimation of UWB channels," *IEEE Communications Letters* vol. 9, no. 8, pp. 709 - 711, Aug. 2005.
- [44] B. M. Sadler, L. Huang and Z. Xu, "Ziv-Zakai time delay estimation bound for ultra-wideband signals," in *Proc. ICASSP*, vol. 3, pp. 549 - 552, Apr. 2007.
- [45] D. Chazan, M. Zakai and J. Ziv, "Improved lower bounds on signal parameter estimation," *IEEE Transactions on Information Theory*, vol. IT-21, pp. 90C93, Jan. 1975.
- [46] A. Weiss and E. Weinstein, "Fundamental limitations in passive time delay estimation - Part I: Narrow-band systems," *IEEE Transactions on Acoustics Speech and Sigal Processing*, vol. 31, pp. 472C 486, Apr. 1983.
- [47] J. Caffery, Jr. and G. L. Stuber, "Subscriber location in CDMA cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 47, no. 2, pp. 406-415, May 1998.
- [48] J. Schroeder, S. Galler, K. Kyamakya and T. Kaiser, "Three-dimensional indoor localization in Non Line of Sight UWB channels" in *Proc. ICUWB 2007*, pp. 89-93, Sep. 2007.
- [49] J. Schroeder, S. Galler, K. Kyamakya and K. Jobmann, "NLOS detection algorithms for Ultra-Wideband localization," in *Proc. WPNC'07*, pp. 159-166, 2007.
- [50] Y. T. Chan, W. Y. Tsui, H. C. So and P. C. Ching, "Time-of- arrival based localization under NLOS conditions," *IEEE Transactions on Vehicular Technology*, vol. 55, no.1, pp. 17-24, Jan. 2006.
- [51] J. Y. Lee, Y. H. Jo, S. H. Kang, A. Y. Kang, D. H. Ha and S. J. Yoon, "Determination of the Existence of LoS Blockage and Its Application to UWB Localization," in *Proc. MILCOM 2006*, pp. 1-4, Oct. 2006.

- [52] M. Heidari, F. O. Akgul and K. Pahlavan, "Identification of the absence of direct path in indoor localization system," in *Proc. PIMRC 2007*, pp. 1-6, Sep. 2007.
- [53] "Nist/sematech e-handbook of statistical methods," 2006. [Online]. Available: <http://www.6sigma.us/handbook/eda/section3/eda35b.htm>
- [54] B. Denis and N. Daniele, "NLOS ranging error mitigation in a distributed positioning algorithm for indoor UWB ad-hoc networks," in *Proc. International Workshop on Wireless Ad-Hoc Networks*, pp. 356-360, 2004.
- [55] B. Alavi and K. Pahlavk, "Modeling of the distance error for indoor geolocation", in *Proc. IEEE WCNC 2003*, vol.1, pp. 668-672, Mar. 2003.
- [56] L. Cong and W. Zhuang, "Nonline-of-sight error mitigation in mobile location," *IEEE Transactions on Wireless Communications*, vol. 4, no. 2, pp. 560-573, Mar. 2005.
- [57] F. Althaus, F. Troesch and A. Wittneben, "UWB geo-regioning in rich multipath environment," in *Proc. IEEE VTC Fall 2005*, pp. 1001-1005, Sep. 2005.
- [58] S. A. Jazzar and J. Caffery, Jr., "NLOS mitigation method for urban environments," in *Proc. IEEE VTC Fall 2004*, vol. 7, pp. 5112-5115, Sep. 2004.
- [59] S. Venkatraman, J. Caffery, Jr. and Y. H. Ryeol, "A novel ToA location algorithm using LoS range estimation for NLoS environments," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 5, pp. 1515-1524, Sep. 2004.
- [60] B. Denis, L. He and L. Ouvry, "A flexible distributed maximum log-likelihood scheme for UWB indoor positioning," in *WPNC '07. 4th Workshop*, pp. 77-86, Mar. 2007.
- [61] B. Denis, J. B. Pierrot and C. Abou-Rjeily, "Joint distributed synchronization and positioning in UWB ad hoc networks using TOA," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 4, pp. 1896 - 1911, Jun. 2006.
- [62] C. Wann, Y. Yeh and C. Hsueh, "Hybrid TDOA/AOA indoor positioning and tracking using extended kalman filters," in *Proc. IEEE VTC*, vol. 3, pp. 1058 - 1062, May 2006.

- [63] C. Morelli, M. Nicoli, V. Rampa and U. Spagnolini, "Hidden markov models for radio localization in mixed LOS/NLOS conditions," *IEEE Transactions on Signal Processing*, vol. 55, no. 4, pp. 1525 - 1542, Apr. 2007.
- [64] A. Rajeswaran, V. S. Somayazulu, and J. R. Foerster, "Rake performance for a pulse based UWB system in a realistic UWB indoor channel," in *Proc. IEEE ICC*, vol. 4, pp. 11-15, May 2003.
- [65] J. Papoulis and S. U. Pillai, *Probability, Random Variables and Stochastic Process*. McGraw-Hill, 2002.
- [66] Q. Shi, S. Kyperountas, N. S. Correal and F. Niu, "Performance analysis of relative location estimation for multihop wireless sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 4, pp. 830-838, Apr. 2005.
- [67] M. H. Ali and K. Pahlavan, "A new statistical model for site-specific indoor radio propagation prediction based on geometric optics and geometric probability," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 9, pp. 1677-1683, Dec. 2002.
- [68] A. H. Muqaibel, "Characterization of ultra wideband communication channels", *Thesis submitted to the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University*, Blacksburg, Virginia, Mar. 2003.