Localization in multipath environments

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

LOCALIZATION IN MULTIPATH
ENVIRONMENTS

LOCALIZATION IN MULTIPATH ENVIRONMENTS

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**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

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LOCALIZATION IN MULTIPATH ENVIRONMENTS

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SUMMARY

SUMMARY

This thesis focuses on the design of localization schemes and algorithms which work in multipath environments. Traditionally, conventional localization schemes work based on the assumption that the reference devices (*RDs*) are always in Line-of-Sight (LOS) with the mobile device (*MD*) to locate the *MD*. However, this assumption will not hold in multipath environment as the *RDs* may be in Non-Line-of-Sight (NLOS) with the *MD* and causes erroneous estimation in the *MD* location. To resolve such inaccuracy, the conventional localization schemes are usually coupled with mitigation schemes to reduce such NLOS error.

In this thesis, we focuses on the design of localization schemes with the intent that they work without any mitigation techniques and yet able to localize the *MD* in the multipath environment where the existence of LOS is not guaranteed. Firstly, a bi-directional localization scheme that detects LOS paths and leverages on their Time of Arrival (TOA) and Angle of Arrival (AOA) measurement data at both the *RDs* and *MD* in a general multipath environment was proposed. It was compared with the conventional localization schemes that coupled with their mitigation schemes. Another bi-directional localization scheme with the enhancement of LOS paths' measurement data was designed and tested out in a real multipath environment.

Next, in order to utilize the non line of sight (NLOS) path that undergoes one bound scattering phenomenon, a bidirectional NLOS localization scheme was designed. As such, both the LOS or NLOS paths can be used for localization. Paths that undergo multiple bound scattering phenomena were successfully discarded using the devised

SUMMARY

multipath detection scheme. This NLOS localization scheme was validated in a real multipath environment.

Finally, a unidirectional localization scheme that uses only the TOA and AOA measurement data at the *RDs* was proposed. It was being validated in a parallel/perpendicular aligned scatterers' multipath environment. Furthermore, a unidirectional localization scheme that provides an enhancement to the LOS path was designed. The scheme's robustness to non parallel/perpendicular aligned scatterer was investigated.

It is worthy to note that in general, all our proposed localization schemes are not only able to localize the *MD* using just one *RD* but also able to achieve better localization accuracy than the conventional localization schemes.

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LIST OF ACRONYMS

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GPS—Global Positioning System

MEO—Medium Earth Orbits

A-GPS—Assisted-Global Positioning System

E-911—Emergency 911

FCC—Federal Communications Commission

LOS—Line-Of-Sight

NLOS—Non-Line-Of-Sight

WLAN—Wireless Local Area Network

UWB—Ultra-WideBand

RD—Reference Device

MD—Mobile Device

TDOA—Time Difference of Arrival

TOA—Time of Arrival

AOA—Angle of Arrival

RSS—Received Signal Strength

OFDM—Orthogonal Frequency Division Multiplex

LS—Least Square

ISI—Inter Symbol Interference

GOA—Gain Of Arrival

EM—Electromagnetic

PDP—Power Delay Profile

RMS—Root Mean Square

DLOS—Direct Line-Of-Sight

LIST OF ACRONYMS

OLOS	Obstructed Line-Of-Sight
DDP	Dominant Direct Path
NDDP	Non Dominant Direct Path
UDP	Undetected Direct Path
DSSS	Direct Sequence Spread Spectrum
PSBE	Parametric Subspace-Based Estimation
DPE	Deterministic Parameter Estimation
MUSIC	Multiple Signal Classification
ESPRIT	Estimation of Signal Parameter via Rotational Invariance Technique
ML	Maximum Likelihood
SAGE	Space Alternating Generalised EM
EM	Expectation Maximization
AWGN	Additive White Gaussian Noise
MAP	Maximum A Posterior
MIMO	Multiple Input Multiple Output
SNR	Signal to Noise Ratio
CRLB	Cramer Rao Lower Bound
LPMD	Line of Possible Mobile Device Location
FIM	Fisher Information Matrix
CDF	Cumulative Distribution Function
ALE	Average Location Error
RMSE	Root Mean Square Error
NTU	Nanyang Technological University

CHAPTER ONE

1 INTRODUCTION

1.1 Motivation

In recent years, there has been a growing demand in both commercial and government applications for wireless localization services that provide the position of a mobile device. Wireless localization systems can be generally classified into either indoor or outdoor localization systems as depicted in Table 1-1 [1]. As shown, outdoor localization systems traditionally relies on Global Positioning System (GPS) which exploits the network of 24 Medium Earth Orbits (MEO) satellites to locate the Mobile Device (*MD*). Terrestrial cellular networks can also be coupled with GPS systems to form the Assisted-GPS (A-GPS) [2] to improve the GPS localization accuracy. Recently, there is a shift of paradigm to advocate the use of the terrestrial cellular network solely for outdoor localization purposes. This is to accommodate the Emergency 911 (E-911) subscriber safety systems [3]-[6] which require the wireless service providers to fulfil the Federal Communications Commission (FCC) mandate of 100 to 300 meters and 50 to 100 meters of localization accuracy for network-centric and mobile-centric localization systems respectively. Besides the provision for E-911 caller systems, cellular systems also facilitate proximity advertisement, location-sensitive billing and intelligent transport tracking system. In the indoor environment, extensive research and development have been also carried out to provide localization

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<u>INDOOR LOCALIZATION SYSTEMS</u>		<u>OUTDOOR LOCALIZATION SYSTEMS</u>
WLAN <ul style="list-style-type: none"> • Client based system design • Client assisted system design 	GPS	
	<ul style="list-style-type: none"> • Requires minimal obstructions • Long acquisition time(30s-15min) • Has to be synchronous 	
UWB <ul style="list-style-type: none"> • A promising approach for geolocation • Can achieve very accurate short distance estimation 	A-GPS	
SENSOR NETWORK	<ul style="list-style-type: none"> • Much higher accuracy • Improve acquisition time (<10s) • Synchronous or asynchronous 	
	CELLULAR NETWORK	
<ul style="list-style-type: none"> • Localization with beacons • Localization with moving beacons • Beacon free localization 	<ul style="list-style-type: none"> • More cost effective than GPS due to high availability of base stations infrastructure. • Little/no hardware changes required for base stations. 	

Table 1-1 Overview of Localization Systems [1]

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information for applications such as fratricide of military forces [7] , as well as the tracking of assets and personnel. As the channel propagation condition for indoor environment is more severe where there is existence of Non-Line-of-Sight (NLOS) path and multipath [8]-[16], dedicated localization sensor systems have been developed that leverage on the existing indoor wireless Local Area Network (WLAN) 802.11x infrastructure or specified radio frequency (RF) technology such as Ultra-Wideband (UWB) [17]-[23].

Specifically, indoor and outdoor localization systems can be further sub-classified as either a mobile centric or network centric localization technique [1], [4], [24]. In mobile centric methodology, the *MD* determines its location from the signals received from the base station (BSs)/reference device (*RDs*) or from the GPS satellites. In the GPS solution, the *MD* receives and measures the signal parameters from at least four satellites out of the network of 24 MEO satellite. Recently, there is also a hybrid solution that uses both the GPS and the terrestrial cellular network. In this case, the cellular network is leveraged on to assist the GPS receiver embedded in the *MD* handset for improved accuracy such as the NOKIA N95 series mobile phone [1], [4], [24]. On the other hand, in the network centric methodology, the location of the *MD* is determined by measuring the *MD*'s signal parameters when received at the cellular network BSs or the WLAN *RDs*. In this methodology, the BSs or *RDs* measure the signals transmitted from the *MD* and relay them to a central site for computational processing and data fusion to provide an estimate of the *MD* location [1],[4],[24].

The signal parameters that are measured by either the *MD* or the BSs/*RDs* are usually the Time Difference of Arrival (TDOA) [25]-[27], Time of Arrival (TOA) [25],[28]-

CHAPTER 1 INTRODUCTION

[30], Angle of Arrival (AOA) [31]-[33], Received Signal Strength (RSS) [17]-[20] or the signal strength of each frequency component of the Orthogonal Frequency Division Multiplex (OFDM) localization system [34],[35]. There are also hybrid localization technique [36], [37] that use a combination of the above mentioned data metrics such as fusion of TDOA/TOA and AOA data for the computation of *MD* location. These signal parameters are usually a function of the geometrical relationship that exists between the *MD* and each BS/*RD*. This geometrical relationship is exploited to establish the Line of Sight (LOS) Euclidean distance between the *MD* and each BS/*RD* so as to identify the physical location of the device.

The main concern that arises with the geometrical localization schemes mentioned above is the reliability of the localization result in heavy multipath induced environments. In these environments, the geometrical relationship established for the sake of localization between the *RD* and *MD* is based on LOS assumption. The measured TOAs and AOA may not necessarily be the LOS TOAs or AOA [8]-[15], [38]-[44]. Similarly, the associated channel parameters such as the propagation attenuation factor that is used in RSS localization schemes are dependent on the locations of the *RDs* and *MD* in question and the associated propagation channel environment. These parameters will be different in different multipath environment scenarios. These disparities will seriously impair the accuracy of the localization effort. Such inaccuracies are commonly resolved by mitigating the NLOS measurement data and placing more emphasis on the LOS measurement data which may be unreliable [29], [45]-[64]. On the other hand, for RSS localization schemes, the estimation errors of the channel parameters are usually statistically minimized. These in turn minimize the estimated location error of the *MD* using advanced machine learning [65], statistical

modelling algorithm [66] or the fingerprinting techniques [20],[67],[68] which may be time consuming.

1.2 Objective and Contributions of the Thesis

The objective of this thesis is to design localization schemes and algorithms that have robust performances in both LOS and multipath environments. The proposed localization schemes, in general, are able to work better than the conventional geometrical localization schemes without any incorporation of mitigation schemes. General and typical multipath environments are also used to evaluate the performances of the proposed localization schemes. To the best of our knowledge, unlike our devised localization schemes, there are no geometrical localization schemes reported in the literature that are able to work without any NLOS signal mitigation techniques.

The major contributions of this thesis are as follows:

- Design of two bi-directional localization schemes that leverage on the joint estimation of the LOS paths' TOA and AOA measurement data at the *MD* and *RDs*. These schemes provide alternative approach for obtaining the *MD*'s location by using just one *RD*. Technique to differentiate the LOS path from the NLOS path in both general and typical multipath environment is presented.
- Design of a comprehensive NLOS localization scheme that leverages on the bidirectional estimation of TOA and AOA of the signals exchanged between the *MD* and *RDs*. The proposed localization scheme requires two or more signal paths, which can be either LOS or NLOS multipath signals that undergo one-

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bound scattering. A novel multipath selection scheme has been devised to discard multiple-bound scattering paths with a high degree of accuracy.

- Design of two localization schemes by using the TOA and AOA measurement data at the *RDs* to locate the omni-directional *MD*. These localization schemes are able to work in a typical indoor multipath environment where the scatterers are smooth surfaces that are aligned parallel or perpendicular to each other.

1.3 Organisation of the Thesis

The thesis is organised into the following chapters:

This chapter has explained the importance of localization application. The motivation, objective and contributions of the thesis are also discussed.

Chapter 2 describes in detail the conventional methodology of localization of *MD*, namely the TOA, AOA, RSS, OFDM localization schemes and the hybrid localization scheme that uses the fusion of TOA and AOA measurement data. Channel impairments that affect the performance of the conventional localization schemes are discussed and the present mitigation schemes to overcome the impairments are mentioned.

Chapter 3 proposes two novel bidirectional localization schemes that require only one *RD* to be in the LOS range with the *MD* in a multipath environment. The first novel bi-directional localization scheme uses the LOS path's TOA and AOA measurement data which are estimated either jointly or disjoint at both the *RD* and the *MD*. A two step least squares (LS) location estimator has been developed that utilizes the TOA and

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AOA information from one or more *RDs*. Methodology to identify the LOS path through the bi-directional AOA is presented. The proposed localization scheme is compared to the conventional TOA and TOA/AOA localization schemes that are coupled with the mitigation schemes, in both light and heavy multipath environment. Another bi-directional two step LS localization scheme that leverages on the LOS paths' TOA and AOA measurement data is also presented. In this localization scheme, methodology to improve the accuracy of the LOS paths' TOA and AOA measurement data is devised. A typical multipath environment at Nanyang Technological University (NTU), School of Electrical and Electronics Engineering (EEE) is chosen to evaluate the performance of the proposed localization scheme against the conventional localization schemes.

Although Chapter 3 proposes two novel bidirectional localization schemes that require only one *RD* to be in LOS range with the *MD* in a multipath environment, the existence of at least one LOS path in the multipath environment is not guaranteed. There are scenarios that all the *RDs* are in NLOS range with the *MD*. As a result, all the conventional localization schemes and even our proposed bidirectional localization schemes described in Chapter 3 will not perform satisfactorily. Chapter 4 presents a NLOS localization scheme that overcomes this limitation by leveraging on the bi-directional estimation of the LOS and NLOS paths' TOA and AOA measurement data. The LS implementation of the proposed NLOS localization scheme will be formulated. It utilizes two or more signal paths which can be either LOS or NLOS multipath signals that undergo one-bound scattering phenomenon. Enhancement to the accuracy of the LOS paths' AOA measurement will be presented. Multipath selection schemes which identify multiple-bound scattering and parallel paths will be shown. Analytical error

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performance and the Cramer Rao Lower Bound (CRLB) of the proposed localization scheme will be derived. Empirical data which obtained through experimentation in a typical multipath environment at NTU is chosen to analyse the performance of our proposed localization scheme and to compare to the existing methods.

The proposed LOS and NLOS approaches mentioned in Chapter 3 and 4 respectively have been able to localize the *MD* with just one *RD* and their performance are much better than the conventional LOS approaches that use three *RDs* in the multipath environment. However, the cost of using antenna array at the *MD* in term of computation and physical implementation for localization is currently expensive. Chapter 5 focuses on the design of two localization schemes that leverages on the TOA and AOA measurement data at the *RDs* only. The *MD* is an omni-directional device. The measurement data can be arisen from the TOA and AOA measurement of the LOS and NLOS paths that undergo one-bound scattering. The first proposed localization scheme will be demonstrated in a typical environment where the scatterers are aligned parallel or perpendicular to each other. Together with the derivation of the analytical error performance, the performance of the second localization scheme which coupled with enhancement technique to improve the LOS path measurement data will be analysed in the parallel/perpendicular scatterers aligned environment. The robustness in the performance towards different scatterers' orientation where they are not aligned parallel or perpendicular to each other is also investigated.

Chapter 6 concludes the thesis and recommends future work to further improve the localization performance in a multipath environment.

CHAPTER TWO

2 LITERATURE REVIEW

This chapter provides a review of existing conventional localization schemes and the channel impairments that will affect the performance of the existing localization schemes. Existing mitigation techniques of the conventional localization schemes are also presented.

2.1 Conventional Localization Schemes/Algorithms

2.1.1 Geometrical Time of Arrival (TOA) and Time Difference of Arrival (TDOA) Localization Algorithm

The TOA localization scheme is one of the most common localization schemes that has been researched and developed due to the ease of implementation. As shown in Fig. 2.1, the TOA localization scheme works by measuring the TOA between the *MD* and a *RD* at the *RD*. The TOA measurement multiplied by the speed of signal produces a measurement of the geometrical LOS Euclidean distance between each *RD* and *MD* known as a pseudorange. Knowing the location of at least three *RDs* and utilizing three pseudoranges, we can derive an estimate of the two dimensional (2-D) physical location of the *MD* via various methods of Least Square (LS) solutions [25],[28]-[30] such as the two step LS or the constrained LS solution. One of the most important

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Fig. 2.1 Conventional Localization Schemes

underlying assumptions in these TOA localization schemes is that the various RD s are in LOS with the MD in order to obtain the correct pseudoranges. Direct transmission path through blocking material is also assumed to be a “LOS path”. The extra delay (relative to the direct LOS path) can be modeled as TOA or distance measurement noise

In the TDOA localization schemes, the TOA information from one of the RD s is used to synchronize the RD s. The TDOA of the associated RD is the time difference between the TOA of the MD signal at the associated RD and that of the chosen RD that is used for the time synchronization [25]-[27].

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2.1.2 Geometrical Angle Of Arrival (AOA) Localization Algorithm

As shown in Fig. 2.1, in the AOA localization scheme, a measurement of the AOA at RD_1 is obtained by measuring the direction of arrival of the MD signal using an antenna array at the RD_1 . An estimate of the MD position can then be obtained by combining and formulating the AOA measurements from the RD s as a least square solution [31]-[33]. The minimum number of RD s that are required for localization process in the 2-D environment for TOA and TDOA localization schemes are three and four respectively while for AOA localization scheme, the number is one less than the TOA localization scheme which is two. Furthermore, the AOA localization scheme does not necessitate the RD clock synchronization. The disadvantage of using AOA localization scheme is that antenna array structure is needed to estimate the angle of arrival which may incur the system cost.

2.1.3 Received Signal Strength (RSS) Localization Algorithm

RSS is defined as the voltage measured by the MD received signal strength indicator circuit. Often RSS is equivalently reported as the measured power, i.e, the square of the signal strength of the RF signal. RSS measurements are very inexpensive as they can be easily obtained during normal data communications and hence RSS localization algorithms are simpler to implement. They remain an important and popular topic of localization due to the prevalent usage of 802.11xx WLAN and cellular systems [17]-[20], [65]-[68]. However, RSS localization performance is not able to match the performance of both the TOA/TDOA and AOA localization scheme due to the

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fluctuating received RF signal strength and the inaccuracy of the propagation constant factor used in the propagation environment such as the flat fading propagation environment. They are not a good choice for robust localization if the number of *RD* available is small. If adopted, their error characteristics must be well studied.

Currently, there are two research arenas of RSS localization schemes, mainly the channel parameters minimization approach and the empirical location estimation approach. For the former, the measured data metric, which is the RSS of the incoming signal is treated as the random variable and is dependent on the locations of the *RDs*, *MD* in question and the associated propagation channel environment. Under this approach, the objective is to statistically minimize the estimation error of the channel parameters or the controlling parameters of the objective function. This in turns minimize the estimated location error of *MD* using either the advanced statistical modelling [17]-[19], [66] or the machine learning [65] algorithm. The second approach which is also known as the fingerprinting technique [20], [67], [68] requires onsite calibration of the radio strength of the measured signal. It compares the measured signal strength to that of the reference signal strength at known locations in the database. The reference signals are previously obtained from onsite calibration such as is conducted for wireless LAN localization. The approach is to maximize the probability likelihood of estimated *MD* location based on prior knowledge of the signal strength measured at known location.

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2.1.4 Orthogonal Frequency Division Multiplex (OFDM) Localization Algorithm

In recent years, OFDM technology has been exploited as one of the technology to provide localization application especially in multipath environment where there is a existence of a dominant LOS signal. The basic principle of OFDM is to split a high data rate stream into a number of lower rate data streams which are transmitted simultaneously over a number of orthogonal sub-carriers. The objective of data rate splitting is used to primarily overcome the Inter Symbol Interference (ISI) in a communication channel with large delay spread. By transmitting data in multiple orthogonal carriers, each carrier experiences only flat fading in which equalization can be easily performed in the frequency domain by the multiplication of a scaling vector for each carrier, thus avoiding complex equalization techniques. In summary, a difficult time equalization problem (when delay spread is large) has been transformed into a simpler frequency domain problem by using the frequency domain equalization.

Because of the leverage of the multiple orthogonal carriers of OFDM, the bandwidth of the OFDM is inherently larger as compared to the conventional narrowband communication systems. Therefore, the delay of the LOS path can be determined with high resolution as compared to the narrowband systems from the frequency channel response of the OFDM system [10], [34], [35]. This articulates the superiority of using high bandwidth system to provide localization application with high accuracy such as that of OFDM systems.

2.1.5 Hybrid Fusion Localization Algorithm

There is also a myriad of hybrid fusion localization algorithms whereby a combination of the above three mentioned data metrics: TOA (TDOA), RSS and AOA [17]-[35] are leveraged on to provide localization information such as the fusion of TDOA and the Gain of Arrival (GOA) data [36] or the TDOA and AOA data [37]. In general, fusion techniques provide a much better accuracy than localization methodology that uses single data metric in a wireless communication channel where there is existence of a dominant LOS path.

2.2 Channel Impairment on the Performance of Conventional Localization Schemes

For single user location estimation, multipath fading and NLOS propagation are mainly the two types of channel impairment that will severely degrade the performance of various localization methodology mentioned earlier on.

2.2.1 Multipath Fading

In a wireless communication system, a signal from the *RD* can travel through various paths before arriving at the *MD*. This phenomenon is known as multipath propagation. There are three basic mechanisms that result in such signal propagation. They are the specular reflection, diffraction and scattering.

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- Specular reflection occurs when a propagating Electromagnetic (EM) wave impinges on a smooth surface with dimensions larger than the signal wavelength λ .
- Diffraction occurs when the path between the *RD* and *MD* is obstructed by a dense body with dimensions larger than the signal wavelength resulting secondary wave propagation.
- Scattering occurs when a propagating EM wave impinges on a rough surface or dimensions on the order of the signal wavelength or less, causing reflected energy to scatter in all direction resulting diffuse reflection.

Such multipath characteristics can usually be described by a 2D temporal channel model [41]-[43] as

$$h(\tau) = \sum_{k=0}^{L-1} \alpha_k \delta(\tau - \tau_k) \quad (2.1)$$

where L is the number of multipath components and α_k and τ_k are the complex amplitude and propagation delay of the k^{th} path respectively. It can also be represented as a 3D temporal spatial model [44] where

$$h(\tau, \theta) = \sum_{k=0}^{L-1} \alpha_k \delta(\tau - \tau_k, \theta - \theta_k) \quad (2.2)$$

and θ_k denotes the k^{th} path's AOA that has certain probability distribution such as Laplacian or uniform probability distribution.

Depicted in Fig. 2.2 [16], discrete Power Delay Profile (PDP) is a plot that manifests the channel multipath (inclusive of the LOS path) signal strength versus the arrival time of the multipath. Various existing statistical channel models [8]-[16] being defined in

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Fig. 2.2 Power Delay Profile (PDP) of Saleh Valenzuela (SV) channel model [16]

terms of discrete Power Delay Profile (PDP) have been formulated for analysis of communication performance. The strength and the arrival time characteristic of the paths are determined such that the root mean square (RMS) delay spread and BER obtained from simulations using these channel profile matched the empirical measurements. However, there is none that is suitable for the analysis of the behaviour of various location metrics for geolocation applications, as they do not take into consideration of the accurate and well calibrated temporal and spatial characteristics that is needed for geolocation purposes. Furthermore, any model that is formulated is usually site specific. Therefore, there is a lot of room for research to create statistical channel models that is suitable for geolocation in a general location.

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The other problem with multipath propagation is the flat fading symptom it manifests for narrowband propagation. The constructive and destructive combination of the signals causes fluctuation in the received signal amplitude, phase and angle of arrival. This manifests as Rayleigh fading and Lognormal fading for the small scale fading and large scale fading (shadowing) respectively. For location estimation, the constructive and destructive combination phenomenon for multipath channel demonstrates the fact that the first arriving ray (in this case let us assume it is the Direct LOS (DLOS) component between the RD and MD) which the location estimation relies on, is succeeded by the multipath components that arrive at the MD within a short time interval after the first ray. If this delay is smaller than the duration of the pulse shape of the transmitted signal from RD , pulse overlapping occurs. This causes errors in the estimation of the TOA, AOA and RSS as the early arriving multipath signals' contribute to the cross - correlation that obscures the location for the peak of the LOS signal. Furthermore, such signal strength fluctuation will result in the RSS algorithm to be completely erroneous. That is one of the reason why the RSS algorithm is not robust enough to multipath presence unless it is coupled with fingerprinting technique and the number of RD s that are involved for location estimation is high. Therefore, we can conclude that the larger the bandwidth of the signal, the smaller the width of its pulse shape, the higher the possibility that its multipath signals are resolvable. This also leads to the explanation why UWB technology [21]-[23] can achieve high accuracy for location estimation due to its inherent large bandwidth. Its multipath signals will not overlap and suffer flat fading but will manifest as frequency selective fading. Each multipath can be resolvable, allowing correct cross correlation to be done to provide accurate detection of direct LOS (DLOS) signal [10].

2.2.2 Non-Line-Of-Sight (NLOS) Propagation

The above mentioned conventional localization algorithms [24]-[37] are built on the assumption of LOS signal existence. They are not robust enough to cater to NLOS propagation, which can occur to any mentioned localization algorithms. NLOS error will result in large positioning bias error whose magnitude depends on the surrounding scatterers' spatial distribution. Any super resolution parameter estimation technique [69]-[90] or any RF technology that has an inherently large bandwidth, such as UWB technology, can only improve the estimation of paths' parameters (TOA, AOA or RSS), but cannot eliminate the NLOS error. Conventional localization schemes can only employ mitigation techniques [29],[45]-[64] to minimize the NLOS error contribution to the best effort.

In any radio propagation channel, there are instances where LOS signal is not the strongest arriving path signal or the earliest arriving path signal if it is completely blocked or partially blocked by a material that impedes its propagating trajectory. Therefore similarly to LOS and obstructed LOS (OLOS) in the telecommunication case, we can classify channel power profile into any of the following three classes :dominant direct path (DDP), non dominant direct path (NDDP) and undetected direct path (UDP) profiles [13]. Fig. 2.3 to Fig. 2.5 illustrate the three classes of channel profiles.

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Fig. 2.3 DDP channel profile [13]

Fig. 2.4 NDDP channel profile [13]

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Fig. 2.5 UDDP channel profile [13]

The DDP channel profile refers to a channel profile that has a dominant direct path with the strongest signal strength α_0 among all the paths and well above the threshold level of the receiver sensitivity. In this channel, the receiver makes no mistake in estimating the LOS signal and hence the correct metric (be it TOA, AOA, RSS) estimate. The occurrence of such channel profile is when the *RD* is always in LOS with the *MD*. This occurs in multipath propagation where there are abundant scatterers but the multipath can be resolvable with the increase of signal bandwidth and the employment of super resolution techniques. On the other hand, the NDDP channel profile has weak direct path with signal strength α_0 well below the signal strength of the strongest multipath signal. However, as this weak direct path signal strength is above the receiver sensitivity, it still can be detected by the receiver. Therefore, the receiver is still able to make correct guess of the metric and thus correct location

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estimation. Normally, shadowing or partially shadowing by obstacles will result in such occurrence where the direct path signal is still noticeable by the receiver. This includes direct transmission path through blocking material. Lastly, for the UDP channel profile, it has a profile that has a direct path undetected by the receiver as its signal strength is well below the receiver sensitivity. In this case, erroneous estimation by the receiver is made as the receiver will acknowledge the next noticeable multipath signal α_1 as the DLOS signal. In this scenario, incorrect metric estimate is made as now multipath signal α_1 is being recognized as the DLOS signal. This type of scenario often takes place in indoor urban environment whereby there are abundant scatterers which obstruct the LOS signal resulting in the UDP channel profile or what we called the NLOS propagation.

2.3 Channel Impairment's Mitigation

2.3.1 Mitigation for Multipath Fading

Due to flat fading for narrowband propagation, it is very difficult to perform TOA, AOA or RSS parameter extraction and estimation. Current existing parameter extraction such as Direct Sequence Spread Spectrum (DSSS) which is used in GPS is not suitable for accurate detection of DLOS signal as it suffers degradation in accuracy in environment such as the indoor scenarios where there will be abundant scatterers which will result in high delay spread and multipath fading. Super resolution spectrum estimation techniques are more suitable [10]. Currently, such super resolution techniques can be classified into three types namely the Spectral estimation, the Parametric Subspace-Based Estimation (PSBE) and the Deterministic Parameter

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Estimation (DPE),. However, spectral estimation algorithms such as IFFT suffer from parameter resolution degradation if the type of window chosen to resolve spectral leakage is not appropriate. The PSBE algorithms such as Multiple Signal Classification (MUSIC), Estimation of Signal Parameter via Rotational Invariance Technique (ESPRIT) and Unitary ESPRIT, JADE ESPRIT [69]-[80] are better choices for estimation. PSBE algorithms make use of the data covariance structure to estimate the desired parameters. For UWB signal parameter estimation, the subspace algorithms that leverage on the data covariance for parameter estimation will suffer resolution degradation, as it cannot directly apply to highly correlated UWB multipath signals. Spatial smoothing may need to be performed but the result is not satisfactory as compared to DPE algorithms, which are based on Maximum Likelihood (ML) approach. Space Alternating Generalised EM (SAGE) or Expectation Maximization (EM) [81]-[90] which are some of the few DPE algorithms, are needed to be adopted.

2.3.2 Mitigation for Non-Line-Of-Sight (NLOS) Propagation

As mentioned earlier, the conventional localization schemes pose a challenge when the channel environment is a multipath-rich medium with numerous scatterers. One or more *RDs* may not be in the LOS range of the *MD*, rendering the geometrical relationship that is derived for LOS localization erroneous. This error from NLOS propagation manifests itself as a bias on the TOA/TDOA measurement and wrong direction estimation if AOA algorithm is employed as generally manifested in Fig. 2.5. We can model such error as follows

$$\mathbf{r}_m = \mathbf{C} + \mathbf{n}_m + \mathbf{b} \quad (2.3)$$

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where $\mathbf{r}_m$ is the measurement vector for the metric. $\mathbf{n}_m$ is the Additive White Gaussian measurement noise (AWGN) vector with zero mean and covariance matrix Σ_m . $\mathbf{C}$ is the actual unperturbed vector for the metric which is defined as

$$\mathbf{C} = \begin{cases} [\mathbf{t}_1, \mathbf{t}_2, \dots, \mathbf{t}_N]^T & \text{for TOA} \\ [\tau_{2,1}, \tau_{3,1}, \dots, \tau_{N,1}]^T & \text{for TDOA} \\ [\phi_1, \phi_2, \dots, \phi_N]^T & \text{for AOA} \end{cases} \quad (2.4)$$

$t_i, \tau_{i,j}, \phi_i$ are the respective TOA, TDOA and AOA due to the i^{th} RD's signals arriving at the MD and $i = 1 \dots N$. $j = 1$ is the 1st RD that is used for synchronization and $\mathbf{b}$ is the bias error vector due to NLOS propagation or UDP channel profile. Various NLOS mitigation technique have emerged to overcome this problem. They can be broadly classified as

- Residual Weighting methodology [45]-[51];
- LOS/NLOS RD identification methodology [52]-[61]; and
- Direct path scattering model [62]-[64]

In residual weighting methodology, the intent is to minimize the contribution of the NLOS error by assigning the various weighting factors to the localization formulation. The weighting factors can be a function of the RDs geometrical layout, a bias term in the inequality of the localization formulation or simply a constraint factor in the optimization of the localization formulation [45]-[51]. However, it has not been found to provide reliable answers in the total elimination of the NLOS error.

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In the LOS/NLOS *RD* identification methodology [52]-[61], the focus is on the identification of LOS and NLOS *RDs*. NLOS *RDs* are identified and discarded. Only LOS *RDs* are involved in the estimation of the *MD* location. The NLOS *RDs* can be identified through the hypothesis testing of the existence of such NLOS *RDs*. Such existence is tested through the observation of the variance of the TOA/TDOA or the AOA measurement data. Normally, the NLOS measurement variance is much larger than the LOS measurement data. Therefore by leveraging on the difference in the variance, the LOS and NLOS *RDs* can be sorted out. The conventional LOS localization algorithm can then be used to derive the *MD* location. The shortcoming of this technique is that prior variance statistics in each location may be needed.

In a multipath rich environment, there are abundant scatterers around both the *RDs* and *MD*. This may result in almost all the *RDs* being in the NLOS region except for one *RD* that is closest to the *MD*. The above two types of NLOS mitigation techniques will not perform satisfactorily as they require that the number of LOS *RDs* that are available to be greater than the number of NLOS *RDs* deployed in the environment. Furthermore, even though the LOS signal is present, it may not be the dominant path in the multipath environment. It has been shown that the performance of the localization scheme is a function of signal-to-noise ratio (SNR) of the received signal [17], [91]. The greater the SNR of the received signal, the smaller the localization error. Therefore, it would be advantageous to be able to perform localization under the multipath environment with as few *RDs* as possible while maintaining a good performance bound by using paths of the received signal that have a maximum SNR even though they may not be the LOS path.

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In the direct path scattering model [62]-[64], one bounce spatial scattering models (ring of scatterers model and disk of scatterers model) based on TOA measurement data have been formulated. The direct path is estimated through the Bayesian estimation (such as Maximum A Posterior (MAP) or Maximum likelihood (ML)) techniques to mitigate the effect of NLOS errors. The underlying assumption about these spatial models is the adopted channel propagation model in which the dominant received path is a single bound scattering path. In reality, propagation may be carried out by LOS path or path that undergoes more than single bound scattering. This can be observed especially in the indoor environment where the dominant path can be a path that undergoes more than two bound scattering [15], [92].

To the best of our knowledge, there is no single robust algorithm that can currently resolve NLOS error effectively.

2.4 Overview of Our Proposed Localization Schemes

In recent years, the Multiple-Input, Multiple-Output (MIMO) system has emerged as the way to provide high bandwidth communication services. MIMO exploits antenna arrays that are coupled with smart antenna technology at both *RDs* and *MD* for the next generation cellular network (4G) and wireless LAN 802.11n [93]-[98]. Localization using the MIMO principle has been explored in [99], where it was used to eliminate the localization error due to a flat fading symptom. An antenna array at both *RD* and *MD* enables the system to carry out AOA estimation at both ends (referred to as bidirectional estimation). It does so while steering the beams to directions that give maximum and secondary maximum SNR for the usual MIMO communication application [69], [82], [83], [93]-[99]. This is very useful, since communication-related applications are the primary objectives of such systems in most scenarios such as wireless LANs and cellular networks and not localization capability. It is not economically to deploy many *RDs* in the vicinity simply to allow for good LOS ranges that will improve localization.

In Chapter 3, we propose two novel localization schemes in which we can couple joint estimation of TOA and AOA at both ends (referred as bidirectional estimation) [73], [74], [77], [78], [80]-[86], [95], [96] while beamforming for communication applications. Only one *RD* is required for localization and this highly enhances the possibility of localization even when the number of *RDs* that are in LOS with the

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Fig. 2.6: NLOS localization schemes that use both LOS and one bound scattering NLOS paths' measurement data at both reference and mobile devices

mobile device is fewer than that required for conventional localization schemes. As the LOS signal is always the direct path with the shortest delay/TOA, the joint estimation of AOA and TOA enables the identification of the correct LOS AOA even in multipath environments as long as the signal strength of the direct path is above the threshold detection level. The presence of such a direct path signal can be determined by leveraging on the above NLOS mitigation techniques (LOS/NLOS *RD* identification methodology) or by using the angle relationship we have devised that exists between the reference and mobile devices for the LOS signal. This will be discussed.

In Chapter 4, we provide a holistic approach for both LOS and NLOS localization in multipath induced environments by utilizing the bidirectional measurement of the TOA

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and AOA data at both the *RD* and *MD*. Geometrical relationships are established that allow the localization scheme to cater to measurement data arising from paths that are either LOS or that undergo one bound scattering. Paths that undergo more than one bound scattering are successfully discarded based on the proximity relationship between the multipaths. Furthermore, we are able to exploit paths that has higher SNR in order to minimize the localization error [17], [91]. This is achieved by leveraging only on one *RD* to perform localization. Fig. 2.6 illustrates the concept of using both LOS and one bound scattering NLOS paths' measurement data at both *RD* and *MD* for localization. Both TOAs and AOAs at the $RD_1(RD_2)$ and *MD* for the LOS(one bound NLOS) signal that exists between them are utilized for localization.

The NLOS approach that is devised in Chapter 4, is able to localize the *MD* with just one *RD*. However, the cost of using antenna array at the mobile device in terms of computation and physical implementation for localization is expensive. In Chapter 5, we will propose two novel NLOS localization schemes that use the TOA and AOA measurement data of the *MD*'s signal arriving at the *RDs* only and yet are able to localize the non directional (omni-directional) *MD* using not only the LOS path but also utilizing the one bound scattering NLOS multipath. The *MD* does not need to be equipped with antenna array (omni-directional). Simulations in a typical environment have shown that the proposed NLOS localization schemes are robust to the detrimental effect of the multiple bound scattering multipaths on the localization accuracy without leveraging on any mitigation or multipath rejection scheme.

CHAPTER THREE

3 BIDIRECTIONAL LINE OF SIGHT (LOS) LOCALIZATION SCHEMES

Non-line-of-sight (NLOS) multipath signals will dramatically degrade the performance of the conventional *MD* location techniques [24]-[37]. Various mitigation schemes [45]-[61] have been devised to reduce the NLOS contribution. However, these schemes will only perform satisfactorily if the number of line of sight (LOS) *RDs* is greater than the number of NLOS *RDs*, which may not be feasible in a general multipath environment. Furthermore, the NLOS Angle of Arrival (AOA) may be mistaken as LOS AOA for the conventional schemes [31]-[33], [37] that obtain Time of Arrival (TOA) and AOA measurement separately.

In this chapter, two novel localization schemes are presented that leverage on the joint estimation of Angle of Arrival (AOA) and Time of Arrival (TOA) of signals received at *MD* and *RDs* (referred as bi-directional estimation). A two step least square (LS) location estimator has been developed that utilizes AOA and TOA information from one or more *RDs*. Cramer Rao Lower Bound (CRLB) and numerical simulation results have demonstrated that our proposed joint localization schemes and its two step LS location estimator give better location accuracy than the conventional TOA and TOA/AOA localization schemes that use three *RDs* and disjoint metric estimation.

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The two proposed methods thus provides an alternative approach to positioning that works better in multipath rich radio environments (especially indoor channel environments) where it is not always feasible to have at least three reference devices.

3.1 Localization of Mobile Device in Multipath Environment using Bi-directional Estimation

In this section, we propose to overcome the NLOS limitations by obtaining the TOA and AOA jointly at both the RD and MD (referred as bi-directional estimation). This is possible due to the advent of beamforming capability at both ends [93]-[97]. For each measured signal path between a pair of RD and MD , we can deduce whether the associated path is a LOS path by using the devised straight line geometrical AOA relationship that is established between the RD and MD . A two step LOS joint Least Square (LS) localization scheme is then formulated. The correlation factor due to the joint estimation of the TOA and the AOA measurement is taken into account [91]. Unlike the conventional techniques [24]-[37] which requires at least three RDs , it allows TOA and AOA measurement data from just a pair of RD and MD without causing any matrix singularity. This allows us to perform localization using just one RD in a multipath environment.

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3.1.1 Concept and Formulation

Fig. 3.1 Localization in a two dimensional plane.

Consider the problem of localization in a two dimensional plane as shown in Fig. 3.1. The RD_j having the known coordinate (x_j, y_j) has a measured AOA α_j and TOA t_j while MD with unknown coordinates (x, y) has a measured AOA β_j and TOA τ_j . It should be noted that MD does not know the position of RD_j . Therefore RD'_j in Fig. 3.1 depicts the assumed but incorrect position of RD_j due to the measured values of τ_j and β_j at MD . Similarly, MD' denotes the assumed but incorrect position of MD due to the inaccuracy of the TOA and AOA (t_j and α_j) measurements at RD_j . We

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infer that a measured path between RD_j and MD is a LOS path if the following devised geometrical relationship is satisfied

$$|\alpha_j - \beta_j| \leq 180^\circ \pm \sigma_j \quad (3.1)$$

where σ_j is chosen to be $\max(3\sigma_{\alpha_j}, 3\sigma_{\beta_j})$. σ_{α_j} and σ_{β_j} are the standard deviation of the AOA measurement noise at the RD_j and MD respectively. Path measured with an angle difference greater than σ_j will be assumed as a NLOS path and rejected.

Next, we will devise the two step joint localization LS scheme. The measured angle and time parameters at the RD_j and MD can be expressed as

$$l_j = ct_j = l_j^o + n_{l_j}, \quad r_j = c\tau_j = r_j^o + n_{r_j}, \quad \alpha_j = \alpha_j^o + n_{\alpha_j}, \quad \beta_j = \beta_j^o + n_{\beta_j} \quad (3.2)$$

where $j = 1 \cdots N$ with N being the number of LOS reference devices and c is the speed of signal propagation. l_j^o, r_j^o and α_j^o, β_j^o are the noise free TOA (in terms of distance) and AOA measurement at RD_j and MD respectively. n_{l_j}, n_{r_j} and $n_{\alpha_j}, n_{\beta_j}$ are the TOA and AOA Gaussian noise measurement at RD_j and MD respectively. They can be expressed in terms of devices' coordinates using (3.2). For the TOA where

$l_j^o = r_j^o = \sqrt{(x - x_j)^2 + (y - y_j)^2}$, they can be expressed as

$$l_j^2 - K_j = -2x_jx - 2y_jy + R + 2l_j^o n_{l_j} + n_{l_j}^2, \quad r_j^2 - K_j = -2x_jx - 2y_jy + R + 2r_j^o n_{r_j} + n_{r_j}^2 \quad (3.3)$$

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where $K_j = x_j^2 + y_j^2$ and $R = x^2 + y^2$. For the AOA α_j , we use the same geometrical relationship in [37] that is being expressed as

$$-x_j \sin \alpha_j + y_j \cos \alpha_j \approx -x \sin \alpha_j + y \cos \alpha_j + l_j^o n_{\alpha_j} \quad (3.4)$$

To have non-singular matrices, we propose to formulate AOA β_j using a different approach as depicted in Fig. 3.2. The chord of the circle (represented by the line RD_j and RD_j') is used to derive the relationship as follows:

$$(x_j' - x_j)^2 + (y_j' - y_j)^2 = \left(2r_j^o \sin \frac{n_{\beta_j}}{2} \right)^2, \quad x_j' = x - r_j^o \cos(\beta_j - \pi), y_j' = y - r_j^o \sin(\beta_j - \pi) \quad (3.5)$$

(3.5) can be rearranged and expressed as

$$K_j + r_j^{o2} - 2r_j^o (x_j \cos \beta_j + y_j \sin \beta_j) = 2(x_j - r_j^o \cos \beta_j)x + 2(y_j - r_j^o \sin \beta_j)y - R + r_j^{o2} n_{\beta_j} n_{\beta_{\max}} \quad (3.6)$$

where $\sin\left(\frac{n_{\beta_j}}{2}\right) \approx \frac{n_{\beta_j}}{2}$ when $|n_{\beta_j}| \leq 1$ and $n_{\beta_{\max}}$ is the upper bound AOA error.

With the unknown MD coordinate vector $\mathbf{Za} = [x, y, R]^T$, (3.3), (3.4) and (3.6) can be assembled as a standard linear matrix equation formulation [29], [37] for $j = 1 \cdots N$

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Fig. 3.2 Geometrical relationship between RD_j and MD

LOS RDs , namely $\mathbf{h} = \mathbf{G}_a \mathbf{Z}_a + \boldsymbol{\psi}_a$ but with

$$\mathbf{h} = [\mathbf{h}_{d1}^T, \dots, \mathbf{h}_{dN}^T, \mathbf{h}_{\theta 1}^T, \dots, \mathbf{h}_{\theta N}^T]^T,$$

$$\mathbf{G}_a = [\mathbf{G}_{d1}, \mathbf{G}_{d1}, \dots, \mathbf{G}_{dN}, \mathbf{G}_{dN}, \mathbf{G}_{\alpha 1}, \mathbf{G}_{\beta 1}, \dots, \mathbf{G}_{\alpha N}, \mathbf{G}_{\beta N}]^T,$$

$$\mathbf{h}_{dj} = [l_j^2 - K_j, r_j^2 - K_j]^T, \mathbf{G}_{dj} = [-2x_j, -2y_j, 1]^T,$$

$$\mathbf{G}_{\alpha j} = [-\sin \alpha_j, \cos \alpha_j, 0]^T,$$

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$$\mathbf{G}_{\beta_j} = \left[2(x_j - r_j^o \cos \beta_j), 2(y_j - r_j^o \sin \beta_j), -1 \right]^T,$$

$$\mathbf{h}_{\theta_j} = \left[-x_j \sin \alpha_j + y_j \cos \alpha_j, K_j + r_j^{o2} - 2r_j^o (x_j \cos \beta_j + y_j \sin \beta_j) \right]^T,$$

$$\boldsymbol{\psi}_a = 2\mathbf{B}\mathbf{n} + \text{diag}(\mathbf{I}_{2N \times 2N}, \mathbf{0}_{2N \times 2N}) \mathbf{n}^2,$$

$$\mathbf{n} = \left[n_{l_1}, n_{r_1}, \dots, n_{l_N}, n_{r_N}, n_{\alpha_1}, n_{\beta_1}, \dots, n_{\alpha_N}, n_{\beta_N} \right]^T,$$

$$\mathbf{n}^2 = \left[n_{l_1}^2, n_{r_1}^2, \dots, n_{l_N}^2, n_{r_N}^2, n_{\alpha_1}^2, n_{\beta_1}^2, \dots, n_{\alpha_N}^2, n_{\beta_N}^2 \right]^T, \text{ and}$$

$$\mathbf{B} = \text{diag} \left\{ l_1^o, r_1^o, \dots, l_N^o, r_N^o, \frac{l_1^o}{2}, \frac{r_1^{o2}}{2} n_{\beta_{\max}}, \dots, \frac{l_N^o}{2}, \frac{r_N^{o2}}{2} n_{\beta_{\max}} \right\}.$$

where $\mathbf{n}^2$ is the Schur product of the noise column vectors [37]. The first step joint LS solution will be given as

$$\mathbf{Z}_a = \left(\mathbf{G}_a^T \boldsymbol{\Psi}^{-1} \mathbf{G}_a \right)^{-1} \mathbf{G}_a^T \boldsymbol{\Psi}^{-1} \mathbf{h} \quad (3.7)$$

where $\boldsymbol{\Psi} = E[\boldsymbol{\psi}_a \boldsymbol{\psi}_a^T] = 4\mathbf{B}\mathbf{Q}\mathbf{B}$ with the second term on the right hand side of $\boldsymbol{\psi}_a$

ignored [29], [37]. $\mathbf{Q} = E(\mathbf{nn}^T) = \left[\begin{array}{c|c} \mathbf{Q}_{11} & \mathbf{Q}_{12} \\ \hline \mathbf{Q}_{21} & \mathbf{Q}_{22} \end{array} \right]$ is the Gaussian noise covariance matrix

which we formulate as

$$\mathbf{Q}_{11} = \text{diag}(\sigma_{l_1}^2, \sigma_{r_1}^2 \dots \sigma_{l_N}^2, \sigma_{r_N}^2), \mathbf{Q}_{22} = \text{diag}(\sigma_{\alpha_1}^2, \sigma_{\beta_1}^2 \dots \sigma_{\alpha_N}^2, \sigma_{\beta_N}^2) \text{ and } \mathbf{Q}_{12} = \mathbf{Q}_{21} \text{ with}$$

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$$\mathbf{Q}_{12} = \text{diag}\left(\rho_r \sigma_{l_1} \sigma_{\alpha_1}, \rho_m \sigma_{r_1} \sigma_{\beta_1}, \dots, \rho_r \sigma_{l_N} \sigma_{\alpha_N}, \rho_m \sigma_{r_N} \sigma_{\beta_N}\right)$$

$\sigma_{l_j}^2, \sigma_{r_j}^2$ and $\sigma_{\alpha_j}^2, \sigma_{\beta_j}^2$ denote the TOA and AOA measurement noise variances at the RD_j and MD respectively. ρ_r, ρ_m are the correlation factors between the TOA and AOA measurements at RD_j and MD respectively [91]. These values can be obtained by cross-correlating the TOA and AOA estimations during the joint estimation process. The correlation factor has been shown to be a function of the signal bandwidth and the number of elements in the antenna array [17], [91].

The second step of the joint LS formulation is the same as in [29] where

$$\begin{aligned} \mathbf{Z}_p &= \begin{bmatrix} x^2, y^2 \end{bmatrix}^T = \left(\mathbf{G}_p^T \mathbf{\Psi}_p^{-1} \mathbf{G}_p \right)^{-1} \mathbf{G}_p^T \mathbf{\Psi}_p^{-1} \mathbf{h}_p \text{ with} \\ \mathbf{h}_p &= \begin{bmatrix} [\mathbf{Z}_a]_1^2 \\ [\mathbf{Z}_a]_2^2 \\ [\mathbf{Z}_a]_3 \end{bmatrix}, \mathbf{G}_p = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}, \mathbf{\Psi}_p = 4\mathbf{B}_p \text{cov}(\mathbf{Z}_a)\mathbf{B}_p, \text{ and} \\ \mathbf{B}_p &= \text{diag}\{x^o, y^o, 0.5\}, \text{cov}(\mathbf{Z}_a) = \left(\mathbf{G}_a^{oT} \mathbf{\Psi}^{-1} \mathbf{G}_a^o \right)^{-1}. \end{aligned} \quad (3.8)$$

$\text{cov}(\mathbf{Z}_a)$ is the covariance matrix of $\mathbf{Z}_a$ and (x^o, y^o) is the true MD coordinates. l_j^o, r_j^o in $\mathbf{B}, \mathbf{h}, \mathbf{G}_a$ are replaced by the measurement data l_j, r_j while (x^o, y^o) , $\mathbf{G}_a^o$ are replaced by the (x, y) in $\mathbf{Z}_a$ and $\mathbf{G}_a$ respectively during estimation. This process is carried out once to render an accurate result. As in [29], the MD coordinate (x, y) is chosen from

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either $+\sqrt{\mathbf{Z}_p}$ or $-\sqrt{\mathbf{Z}_p}$ with the criteria that the sign of x and y should coincide with the sign of $[\mathbf{Z}_a]_1$ and $[\mathbf{Z}_a]_2$ respectively.

3.1.2 Simulation and Discussion

Light and heavy multipath environments of dimension $20\text{ m} \times 20\text{ m}$ are simulated to illustrate the performance of our proposed localization scheme with the conventional schemes [29], [37]. The RD s are placed at $(0\text{ m}, 0\text{ m})$, $(0\text{ m}, 20\text{ m})$ and $(20\text{ m}, 0\text{ m})$. The probability that each RD is in the LOS with MD is assumed to be 80% and 20% for the light and heavy multipath environments respectively. The scatterers are simulated to be uniformly distributed in both environments [15]. The standard variations of the TOA noise σ_t, σ_r are assumed to be 1 m while the RD s' AOA noise standard variations (σ_α) are 5° and MD 's AOA noise standard variation (σ_β) is varied from 1° to 20° [93],[95],[96]. ρ_r, ρ_m are equated to 0.5 while $n_{\beta_{\max}}$ is 20° . 10 000 MD locations which are uniformly distributed in the environment are simulated to obtain the Average Location Error (ALE) performance comparison between our proposed localization scheme and the conventional TOA, TOA/AOA (modified from TDOA/AOA scheme to TOA/AOA scheme for stricter comparison as TOA/AOA scheme has better performance than TDOA/AOA scheme) localization schemes [29], [37]. The conventional TOA localization scheme [29] has its own NLOS mitigation technique while the conventional TOA/AOA localization scheme [37] is coupled with the NLOS mitigation technique in [54].

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Fig. 3.3 ALE performance comparisons for 10 000 uniformly distributed MD locations with $\sigma_l, \sigma_r = 1m$, $\sigma_\alpha = 5^\circ$ with varying σ_β in the multipath environment.

Fig. 3.3 depicts the ALE performance comparison between our proposed localization scheme that uses one LOS RD with bi-directional estimation and the conventional localization schemes that use three RD s with uni-directional estimation. As shown, our proposed localization scheme is able to outperform all conventional localization schemes for all varying σ_β , with an average error of $2m$. This is compared to an average error of $10m$ and $8m$ for TOA and TOA/AOA localization schemes respectively. A similar trend is observed if σ_α is doubled. In conclusion, our proposed bidirectional localization scheme that uses one LOS RD is not only able to obtain low

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location error at large angle variations but also provide suitable performance stability in relation to variations in the location of the MD in the multipath environment.

3.2 A Line-of-Sight (LOS) Localization Scheme with Metrics Enhancement using Bi-directional Estimation in a Multipath Environment

In the previous section, we derive a LOS bidirectional localization scheme that leverages on the joint estimation of TOA and AOA. However, we did not capitalize on the advantage of bidirectional estimation. Bidirectional estimation allows the design of an enhancement technique to re-adjust and improve the accuracy of the AOA measurement values at both the RD and MD . Through these re-adjustments, the accuracy of identifying the MD 's location is further improved.

In this section, we will exploit the bi-directional measurement information to design a new LOS bidirectional localization scheme coupled with an AOA enhancement technique. Our proposed localization algorithm performs better than conventional unidirectional localization schemes, especially under NLOS scenarios. In general, when coupled with the NLOS path detection and AOA adjustment techniques devised here, our proposed localization scheme generally performs better than the conventional unidirectional schemes with three RD s, even though it uses only one LOS RD with bi-directional measurement. Section 3.2.1 describes the derivation of a new two-step LS estimator, first introduced in [26] for a TDOA localization scheme, to solve the nonlinear localization equations for our joint estimation. The NLOS path rejection and

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the AOA adjustment techniques will also be derived. The CRLB and the performance of the proposed scheme are evaluated via computer simulation in Section 3.2.2.

3.2.1 Concept and Formulation

In this section, we derive the location estimator to solve the joint estimation localization equation, and thus locate the *MD*. As the CRLB of the TDOA/AOA localization scheme is much higher than that of the TOA/AOA localization scheme (since one of the time observations has to be sacrificed for time synchronization), we extend the AOA formulation for the localization equation in [37] into the TOA localization scheme in [29]. This is to develop a TOA/AOA localization scheme that enables a stricter comparison with the proposed joint localization scheme. In our formulation, the LOS TOA and AOA measurement noise errors for each *RD/MD* are modeled as correlated Gaussian random variables with a zero mean, known variances and correlation factor ρ . These assumptions are reasonable as both TOA and AOA measurements are corrupted by Gaussian noise when they are estimated independently. Since they are jointly estimated, a correlation factor will be involved [91], [95], [96]. The conditional joint TOA/AOA probability distribution will be a multivariate Gaussian probability distribution [95], [96],

$$f(\mathbf{x} | \mathbf{z}) = \frac{1}{(2\pi)^{\frac{N}{2}} |\mathbf{Q}|^{\frac{1}{2}}} \exp \left[-\frac{1}{2} (\mathbf{x} - \mathbf{u})^T \mathbf{Q}^{-1} (\mathbf{x} - \mathbf{u}) \right] \quad (3.9)$$

where

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$$\mathbf{x} = [l_1, r_1 \cdots l_N, r_N, \alpha_1, \beta_1 \cdots \alpha_N, \beta_N]^T, \text{ and}$$

$$\mathbf{u} = [l_1^o, r_1^o \cdots l_N^o, r_N^o, \alpha_1^o, \beta_1^o \cdots \alpha_N^o, \beta_N^o]^T.$$

and vector $\mathbf{z} = [x^o, y^o]$ contains the actual coordinates of the mobile device. As depicted in (3.2), l_j, r_j and α_j, β_j (l_j^o, α_j^o and α_j^o, β_j^o) denote the measured TOAs and AOAAs (actual TOAs and AOAAs) at RD_j and MD . $\mathbf{Q}$ is defined as the covariance matrix of the joint distribution (3.9) and is given as in (3.7).

A. Formulation of the 2 step LS estimator with readjustment of AOA measurement

To re-illustrate, consider the case depicted in Fig. 3.1, the measured TOA is related to the distance between RD_j and MD (l_j and r_j) by the following relationships as in (3.2). Both the actual distance and the angles can be further expressed in terms of the devices' coordinates as

$$\alpha_j^o = \tan^{-1} \left(\frac{y - y_j}{x - x_j} \right) \quad (3.10)$$

$$\beta_j^o = \pi + \tan^{-1} \left(\frac{y - y_j}{x - x_j} \right) \quad (3.11)$$

$$l_j^o = r_j^o = \sqrt{(x - x_j)^2 + (y - y_j)^2} \quad (3.12)$$

In order to formulate the joint localization scheme using the two step LS estimator from [26], we need to include the TOA and AOA equations (3.2) into the formulation and express them as a function of the unknown MD coordinates (x, y) .

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For TOA, (3.12) can be expanded using (3.2) and expressed as

$$\begin{aligned}
 l_j^2 - 2l_j^o n_{l_j} - n_{l_j}^2 &= r_j^2 - 2r_j^o n_{r_j} - n_{r_j}^2 \\
 &= K_j - 2x_j x - 2y_j y + R, \\
 l_j^2 - K_j &= -2x_j x - 2y_j y + R + 2l_j^o n_{l_j} + n_{l_j}^2, \text{ and} \\
 r_j^2 - K_j &= -2x_j x - 2y_j y + R + 2r_j^o n_{r_j} + n_{r_j}^2
 \end{aligned} \tag{3.13}$$

where $K_j = x_j^2 + y_j^2$ and $R = x^2 + y^2$.

For the AOA α_j , (3.10) can be expressed as

$$\begin{aligned}
 \frac{y - y_j}{x - x_j} &= \frac{\sin \alpha_j^o}{\cos \alpha_j^o} \\
 x_j \sin \alpha_j^o - y_j \cos \alpha_j^o &= x \sin \alpha_j^o - y \cos \alpha_j^o
 \end{aligned}$$

With noise perturbation, α_j^o will be replaced by α_j in (3.2) and will be given by

$$x_j \sin \alpha_j - y_j \cos \alpha_j = x \sin \alpha_j - y \cos \alpha_j \tag{3.14}$$

In order to have a non-singular matrix or full column rank, we propose to formulate β_j using a different approach as shown similarly in Fig. 3.2. The chord of the circle (represented by the line RD_j and RD_j') can be used to derive the relationship between the devices as follows:

$$\left(x_j' - x_j\right)^2 + \left(y_j - y_j'\right)^2 = \left(2r_j^o \sin \frac{n_{\beta_j}}{2}\right)^2 \tag{3.15}$$

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and

$$\begin{aligned}x_j' &= x - r_j^o \cos(\beta_j - \pi) \\y_j' &= y - r_j^o \sin(\beta_j - \pi)\end{aligned}\tag{3.16}$$

Inserting x_j' and y_j' from (3.16) into (3.15), we obtain

$$R + r_j^{o2} + K_j - 2(x_j - r_j^o \cos \beta_j)x - 2(y_j - r_j^o \sin \beta_j)y - 2r_j^o(x_j \cos \beta_j + y_j \sin \beta_j) = 4r_j^{o2} \left(\sin \frac{n_{\beta_j}}{2} \right)^2\tag{3.17}$$

For a $3\sigma_{\beta_j}$ confidence interval and assuming that $\sigma_{\beta_j} \leq 20^\circ$, $\sin\left(\frac{n_{\beta_j}}{2}\right) \approx \frac{n_{\beta_j}}{2}$, as was

done in [37], the above equation can be rewritten as

$$K_j + r_j^{o2} - 2r_j^o(x_j \cos \beta_j + y_j \sin \beta_j) \approx 2(x_j - r_j^o \cos \beta_j)x + 2(y_j - r_j^o \sin \beta_j)y - R + r_j^{o2}n_{\beta_j}^2\tag{3.18}$$

The accuracy of α_j and β_j in (3.14) and (3.18) can be further improved by the straight-line angle relationship that exists between them in the LOS path as shown in Fig. 3.4. This is an advantage which cannot be realized when using unidirectional estimation in Fig. 3.4, α_j' and β_j' have the following relationships with α_j and β_j

$$\begin{aligned}\alpha_j' &= \alpha_j \\ \beta_j' &= 360^\circ - \beta_j\end{aligned}\tag{3.19}$$

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Fig. 3.4 Geometrical relationship between the angle of arrival for a LOS path

In ideal conditions with no noise perturbation, the following relationship will always hold

$$\alpha_j' + \beta_j' = \alpha_j^o + \beta_j^o = 180^\circ \quad (3.20)$$

as α_j and β_j are equal to α_j^o and β_j^o respectively. With measurement noise, (3.20) becomes an inequality because of the noise perturbation of α_j and β_j . However, the equality relationship can be reestablished by readjusting the values of α_j' and β_j' through the following proposed criteria:

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$$e_j = \alpha'_j + \beta'_j - 180^\circ \quad (3.21)$$

$$\begin{aligned} \alpha'_j &= \alpha_j - e_j f_{\alpha_j} \\ \beta'_j &= \beta_j - e_j f_{\beta_j} \end{aligned} \quad (3.22)$$

e_j is defined as the noise angle difference for RD_j and $f_{\alpha_j}, f_{\beta_j}$ are the error weighting factors given as

$$f_{\alpha_j} = \frac{\sigma_{\alpha_j}}{\sigma_{\alpha_j} + \sigma_{\beta_j}}, f_{\beta_j} = \frac{\sigma_{\beta_j}}{\sigma_{\alpha_j} + \sigma_{\beta_j}} \quad (3.23)$$

Substituting α_j, β_j from (3.2) into (3.19) and (3.21), e_j can be further refined in terms of angle noise errors as

$$e_j = \begin{cases} n_{\alpha_j} - n_{\beta_j} & \text{if } 0^\circ < \alpha_j \leq 90^\circ, 270^\circ < \alpha_j \leq 360^\circ \\ n_{\beta_j} - n_{\alpha_j} & \text{if } 90^\circ < \alpha_j \leq 180^\circ, 180^\circ < \alpha_j \leq 270^\circ \end{cases} \quad (3.24)$$

Putting (3.24) into (3.22) and subsequently into (3.19), it can be found that

$$\alpha_j = \alpha_j^o + n_{\alpha_j}', \beta_j = \beta_j^o + n_{\beta_j}' \quad (3.25)$$

where n_{α_j}' and n_{β_j}' are the modified noise errors of the AOA α_j and β_j respectively

and are given as

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$$\begin{aligned} n'_{\alpha_j} &= n_{\alpha_j} - (n_{\alpha_j} - n_{\beta_j}) f_{\alpha_j} \\ n'_{\beta_j} &= n_{\beta_j} + (n_{\alpha_j} - n_{\beta_j}) f_{\beta_j} \end{aligned} \quad (3.26)$$

From (3.25), it can be easily seen that the modification in (3.22) is to minimize measurement noise, and thus attempt to provide the true AOA values of α_j^o and β_j^o .

The AOA formulations are readjusted by substituting (3.25) into (3.14) and (3.18). With these two readjusted AOA formulations and (3.13), the joint localization equation can now be expressed as

$$\mathbf{h} = \mathbf{G}_a \mathbf{Z}_a + \boldsymbol{\psi}_a \quad (3.27)$$

where

$$\mathbf{h} = \begin{bmatrix} l_1^2 - K_1 \\ r_1^2 - K_1 \\ \vdots \\ l_N^2 - K_N \\ r_N^2 - K_N \\ x_1 \sin \alpha_1^o - y_1 \cos \alpha_1^o \\ K_1 + r_1^{o2} - 2r_1^o (x_1 \cos \beta_1^o + y_1 \sin \beta_1^o) \\ \vdots \\ x_N \sin \alpha_N^o - y_N \cos \alpha_N^o \\ K_N + r_N^{o2} - 2r_N^o (x_N \cos \beta_N^o + y_N \sin \beta_N^o) \end{bmatrix}, \text{ and}$$

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$$\mathbf{G}_a = \begin{bmatrix} -2x_1 & -2y_1 & 1 \\ -2x_1 & -2y_1 & 1 \\ \vdots & \vdots & \vdots \\ -2x_N & -2y_N & 1 \\ -2x_N & -2y_N & 1 \\ \sin \alpha_1^o & -\cos \alpha_1^o & 0 \\ 2(x_1 - r_1^o \cos \beta_1^o) & 2(y_1 - r_1^o \sin \beta_1^o) & -1 \\ \vdots & \vdots & \vdots \\ \sin \alpha_N^o & -\cos \alpha_N^o & 0 \\ 2(x_N - r_N^o \cos \beta_N^o) & 2(y_N - r_N^o \sin \beta_N^o) & -1 \end{bmatrix} \quad (3.28)$$

where $\mathbf{Z}_a = [x, y, R]^T$ and the noise matrix is given by

$$\boldsymbol{\psi}_a = 2\mathbf{B}\mathbf{n}_1 + \mathbf{C}\mathbf{n}_2 + \mathbf{D}\mathbf{n}_3 + \mathbf{E}\mathbf{n}_4 + \mathbf{F}\mathbf{n}_5 + \mathbf{G}\mathbf{n}_6$$

$$\mathbf{B} = \text{diag} \left\{ l_1^o, r_1^o, \dots, l_N^o, r_N^o, \frac{1}{2}(1 - f_{\alpha_1})\lambda_1, r_1^o(1 - f_{\beta_1})\gamma_1, \dots, \frac{1}{2}(1 - f_{\alpha_N})\lambda_N, r_N^o(1 - f_{\beta_N})\gamma_N \right\}$$

$$\mathbf{C} = \text{diag} \left\{ 0, 0, \dots, 0, 0, f_{\alpha_1}\lambda_1, 2f_{\beta_1}r_1^o\gamma_1, \dots, f_{\alpha_N}\lambda_N, 2f_{\beta_N}r_N^o\gamma_N \right\}$$

$$\mathbf{D} = \text{diag} \left\{ 0, 0, \dots, 0, 0, f_{\alpha_1}\kappa_1 n_{\alpha_1}^{\max}, (2f_{\beta_1}r_1^o\upsilon_1 + r_1^{o2})n_{\beta_1}^{\max}, \dots, f_{\alpha_N}\kappa_N n_{\alpha_N}^{\max}, (2f_{\beta_N}r_N^o\upsilon_N + r_N^{o2})n_{\beta_N}^{\max} \right\}$$

$$\mathbf{E} = \text{diag} \left\{ 0, 0, \dots, 0, 0, f_{\alpha_1}^2\lambda_1, 2f_{\beta_1}^2r_1^o\gamma_1, \dots, f_{\alpha_N}^2\lambda_N, 2f_{\beta_N}^2r_N^o\gamma_N \right\}$$

$$\mathbf{F} = \text{diag} \left\{ 0, 0, \dots, 0, 0, (f_{\alpha_1}^2 - f_{\alpha_1})\kappa_1, 2(f_{\beta_1}^2 - f_{\beta_1})r_1^o\upsilon_1, \dots, (f_{\alpha_N}^2 - f_{\alpha_N})\kappa_N, 2(f_{\beta_N}^2 - f_{\beta_N})r_N^o\upsilon_N \right\}$$

$$\mathbf{G} = \text{diag} \{ 1, 1, \dots, 1, 1, 0, 0 \dots 0, 0 \}$$

(3.29)

where

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$$\begin{aligned}
 \lambda_j &= \cos \alpha_j^o (x^o - x_j) + \sin \alpha_j^o (y^o - y_j), \\
 \gamma_j &= \cos \beta_j^o (y_j - y^o) - \sin \beta_j^o (x_j - x^o), \\
 \kappa_j &= \sin \alpha_j^o (x^o - x_j) - \cos \alpha_j^o (y^o - y_j) \text{ and} \\
 \nu_j &= \cos \beta_j^o (x_j - x^o) + \sin \beta_j^o (y_j - y^o) \quad j = 1 \cdots N
 \end{aligned} \tag{3.30}$$

and

$$\begin{aligned}
 \mathbf{n}_1 &= [n_{l_1}, n_{r_1}, \cdots, n_{l_N}, n_{r_N}, n_{\alpha_1}, n_{\beta_1}, \cdots, n_{\alpha_N}, n_{\beta_N}]^T, \\
 \mathbf{n}_2 &= [0, 0, \cdots, 0, 0, n_{\beta_1}, n_{\alpha_1}, \cdots, n_{\beta_N}, n_{\alpha_N}]^T, \\
 \mathbf{n}_3 &= [0, 0, \cdots, 0, 0, n_{\alpha_1}, n_{\beta_1}, \cdots, n_{\alpha_N}, n_{\beta_N}]^T, \\
 \mathbf{n}_4 &= [0, 0, \cdots, 0, 0, n_{\alpha_1}^2 n_{\beta_1}, n_{\beta_1}^2 n_{\alpha_1}, \cdots, n_{\alpha_N}^2 n_{\beta_N}, n_{\beta_N}^2 n_{\alpha_N}]^T, \\
 \mathbf{n}_5 &= [0, 0, \cdots, 0, 0, n_{\alpha_1} n_{\beta_1}, n_{\alpha_1} n_{\beta_1}, \cdots, n_{\alpha_N} n_{\beta_N}, n_{\alpha_N} n_{\beta_N}]^T, \text{ and} \\
 \mathbf{n}_6 &= [n_{l_1}^2, n_{r_1}^2, \cdots, n_{l_N}^2, n_{r_N}^2, 0, 0, \cdots, 0, 0]^T
 \end{aligned} \tag{3.31}$$

$n_{\alpha_j}^{\max}$ and $n_{\beta_j}^{\max}$ are defined as the upper bound of the AOA errors for n_{α_j} and n_{β_j} respectively and are equated to $3\sigma_{\alpha_j}$ and $3\sigma_{\beta_j}$ respectively in the experiment and simulation. Similarly as in [26], [29], $\mathbf{n}_6$ is neglected. Acknowledging that the odd

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order moment of a Gaussian random variable is null (moment of $\mathbf{n}_4$), the above joint estimator will be an unbiased estimator.

The first-step LS solution will be given as

$$\mathbf{Z}_a = \left(\mathbf{G}_a^T \Psi^{-1} \mathbf{G}_a \right)^{-1} \mathbf{G}_a^T \Psi^{-1} \mathbf{h} \quad (3.32)$$

where

$$\begin{aligned} \Psi = E \left[\boldsymbol{\psi}_a \boldsymbol{\psi}_a^T \right] = & 4\mathbf{B}\mathbf{Q}\mathbf{B} + 2\mathbf{B}\mathbf{Q}_{12}\mathbf{C} + 2\mathbf{B}\mathbf{Q}_{13}\mathbf{D} + 2\mathbf{B}\mathbf{Q}_{14}\mathbf{E} + \\ & 2\mathbf{C}\mathbf{Q}_{21}\mathbf{B} + \mathbf{C}\mathbf{Q}_{22}\mathbf{C} + \mathbf{C}\mathbf{Q}_{23}\mathbf{D} + \mathbf{C}\mathbf{Q}_{24}\mathbf{E} + \\ & 2\mathbf{D}\mathbf{Q}_{31}\mathbf{B} + \mathbf{D}\mathbf{Q}_{32}\mathbf{C} + \mathbf{D}\mathbf{Q}_{33}\mathbf{D} + \mathbf{D}\mathbf{Q}_{34}\mathbf{E} + \\ & 2\mathbf{E}\mathbf{Q}_{41}\mathbf{B} + \mathbf{E}\mathbf{Q}_{42}\mathbf{C} + \mathbf{E}\mathbf{Q}_{43}\mathbf{D} + \mathbf{E}\mathbf{Q}_{44}\mathbf{E} + \mathbf{F}\mathbf{Q}_{55}\mathbf{F} \end{aligned} \quad (3.33)$$

with $\mathbf{Q}$ being the noise covariance matrix and expressed as in (3.7) while

$$\begin{aligned} \mathbf{Q}_{12} = E \left[\mathbf{n}_1 \mathbf{n}_2^T \right] \\ = \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{g}_{12_1} \cdots \mathbf{g}_{12_N}) \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{12_1} \cdots \mathbf{k}_{12_N}) \end{array} \right], \mathbf{k}_{12_j} = \left[\begin{array}{c|c} 0 & \sigma_{\alpha_j}^2 \\ \hline \sigma_{\beta_j}^2 & 0 \end{array} \right] \end{aligned}$$

$$\mathbf{g}_{12_j} = \left[\begin{array}{c|c} 0 & \rho_{r_j} \sigma_{l_j} \sigma_{\alpha_j} \\ \hline \rho_{m_j} \sigma_{r_j} \sigma_{\beta_j} & 0 \end{array} \right]$$

$$\begin{aligned} \mathbf{Q}_{13} = E \left[\mathbf{n}_1 \mathbf{n}_3^T \right] \\ = \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{g}_{13_1} \cdots \mathbf{g}_{13_N}) \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{13_1} \cdots \mathbf{k}_{13_N}) \end{array} \right], \mathbf{k}_{13_j} = \left[\begin{array}{c|c} \sigma_{\alpha_j}^2 & 0 \\ \hline 0 & \sigma_{\beta_j}^2 \end{array} \right] \end{aligned}$$

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$$\mathbf{g}_{13_j} = \left[\begin{array}{c|c} \rho_{r_j} \sigma_{l_j} \sigma_{\alpha_j} & 0 \\ \hline 0 & \rho_{m_j} \sigma_{r_j} \sigma_{\beta_j} \end{array} \right]$$

$$\begin{aligned} \mathbf{Q}_{14} &= E[\mathbf{n}_1 \mathbf{n}_4^T] \\ &= \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{g}_{14_1} \cdots \mathbf{g}_{14_N}) \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{14_1} \cdots \mathbf{k}_{14_N}) \end{array} \right], \mathbf{k}_{14_j} = \left[\begin{array}{c|c} 0 & \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 \\ \hline \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 & 0 \end{array} \right] \end{aligned}$$

$$\mathbf{g}_{14_j} = \left[\begin{array}{c|c} 0 & \rho_{r_j} \sigma_{l_j} \sigma_{\alpha_j} \sigma_{\beta_j}^2 \\ \hline \rho_{m_j} \sigma_{r_j} \sigma_{\beta_j} \sigma_{\alpha_j}^2 & 0 \end{array} \right]$$

$$\begin{aligned} \mathbf{Q}_{22} &= E[\mathbf{n}_2 \mathbf{n}_2^T] \\ &= \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{22_1} \cdots \mathbf{k}_{22_N}) \end{array} \right], \mathbf{k}_{22_j} = \left[\begin{array}{c|c} \sigma_{\beta_j}^2 & 0 \\ \hline 0 & \sigma_{\alpha_j}^2 \end{array} \right] \end{aligned}$$

$$\begin{aligned} \mathbf{Q}_{23} &= E[\mathbf{n}_2 \mathbf{n}_3^T] \\ &= \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{23_1} \cdots \mathbf{k}_{23_N}) \end{array} \right], \mathbf{k}_{23_j} = \left[\begin{array}{c|c} 0 & \sigma_{\beta_j}^2 \\ \hline \sigma_{\alpha_j}^2 & 0 \end{array} \right] \end{aligned}$$

$$\begin{aligned} \mathbf{Q}_{24} &= E[\mathbf{n}_2 \mathbf{n}_4^T] \\ &= \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{24_1} \cdots \mathbf{k}_{24_N}) \end{array} \right], \mathbf{k}_{24_j} = \left[\begin{array}{c|c} \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 & 0 \\ \hline 0 & \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 \end{array} \right] \end{aligned}$$

$$\begin{aligned} \mathbf{Q}_{33} &= E[\mathbf{n}_3 \mathbf{n}_3^T] \\ &= \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{33_1} \cdots \mathbf{k}_{33_N}) \end{array} \right], \mathbf{k}_{33_j} = \left[\begin{array}{c|c} \sigma_{\alpha_j}^2 & 0 \\ \hline 0 & \sigma_{\beta_j}^2 \end{array} \right] \end{aligned}$$

$$\begin{aligned} \mathbf{Q}_{34} &= E[\mathbf{n}_3 \mathbf{n}_4^T] \\ &= \left[\begin{array}{c|c} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \hline \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{34_1} \cdots \mathbf{k}_{34_N}) \end{array} \right], \mathbf{k}_{34_j} = \left[\begin{array}{c|c} 0 & \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 \\ \hline \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 & 0 \end{array} \right] \end{aligned}$$

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$$\begin{aligned}
 \mathbf{Q}_{44} &= E[\mathbf{n}_4 \mathbf{n}_4^T] \\
 &= \begin{bmatrix} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{44_1} \cdots \mathbf{k}_{44_N}) \end{bmatrix}, \mathbf{k}_{44_j} = \begin{bmatrix} 3\sigma_{\alpha_j}^4 \sigma_{\beta_j}^2 & 0 \\ 0 & 3\sigma_{\beta_j}^4 \sigma_{\alpha_j}^2 \end{bmatrix} \\
 \mathbf{Q}_{55} &= E[\mathbf{n}_5 \mathbf{n}_5^T] \\
 &= \begin{bmatrix} \mathbf{0}_{2N \times 2N} & \mathbf{0}_{2N \times 2N} \\ \mathbf{0}_{2N \times 2N} & \text{diag}(\mathbf{k}_{55_1} \cdots \mathbf{k}_{55_N}) \end{bmatrix}, \mathbf{k}_{55_j} = \begin{bmatrix} \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 & \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 \\ \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 & \sigma_{\alpha_j}^2 \sigma_{\beta_j}^2 \end{bmatrix} \quad j = 1 \cdots N
 \end{aligned} \tag{3.34}$$

$$\mathbf{Q}_{nm} = \mathbf{Q}_{mn}' \quad m = 1 \cdots 5, n = 1 \cdots 5, m \neq n$$

To solve for $\mathbf{Z}_a$ in (3.32), we need the matrices Ψ , $\mathbf{h}$ and $\mathbf{G}_a$ which require the unknown actual distances l_j^o, r_j^o and angles α_j^o, β_j^o for $j=1 \cdots N$. Therefore, we first use the measured values $l_j, r_j, \alpha_j, \beta_j$ instead of the actual values, and set $\Psi = \mathbf{I}_{4N \times 4N}$ to estimate an initial solution. The corresponding matrices Ψ , $\mathbf{h}$ and $\mathbf{G}_a$ are recalculated with the new estimated l_j, r_j using this initial solution. α_j, β_j in the above matrices are also readjusted using (3.22). A better estimate of $\mathbf{Z}_a$ is obtained by using the new matrices Ψ , $\mathbf{h}$ and $\mathbf{G}_a$. The process can be repeated until the solution converges. Our simulations show that one iteration is sufficient for obtaining a good estimation of $\mathbf{Z}_a$.

The second-step LS approach for obtaining the MD coordinate $\mathbf{Z} = [x, y]^T$ will be obtained similarly as in (3.8) as in $\mathbf{Z}_p = [x^2, y^2]^T$, $\mathbf{Z} = \pm \sqrt{\mathbf{Z}_p}$ and

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$$\mathbf{Z}_p = \left(\mathbf{G}_p^T \mathbf{\Psi}_p^{-1} \mathbf{G}_p \right)^{-1} \mathbf{G}_p^T \mathbf{\Psi}_p^{-1} \mathbf{h}_p \quad (3.35)$$

where

$$\mathbf{h}_p = \begin{bmatrix} [\mathbf{Z}_a]_1^2 \\ [\mathbf{Z}_a]_2^2 \\ [\mathbf{Z}_a]_3 \end{bmatrix}, \mathbf{G}_p = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}, \mathbf{\Psi}_p = 4\mathbf{B}_p \text{cov}(\mathbf{Z}_a) \mathbf{B}_p, \text{ and} \quad (3.36)$$

$$\mathbf{B}_p = \text{diag}\{x^o, y^o, 0.5\}, \text{cov}(\mathbf{Z}_a) = \left(\mathbf{G}_a^{oT} \mathbf{\Psi}^{-1} \mathbf{G}_a^o \right)^{-1}.$$

$\text{cov}(\mathbf{Z}_a)$ is the covariance matrix of $\mathbf{Z}_a$ and (x^o, y^o) are the actual coordinates of MD .

Similarly, (x^o, y^o) and $\mathbf{G}_a^o$ can be replaced by the (x, y) in $\mathbf{Z}_a$ and $\mathbf{G}_a$ respectively

during estimation. This process is carried out once to render an accurate result. As in

[29], $\mathbf{Z}$ is chosen from either $+\sqrt{\mathbf{Z}_p}$ or $-\sqrt{\mathbf{Z}_p}$ with the criteria that the sign of x and

y should coincide with the sign of $[\mathbf{Z}_a]_1$ and $[\mathbf{Z}_a]_2$ respectively. Fig. 3.5 depicts the

process flow of the proposed algorithm.

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1. Obtain an initial solution of $\mathbf{Z}_a$ in (3.32) using the measured values of $l_j, r_j, \alpha_j, \beta_j$ in place of $l_j^o, r_j^o, \alpha_j^o, \beta_j^o$ to calculate the matrices $\mathbf{h}, \mathbf{G}_a$ that are defined in (3.28). $\mathbf{\Psi}$ in (3.33) is defined to be an identity matrix of dimension $4N \times 4N$
2. Perform readjustment of the values of α_j and β_j using (3.22) and (3.23). Recalculate the values of l_j, r_j using the initial solution of $\mathbf{Z}_a$ obtained in the earlier step.
3. Recalculate the matrices $\mathbf{h}, \mathbf{G}_a, \mathbf{\Psi}$ in (3.28) and (3.33) using the values of $l_j, r_j, \alpha_j, \beta_j$ that are obtained in step 2.
4. Obtain a solution of $\mathbf{Z}_a$ in (3.32) using the calculated matrices $\mathbf{h}, \mathbf{G}_a, \mathbf{\Psi}$ that are obtained in step 3.
5. Calculate $\mathbf{Z}_p$ in (3.35) and obtain the mobile location $\mathbf{Z}$ from either $+\sqrt{\mathbf{Z}_p}$ or $-\sqrt{\mathbf{Z}_p}$. The choice will be the one that has the sign of x and y coincide with the sign of $[\mathbf{Z}_a]_1$ and $[\mathbf{Z}_a]_2$ respectively.

Fig. 3.5 Process flow of the proposed bidirectional localization scheme

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B. NLOS path rejection technique

We are able to infer whether a path is a LOS or NLOS path by exploiting the bi-directional AOA estimation technique, as it helps us devise a formulation for rejecting NLOS paths. This formula arises out of (3.21) and (3.22), which provide the adjustments for the LOS path's AOAs as depicted in Fig. 3.4. In (3.21), the noise angle difference e_j is based on the difference between 180° and $\alpha'_j + \beta'_j$. If e_j is greater than a certain threshold, in this case $3\sigma_{\alpha_j}$ or $3\sigma_{\beta_j}$, it will most likely be a NLOS path, and there will thus be no need to adjust the AOAs. Therefore, we infer that a path between RD_j and MD is assumed to be a LOS path when

$$|\alpha_j - \beta_j| \leq 180^\circ \pm \sigma_j \quad (3.37)$$

and $\sigma_j = \max(3\sigma_{\alpha_j}, 3\sigma_{\beta_j})$. Any path with an angle difference greater than σ_j will be assumed to be a NLOS path, and will be rejected.

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3.2.2 Simulation and Discussion

The performance of the joint localization scheme is assessed by a simulation using (3.35), and by comparing it with the TOA localization scheme in [29] and the modified TOA/AOA localization scheme in [37]. As shown in Fig.3.6, three reference devices were located at $RD_1(25,9)$, $RD_2(18,4)$, $RD_3(3,14)$ in a typical indoor environment at Nanyang Technological University's School of Electrical and Electronics Engineering NTU (EEE), Block S1, Level B3 (S1-B3) [100]. The scatterers shown in the plot are concrete walls. Channel measurements were taken and the measured metrics (AOAs and TOAs) for the paths that first arrived at the RDs were verified by using the traditional ray tracing methodology [100]-[102]. Fig.3.6 shows the three scenarios that were used to examine the performance of our joint bidirectional localization scheme:

- Case A - all RDs are in LOS with MD ,
- Case B - two RDs are in LOS with MD ,
- Case C - one RD is in LOS with MD ,

The actual data metrics ($t_{j,m}^o, \tau_{j,m}^o, \theta_{j,m}^o, \phi_{j,m}^o$) were obtained by correlating ray tracing methodology with the measurement data. For a rigorous comparison with the existing localization schemes, the actual data metrics were subjected to noise effects using Gaussian random noise with a zero mean and known variances (the variances of all the devices were identical unless otherwise specified). These parameters were assumed to be obtained a priori, as in [18], [24]-[29], [33], [37]. Similarly, their correlation factors

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Fig.3.6 Geometrical layout for the experiment at Nanyang Technological University, EEE S1, level B3 (S1-B3)

ρ_r, ρ_m were assumed to be the same unless otherwise specified, and were equated to ρ with a value of 0.5. The location RMS error σ_{rms} , which is equal to $\sqrt{E[(x - x^o)^2 + (y - y^o)^2]}$ is computed based on 10,000 independent runs. For the first conventional unidirectional scheme, the modified TOA/AOA localization scheme [37], three reference devices that utilize 3 TOA and 3 AOA measurements were used. The LOS reference devices detection scheme [54] was used for its NLOS mitigation. The second conventional scheme, the TOA algorithm in [29], used 3 TOA measurements and was coupled with its own mitigation technique. $n_{\alpha_j}^{\max}$ and $n_{\beta_j}^{\max}$ were set to $3\sigma_{\alpha_j}$ and $3\sigma_{\beta_j}$ respectively.

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A. Performance probability distribution due to effect of TOA, AOA inaccuracy

Fig. 3.7 CDF performance comparison when the distance standard deviation $\sigma_d=2\text{m}$, and the AOA standard deviation $\sigma_\alpha=\sigma_\beta=5^\circ$, with the actual MD location at coordinates (13.0m, 13.0m). Case A- All RDs are in LOS with the MD .

Fig. 3.7 depicts the location accuracy of the proposed joint localization scheme by comparing it to the TOA/AOA and the TOA localization schemes via their cumulative probability distribution functions (CDF). The AOA standard deviation $\sigma_\alpha, \sigma_\beta$ for all the devices is 5° while the standard deviation for the distance σ_d ($\sigma_d = \sigma_l = \sigma_r$) is 2m [18], [85], [93] with the MD located at point A (13.0m, 13.0m). All the RDs are in LOS with the MD . As observed, our joint LS scheme that uses one LOS RD performed better than the conventional TOA scheme; however, it did not perform as well as the TOA/AOA scheme.

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Fig. 3.8 CDF performance comparison when the distance standard deviation $\sigma_d=2\text{m}$ and the AOA standard deviation $\sigma_\alpha=\sigma_\beta=5^\circ$, with the actual MD location at coordinates (17.0m, 12.5m). Case B- Two RDs are in LOS with the MD .

Fig. 3.8 depicts the performance when the MD was located at point B (17.0m, 12.5m). RD_1 is in NLOS with the MD and underwent one bound reflection at the concrete wall (13.0m, 11.6m). As depicted, the conventional TOA/AOA scheme was able to detect this NLOS path and discard it. However, our joint LS scheme that uses one LOS RD (and 2 TOA and 2 AOA measurements) performed better than the two conventional schemes.

Fig. 3.9 illustrates the case when the MD was located at point C (10.0m, 4.0m). Only RD_2 was in LOS with the MD , and both RD_1 and RD_3 underwent multiple bound scattering. As depicted, the conventional schemes with their own NLOS mitigation schemes could not correctly detect the outliers, as the number of NLOS RDs was

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Fig. 3.9 CDF performance comparison when the distance standard deviation $\sigma_d=2\text{m}$ and the AOA standard deviation $\sigma_\alpha=\sigma_\beta=5^\circ$, with the actual MD location at coordinates (10.0m, 4.0m). Case C- One *RD* is in LOS with the *MD*

more than the number of LOS *RDs*. In this case, the conventional TOA scheme performed better than the conventional TOA/AOA scheme, as the *RDs*' angles were not LOS angles. Our proposed joint LS scheme detected the NLOS outliers by using our proposed NLOS path rejection technique (3.37). As a result, our joint LS scheme that uses one LOS *RD* outperformed both conventional schemes.

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B. Performance limit and CRLB comparison

Fig. 3.10 illustrates how various schemes perform in terms of their Average Location Error (ALE) when the MD 's location is uniformly distributed within the environment throughout the 10 000 runs. The standard deviations for the distance and the angle (σ_d and σ_α) are chosen to be 2 m and $5^\circ, 10^\circ$ to illustrate the performance of the proposed scheme when σ_β is varied. As depicted, our proposed joint LS scheme using one LOS RD outperforms the conventional schemes for all variations in σ_β . As σ_β escalates, the proposed joint LS scheme's ALE does not escalate substantively, because of the introduction of the bi-directional angle relationship (3.22). This indicates that low-resolution antenna arrays can be used at the MD , making it more cost effective. On the other hand, Fig. 3.11 depicts ALE performance as σ_d escalates while both $\sigma_\alpha = \sigma_\beta = 5^\circ, 10^\circ$. As shown, the proposed joint LS scheme using one LOS RD outperforms the conventional schemes and saturates at a value close to the conventional TOA/AOA scheme. It is worth noting that the proposed localization scheme is not sensitive to changes in $f_{\alpha_j}, f_{\beta_j}$ due to changes in $\sigma_\alpha, \sigma_\beta$ as shown in Fig. 3.10 and Fig. 3.11. This reflects the robustness of the AOA adjustment technique.

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Fig. 3.10 Average Location Error (ALE) when the distance standard deviation $\sigma_d=2\text{m}$, the AOA standard deviation $\sigma_\alpha=5^\circ, 10^\circ$ and σ_β varies

Fig. 3.11 Average Location Error (ALE) when the AOA standard deviation $\sigma_\alpha=\sigma_\beta=5^\circ, 10^\circ$ and σ_d varies

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RMS Error(m)	$\sigma_\beta = 2^\circ$	$\sigma_\beta = 4^\circ$	$\sigma_\beta = 5^\circ$	$\sigma_\beta = 10^\circ$	$\sigma_\beta = 15^\circ$	$\sigma_\beta = 20^\circ$
TOA LS	22.624	22.624	22.624	22.624	22.624	22.624
TOA/AOA LS	8.080	8.080	8.080	8.080	8.080	8.080
1 RD J. Est. LS $\rho_m = 0.2$	1.258	1.346	1.359	1.398	1.448	1.547
1 RD J. Est. LS $\rho_m = 0.5$	1.261	1.359	1.376	1.410	1.464	1.609
1 RD J. Est. LS $\rho_m = 0.8$	1.278	1.359	1.410	1.468	1.617	1.800

Table 3-1 ALE performance comparison when the MD correlation factor ρ_m varies, with $\rho_r = 0.5$, the distance standard deviation $\sigma_d = 2m$, the AOA standard deviation $\sigma_\alpha = 5^\circ$, and σ_β varies

RMS Error(m)	$\sigma_d = 1m$	$\sigma_d = 2m$	$\sigma_d = 5m$	$\sigma_d = 6m$	$\sigma_d = 8m$	$\sigma_d = 10m$
1 RD J. Est. LS $\rho_m = 0$	0.828	1.323	3.421	4.102	5.731	7.251
1 RD J. Est. LS CRLB $\rho_m = 0$	0.706	1.324	3.308	3.978	5.323	6.680
1 RD J. Est. LS $\rho_m = 0.2$	0.829	1.359	3.422	4.107	5.755	7.257
1 RD J. Est. LS CRLB $\rho_m = 0.2$	0.718	1.353	3.385	4.072	5.448	6.826
1 RD J. Est. LS $\rho_m = 0.5$	0.830	1.376	3.484	4.149	5.780	7.287
1 RD J. Est. LS CRLB $\rho_m = 0.5$	0.722	1.375	3.444	4.142	5.542	6.945

Table 3-2 Average CRLB comparison for the proposed joint LS scheme with the distance standard deviation σ_d varying and the AOA standard deviation $\sigma_\alpha = \sigma_\beta = 5^\circ$.

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Table 3-1 depicts the ALE performance of various schemes across a range of values of the *MD* correlation factor (ρ_m), while the *RDs'* correlation factor (ρ_r) is set to 0.5. As illustrated, the higher the correlation factor, the higher the RMS error will be. Nevertheless, the proposed localization scheme outperforms the conventional schemes. A low correlation factor can also be easily obtained by increasing the bandwidth and using more antenna array elements [91]. Table 3-2 compares the proposed joint localization scheme's Average CRLB and its LS implementation in terms of ALE. The average CRLB is calculated by averaging the total CRLB across the 10,000 uniformly distributed *MD* locations. The results indicate that there is a close match between the ALE and its CRLB.

3.3 Conclusion

Two novel approaches for source localization using bi-directional joint estimation of TOA/AOA and only one LOS *RD* have been proposed. The joint LS implementations coupled with the AOA adjustment and NLOS path rejection techniques have been devised. The two new approaches are compared to the two conventional localization schemes, namely the unidirectional TOA scheme and the disjoint unidirectional TOA/AOA scheme, in both general and typical environments. The ALE simulation results indicate that the joint LS schemes, which use only one LOS *RD*, outperforms the conventional schemes for all cases of error variations with a much higher margin.

CHAPTER FOUR

4 Non-Line-of-Sight (NLOS) Localization Scheme

The two novel bidirectional localization schemes described in Chapter 3 allow the use of only one *RD* that is in LOS range with the *MD* to perform localization of the *MD* in a multipath environment. However, in general, the existence of at least one LOS path in the multipath environment is not guaranteed. There are scenarios that all the *RDs* are in NLOS range with the *MD*. As a result, all the conventional localization schemes and even our proposed bidirectional localization schemes described in Chapter 3 will not perform satisfactorily. Furthermore, even though the LOS signal is present, it may not be the dominant path in the multipath environment. It has been shown that the performance of the localization scheme is a function of signal to noise ratio (SNR) of the received signal [17], [91]. The greater the SNR of the received signal, the smaller the localization error. Therefore, it would be advantageous to be able to perform localization under the multipath environment with as few reference devices as possible while maintaining a good performance bound by using paths of the received signal that have maximum SNR even though they may not be the LOS path.

[103], [104] try to explore the use of bidirectional estimates of NLOS TOA and AOA. [103] constructs the first order iterative Taylor Series approach to obtain the mobile device's location in terms of one bound scattering paths. However, use of the Taylor

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series approach requires the availability of an accurate initial guess of the mobile device's location in order to allow for a convergence of the estimation result. Furthermore, the standard deviation of the TOA and the AOA measurement data must be small to prevent non-convergence. If the receiving path is a LOS or NLOS signal that has a small angle of difference between the incident ray on the scatterer and its scattered ray, the systems suffer singularity in their designed localization matrix that results in poor performance. This is the case in both [103], [104].

In a realistic multipath environment, a combination of LOS and NLOS signals is always available among the reference devices. Firstly, there must be a means to detect and extract the LOS and the NLOS (one bound scattering paths) signals from among the multiple bound scattering paths. Secondly, there must be a mechanism in place to select paths that are non-parallel to one another as the intersection of parallel paths will result in non convergence in the estimation result. Unfortunately, the authors [103] and [104] do not address these issues. In the following section, we propose a novel two-step detection and localization scheme that first identifies the LOS and NLOS signal paths and then differentiates them from multiple bound scattering paths by using the proximity relationship that exists between them. We also include methodology to reject parallel paths. For the LOS signal, further exploitation of the bidirectional AOA measurement data is done to ingeniously adjust the LOS measurement data to ensure that the localization performance is better than that of conventional LOS localization schemes. The proposed scheme requires the use of just two signal paths from any reference device and yet outperforms the conventional LOS and the existing NLOS localization schemes in all cases.

4.1 Theory and Formulation

4.1.1 Concept of Non-Line-Of-Sight (NLOS) Localization

Fig. 4.1 Reference and mobile devices are shown with their respective propagation paths in a typical multipath environment.

In a multipath environment as shown in Fig. 4.1, there will be clusters of LOS and NLOS signal paths (both single and multiple bound scattering paths) surrounding the RDs. Consider the case of a one bound scattering path depicted in Fig. 4.2. The j^{th} reference device (RD_j) with the known location coordinate (x_j, y_j) has a measured data metric AOA $\theta_{j,m}$ and TOA $t_{j,m}$ for the m^{th} received signal path where $j=1, 2, \dots, N$, with N being the number of reference devices. $m=1, 2, \dots, M$ denotes the

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- actual m^{th} path scatterer for $RD_j - S_{j,m}$
- measured metrics by $RD_j - \theta_{j,m}, t_{j,m}(d_{j,m})$
- measured metrics by $MD - \phi_{j,m}, \tau_{j,m}(r_{j,m})$
- actual m^{th} path scatterer circle for $S_{j,m} - C_m$
- actual MD location- (x, y)
- assumed possible m^{th} path scatterer for $RD_j : S'_{j,m}$
- assumed possible m^{th} path scatterer circle for $S'_{j,m} : C'_m$
- assumed possible MD location $(MD') : (x', y')$

Fig. 4.2 Geometrical depiction of the Line of Possible Mobile Device location (LPMD)

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LOS ($m = 1$) and the $M - 1$ one bound scattering multipath signals. The mobile device (MD) with unknown coordinate (x, y) has a measured AOA $\phi_{j,m}$ and TOA $\tau_{j,m}$. The measured TOAs are related to the received path lengths in the following manner:

$$d_{j,m} = c\tau_{j,m} \quad (4.1)$$

where c is the speed of wave propagation, and

$$r_{j,m} = c\tau_{j,m} \quad (4.2)$$

In Fig. 4.2, the actual location of the m^{th} path scatterer $S_{j,m}$ lies along the the line that is initiated from RD_j with an AOA angle $\theta_{j,m}$. Given the measured set of $\theta_{j,m}$, $\phi_{j,m}$ and $d_{j,m}(r_{j,m})$, it should be noted that the location of $S_{j,m}$ is not unique. One possible location of the scatterer $(S'_{j,m})$ along the line is shown in the figure. It has a path length of $r'_{s_{j,m}}$, which is the distance between $S'_{j,m}$ and the possible MD location $MD'(x', y')$. The path length $r'_{s_{j,m}}$ is also the radius of the possible m^{th} path scatterer circle C'_m with its centre located at $S'_{j,m}$. The MD' may be located at any point along the circumference of C'_m . However, given AOA $\phi_{j,m}$, it is relatively easy to identify the only possible MD' location on the circumference of C'_m . As such, all possible MD locations can be identified by forming sets of scatterer circles. One of these is the actual m^{th} path scatterer circle C_m that comprises of the actual scatterer $S_{j,m}$ and the actual MD location (x, y) . It can be shown that all possible MD locations that lie on

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the circumference of their respective scatterer circles will form a straight line when they are joined together. This line is referred to as the Line of Possible MD location (LPMD) for the m^{th} signal path. The exact location of MD can be determined by constructing another LPMD using another signal path between RD_j (or another reference device) and MD , and by locating the intersection of these two LPMDs. For N reference devices with M paths each (an overdetermined case), the exact location of MD will be resolved using the Least Square (LS) approach with MN sets of LPMDs. This conceptual principle forms the working basis of our NLOS localization scheme.

4.1.2 Least Square(LS) Equation Formulation

A. *Non Existence of Line-Of-Sight Path*

We assume that a path between RD_j and MD is a LOS path if $|\theta_{j,1} - \phi_{j,1}| \leq 180^\circ \pm \sigma_j$.

We choose $\sigma_j = \max(3\sigma_{\theta_j}, 3\sigma_{\phi_j})$ where σ_{θ_j} , σ_{ϕ_j} represent the maximum standard deviation of the AOA measurement noise of RD_j and MD respectively. For ease of discussion, we will at this moment assume that all the $M-1$ paths ($m = 2 \cdots M$) that undergo the one bound scattering phenomenon have been identified in the multipath selection scheme (to be mentioned in next subsection).

The exact location of the MD will be identified from the intersection of all the LPMDs. The gradient and the y-intercept of these lines must be found and equated to provide a LS solution. With reference to Fig. 4.2, each LPMD path gradient and y-intercept can be found by locating two end points of the LPMD, given as

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$$x_{o1} = x_j - r_{j,m} \cos \phi_{j,m} , y_{o1} = y_j - r_{j,m} \sin \phi_{j,m} \quad (4.3)$$

$$x_{o2} = x_j + d_{j,m} \cos \theta_{j,m} , y_{o2} = y_j + d_{j,m} \sin \theta_{j,m} \quad (4.4)$$

By utilizing (4.3) and (4.4), the gradient (μ) and the y intercept (y_{int}) of the LPMD will be formulated respectively as

$$\mu = \left(\frac{\mu_{N_{j,m}}}{\mu_{D_{j,m}}} \right) \quad (4.5)$$

where

$$\mu_{N_{j,m}} = d_{j,m} \sin \theta_{j,m} + r_{j,m} \sin \phi_{j,m} \quad (4.6)$$

$$\mu_{D_{j,m}} = d_{j,m} \cos \theta_{j,m} + r_{j,m} \cos \phi_{j,m}$$

and

$$y_{\text{int}} = y_j + d_{j,m} \sin \theta_{j,m} - \mu (x_j + d_{j,m} \cos \theta_{j,m}) \quad (4.7)$$

Using (4.5)-(4.7), the LPMD equation for the m^{th} path of RD_j can be written as

$$y = \mu x + y_{\text{int}} = \mu x + y_j + d_{j,m} \sin \theta_{j,m} - \mu (x_j + d_{j,m} \cos \theta_{j,m}) \quad (4.8)$$

where x, y is the coordinate of MD .

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Rearranging (4.8) and expressing it as a function of MD and RD_j coordinates,

$$\mu_{N_{j,m}} x_j - \mu_{D_{j,M}} y_j + d_{j,m} r_{j,m} \sin(\phi_{j,m} - \theta_{j,m}) = \mu_{N_{j,m}} x - \mu_{D_{j,M}} y \quad (4.9)$$

For N reference devices each with $M-1$ multipaths, (4.9) can be further arranged in the matrix form as

$$\mathbf{h} = \mathbf{G}\mathbf{Z} \quad (4.10)$$

where

$$\mathbf{G} = \begin{bmatrix} \mu_{N_{1,2}} & \cdots & \mu_{N_{1,M}} & \cdots & \mu_{N_{N,2}} & \cdots & \mu_{N_{N,M}} \\ -\mu_{D_{1,2}} & \cdots & -\mu_{D_{1,M}} & \cdots & -\mu_{D_{N,2}} & \cdots & -\mu_{D_{N,M}} \end{bmatrix}^T,$$

$$\mathbf{h} = \begin{bmatrix} \mu_{N_{1,2}} x_1 - \mu_{D_{1,2}} y_1 + d_{1,2} r_{1,2} \sin(\phi_{1,2} - \theta_{1,2}) \\ \vdots \\ \mu_{N_{1,M}} x_1 - \mu_{D_{1,M}} y_1 + d_{1,M} r_{1,M} \sin(\phi_{1,M} - \theta_{1,M}) \\ \vdots \\ \mu_{N_{N,2}} x_N - \mu_{D_{N,2}} y_N + d_{N,2} r_{N,2} \sin(\phi_{N,2} - \theta_{N,2}) \\ \vdots \\ \mu_{N_{N,M}} x_N - \mu_{D_{N,M}} y_N + d_{N,M} r_{N,M} \sin(\phi_{N,M} - \theta_{N,M}) \end{bmatrix}, \text{ and} \quad (4.11)$$

$$\mathbf{Z} = \begin{bmatrix} x & y \end{bmatrix}^T$$

Therefore, the LS solution for (4.10) will be simply given as

$$\mathbf{Z} = (\mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T \mathbf{h} \quad (4.12)$$

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B. *Existence of Line-Of-Sight Path*

If the LOS path ($m=1$) exists and is dominant, the gradient of the LPMD equation for the LOS path of RD_j will be given as

$$\mu = \left(\frac{\sin \theta_{j,1}}{\cos \theta_{j,1}} \right) \quad (4.13)$$

and the gradient of the straight line LPMD will be given as

$$\begin{aligned} y &= \mu x + y_j - \mu x_j \\ \sin \theta_{j,1} x_j - \cos \theta_{j,1} y_j &= \sin \theta_{j,1} x - \cos \theta_{j,1} y \end{aligned} \quad (4.14)$$

Finally, the matrices $\mathbf{h}$ and $\mathbf{G}$ will be a combination of (4.9) and (4.14).

In the presence of measurement noise, $\theta_{j,m}$ and $\phi_{j,m}$ will not be accurate. However, the accuracy of $\theta_{j,1}$ and $\phi_{j,1}$ can be ingeniously improved in relation to the LOS path because of the geometrical relationship that exists between $\theta_{j,1}$ and $\phi_{j,1}$ as shown in Fig. 4.3. This is an advantage which can not be realized in unidirectional estimation. In Fig. 4.3, $\theta'_{j,1}$ and $\phi'_{j,1}$ has the following relationship with $\theta_{j,1}$ and $\phi_{j,1}$

$$\theta'_{j,1} = \theta_{j,1}, \quad \phi'_{j,1} = 360^\circ - \phi_{j,1} \quad (4.15)$$

with

$$\theta_{j,1} = \theta_{j,1}^o + n_{\theta_{j,1}}, \quad \phi_{j,1} = \phi_{j,1}^o + n_{\phi_{j,1}} \quad (4.16)$$

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Fig. 4.3 Geometrical relationship between the angle of arrival for the LOS path

where $\theta_{j,1}^o$ and $\phi_{j,1}^o$ are the true AOA values of the LOS path for RD_j and MD respectively and $n_{\theta_{j,1}}$, $n_{\phi_{j,1}}$ denote the measurement noise associated with each.

Under such ideal circumstance in which measurement noise is absent, the following angle relationship will always hold:

$$\theta_{j,1}' + \phi_{j,1}' = \theta_{j,1}^{o'} + \phi_{j,1}^{o'} = 180^\circ \quad (4.17)$$

as $\theta_{j,1}$ and $\phi_{j,1}$ are equal to $\theta_{j,1}^o$ and $\phi_{j,1}^o$ respectively. Also, $\theta_{j,1}^{o'}$ and $\phi_{j,1}^{o'}$ are the noise free values of $\theta_{j,1}'$ and $\phi_{j,1}'$ respectively. The impact of measurement noise on $\theta_{j,1}$ and

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$\phi_{j,1}$ will render (4.17) an inequality. However, we can minimize the noise error in $\theta_{j,1}$ and $\phi_{j,1}$ and reestablish the equality relationship by adjusting the values of $\theta'_{j,1}$ and $\phi'_{j,1}$ using the following criteria:

$$e_j = \theta'_{j,1} + \phi'_{j,1} - 180^\circ \quad (4.18)$$

$$\theta'_{j,1} = \theta_{j,1} - e_j \cdot f_{\theta_j}, \quad \phi'_{j,1} = \phi_{j,1} - e_j \cdot f_{\phi_j} \quad (4.19)$$

where e_j is defined as the noise angle difference for RD_j and f_{θ_j} , f_{ϕ_j} are the error weighting factors that are given as

$$f_{\theta_j} = \frac{\sigma_{\theta_j}}{\sigma_{\theta_j} + \sigma_{\phi_j}}, \quad f_{\phi_j} = \frac{\sigma_{\phi_j}}{\sigma_{\theta_j} + \sigma_{\phi_j}} \quad (4.20)$$

4.1.3 Multipath Selection

A. *Multiple-Bound Scattering Path Rejection*

In the multipath environment, there will be paths that are subject to more than one bound scattering which are dominant in signal strength such as multiple specular reflection and multiple bound diffraction [92], [101], [102]. Furthermore, in such scenarios, there may be an absence of LOS and single bound scattering paths for some RDs . As a result, such dominant multiple bound scattering paths will often be mistakenly treated as LOS paths or single bound scattering paths. This can cause erroneous location estimation if there is no mechanism to detect and discard them.

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Fig. 4.4 Scatterplot for the paths' LPMD at one of the measurement sites located at the faculty block of Nanyang Technological University, School of EEE. The MD location is at coordinate (16,8). [Refer to Case D in Fig. 4.7]

A two step proximity detection scheme is used in our approach to detect and discard such multiple bound scattering paths as shown in the LPMDs plot of Fig. 4.4. As shown, the multiple bound scattering path LPMDs usually exist as outliers in the LPMD scatterplot. It can be easily discarded using the statistical proximity test [105]. This is an advantage of using line intersection for localization over conventional localization schemes as it facilitates the easy identification of multiple bound scattering paths.

The first step of the test is to find the centroid of the LPMD for all the paths in which we define as

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$$\begin{aligned}
\mathbf{C} &= E[\mathbf{z}_o] \\
&= \frac{1}{NMP} \sum_{j=1}^N \sum_{m=1}^M \sum_{\substack{p=1 \\ w_{j,m} > 0.1}}^P [\mathbf{z}_{o,j,m,p}]
\end{aligned} \tag{4.21}$$

where $\mathbf{z}_o = (x_o, y_o)$ is the point along each path LPMD and

$$w_{j,m} = \frac{\frac{1}{NM} \sum_{j=1}^N \sum_{m=1}^M (t_{j,m} + \tau_{j,m})}{0.5(t_{j,m} + \tau_{j,m})} \tag{4.22}$$

is the normalized path weighting factor for the m^{th} path of RD_j . It ranges between 0 and 1. This path weighting factor will in general provide more weight to the LOS and the one bound scattering paths than the multiple bound scattering paths. This is because, in general, multiple bound scattering paths have larger a TOA than LOS and one bound scattering paths. For our experiment, a 10% (0.1) weighting decision is stringent enough to provide good calculation for the centroid $\mathbf{C}$. This means that only paths that have a path weighting factor of over 0.1 will be included in the calculation of $\mathbf{C}$. For each path's LPMD, it is sufficient to use three points ($P=3$) to render the identification of the multiple bound scattering paths accurate. The first two points $[\mathbf{z}_o]_{j,m,1}$ and $[\mathbf{z}_o]_{j,m,3}$ will be the end points of the path. They are as in (4.3) and (4.4) respectively. The third point will be the midpoint between the two endpoints. This is shown in Fig. 4.4 for the first path of RD_3 . Fig. 4.5 depicts the case where the number of multiple bound scattering paths is more than the number of LOS or single bound

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Fig. 4.5 Scatterplot of the paths' LPMD as measured in the faculty block of Nanyang Technology University's, School of EEE. The MD location is at coordinate (24,15). [Refer to Case E in Fig. 4.7]

scattering paths. There is only one LOS path and one single bound scattering path in the example, while the number of multiple bound scattering paths is four. Using our approach, we are able to find the correct centroid near the LOS path and the single bound scattering path LPMDs. This success speaks strongly for the robustness of our scheme.

The second step is to calculate the normalized Euclidean distance between the midpoint of each path and the estimated centroid. It is formulated as

$$\delta_{j,m} = \frac{\|\mathbf{z}_{oj,m,2} - \mathbf{C}\|}{\sum_{j=1}^N \sum_{m=1}^M \delta_{j,m}} \quad (4.23)$$

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where $\delta_{j,m}$ is the normalized Euclidean distance between the m^{th} path of RD_j and the centroid. $\delta_{j,m}$ ranges between 0 and 1. A path $p_{j,m}$ is considered a multiple bound scattering path if its associated $\delta_{j,m}$ is greater than a pre-stipulated bound. For our experiment, the bound is set as 0.2 which is 20% of the maximum limit. It is found to be sufficient to provide the correct rejection.

B. *Parallel Path Rejection*

Under ideal condition in which measurement noise is completely absent, the LPMD of two paths will intersect accurately. However, measurement noise is unavoidable and it causes the LPMDs to deviate from their ideal position. This occurs in a manner similar to conventional LOS localization schemes in which the circles of intersection may be aligned to each other. In some situations, the LPMD of the two paths may be almost parallel to each other, bringing about an erroneous intersection. Therefore, the selection of two paths for intersection must be carefully done in order to give the best intersection point. Unlike the LOS localization schemes, this issue can be easily resolved using the dot product of two vectors. Each path's LPMD can be treated as a vector whereby

$$\overrightarrow{p_{j,m}} = \mathbf{z}_{\mathbf{o}_{j,m,3}} - \mathbf{z}_{\mathbf{o}_{j,m,1}} \quad (4.24)$$

and

$$\cos \vartheta_{(j,m)(k,n)} = \frac{\overrightarrow{p_{j,m}} \cdot \overrightarrow{p_{k,n}}}{\|\overrightarrow{p_{j,m}}\| \|\overrightarrow{p_{k,n}}\|} \quad (4.25)$$

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with $\mathcal{G}_{(j,m),(k,n)}$ as the angle that arises between vector paths $\overrightarrow{p_{j,m}}$ and $\overrightarrow{p_{k,n}}$. Any two paths can be easily rejected as a poor intersection pair once the cosine of the angle is close to 1. For our experiment, a cosine value of 0.95 ($\mathcal{G} \approx 18^\circ$) is set as the guideline for rejection.

4.2 Analytical Performance Bound

In all estimator design problems, it is necessary to determine the performance of the proposed estimator analytical so that we can understand the performance of the estimator at a glance without having to run tedious simulations. The two main criteria are the mean and noise variance. To this end, it is best that we obtain an efficient unbiased estimator which has a noise variance near the Cramer Rao Lower Bound (CRLB) [106].

CRLB is defined as the lower bound on the variance of the desired parameters of the estimator (in our case, this is the localization parameter $\mathbf{z}$). The bound states that the variance of any unbiased estimator is at least as high as the inverse of the Fisher Information. An unbiased estimator which achieves this bound is said to be an efficient estimator that provides the lowest possible Minimum Mean Square Error (MMSE).

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4.2.1 Proposed Localization Scheme Performance Bound

The covariance matrix of $\mathbf{Z}$ is related to the variance of the localization error. It is obtained by computing the expected value of $\mathbf{Z}$ and $\mathbf{Z}\mathbf{Z}^T$. The perturbation approach denoted in [26] is adopted, and we define $\mathbf{G} = \mathbf{G}^o + \Delta\mathbf{G}$, $\mathbf{h} = \mathbf{h}^o + \Delta\mathbf{h}$ and $\mathbf{Z} = \mathbf{Z}^o + \Delta\mathbf{Z}$. $\mathbf{G}^o$, $\mathbf{h}^o$ and $\mathbf{Z}^o$ are the noise-free matrices, while $\Delta\mathbf{G}$, $\Delta\mathbf{h}$ and $\Delta\mathbf{Z}$ are the noise or perturbation matrices. Defining the error vector as

$$\boldsymbol{\psi} = \mathbf{h} - \mathbf{G}\mathbf{Z} = \Delta\mathbf{h} - \Delta\mathbf{G}\mathbf{Z}^o \quad (4.26)$$

and from (4.12),

$$\left(\mathbf{G}^o + \Delta\mathbf{G}\right)^T \left(\mathbf{G}^o + \Delta\mathbf{G}\right) \left(\mathbf{Z}^o + \Delta\mathbf{Z}\right) = \left(\mathbf{G}^o + \Delta\mathbf{G}\right)^T (\mathbf{h} + \Delta\mathbf{h}) \quad (4.27)$$

By retaining the first order linear perturbation,

$$\Delta\mathbf{Z} = \left(\mathbf{G}^{oT} \mathbf{G}^o\right)^{-1} \mathbf{G}^{oT} \boldsymbol{\psi} \quad (4.28)$$

$$E[\Delta\mathbf{Z}] = \left(\mathbf{G}^{oT} \mathbf{G}^o\right)^{-1} \mathbf{G}^{oT} E[\boldsymbol{\psi}] \quad (4.29)$$

$$\text{cov}(\mathbf{Z}) = E[\Delta\mathbf{Z}\Delta\mathbf{Z}^T] = \left(\mathbf{G}^{oT} \mathbf{G}^o\right)^{-1} \mathbf{G}^{oT} E[\boldsymbol{\psi}\boldsymbol{\psi}^T] \mathbf{G}^o \left(\mathbf{G}^{oT} \mathbf{G}^o\right)^{-1} \quad (4.30)$$

The error vector $\boldsymbol{\psi}$ in (4.26) is expanded by putting

$\theta_{j,m} = \theta_{j,m}^o + n_{\theta_{j,m}}$, $\phi_{j,m} = \phi_{j,m}^o + n_{\phi_{j,m}}$, $d_{j,m} = d_{j,m}^o + n_{d_{j,m}}$, $r_{j,m} = r_{j,m}^o + n_{r_{j,m}}$ into (4.10) and

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(4.11) to derive $\Delta \mathbf{h}$ and $\Delta \mathbf{G}$. $\theta_{j,m}^o$, $\phi_{j,m}^o$, $d_{j,m}^o$ and $r_{j,m}^o$ are the true AOA and TOA (distance) values of the m^{th} path of RD_j while $n_{\theta_{j,m}}$, $n_{\phi_{j,m}}$, $n_{d_{j,m}}$, $n_{r_{j,m}}$ are the respective AOA and TOA measurement noise errors. $\mathbf{Z}^o$ is defined to contain the true MD coordinate $(x^o, y^o)^T$.

A. Non-Line-Of-Sight Path Localization Noise Error Variance

For the NLOS path, each element of $\boldsymbol{\psi}$ can be expressed as

$$\boldsymbol{\psi}_{j,m} = \boldsymbol{\psi}_{j,m,1} + \boldsymbol{\psi}_{j,m,2} + \boldsymbol{\psi}_{j,m,3} + \boldsymbol{\psi}_{j,m,4} + \boldsymbol{\psi}_{j,m,5} \quad (4.31)$$

where

$$\boldsymbol{\psi}_{j,m,1} = \begin{bmatrix} \left(d_{j,m}^o + n_{d_{j,m}} \right) \begin{pmatrix} \cos \theta_{j,m}^o (x_j - x^o) \\ + \sin \theta_{j,m}^o (y_j - y^o) \end{pmatrix} - \\ \left(d_{j,m}^o r_{j,m}^o + d_{j,m}^o n_{r_{j,m}} \right) \cos(\phi_{j,m}^o - \theta_{j,m}^o) \\ + r_{j,m}^o n_{d_{j,m}} + n_{d_{j,m}} n_{r_{j,m}} \end{bmatrix} n_{\theta_{j,m}},$$

$$\boldsymbol{\psi}_{j,m,2} = \begin{bmatrix} \left(r_{j,m}^o + n_{r_{j,m}} \right) \begin{pmatrix} \cos \phi_{j,m}^o (x_j - x^o) \\ + \sin \phi_{j,m}^o (y_j - y^o) \end{pmatrix} + \\ \left(d_{j,m}^o r_{j,m}^o + d_{j,m}^o n_{r_{j,m}} \right) \cos(\phi_{j,m}^o - \theta_{j,m}^o) \\ + r_{j,m}^o n_{d_{j,m}} + n_{d_{j,m}} n_{r_{j,m}} \end{bmatrix} n_{\phi_{j,m}},$$

$$\boldsymbol{\psi}_{j,m,3} = \begin{bmatrix} \sin \theta_{j,m}^o (x_j - x^o) - \cos \theta_{j,m}^o (y_j - y^o) \\ + r_{j,m}^o \sin(\phi_{j,m}^o - \theta_{j,m}^o) \end{bmatrix} n_{d_{j,m}},$$

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$$\psi_{j,m,4} = \begin{bmatrix} \sin \phi_{j,m}^o (x_j - x^o) - \cos \phi_{j,m}^o (y_j - y^o) \\ + d_{j,m}^o \sin(\phi_{j,m}^o - \theta_{j,m}^o) \end{bmatrix} n_{r_{j,m}}, \text{ and} \quad (4.32)$$

$$\psi_{j,m,5} = n_{d_{j,m}} n_{r_{j,m}} \sin(\phi_{j,m}^o - \theta_{j,m}^o)$$

Assuming that the *RD/MD* devices' TOA and AOA disjoint measurement noises are modeled as independent Gaussian random variables with zero means and known variances, the conditional TOA/AOA probability distribution will be given as a multivariate Gaussian probability distribution [95], [96] with

$$f(\mathbf{X}|\mathbf{Z}) = \frac{1}{(2\pi)^{\frac{N}{2}} |\mathbf{Q}|^{\frac{1}{2}}} e^{-\frac{1}{2}(\mathbf{X}-\boldsymbol{\mu})^T \mathbf{Q}^{-1}(\mathbf{X}-\boldsymbol{\mu})}$$

where

$$\begin{aligned} \mathbf{X} &= [\mathbf{v}^T, \boldsymbol{\alpha}^T]^T, \boldsymbol{\mu} = [\boldsymbol{\mu}_v^T, \boldsymbol{\mu}_\alpha^T]^T \\ \mathbf{v} &= [t_{1,1}, t_{1,2} \cdots t_{N,M}, \tau_{1,1}, \tau_{1,2} \cdots \tau_{N,M}]^T, \\ \boldsymbol{\alpha} &= [\theta_{1,1}, \theta_{1,2} \cdots \theta_{N,M}, \phi_{1,1}, \phi_{1,2} \cdots \phi_{N,M}]^T, \\ \boldsymbol{\mu}_v &= [t_{1,1}^o, t_{1,2}^o \cdots t_{N,M}^o, \tau_{1,1}^o, \tau_{1,2}^o \cdots \tau_{N,M}^o]^T, \text{ and} \\ \boldsymbol{\mu}_\alpha &= [\theta_{1,1}^o, \theta_{1,2}^o \cdots \theta_{N,M}^o, \phi_{1,1}^o, \phi_{1,2}^o \cdots \phi_{N,M}^o]^T. \end{aligned} \quad (4.33)$$

The inclusion of 'o' in the superscript of the column vectors $\boldsymbol{\mu}_v$ and $\boldsymbol{\mu}_\alpha$ denotes the true values of the TOA and AOA without noise perturbation. $\mathbf{Q}$ is defined as the covariance matrix of the probability distribution and is given as

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$$\mathbf{Q} = \left[\begin{array}{c|c} \mathbf{Q}_{11} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{Q}_{22} \end{array} \right] \quad (4.34)$$

where

$$\mathbf{Q}_{11} = \text{diag}(\sigma_{t_{1,1}}^2, \sigma_{t_{1,2}}^2 \cdots \sigma_{t_{N,M}}^2, \sigma_{\tau_{1,1}}^2, \sigma_{\tau_{1,2}}^2 \cdots \sigma_{\tau_{N,M}}^2), \text{ and}$$

$$\mathbf{Q}_{22} = \text{diag}(\sigma_{\theta_{1,1}}^2, \sigma_{\theta_{1,2}}^2 \cdots \sigma_{\theta_{N,M}}^2, \sigma_{\phi_{1,1}}^2, \sigma_{\phi_{1,2}}^2 \cdots \sigma_{\phi_{N,M}}^2)$$

$\sigma_{t_{j,m}}^2, \sigma_{\tau_{j,m}}^2$ denote the variance of the TOA measurement of the m^{th} path of RD_j and MD respectively. $\sigma_{\theta_{j,m}}^2, \sigma_{\phi_{j,m}}^2$ represent the variance of the AOA measurement of the m^{th} path of RD_j and MD respectively.

Since the measurement noises arising out of the TOA (distance) and AOA both have zero means, taking expectation of (4.31) will result a null. As a result, $E[\boldsymbol{\psi}]$ equals to 0. This implies that $E[\Delta \mathbf{Z}]$ in (4.29) is zero, which in turn results in an unbiased LS estimator for the NLOS path. Accepting that the odd order moment of the Gaussian distribution is zero, and its fourth and sixth order moments are

$$E \left[n_{d_{j,m}} n_{d_{j,m}}^T n_{\theta_{j,m}} n_{\theta_{j,m}}^T \right] = \sigma_{d_{j,m}}^2 \sigma_{\theta_{j,m}}^2$$

$$E \left[n_{d_{j,m}} n_{d_{j,m}}^T n_{r_{j,m}} n_{r_{j,m}}^T n_{\theta_{j,m}} n_{\theta_{j,m}}^T \right] = \sigma_{d_{j,m}}^2 \sigma_{r_{j,m}}^2 \sigma_{\theta_{j,m}}^2$$

$E[\boldsymbol{\psi} \boldsymbol{\psi}^T]$ can be computed as

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$$E[\boldsymbol{\psi}\boldsymbol{\psi}^T] = \text{diag}(E[\boldsymbol{\psi}_{1,1}\boldsymbol{\psi}_{1,1}^T] \cdots E[\boldsymbol{\psi}_{N,M}\boldsymbol{\psi}_{N,M}^T]) \quad (4.35)$$

where

$$E[\boldsymbol{\psi}_{j,m}\boldsymbol{\psi}_{j,m}^T] = \sum_{n=1}^5 E[\boldsymbol{\psi}_{j,m,n}\boldsymbol{\psi}_{j,m,n}^T] \quad (4.36)$$

and $\boldsymbol{\psi}_{j,m,n}$ is defined in (4.32) such that

$$\begin{aligned} E[\boldsymbol{\psi}_{j,m,1}\boldsymbol{\psi}_{j,m,1}^T] &= \begin{bmatrix} \cos \theta_{j,m}^o (x_j - x^o) + \\ \sin \theta_{j,m}^o (y_j - y^o) \end{bmatrix}^2 \begin{bmatrix} d_{j,m}^{o2} \sigma_{\theta_{j,m}}^2 + \\ \sigma_{d_{j,m}}^2 \sigma_{\theta_{j,m}}^2 \end{bmatrix} - \\ &2 \cos(\phi_{j,m}^o - \theta_{j,m}^o) \begin{bmatrix} \cos \theta_{j,m}^o (x_j - x^o) + \\ \sin \theta_{j,m}^o (y_j - y^o) \end{bmatrix} \begin{bmatrix} d_{j,m}^{o2} r_{j,m}^o \sigma_{\theta_{j,m}}^2 + \\ r_{j,m}^o \sigma_{d_{j,m}}^2 \sigma_{\theta_{j,m}}^2 \end{bmatrix} + \\ &\cos^2(\phi_{j,m}^o - \theta_{j,m}^o) \begin{bmatrix} d_{j,m}^{o2} r_{j,m}^{o2} \sigma_{\theta_{j,m}}^2 + d_{j,m}^{o2} \sigma_{r_{j,m}}^2 \sigma_{\theta_{j,m}}^2 + \\ r_{j,m}^{o2} \sigma_{d_{j,m}}^2 \sigma_{\theta_{j,m}}^2 + \sigma_{d_{j,m}}^2 \sigma_{r_{j,m}}^2 \sigma_{\theta_{j,m}}^2 \end{bmatrix}, \\ E[\boldsymbol{\psi}_{j,m,2}\boldsymbol{\psi}_{j,m,2}^T] &= \begin{bmatrix} \cos \phi_{j,m}^o (x_j - x^o) + \\ \sin \phi_{j,m}^o (y_j - y^o) \end{bmatrix}^2 \begin{bmatrix} r_{j,m}^{o2} \sigma_{\phi_{j,m}}^2 + \\ \sigma_{r_{j,m}}^2 \sigma_{\phi_{j,m}}^2 \end{bmatrix} + \\ &2 \cos(\phi_{j,m}^o - \theta_{j,m}^o) \begin{bmatrix} \cos \phi_{j,m}^o (x_j - x^o) + \\ \sin \phi_{j,m}^o (y_j - y^o) \end{bmatrix} \begin{bmatrix} r_{j,m}^{o2} d_{j,m}^o \sigma_{\phi_{j,m}}^2 + \\ d_{j,m}^o \sigma_{r_{j,m}}^2 \sigma_{\phi_{j,m}}^2 \end{bmatrix} + \\ &\cos^2(\phi_{j,m}^o - \theta_{j,m}^o) \begin{bmatrix} d_{j,m}^{o2} r_{j,m}^{o2} \sigma_{\phi_{j,m}}^2 + d_{j,m}^{o2} \sigma_{r_{j,m}}^2 \sigma_{\phi_{j,m}}^2 + \\ r_{j,m}^{o2} \sigma_{d_{j,m}}^2 \sigma_{\phi_{j,m}}^2 + \sigma_{d_{j,m}}^2 \sigma_{r_{j,m}}^2 \sigma_{\phi_{j,m}}^2 \end{bmatrix}, \\ E[\boldsymbol{\psi}_{j,m,3}\boldsymbol{\psi}_{j,m,3}^T] &= \begin{bmatrix} \sin \theta_{j,m}^o (x_j - x^o) - \\ \cos \theta_{j,m}^o (y_j - y^o) + r_{j,m}^o \sin(\phi_{j,m}^o - \theta_{j,m}^o) \end{bmatrix}^2 \sigma_{d_{j,m}}^2, \end{aligned}$$

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$$E\left[\psi_{j,m,4}\psi_{j,m,4}^T\right] = \left[\begin{array}{c} \sin \phi_{j,m}^o (x_j - x^o) - \\ \cos \phi_{j,m}^o (y_j - y^o) + d_{j,m}^o \sin(\phi_{j,m}^o - \theta_{j,m}^o) \end{array} \right]^2 \sigma_{r_{j,m}}^2, \text{ and}$$

$$E\left[\psi_{j,m,5}\psi_{j,m,5}^T\right] = \sin^2(\phi_{j,m}^o - \theta_{j,m}^o) \sigma_{d_{j,m}}^2 \sigma_{r_{j,m}}^2$$

(4.37)

$\sigma_{d_{j,m}}^2$ and $\sigma_{r_{j,m}}^2$ are the variances of the TOA measurement in term of distance whereby

$$\sigma_{d_{j,m}} = c\sigma_{t_{j,m}}, \quad \sigma_{r_{j,m}} = c\sigma_{\tau_{j,m}}.$$

B. Line-Of-Sight Path Localization Noise Error Variance

The modified noise error arising out of the AOA measurement has to be computed before we are able to derive the variance in the localization error in the LOS path. This is because of the modification done in (4.19). By substituting (4.16) into (4.15) and then (4.18), the noise angle difference e_j can be found as follows:

$$e_j = \begin{cases} n_{\theta_{j,1}} - n_{\phi_{j,1}} & \text{if } 0^\circ < \theta_{j,1} \leq 90^\circ, 270^\circ < \theta_{j,1} \leq 360^\circ \\ n_{\phi_{j,1}} - n_{\theta_{j,1}} & \text{if } 90^\circ < \theta_{j,1} \leq 180^\circ, 180^\circ < \theta_{j,1} \leq 270^\circ \end{cases} \quad (4.38)$$

Putting (4.38) into (4.19) and subsequently into (4.15), it can be found that

$$\theta_{j,1} = \theta_{j,1}^o + n_{\theta_{j,1}}, \quad \phi_{j,1} = \phi_{j,1}^o + n_{\phi_{j,1}} \quad (4.39)$$

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where $n_{\theta_{j,1}}'$ and $n_{\phi_{j,1}}'$ are the modified noise error arising from $\theta_{j,1}$ and $\phi_{j,1}$ respectively.

These are formulated as follows:

$$n_{\theta_{j,1}}' = n_{\theta_{j,1}} - (n_{\theta_{j,1}} - n_{\phi_{j,1}})f_{\theta_j}, \quad n_{\phi_{j,1}}' = n_{\phi_{j,1}} + (n_{\theta_{j,1}} - n_{\phi_{j,1}})f_{\phi_j} \quad (4.40)$$

From (4.40), it is clear that the modification in (4.19) serves to minimize the measurement noise and seeks to provide the true AOA values of $\theta_{j,1}^o$ and $\phi_{j,1}^o$. It is indeed advantageous to use bidirectional estimation in localization instead of more conventional LOS localization methods. Substituting (4.39) into (4.14) and by obtaining the value of ψ from (4.26), it can be concluded that

$$\psi_{j,1} = \psi_{j,1,1} + \psi_{j,1,2} + \psi_{j,1,3} + \psi_{j,1,4} \quad (4.41)$$

and

$$\begin{aligned} \psi_{j,1,1} &= f_{\theta_j} \left[\sin \theta_{j,1}^o (x_j - x^o) - \cos \theta_{j,1}^o (y_j - y^o) \right] n_{\theta_{j,1}}^2 \\ \psi_{j,1,2} &= (1 - f_{\theta_j}) \left[\cos \theta_{j,1}^o (x_j - x^o) + \sin \theta_{j,1}^o (y_j - y^o) \right] n_{\theta_{j,1}} \\ \psi_{j,1,3} &= f_{\theta_j} \left[\cos \theta_{j,1}^o (x_j - x^o) + \sin \theta_{j,1}^o (y_j - y^o) \right] n_{\phi_{j,1}} \\ \psi_{j,1,4} &= f_{\theta_j} \left[\cos \theta_{j,1}^o (y_j - y^o) - \sin \theta_{j,1}^o (x_j - x^o) \right] n_{\theta_{j,1}} n_{\phi_{j,1}} \end{aligned} \quad (4.42)$$

Taking the Expectation of (4.41), the mean error is

$$E[\psi_{j,1}] = f_{\theta_j} \left[\sin \theta_{j,1}^o (x_j - x^o) - \cos \theta_{j,1}^o (y_j - y^o) \right] \sigma_{\theta_{j,1}}^2 \text{ which is not equal to zero.}$$

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However, as $\sigma_{\theta_{j,1}}^2$ is very small as the computation of AOA variance is in radian square, the unbiasedness for the LOS path can be maintained. The variance can be similarly computed as

$$E[\psi_{j,1}\psi_{j,1}^T] = \sum_{n=1}^4 E[\psi_{j,1,n}\psi_{j,1,n}^T] \quad (4.43)$$

where

$$\begin{aligned} E[\psi_{j,1,1}\psi_{j,1,1}^T] &= f_{\theta_j}^2 \left[\sin \theta_{j,1}^o (x_j - x^o) - \cos \theta_{j,1}^o (y_j - y^o) \right]^2 3\sigma_{\theta_{j,1}}^4, \\ E[\psi_{j,1,2}\psi_{j,1,2}^T] &= (1 - f_{\theta_j})^2 \left[\cos \theta_{j,1}^o (x_j - x^o) + \sin \theta_{j,1}^o (y_j - y^o) \right]^2 \sigma_{\theta_{j,1}}^2, \\ E[\psi_{j,1,3}\psi_{j,1,3}^T] &= f_{\theta_j}^2 \left[\cos \theta_{j,1}^o (x_j - x^o) + \sin \theta_{j,1}^o (y_j - y^o) \right]^2 \sigma_{\phi_{j,1}}^2, \text{ and} \\ E[\psi_{j,1,4}\psi_{j,1,4}^T] &= f_{\theta_j}^2 \left[\cos \theta_{j,1}^o (y_j - y^o) - \sin \theta_{j,1}^o (x_j - x^o) \right]^2 \sigma_{\theta_{j,1}}^2 \sigma_{\phi_{j,1}}^2 \end{aligned} \quad (4.44)$$

Using (4.36) and (4.43) for (4.35), the covariance of the localization error can be found in (4.30).

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4.2.2 Non-Line-Of-Sight (NLOS) Cramer Rao Lower Bound (CRLB)

The Fisher Information Matrix (FIM) for the multivariate Gaussian probability distribution given in (4.33) is

$$\mathbf{I}(\mathbf{Z}) = E \left[\left(\frac{\partial}{\partial \mathbf{Z}} \ln f(\mathbf{X} | \mathbf{Z}) \right) \left(\frac{\partial}{\partial \mathbf{Z}} \ln f(\mathbf{X} | \mathbf{Z}) \right)^T \right] \quad (4.45)$$

The CRLB is evaluated from the inverse of the FIM and is given as

$$E \left[\left(\hat{\mathbf{Z}} - \mathbf{Z} \right) \left(\hat{\mathbf{Z}} - \mathbf{Z} \right)^T \right] \geq \mathbf{I}^{-1}(\mathbf{Z}) \quad (4.46)$$

with $\hat{\mathbf{Z}}$ being the estimated MD coordinate. The partial derivative of $\ln f(\mathbf{X} | \mathbf{Z})$ with respect to $\mathbf{Z}$ is

$$\begin{aligned} \frac{\partial}{\partial \mathbf{Z}} \ln f(\mathbf{X} | \mathbf{Z}) &= \frac{\partial}{\partial \mathbf{Z}} \left\{ -\frac{N}{2} \ln 2\pi - \frac{1}{2} \ln |\mathbf{Q}| - \frac{1}{2} (\mathbf{X} - \boldsymbol{\mu})^T \mathbf{Q}^{-1} (\mathbf{X} - \boldsymbol{\mu}) \right\} \\ &= \frac{\partial \boldsymbol{\mu}^T}{\partial \mathbf{Z}} \mathbf{Q}^{-1} (\mathbf{X} - \boldsymbol{\mu}) \end{aligned} \quad (4.47)$$

Substituting (4.47) into (4.45), the FIM is expressed as

$$\begin{aligned} \mathbf{I}(\mathbf{Z}) &= E \left[\frac{\partial \boldsymbol{\mu}^T}{\partial \mathbf{Z}} \mathbf{Q}^{-1} (\mathbf{X} - \boldsymbol{\mu}) (\mathbf{X} - \boldsymbol{\mu})^T \mathbf{Q}^{-1} \frac{\partial \boldsymbol{\mu}}{\partial \mathbf{Z}} \right] \\ &= \frac{\partial \boldsymbol{\mu}^T}{\partial \mathbf{Z}} \mathbf{Q}^{-1} \frac{\partial \boldsymbol{\mu}}{\partial \mathbf{Z}} \end{aligned} \quad (4.48)$$

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Fig. 4.6 Elliptical illustration of the one bound scattering path for the NLOS CRLB derivation

With reference to Fig. 4.6, the NLOS CRLB can be derived using the elliptical concept whereby the one bound scattering path is contained within the ellipse. The mean vector $\boldsymbol{\mu}$ of the distribution is given in (4.33) and can be rewritten as a function of the MD coordinate such that

$$\begin{aligned}\boldsymbol{\mu}_v &= \frac{1}{c} \left[d_{1,1}^o, d_{1,2}^o \cdots d_{N,M}^o, r_{1,1}^o, r_{1,2}^o \cdots r_{N,M}^o \right]^T \\ \boldsymbol{\mu}_\alpha &= \left[\theta_{1,1}^o, \theta_{1,2}^o \cdots \theta_{N,M}^o, \phi_{1,1}^o, \phi_{1,2}^o \cdots \phi_{N,M}^o \right]^T\end{aligned}\tag{4.49}$$

where

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$$\begin{aligned}
 d_{j,m}^o &= r_{j,m}^o = \frac{\sqrt{(x^o - x_j)^2 + (y^o - y_j)^2}}{e_{j,m}} \\
 \theta_{j,m}^o &= \cos^{-1} \omega_{\theta_{j,m}} + \beta_{j,m} \\
 \phi_{j,m}^o &= \cos^{-1} \omega_{\phi_{j,m}} + \beta_{j,m} \\
 \omega_{\theta_{j,m}} &= \frac{d_{j,m,1}^{o2} - d_{j,m,2}^{o2} + 4C_j^2}{-4d_{j,m,1}^o C_j} \\
 \omega_{\phi_{j,m}} &= \frac{r_{j,m,2}^{o2} - r_{j,m,1}^{o2} + 4C_j^2}{4r_{j,m,2}^o C_j}
 \end{aligned} \tag{4.50}$$

and $e_{j,m}$ is the eccentricity of the ellipse ($0 \leq e_{j,m} < 1$) for the m^{th} path of RD_j . $e_{j,m}$

is obtained as follows:

$$\begin{aligned}
 d_{j,m}^o &= r_{j,m}^o = d_{j,m,1}^o + d_{j,m,2}^o = r_{j,m,1}^o + r_{j,m,2}^o \\
 &= \frac{\frac{d_{j,m}^o}{2}(1 - e_{j,m}^2)}{1 + e_{j,m} \cos(\theta_{j,m}^o - \beta_{j,m})} + \frac{\frac{d_{j,m}^o}{2}(1 - e_{j,m}^2)}{1 - e_{j,m} \cos(\phi_{j,m}^o - \beta_{j,m})}
 \end{aligned} \tag{4.51}$$

Solving (4.51), $e_{j,m}$ is derived such that:

$$e_{j,m} = \frac{1 - \cos\left((\phi_{j,m}^o - \beta_{j,m}) \pm (\theta_{j,m}^o - \beta_{j,m})\right)}{\cos(\phi_{j,m}^o - \beta_{j,m}) - \cos(\theta_{j,m}^o - \beta_{j,m})} \tag{4.52}$$

$\beta_{j,m}$ and C_j in (4.50) are the titled angle of the ellipse and the distance from the centre of the ellipse to RD_j/MD respectively. These values are derived in the following manner:

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$$\beta_{j,m} = \tan^{-1} \left(\frac{y_j - y^o}{x_j - x^o} \right), C_j = \frac{\sqrt{(x^o - x_j)^2 + (y^o - y_j)^2}}{2} \quad (4.53)$$

If there is a LOS path for RD_j , only angle measurements are involved.

$$\theta_{j,1}^o = \tan^{-1} \left(\frac{y_j - y^o}{x_j - x^o} \right) + \pi, \phi_{j,1}^o = \tan^{-1} \left(\frac{y_j - y^o}{x_j - x^o} \right) \quad (4.54)$$

The partial derivative of $\boldsymbol{\mu}$ with respect to $\mathbf{Z}$ is computed as

$$\frac{\partial \boldsymbol{\mu}^T}{\partial \mathbf{Z}} = \left[\frac{\partial \boldsymbol{\mu}_v^T}{\partial \mathbf{Z}}, \frac{\partial \boldsymbol{\mu}_\alpha^T}{\partial \mathbf{Z}} \right] \quad (4.55)$$

where

$$\begin{aligned} \left[\frac{\partial \boldsymbol{\mu}_v^T}{\partial \mathbf{Z}} \right]_{1,M(j-1)+m} &= \left[\frac{\partial \boldsymbol{\mu}_v^T}{\partial \mathbf{Z}} \right]_{1,NM+M(j-1)+m} = \frac{1}{c} \left[\frac{x^o - x_j}{2e_{j,m}C_j} \right] \\ \left[\frac{\partial \boldsymbol{\mu}_v^T}{\partial \mathbf{Z}} \right]_{2,M(j-1)+m} &= \left[\frac{\partial \boldsymbol{\mu}_v^T}{\partial \mathbf{Z}} \right]_{2,NM+M(j-1)+m} = \frac{1}{c} \left[\frac{y^o - y_j}{2e_{j,m}C_j} \right] \end{aligned} \quad (4.56)$$

and

$$\begin{aligned} \left[\frac{\partial \boldsymbol{\mu}_\alpha^T}{\partial \mathbf{Z}} \right]_{1,M(j-1)+m} &= -\frac{1}{\sqrt{1-\omega_{\theta_{j,m}}^2}} \frac{\partial \omega_{\theta_{j,m}}}{\partial C_j} \frac{\partial C_j}{\partial x} + \left(\frac{y_j - y^o}{4C_j^2} \right) \\ \left[\frac{\partial \boldsymbol{\mu}_\alpha^T}{\partial \mathbf{Z}} \right]_{1,NM+M(j-1)+m} &= -\frac{1}{\sqrt{1-\omega_{\phi_{j,m}}^2}} \frac{\partial \omega_{\phi_{j,m}}}{\partial C_j} \frac{\partial C_j}{\partial x} + \left(\frac{y_j - y^o}{4C_j^2} \right) \\ \left[\frac{\partial \boldsymbol{\mu}_\alpha^T}{\partial \mathbf{Z}} \right]_{2,M(j-1)+m} &= -\frac{1}{\sqrt{1-\omega_{\theta_{j,m}}^2}} \frac{\partial \omega_{\theta_{j,m}}}{\partial C_j} \frac{\partial C_j}{\partial y} - \left(\frac{x_j - x^o}{4C_j^2} \right) \\ \left[\frac{\partial \boldsymbol{\mu}_\alpha^T}{\partial \mathbf{Z}} \right]_{2,NM+M(j-1)+m} &= -\frac{1}{\sqrt{1-\omega_{\phi_{j,m}}^2}} \frac{\partial \omega_{\phi_{j,m}}}{\partial C_j} \frac{\partial C_j}{\partial y} - \left(\frac{x_j - x^o}{4C_j^2} \right) \end{aligned} \quad (4.57)$$

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where $j = 1 \cdots N; m = 2 \cdots M$. For RD_j having LOS path,

$$\begin{aligned} \left[\frac{\partial \boldsymbol{\mu}_{\alpha}^T}{\partial \mathbf{Z}} \right]_{1, M(j-1)+1} &= \left[\frac{\partial \boldsymbol{\mu}_{\alpha}^T}{\partial \mathbf{Z}} \right]_{1, NM+M(j-1)+1} = \left(\frac{y_j - y^o}{4C_j^2} \right) \\ \left[\frac{\partial \boldsymbol{\mu}_{\alpha}^T}{\partial \mathbf{Z}} \right]_{2, M(j-1)+1} &= \left[\frac{\partial \boldsymbol{\mu}_{\alpha}^T}{\partial \mathbf{Z}} \right]_{2, NM+M(j-1)+1} = - \left(\frac{x_j - x^o}{4C_j^2} \right) \end{aligned} \quad (4.58)$$

Putting (4.55)-(4.58) into (4.48), and taking the inverse and trace of it will produce the MMSE localization error.

4.3 Experimental and Simulation Results

To evaluate the performance of our proposed localization scheme, three reference devices were placed in block S1, Nanyang Technological University (NTU), School Electrical and Electronic Engineering (EEE) (See Fig. 4.7). Channel measurements were taken and the measured data metrics were verified according to traditional ray tracing methodology [92], [100]-[102]. The delay profile measurements were taken from 1.3GHz to 1.7GHz in 1MHz step using a network analyzer. This provides an effective bandwidth of 400MHz. Fig. 4.7 traces the actual rays that run between the three RDs and the MD . This is based on the correlation between the measured data metrics and the ray tracing methodology used in this paper. The three RDs were located at $RD_1(25,9)$, $RD_2(18,4)$, $RD_3(3,14)$, and concrete walls served as the scatterers as shown in the plot. The scatterers are considered smooth surfaces as the wavelength of the signal is large compared to the roughness of the surface of the scatterers. For the sake of simplicity, the two most dominant paths ($M = 2$) are extracted from each RD and MD pair as shown in the plot, and used for performance analysis each. In total, there are six paths from the reference devices that can be used for multipath selection (multiple bound scattering path rejection and parallel path rejection). The following five scenarios will be illustrated to examine the performance of our NLOS LS localization scheme:

- Case A - all RDs are in LOS with MD ,
- Case B - two RDs are in LOS with MD ,
- Case C - one RD is in LOS with MD ,

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Fig. 4.7 Ray Tracing between the *RDs* and the *MD* for the various locations in Nanyang Technological University, EEE S1, level B3 (S1-B3)

- Case D - no *RD* is in LOS with *MD* ,
- Case E - one *RD* is in LOS with *MD* and the number of multiple bound scattering paths is dominant.

The mobile obstacle at (16.6, 6.5) will be used in scenario D. It blocks the LOS path between RD_2 and *MD* resulting in a single bound diffraction.

The actual data metrics $(t_{j,m}^o, \tau_{j,m}^o, \theta_{j,m}^o, \phi_{j,m}^o)$ are obtained by correlating ray tracing methodology with measurement data. For the sake of thorough comparison with the

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existing localization schemes, the actual data metrics will be subjected to noise effects using Gaussian random variable noise with a mean of zero, and known variances (variances of all devices are identical unless otherwise specified). The Root Mean Square (RMS) error σ_{rms} that pertains to the true MD location is calculated as $\sqrt{(x - x^o)^2 + (y - y^o)^2}$, and is computed based on 10,000 independent simulation runs.

The conventional LOS localization schemes used for performance analysis are the TOA localization scheme [29], and the TOA/AOA localization scheme with the LOS reference devices detection scheme [54] that is brought about by the modification of the TDOA/AOA localization scheme in [37]. The rationale for modifying [37] into a TOA/AOA localization scheme by extending the AOA formulation in [37] into TOA formulation in [29] is to allow for stricter comparison. The TOA/AOA localization scheme will have a lower CRLB than the TDOA/AOA localization scheme because the latter sacrifices one time observation for the sake of time synchronization.

As the NLOS algorithms presented in Li et al [103] and Miao et al [104] do not include multipath selection schemes to detect LOS and single bound scattering paths, we will use our multipath selection scheme designed here with each of these algorithms in order to facilitate a fair comparison. For the algorithm demonstrated by Li et al [103], we will set the initial estimate of the mobile device's location at 5% of the distance between the nearest RD and MD away from the true MD location as recommended in [103].

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4.3.1 Performance Probability Distribution due to TOA, AOA inaccuracy

Fig. 4.8 depicts the location accuracy of the proposed NLOS localization scheme and compares it with the existing localization schemes via their cumulative probability distribution (CDF). The AOA standard deviations σ_θ , σ_ϕ for all the devices are chosen to be 2° , while the distance standard deviations σ_d , σ_r are 1 m . In this scenario, the MD is located at A (16,12) where all the reference devices are in LOS with it. With reference to Fig. 4.7, all the secondary paths of the RDs are one bound reflection paths. As shown in Fig. 4.8, the proposed localization LS scheme that uses bidirectional LOS metrics of just two reference devices (2 RD LOS BiDir LS) clearly outperforms the two conventional LOS schemes. It is worth noting that we are using just four LOS angle measurement metrics (two AOAs at each of the two RD and MD pairs of the two paths) compared to the six measurement metrics that are used in the conventional LOS TOA/AOA localization scheme (three TOAs and three AOAs). Our proposed one reference device NLOS LS (indicated by 1 RD NLOS LS in the plot legend) uses one NLOS path (the smallest δ as defined in (4.23)) and its accompanying LOS path (if their intersection is not parallel). Its performance is close to that of the conventional LOS TOA/AOA localization scheme. For NLOS algorithms, the localization schemes illustrated for both [103] and [104] were not able to outperform the conventional LOS localization schemes.

Fig. 4.9 depicts the CDF performance at location MD at the point B (16, 10). In this scenario, RD_3 is in NLOS with the MD . The dominant path for RD_3 is a one bound scattering path arising out of the reflection at the wall (6.61, 16.5). Both the conventional LOS TOA and TOA/AOA localization schemes are coupled with their

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Fig. 4.8 Comparison of the CDF performance using distance standard deviations σ_d , $\sigma_r=1\text{m}$ and AOA standard deviations $\sigma_\theta, \sigma_\phi=2^\circ$ for an actual MD located at (16,12). Case A- All RDs are in LOS with MD

Fig. 4.9 Comparison of the CDF performance using σ_d , $\sigma_r=1\text{m}$ and $\sigma_\theta, \sigma_\phi=2^\circ$ for an actual MD located at (16,10). Case B- Two RDs are in LOS with MD.

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own NLOS mitigation schemes. For the LOS TOA/AOA localization scheme, this NLOS path is successfully detected and discarded in all the 10,000 runs. However, our proposed localization scheme's 2 RD LOS BiDir LS outperforms the conventional LOS TOA/AOA localization scheme that is coupled with its NLOS detection. The NLOS algorithms in [103] and [104] could not outperform the conventional LOS TOA/AOA, and our proposed one RD NLOS localization scheme.

Fig. 4.10 illustrates the case where only RD_2 is in LOS with the MD that is located at C (16, 8). RD_1 has a dominant one bound scattering path that arises out of the specular reflection at the wall (21.14, 12) with a secondary dominant path that undergoes double reflection at (20,12) and (13, 9.8). For RD_3 , the dominant path is a triple bound scattering path that undergoes three reflection at the walls (8, 16.5), (18, 12.5) and (13, 9.5). Its secondary dominant path is a single diffraction path at (13, 11.9). As shown, both the conventional LOS schemes' NLOS mitigation schemes completely breakdown as the number of NLOS paths is greater than the number of LOS paths. On the other hand, our multipath selection scheme is able to detect and discard the multiple bound scattering paths at RD_1 and RD_3 in all the 10,000 runs, demonstrating the robustness of our proposed scheme. It clearly outperforms the conventional schemes. Existing NLOS algorithms can in fact, outperform conventional LOS algorithms by using our multipath selection scheme. It is worth noting that the performance of the Li et al [103] algorithm improves in Case B and C over Case A. This is because the assumed initial MD location is more accurate for Case B and C as the shortest path between the RD_2 and MD is assumed (error is 5% of the actual distance).

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Fig. 4.10 Comparison of the CDF performance using $\sigma_d, \sigma_r=1\text{m}$ and $\sigma_\theta, \sigma_\phi=2^\circ$ for an actual *MD* located at (16,8). Case C- One *RD* is in LOS with the *MD*.

To demonstrate the capability of our proposed localization scheme that has the ability to work in all *RDs* in NLOS scenarios, an obstruction material is placed between *RD*₂ and the *MD* to result in total LOS blockage (case D). The dominant path that results is a single reflection path at the wall (13, 6.5). The secondary dominant path undergoes diffraction at the edge (17, 6.9) of the material. The comparison between the performance of the schemes is illustrated in Fig. 4.11. As shown, our proposed one *RD* NLOS scheme still superiorly outperforms the LOS localization schemes. All the outliers (multiple bound scattering paths) are successfully detected in all the runs. The algorithms in [103] and [104] could not outperform our proposed localization scheme. In fact, the localization scheme proposed by Li et al [103] performed very badly as it is

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Fig. 4.11 Comparison of the CDF performance using $\sigma_d, \sigma_r=1\text{m}$ and $\sigma_\theta, \sigma_\phi=2^\circ$ for an actual *MD* located at (16,8). Case D - All *RDs* are in NLOS with *MD*.

more sensitive to small angular difference between the incident ray and the scattered ray (diffraction path at (17,6.9)).

To further demonstrate the robustness of our proposed scheme under heavy multiple bound scattering path environments, Fig. 4.12 depicts the case whereby only RD_1 has a LOS and one bound scattering path, while the rest of the *RDs* have multiple bound scattering paths. As shown, our proposed single *RD* localization scheme superiorly outperforms all others.

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Fig. 4.12 Comparison of the CDF performance using $\sigma_d, \sigma_r=1\text{m}$ and $\sigma_\theta, \sigma_\phi=2^\circ$ for an actual *MD* located at (24,15). Case E - One *RD* is in LOS with *MD* .

4.3.2 Performance Bounds

Fig. 4.13 and Fig. 4.14 illustrate the performance of the schemes at *MD* location C (16, 8) and D (16, 8) when all *RDs* are in NLOS. The AOA standard deviation at the *RDs* (σ_θ) is set to 2° , while the AOA standard deviation at the *MD* (σ_ϕ) is escalated from 1° to 10° to demonstrate the performance of our proposed localization scheme when the antenna array at the *MD* is of a low resolution. In most applications, prior knowledge of σ_θ and σ_ϕ may not be available. Therefore, for such cases, we can assume that both σ_θ and σ_ϕ are the same, resulting in $f_\theta = 0.5$ as in the previous subsection. In both scenarios, our

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Fig. 4.13 Comparison of performance using σ_d , $\sigma_r=1\text{m}$ and $\sigma_\theta=2^\circ$ with varying σ_ϕ for an actual MD located at (16,8). Case C- One RD is in LOS with MD

proposed one RD NLOS LS scheme achieves a much better performance bound than the other localization schemes for all escalations of σ_ϕ . This implies that we may utilize a low resolution antenna array at MD . This is cost effective and yet provides a better performance bound. The performance of the Li et al [103] algorithm is not shown in Case D. Its performance bound is in the order of 100m due to its sensitivity to the small angle of difference between the incident and scattered ray.

Table 4-1 illustrates the multiple bound scattering path rejection rate. As shown, our proposed scheme is able to reject multiple bound scattering paths that arrive at RD_1 and

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Fig. 4.14 Comparison of the performance using σ_d , $\sigma_r=1\text{m}$ and $\sigma_\theta = 2^\circ$ with varying σ_ϕ for an actual *MD* located at (16,8). Case D- All *RDs* are in NLOS with *MD*.

*RD*₃ for all cases of escalation of σ_ϕ and over more than 98% of the 10,000 simulation runs. The multiple bound scattering paths are two bound scattering path for *RD*₁ and three bound scattering path for *RD*₃. The numbers in parentheses besides the percentage ratings in the table are the number of multiple bound scattering paths that the scheme could not successfully detect and discard out of the 10,000 runs.

Fig. 4.15 and Fig. 4.16 depict the performance comparison between the RMS error of our proposed localization scheme, using (4.12), and that of the derived analytical RMS error expression for our proposed scheme (square root of the trace of (4.30)) and its CRLB

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Rejection Rate	Case C	Case D
$\sigma_\phi = 1^\circ$	100%(0)	100%(0)
$\sigma_\phi = 2^\circ$	100%(0)	100%(0)
$\sigma_\phi = 3^\circ$	100%(0)	100%(0)
$\sigma_\phi = 4^\circ$	100%(0)	100%(0)
$\sigma_\phi = 5^\circ$	100%(0)	100%(0)
$\sigma_\phi = 6^\circ$	100%(0)	100%(0)
$\sigma_\phi = 7^\circ$	100%(0)	99.99%(1)
$\sigma_\phi = 8^\circ$	100%(0)	99.99%(1)
$\sigma_\phi = 9^\circ$	99.99%(1)	99.81%(19)
$\sigma_\phi = 10^\circ$	99.87%(13)	98.79%(121)

Table 4-1 Multiple bound scattering path rejection rate for Case C and D, out of 10,000 runs

(square root of the trace of (4.46)). For uniform comparison, the paths used for localization in Fig. 4.15 are all from RD_2 . For Fig. 4.16, the paths used for comparison are the dominant paths from RD_1 and RD_2 . As shown in the both plots, the difference between the analytical RMS expression and the actual localization scheme RMS error is subtle, thus supporting the accuracy of our derived analytical expression. As illustrated, while the error performance of our proposed localization scheme is not equivalent to the CRLB bound, it does not deviate much from the CRLB limit.

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NLOS LS performance comparison with analytical expression and CRLB at MD location (16,8)

Fig. 4.15 CRLB and analytical comparison using σ_d , $\sigma_r=1\text{m}$ and $\sigma_\theta=2^\circ$ with varying σ_ϕ for an actual MD located at (16,8). Case C- One RD is in LOS with the MD . The paths used for localization are all from RD_2

Finally, Fig. 4.17 depicts the Average Location Error (ALE) performance of all the schemes with 10,000 simulated MD locations. These are uniformly distributed in the environment to demonstrate the robustness of our proposed scheme. The localization schemes of Li et al [103] and Miao et al [104] are not shown, as their error performance bounds are above the 100m and 30m orders respectively. As shown, our proposed scheme achieves an average error bound of less than 2m, thus demonstrating suitable performance stability in relation to variations in the location of the MD .

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NLOS LS performance comparison with analytical expression and CRLB at MD location (16,8)

Fig. 4.16 CRLB and analytical expression using σ_d , $\sigma_r=1\text{m}$ and $\sigma_\theta = 2^\circ$ with varying σ_ϕ for an actual MD located at (16,8). Case D- All RDs are in NLOS with the MD. The paths used for localization are the dominant paths from RD_1 and RD_2 .

Average Location Estimation(ALE) Performance of proposed NLOS LS performance

Fig. 4.17 ALE performance comparison

4.4 Conclusion

A holistic approach to source localization using bidirectional estimation of the multipath TOA/AOA has been proposed. This method has the ability to work with just two signal paths that are either LOS or one bound scattering NLOS paths. Its robustness to multiple bound scattering paths has been demonstrated along with the superiority of its performance to that of existing localization schemes in all instances and scenarios. The analytical performance of the scheme has been mathematically derived in terms of RMS error. It is approximately the same as the localization RMS error obtained from experimental simulation, and is close to the CRLB limit.

CHAPTER FIVE

5 NON-LINE-OF-SIGHT(NLOS)

UNIDIRECTIONAL LOCALIZATION SCHEMES

A holistic approach to source localization using bidirectional estimation of the multipath TOA/AOA has been proposed in Chapter 4. This method has the ability to work with just two paths. Its robustness to multiple bound scattering paths has been demonstrated along with the superiority of its performance to that of existing localization schemes in all instances and scenarios. The analytical performance of the scheme has been mathematically derived in terms of RMS error. It is approximately the same as the localization RMS error obtained from experimental simulation, and is close to the CRLB limit.

The proposed LOS and NLOS approaches that are mentioned in Chapter 3 and 4 are able to localize the mobile device with just one *RD* and their performances are much better than the conventional LOS approach that use three *RDs* in multipath environment. However, the cost of using antenna array at the mobile device in term of computation and physical implementation for localization is expensive.

In this chapter, we will propose two novel NLOS localization schemes that remove the above mentioned limitation pertaining to the NLOS approach. It just uses the TOA and

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AOA measurement data of the mobile device's signal arriving at the reference devices and yet able to localize the non directional mobile device using not only the LOS path but also utilizing the one bound scattering NLOS multipath. The mobile device does not need to be equipped with antenna array (omni-directional).

5.1 Non-Line-Of-Sight (NLOS) Unidirectional Mobile Localization In Multipath Environment

In this section, a novel non-line of sight localization scheme in a multipath environment where the scatterers are aligned parallel or perpendicular to each other is presented. It leverages on the time of arrival and angle of arrival measurement at the reference devices from the line of sight paths and signal paths that undergo one bound scattering, to locate the mobile device.

We will derive the Line of Possible Mobile Device location (LPMD) for the LOS and NLOS single bound scattering paths based on the measurement of the paths' Time of Arrival (TOA) and Angle of Arrival (AOA) at the reference devices (referred as unidirectional estimation to differentiate it from the bidirectional estimation using TOA and AOA at both the reference and mobile devices described in Chapter 4). Leveraging on these LPMDs, the centriod where the *MD* is likely to be located, is found. This centriod has been found to be situated near the LPMDs of the LOS and NLOS single bound scattering paths in all cases and segregated from the LPMDs of the NLOS paths that undergo multiple bound scattering. Without using any mitigation technique, the *MD* location can be precisely located by selecting an appropriate pair of LPMDs that

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has the shortest Euclidean distance from the centroid. The intersection of this pair of LPMDs will be the MD location.

5.1.1 Concept and Formulation

Consider a typical environment where all scatterers are smooth surfaces that are aligned parallel or perpendicular to each other [100]-[102] as shown in Fig. 5.1. The three RD s were located at RD_1 (25, 9), RD_2 (18, 4) and RD_3 (3, 14). Two dominant signal paths arriving at each RD are shown. For illustration, consider the signal path that is arriving at RD_2 which undergoes one bound reflection at the scatterer $S_{2,2}$. The subscript “2” and “2” in the notation $S_{2,2}$ indicate the scatterer associated with RD_2 and the second dominant signal path received at RD_2 respectively. With the measured TOA $t_{2,2}$, AOA $\theta_{2,2}$ of this signal path at RD_2 and no prior knowledge on the location of $S_{2,2}$, there will be two lines of possible MD locations that are due to reflection from the horizontal and vertical planes of $S_{2,2}$. The first line is a straight horizontal line that stretches from the LOS point $(x_{o2,2}, y_{o2,2})$ to the point $(x_{v2,2}, y_{v2,2})$ while the second line is a vertical line that stretches from the LOS point $(x_{o2,2}, y_{o2,2})$ to the point $(x_{h2,2}, y_{h2,2})$. The horizontal (vertical) line arises from signal path that undergoes one bound scattering at the vertical (horizontal) plane of $S_{2,2}$. This line is referred as the LPMD for the vertical (horizontal) plane, $LPMD_v$ ($LPMD_h$), that contains all possible mobile locations. As shown, the true MD location $MD(x, y)$ lies on the $LPMD_v$ while MD' which is one of the possible MD location lies on the vertical line

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Fig. 5.1 Ray Tracing between RD s and the MD at (16,8) at Nanyang Technological University, EEE S1, level B3 (S1-B3).

_____ LOS path
 - - - - - one bound scattering path
 multiple bound scattering path

$LPMD_h$. If the path is a LOS path, the two LPMDs will intersect and give rise to the LOS point $(x_{o2,2}, y_{o2,2})$. In general, the two end points for $LPMD_h$ and $LPMD_v$ for the m^{th} signal path of RD_n which has a TOA $t_{n,m}$ and AOA $\theta_{n,m}$ are defined as

$$\begin{aligned}
 LPMD_{h,n,m} : \mathbf{Z}_{h,n,m,1} &= [x_{hn,m}, y_{hn,m}]^T, \mathbf{Z}_{h,n,m,2} = [x_{on,m}, y_{on,m}]^T \\
 LPMD_{v,n,m} : \mathbf{Z}_{v,n,m,1} &= [x_{vn,m}, y_{vn,m}]^T, \mathbf{Z}_{v,n,m,2} = \mathbf{Z}_{h,n,m,2}
 \end{aligned} \tag{5.1}$$

where

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$$\begin{aligned}
x_{hn,m} &= x_n + d_{n,m} \cos \theta_{n,m} & , y_{hn,m} &= y_n - d_{n,m} \sin \theta_{n,m} \\
x_{vm,m} &= x_n - d_{n,m} \cos \theta_{n,m} & , y_{vm,m} &= y_n + d_{n,m} \sin \theta_{n,m} \\
x_{on,m} &= x_n + d_{n,m} \cos \theta_{n,m} & , y_{on,m} &= y_n + d_{n,m} \sin \theta_{n,m}
\end{aligned} \tag{5.2}$$

and $d_{n,m} = ct_{n,m}$ with c as the speed of propagation. (x_n, y_n) is the position coordinate of RD_n and $n = 1 \cdots N, m = 1 \cdots M$

The centriod $\mathbf{C}$ which is the first estimation of the true MD location can be found as

$$\mathbf{C} = \left[\frac{\sum_{n=1}^N \sum_{m=1}^M w_{n,m} x_{hn,m}}{\sum_{n=1}^N \sum_{m=1}^M w_{n,m}}, \frac{\sum_{n=1}^N \sum_{m=1}^M w_{n,m} y_{vm,m}}{\sum_{n=1}^N \sum_{m=1}^M w_{n,m}} \right]^T \tag{5.3}$$

where $w_{n,m}$ is the path weight associated with m^{th} path of RD_n and is given by

$$w_{n,m} = \frac{1}{d_{n,m}^2} e^{-(\sigma_{dn,m}^2 + d_{n,m}^2 \sigma_{\theta n,m}^2)} \tag{5.4}$$

It is an inverse function of the square of propagation distance $d_{n,m}$. The longer the propagation distance the path has, the lesser the weight is assigned to this path. This is because in general, the multiple bound scattering path has longer propagation distance [100]-[102]. $\sigma_{dn,m}$ and $d_{n,m} \sigma_{\theta n,m}$ are the standard deviation of the TOA and AOA noises (in terms of distance) respectively. Similarly, the higher the standard deviations

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Fig. 5.2 Plot of LPMDs for MD at (16,8). $\sigma_d = \sigma_{d_{n,m}} = 1m$, $\sigma_\theta = \sigma_{\theta_{n,m}} = 5^\circ$

are, the lower the weight is assigned to the path. Fig. 5.2 depicts the LPMDs for all the paths arriving at the reference devices in the environment shown in Fig. 5.1. Only RD_2 is in LOS with MD that is located at (16,8). As depicted, the centroid is estimated close to the actual MD location, demonstrating the accuracy of our estimation.

The next step is to choose a pair of LPMDs (one each from $LPMD_h$ and $LPMD_v$) that has the smallest sum of the Euclidean distances between the centroid and the midpoint of the LPMD pair. The sum of the Euclidean distances can be calculated as

$$\delta_{(h_{n,m}), (v_{j,k})} = \left\| \mathbf{C} - 0.5 \sum_{i=1}^2 \mathbf{Z}_{h_{n,m},i} \right\| + \left\| \mathbf{C} - 0.5 \sum_{i=1}^2 \mathbf{Z}_{v_{j,k},i} \right\| \quad (5.5)$$

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where $n = 1 \cdots N, m = 1 \cdots M, j = 1 \cdots N, k = 1 \cdots M$

Once the pair of $LPMD_h$ and $LPMD_v$ that has the minimum δ is selected, the MD location can be found through the intersection point of this pair of LPMDs and is given as

$$\mathbf{Z} = [x, y]^T = [x_{hn,m}, y_{vj,k}]_{\min \delta}^T \quad (5.6)$$

5.1.2 Simulation and Discussion

Fig. 5.1 depicts the environment at Nanyang Technological University, School of Electrical and Electronic Engineering (EEE), block S1, level B3 [100] that is used to evaluate the performance of our proposed localization scheme with the conventional localization schemes. The scatterers are concrete walls. For simplicity, two dominant paths ($M = 2$) are extracted from each RD . The paths' parameters (TOA and AOA) are obtained through the ray tracing methodology [100], [102] and subject to Gaussian random variable noise with zeros mean. The standard variations of the TOA noise σ_d (in terms of distance) for all the path of RDs are assumed to be 1m while the standard variations of AOA noise (σ_θ) are varied from 1° to 20° [93]. 10 000 MD locations which are uniformly distributed in the environment are simulated to obtain the Average Location Error (ALE) performance comparison between our proposed localization scheme and the conventional TOA, TOA/AOA (modified from TDOA/AOA scheme to TOA/AOA scheme for stricter comparison as TOA/AOA scheme has better performance than TDOA/AOA scheme) localization schemes with three RDs [29], [37].

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Fig. 5.3 ALE performance comparisons for 10 000 uniformly distributed MD locations with $\sigma_d = 1\text{m}$ and varying σ_θ .

The conventional TOA localization scheme [29] has its own mitigation technique while the conventional TOA/AOA localization scheme [37] is coupled with the mitigation technique in [54].

Fig. 5.3 depicts the ALE performance comparison between our proposed localization scheme and the conventional localization schemes with three RDs . As shown, our proposed localization scheme is able to outperform all conventional localization schemes for all varying σ_θ , with an average error of 2m. This is compared to an average error of 25m and 10m for TOA and TOA/AOA localization schemes

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respectively. Similarly, for varying distance standard deviation from 1m to 5m with $\sigma_\theta = 5^\circ$, our proposed localization scheme is able to obtain an average error of 3m as compared to an average error of 27m and 7m for TOA and TOA/AOA localization schemes respectively. In conclusion, with the assumption that the scatterers are smooth surfaces which are aligned parallel or perpendicularly to each other, our proposed localization scheme is not only able to obtain low location error at large angle, distance variations but also demonstrates suitable performance stability in relation to variations in the location of the MD .

5.2 Localization Of Omni-directional Mobile In Multipath Environment

The next proposed NLOS unidirectional mobile localization scheme is a two step Determination and Selection (two step DS) scheme. It is robust to the detrimental effect of the multiple bound scattering multipaths on the localization accuracy without leveraging on any mitigation or multipath rejection scheme. The proposed two step DS localization scheme comprises of determining the centriod (the likely mobile device location) among the cluster of Line of Possible Mobile Device Location (LPMD). These LPMDs are the lines that contain the possible mobile device location. They are constructed using the LOS and the one bound scattering NLOS paths' TOA and AOA measurement data at the reference devices. The one bound scattering NLOS propagation paths arise from the specular reflection at the scatterers that are aligned parallel and perpendicular to each other. This centriod is found to be situated near the LPMDs of the LOS and one bound scattering NLOS paths. It segregates from the LPMDs of the multiple bound scattering paths. We will delve into the construction of these LPMDs in next section. The second step of the two step DS localization scheme is to find the appropriate pair of LPMDs that has the shortest Euclidean distance from the centriod and select it as the mobile device location. Another novel concept that is conceived in this proposed localization scheme is the adjustment of the TOA and the AOA measurement data of the LOS paths arriving at the reference devices so that these measurement data are close to the actual values once the centriod is determined. This renders more accurate location estimation. Section 5.2.1 will show the formulation of the proposed two step DS localization scheme while section 5.2.2 will delve into the derivation of analytical localization error of our proposed localization scheme. Section

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5.2.3 analyses the performance of our proposed scheme through the experimental and simulation results in a typical environment at the Nanyang Technological University, School of Electrical and Electronics Engineering (EEE). It has been demonstrated that our proposed two step DS localization scheme outperforms the conventional LOS

5.2.1 Theory and Formulation

A. Concept of Line of Possible Mobile Device Location (LPMD)

Consider a typical multipath environment [92], [100]-[102] where the scatterers are smooth surfaces and are aligned parallel and perpendicular to each other as shown in Fig. 5.4 . Three reference devices (RDs) were placed at RD_1 ($25\text{ m}, 9\text{ m}$), RD_2 ($18\text{ m}, 4\text{ m}$) and RD_3 ($3\text{ m}, 14\text{ m}$) with MD at ($20\text{ m}, 10.8\text{ m}$). The first dominant signal path arriving at each RD are shown. RD_1 and RD_3 are in LOS with the MD while RD_2 is in NLOS with the MD . To illustrate the concept of LPMD, consider the signal path that is arriving at RD_2 that has undergone one bound scattering (reflection) phenomenon at the scatterer $S_{2,1}$. The subscript “2” and “1” in the notation $S_{2,1}$ indicate the scatterer associated with RD_2 and the first dominant signal path received at RD_2 respectively. With the measured TOA $t_{2,1}$, AOA $\alpha_{2,1}$ of the one bound scattering signal path at RD_2 and no prior knowledge of the location of the scatterer $S_{2,1}$, there will be two possible lines of mobile device (MD) locations. These two lines

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Fig. 5.4 Line of Possible Mobile Device Location (LPMD) for MD at $(20\text{ m}, 10.8\text{ m})$ due to NLOS signal received at RD_2 at Nanyang Technological University, School of EEE, Block S1, Level 3 (S1-B3).

arise from the reflection at the horizontal and vertical planes of $S_{2,1}$. The first line is a straight horizontal line that extends from the point MD_{LOS} and passes through the actual MD location (MD). This horizontal line arises from the signal path that undergoes one bound scattering at the vertical plane of $S_{2,1}$ and is referred as the LPMD of RD_2 for the vertical plane of the scatterer, $LPMD_{v_{2,1}}$. MD_{LOS} is the perceived MD location if the signal path is a LOS path that arrives at RD_2 with a TOA $t_{2,1}$ and AOA $\alpha_{2,1}$. The second line is a vertical line that extends from MD_{LOS} and passes through the point MD' . This vertical line arises from the signal path that undergoes one bound scattering at the horizontal plane of $S_{2,1}$ and is referred as the

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LPMD of RD_2 for the horizontal plane of the scatterer, $LPMD_{h_{2,1}}$. Therefore, both $LPMD_{v_{2,1}}$ and $LPMD_{h_{2,1}}$ which contain all possible MD locations, form a set of LPMDs for each signal path with a given TOA and AOA measurement data. As shown, for RD_2 with TOA $t_{2,1}$, AOA $\alpha_{2,1}$ measurement data and an unknown scatterer $S_{2,1}$, the actual MD location will lie on the $LPMD_{v_{2,1}}$ while MD' which is one of the possible MD location will lie on the $LPMD_{h_{2,1}}$. If the path is a LOS path, the two LPMDs will intersect and give rise to the LOS point, MD_{LOS} . The exact location of MD can be determined by constructing another set of LPMDs (one $LPMD_v$ and one $LPMD_h$) using another signal path between RD_2 (or another reference device) and MD , and by locating the intersection of these two sets of LPMDs. For N reference devices with M paths each, the exact location of MD can be resolved using $2NM$ lines of LPMDs. This conceptual principle forms the working basis of our NLOS localization scheme. Fig. 5.5 illustrates the plot of the LPMDs for all the RD s each with a single dominant path with MD at $(20\text{ m}, 10.8\text{ m})$.

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B. Two Step DS localization Scheme

i. Determination of the Centroid

Fig. 5.5 Plot of LPMDs for all the RDs for MD at $(20\text{ m}, 10.8\text{ m})$ at Nanyang Technological University, School of EEE, Block S1, Level 3 (S1-B3). The TOA standard deviation (in terms of distance) is 1 m while AOA standard deviation is 2° .

With reference to Fig. 5.4 and Fig. 5.5, the x axis of $LPMD_{h_{n,m}}$ and y axis of $LPMD_{v_{n,m}}$ of the RDs are utilized to determine the centroid $\mathbf{C}$, which is the first estimation of the true MD location. $n = 1 \cdots N$ and $m = 1 \cdots M$ where N is the number of RDs and M is the number of dominant paths associated with each RD . In general, for N reference devices with M paths each, the centroid $\mathbf{C}$ can be found as

$$\mathbf{C} = \left[\frac{\sum_{n=1}^N \sum_{m=1}^M w_{n,m} x_{h_{n,m}}}{w_{n,m}}, \frac{\sum_{n=1}^N \sum_{m=1}^M w_{n,m} y_{v_{n,m}}}{w_{n,m}} \right]^T \quad (5.7)$$

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where $x_{h_{n,m}}$ and $y_{v_{n,m}}$ are the x coordinate of the $LPMD_{h_{n,m}}$ and y coordinate of the $LPMD_{v_{n,m}}$ of the m^{th} path of RD_n respectively. They are given as

$$x_{h_{n,m}} = x_n + d_{n,m} \cos \alpha_{n,m}, \quad y_{v_{n,m}} = y_n + d_{n,m} \sin \alpha_{n,m} \quad (5.8)$$

with $\mathbf{Z}_n = [x_n, y_n]^T$ as the position coordinate of RD_n and $d_{n,m} = ct_{n,m}$. $t_{n,m}$ and $\alpha_{n,m}$ are the TOA and AOA of the m^{th} signal path of RD_n respectively. c is the speed of propagation and $w_{n,m}$ is the path weight associated with the m^{th} path of RD_n . It is given by

$$w_{n,m} = \frac{1}{d_{n,m}^2} e^{-\left(\sigma_{d_{n,m}}^2 + d_{n,m}^2 \sigma_{\alpha_{n,m}}^2\right)} \quad (5.9)$$

This path weight is an inverse function of the square of the propagation distance $d_{n,m}$. The longer the propagation distance the path has, the lesser the weight is being assigned to this path. The rationale is that in general, the multiple bound scattering path will have longer propagation distance [92], [100], [102]. By assigning lesser weight, we are able to segregate our centroid from the LPMDs of the multiple bound scattering path. $\sigma_{d_{n,m}}$, $d_{n,m} \sigma_{\alpha_{n,m}}$ are the standard deviation of TOA and AOA measurement noises (in terms of distances) respectively where $\sigma_{d_{n,m}} = c \sigma_{t_{n,m}}$. $\sigma_{t_{n,m}}$, $\sigma_{\alpha_{n,m}}$ are the actual standard deviation of TOA and AOA measurement noises respectively. Similarly, the higher the standard deviations are, the lower the weight is assigned to the associated path. Fig. 5.5 depicts the LPMDs of all the paths arriving at the RDs where

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$N = 3, M = 1$ for MD located at $(20\text{ m}, 10.8\text{ m})$ with $\sigma_{d_{n,m}} = 1\text{ m}$ and $\sigma_{\alpha_{n,m}} = 2^\circ$. As shown, the centroid is estimated close to the actual MD location.

ii. Selection of the intersection point

The next step is to determine the MD location by selecting a pair of LPMDs (a $LPMD_h$ and a $LPMD_v$) that has the smallest Euclidean distance between the intersection point of such pair of LPMDs and the centroid $\mathbf{C}$. For $2NM$ number of LPMDs (one $LPMD_h$ and one $LPMD_v$ for each path), there will be $(NM)^2$ number of intersection points. The Euclidean distance between the centroid and the intersection point of a pair of LPMDs can be calculated as

$$\xi_{(h_{n,m}), (v_{j,k})} = \left\| \mathbf{C} - \mathbf{Z}_{(h_{n,m}), (v_{j,k})} \right\| \quad (5.10)$$

where $\mathbf{Z}_{(h_{n,m}), (v_{j,k})} = \begin{bmatrix} x_{h_{n,m}}, y_{v_{j,k}} \end{bmatrix}^T$ is the intersection point of a pair of $LPMD_{h_{n,m}}$ and $LPMD_{v_{j,k}}$. $n = 1 \cdots N, j = 1 \cdots N, m = 1 \cdots M, k = 1 \cdots M$. Therefore the MD location $\mathbf{Z} = [x, y]^T$ can be found through the intersection point of a pair of LPMDs that has the minimum ξ and is given as

$$\begin{aligned} \mathbf{Z} = [x, y]^T &= \mathbf{Z}_{(h_{n,m}), (v_{j,k})} \min \xi \\ &= \begin{bmatrix} x_{h_{n,m}}, y_{v_{j,k}} \end{bmatrix}_{\min \xi}^T \end{aligned} \quad (5.11)$$

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To illustrate the concept, consider Fig. 5.5 where $n, j = 1 \cdots 3$ and $m, k = 1$. As shown in the diagram, the pair of LPMDs that has the minimum ξ is the $LPMD_h$ and $LPMD_v$ that arises both from RD_1 . As the result, the calculated MD is given as $\mathbf{Z} = \mathbf{Z}_{(h_{1,1})(v_{1,1})} = [x_{h_{1,1}}, y_{v_{1,1}}]^T$. This is very close to the actual MD located at $(20m, 10.8m)$ as shown.

C. LOS path identification and enhancement technique

With the calculated centroid $\mathbf{C}$ in (5.7), we can obtain an estimated LOS TOA and AOA measurement data between the centroid and the reference device which is calculated as

$$\begin{aligned} r_{n,1} &= \|\mathbf{C} - \mathbf{Z}_n\| \\ \beta_{n,1} &= \tan^{-1} \left(\frac{[\mathbf{C}]_2 - [\mathbf{Z}_n]_2}{[\mathbf{C}]_1 - [\mathbf{Z}_n]_1} \right) \end{aligned} \quad (5.12)$$

where $r_{n,1}, \beta_{n,1}$ are the calculated LOS TOA (in terms of distance) and AOA at the centroid respectively. $[\mathbf{C}]_1$ and $[\mathbf{Z}_n]_1$ are the x or first component of the column vector $[\mathbf{C}]$ and $[\mathbf{Z}_n]$ respectively. Similarly, $[\mathbf{C}]_2$ and $[\mathbf{Z}_n]_2$ are the y or second component of the column vector $[\mathbf{C}]$ and $[\mathbf{Z}_n]$ respectively. Therefore, a measurement path can be considered a LOS path if

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$$\begin{aligned} |\alpha_{n,1} - \beta_{n,1}| &\leq 180^\circ \pm 3\sigma_{\alpha_n} \\ |d_{n,1} - r_{n,1}| &\leq 3\sigma_{d_n} \end{aligned} \quad (5.13)$$

where σ_{d_n} and σ_{α_n} represent the maximum standard deviation of the TOA (in terms of distance) and AOA measurement noise at RD_n respectively. We will use the notation that $m = 1$ is the LOS path since it is always the shortest path.

In relation to a LOS path that has been confirmed by satisfying the criteria in (5.13), we can ingeniously improve the accuracy of $\alpha_{n,1}$ because of the geometrical relationship that exists between $\alpha_{n,1}$ and $\beta_{n,1}$ as shown in Fig. 5.6. As shown, $\alpha'_{n,1}$ and $\beta'_{n,1}$ has the following relationship with $\alpha_{n,1}$ and $\beta_{n,1}$

$$\alpha'_{n,1} = \alpha_{n,1}, \quad \beta'_{n,1} = 360^\circ - \beta_{n,1} \quad (5.14)$$

with

$$\alpha_{n,1} = \alpha_{n,1}^o + n_{\alpha_{n,1}}, \quad \beta_{n,1} = \beta_{n,1}^o + n_{\beta_{n,1}} \quad (5.15)$$

where $\alpha_{n,1}^o$ and $\beta_{n,1}^o$ denote the true noise free AOA values of the LOS path for RD_n and the centroid **C** respectively. $n_{\alpha_{n,1}}$ and $n_{\beta_{n,1}}$ represent the Gaussian noise associated with each. Under ideal circumstance where the noises are absent, the following angle relationship will always hold:

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Fig. 5.6 Geometrical relationship between AOAs for the LOS path measurement data adjustment.

$$\alpha'_{n,1} + \beta'_{n,1} = \alpha^o_{n,1} + \beta^o_{n,1} = 180^\circ \quad (5.16)$$

The impact of measurement noise on $\alpha_{n,1}$ and $\beta_{n,1}$ will render (5.16) an inequality.

However, we can minimize the noise error in $\alpha_{n,1}$ and $\beta_{n,1}$ and reestablish the equality

relationship by adjusting the values of $\alpha_{n,1}$ and $\beta_{n,1}$ using the following criteria:

$$e_n = \alpha'_{n,1} + \beta'_{n,1} - 180^\circ \quad (5.17)$$

$$\alpha'_{n,1} = \alpha'_{n,1} - e_n f_{\alpha_n}, \quad \beta'_{n,1} = \beta'_{n,1} - e_n f_{\beta_n} \quad (5.18)$$

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where e_n is defined as the noise angle difference for RD_n and $f_{\alpha_n}, f_{\beta_n}$ are the respective error weighting factors which are calculated as

$$f_{\alpha_n} = \frac{\sigma_{\alpha_n}}{\sigma_{\alpha_n} + \sigma_{\beta_n}}, f_{\beta_n} = \frac{\sigma_{\beta_n}}{\sigma_{\alpha_n} + \sigma_{\beta_n}} \quad (5.19)$$

σ_{β_n} is the standard deviation of the calculated AOA of the LOS path at the centroid.

As for the TOA of the LOS path, the measured $d_{n,1}$ is replaced by the calculated $r_{n,1}$ in (5.12). Therefore by using (5.12), (5.13) and (5.18), the accuracy of both the measured TOA and AOA of the LOS path can be improved. By recalculating the centroid $\mathbf{C}$ in (5.7) and the new intersection point ξ in (5.10) once again with the adjusted LOS path's TOA and AOA, the MD location accuracy is further improved.

5.2.2 Analytical Performance Bound

In all estimator design problems, it is important to determine the performance of the proposed estimator analytically so that we can understand the performance of the estimator at a glance without resorting to tedious simulation. One of the main criteria on the performance of the estimator is the Mean Square Error (MSE) variance of the estimator [106]. In the following sections, we will derive both the LOS and NLOS path localization error variance for our two step DS localization scheme.

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A. Proposed NLOS path localization error variance

Assume that the unidirectional measurement data $d_{n,m}$, $\alpha_{n,m}$ are independent Gaussian random variables, such that $d_{n,m} \sim N(d_{n,m}^o, \sigma_{d_{n,m}}^2)$ and $\alpha_{n,m} \sim N(\alpha_{n,m}^o, \sigma_{\alpha_{n,m}}^2)$ [24]-[37], $d_{n,m}^o$ and $\alpha_{n,m}^o$ are the actual values of the TOA and AOA of the m^{th} path of RD_n respectively. $\sigma_{d_{n,m}}^2$ and $\sigma_{\alpha_{n,m}}^2$ are the noise variances of the TOA and AOA of the m^{th} path of RD_n respectively.

Defining $\boldsymbol{\theta} = [\mathbf{d}^T, \boldsymbol{\alpha}^T]^T$ where $\mathbf{d}^o = [d_{1,1}^o \cdots d_{N,M}^o]^T$, $\mathbf{d} = [d_{1,1} \cdots d_{N,M}]^T$, $\boldsymbol{\alpha}^o = [\alpha_{1,1}^o \cdots \alpha_{N,M}^o]^T$, $\boldsymbol{\alpha} = [\alpha_{1,1} \cdots \alpha_{N,M}]^T$. We also let the variance $\boldsymbol{\sigma}_d^2 = [\sigma_{d_{1,1}}^2 \cdots \sigma_{d_{N,M}}^2]^T$ and $\boldsymbol{\sigma}_\alpha^2 = [\sigma_{\alpha_{1,1}}^2 \cdots \sigma_{\alpha_{N,M}}^2]^T$. For small variance of the measurement data, we can adopt the Taylor series first order expansion [106] and approximate the estimated coordinates of the MD from the minimum ξ (5.11) as

$$\begin{aligned} x_{h_{n,m}}(\boldsymbol{\theta}) &\approx x_{h_{n,m}}(\boldsymbol{\theta}^o) + \nabla x_{h_{n,m}}(\boldsymbol{\theta}^o)(\boldsymbol{\theta} - \boldsymbol{\theta}^o) \\ y_{v_{j,k}}(\boldsymbol{\theta}) &\approx y_{v_{j,k}}(\boldsymbol{\theta}^o) + \nabla y_{v_{j,k}}(\boldsymbol{\theta}^o)(\boldsymbol{\theta} - \boldsymbol{\theta}^o) \end{aligned} \quad (5.20)$$

where

$$\begin{aligned} \nabla x_{h_{n,m}}(\boldsymbol{\theta}^o) &= \frac{\partial x_{h_{n,m}}(\boldsymbol{\theta}^o)}{\partial \boldsymbol{\theta}^T} \in \Re^{1 \times 2NM} \\ \nabla y_{v_{j,k}}(\boldsymbol{\theta}^o) &= \frac{\partial y_{v_{j,k}}(\boldsymbol{\theta}^o)}{\partial \boldsymbol{\theta}^T} \in \Re^{1 \times 2NM} \end{aligned} \quad (5.21)$$

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and subject to the constraint that

$$\xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o) + \sqrt{E \left[\left(\xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}) - \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o) \right)^2 \right]} \quad (5.22)$$

is minimum. (5.22) is the sum of the mean and Root Mean Square (RMS) of $\xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta})$. This implies that we would always choose a set of $LPMD_h$ and $LPMD_v$ that ensures the minimum of (5.22) for each varying instantaneous $\boldsymbol{\theta}$ before computing (5.21). The $E \left[(\cdot)^2 \right]$ in (5.22) can be derived by using Taylor series expansion as follows where

$$\xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}) \approx \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o) + \nabla \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o) (\boldsymbol{\theta} - \boldsymbol{\theta}^o) \quad (5.23)$$

with

$$\nabla \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o) = \frac{\partial \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o)}{\partial \boldsymbol{\theta}^T} \in \Re^{1 \times 2NM} \quad (5.24)$$

However, only four elements in the row vector in (5.24) which correspond to the set of measurement variables that arises from an associated pair of $LPMD_h$ and $LPMD_v$ are not null. In other words,

$$\frac{\partial \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o)}{\partial d_{n,m}}, \frac{\partial \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o)}{\partial d_{v,k}}, \frac{\partial \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o)}{\partial \alpha_{n,m}}, \frac{\partial \xi_{(h_{n,m}), (v_{j,k})}(\boldsymbol{\theta}^o)}{\partial \alpha_{v,k}} \neq 0$$

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where $d_{n,m}, d_{v,k}, \alpha_{n,m}, \alpha_{v,k}$ arise from a particular pair of $LPMD_{h_{n,m}}$ and $LPMD_{v_{j,k}}$

which generates the $\xi_{(h_{n,m}), (v_{j,k})}(\theta^o)$ that is in consideration. Next, by rearranging

(5.23) and taking the square and Expectation on both sides,

$$\begin{aligned} & E \left[\left(\xi_{(h_{n,m}), (v_{j,k})}(\theta) - \xi_{(h_{n,m}), (v_{j,k})}(\theta^o) \right)^2 \right] \\ & \approx \nabla \xi_{(h_{n,m}), (v_{j,k})}(\theta^o) E \left[(\theta - \theta^o)(\theta - \theta^o)^T \right] \nabla \xi_{(h_{n,m}), (v_{j,k})}^T(\theta^o) \end{aligned} \quad (5.25)$$

with

$$E \left[(\theta - \theta^o)(\theta - \theta^o)^T \right] = \text{diag}(\sigma_d^{2T}, \sigma_a^{2T}) \quad (5.26)$$

Similarly, rearranging (5.20) and taking the square and Expectation on both sides,

$$\begin{aligned} & E \left[\left(x_{h_{n,m}}(\theta) - x_{h_{n,m}}(\theta^o) \right)^2 \right] \approx \nabla x_{h_{n,m}}(\theta^o) E \left[(\theta - \theta^o)(\theta - \theta^o)^T \right] \nabla x_{h_{n,m}}^T(\theta^o) \\ & E \left[\left(y_{v_{j,k}}(\theta) - y_{v_{j,k}}(\theta^o) \right)^2 \right] \approx \nabla y_{v_{j,k}}(\theta^o) E \left[(\theta - \theta^o)(\theta - \theta^o)^T \right] \nabla y_{v_{j,k}}^T(\theta^o) \end{aligned} \quad (5.27)$$

Finally, the variance of the localization error for our proposed NLOS localization scheme in (5.11) can be derived as

$$\begin{aligned} & E \left[\left(x - x^o \right)^2 \right] \approx E \left[\left(x_{h_{n,m}}(\theta^o) - x^o \right)^2 \right] + E \left[\left(x_{h_{n,m}}(\theta) - x_{h_{n,m}}(\theta^o) \right)^2 \right] \\ & E \left[\left(y - y^o \right)^2 \right] \approx E \left[\left(y_{v_{j,k}}(\theta^o) - y^o \right)^2 \right] + E \left[\left(y_{v_{j,k}}(\theta) - y_{v_{j,k}}(\theta^o) \right)^2 \right] \end{aligned} \quad (5.28)$$

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where $\begin{bmatrix} x^o, y^o \end{bmatrix}^T$ is the true MD location coordinate. From (5.28), the RMS localization error (RMSE) for our proposed NLOS localization scheme will then be given as $\sqrt{E\left(\left[(x-x^o)^2\right]\right) + E\left(\left[(y-y^o)^2\right]\right)}$.

B. Proposed LOS path localization error variance

If there is a LOS path, the variance in (5.26) pertaining to the LOS path need to be altered due to the readjustment of the measurement data $t_{n,1}$ and $\alpha_{n,1}$ for the LOS path of RD_n . The modified noise error arising out of the AOA measurement has to be computed before we are able to derive the variance in the localization error in the LOS path. By substituting (5.15) into (5.14) and then (5.17), the noise angle difference e_n can be computed as follows:

$$e_n = \begin{cases} n_{\alpha_{n,1}} - n_{\beta_{n,1}} & \text{if } 0^\circ < \alpha_{n,1} \leq 90^\circ, 270^\circ < \alpha_{n,1} \leq 360^\circ \\ n_{\beta_{n,1}} - n_{\alpha_{n,1}} & \text{if } 90^\circ < \alpha_{n,1} \leq 180^\circ, 180^\circ < \alpha_{n,1} \leq 270^\circ \end{cases} \quad (5.29)$$

Putting (5.29) into (5.18) and subsequently into (5.14), it can be found that

$$\alpha_{n,1} = \alpha_{n,1}^o + n'_{\alpha_{n,1}}, \quad n'_{\alpha_{n,1}} = n_{\alpha_{n,1}} - \left(n_{\alpha_{n,1}} - n_{\beta_{n,1}}\right) f_{\alpha_n} \quad (5.30)$$

where $n'_{\alpha_{n,1}}$ is the modified noise error arising from the $\alpha_{n,1}$. From (5.30), it is clear that modification in (5.18) serves to minimize the measurement noise and seeks to provide

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the true AOA value of $\alpha_{n,1}^o$. Therefore, by putting (5.30) into (5.26) for the AOA of the LOS path, the new $\sigma_{\alpha_{n,1}}^2$ in (5.26) is given as

$$\begin{aligned} E\left[\left(\alpha_{n,1} - \alpha_{n,1}^o\right)\left(\alpha_{n,1} - \alpha_{n,1}^o\right)^T\right] &= E\left[n_{\alpha_{n,1}} n_{\alpha_{n,1}}^T\right] = E\left[\left(f_{\alpha_n} - 1\right)^2 n_{\alpha_{n,1}}^2 + f_{\alpha_n}^2 n_{\beta_{n,1}}^2\right] \\ &= \left(f_{\alpha_n} - 1\right)^2 \sigma_{\alpha_{n,1}}^2 + f_{\alpha_n}^2 \sigma_{\beta_{n,1}}^2 \end{aligned} \quad (5.31)$$

where $\sigma_{\beta_{n,1}}^2$ can be obtained similarly from Taylor series expansion of $\beta_{n,1}(\alpha_{n,1}, d_{n,1})$ and is given as:

$$\begin{aligned} \sigma_{\beta_{n,1}}^2 &= E\left[\left(\beta_{n,1}(\alpha_{n,1}, d_{n,1}) - \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o)\right)^2\right] \\ &\approx \nabla \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) \text{diag}(\sigma_{\alpha_{n,1}}^2, \sigma_{d_{n,1}}^2) \nabla \beta_{n,1}^T(\alpha_{n,1}^o, d_{n,1}^o) \end{aligned} \quad (5.32)$$

with

$$\begin{aligned} \beta_{n,1}(\alpha_{n,1}, d_{n,1}) &\approx \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) + \nabla \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) \text{diag}(\alpha_{n,1} - \alpha_{n,1}^o, d_{n,1} - d_{n,1}^o) \\ \nabla \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) &= \left[\frac{\partial \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o)}{\partial \alpha_{n,1}}, \frac{\partial \beta_{n,1}(\alpha_{n,1}^o, d_{n,1}^o)}{\partial d_{n,1}} \right] \in \Re^{1 \times 2} \end{aligned}$$

To find out the new TOA variance of the LOS path that has undergone readjustment of the measurement data, we can adopt the same approach in which the new $\sigma_{d_{n,1}}^2$ ($=\sigma_{r_{n,1}}^2$ after LOS adjustment) can be recalculated as

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$$\begin{aligned}\sigma_{r_{n,1}}^2 &= E\left[\left(r_{n,1}(\alpha_{n,1}, d_{n,1}) - d_{n,1}^o\right)^2\right] \\ &\approx \nabla r_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) \text{diag}(\sigma_{\alpha_{n,1}}^2, \sigma_{d_{n,1}}^2) \nabla r_{n,1}^T(\alpha_{n,1}^o, d_{n,1}^o)\end{aligned}\quad (5.33)$$

with

$$\begin{aligned}r_{n,1}(\alpha_{n,1}, d_{n,1}) &\approx r_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) + \nabla r_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) \text{diag}(\alpha_{n,1} - \alpha_{n,1}^o, d_{n,1} - d_{n,1}^o) \\ \nabla r_{n,1}(\alpha_{n,1}^o, d_{n,1}^o) &= \left[\frac{\partial r_{n,1}(\alpha_{n,1}^o, d_{n,1}^o)}{\partial \alpha_{n,1}}, \frac{\partial r_{n,1}(\alpha_{n,1}^o, d_{n,1}^o)}{\partial d_{n,1}} \right] \in \Re^{1 \times 2}\end{aligned}$$

Therefore, the new calculated $\sigma_{\alpha_{n,1}}^2$ in (5.31) and $\sigma_{d_{n,1}}^2$ in (5.33) for the LOS path are substituted into (5.26) to form the variance matrix to calculate RMS localization error.

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5.2.3 Experimental and Simulation Results

Fig. 5.7 Ray Tracing between the RD s and various MD locations at Nanyang Technological University, School of EEE, Block S1, level B3 (S1-B3)

To evaluate the performance of our proposed localization scheme, a typical environment at Nanyang Technological University, School of Electrical and Electronic Engineering (EEE), Block S1, Level B3 (S1-B3) [100] is exploited as shown in Fig. 5.7. Channel measurements were taken and the measured data metrics (TOAs and AOAs) were verified accordingly to the traditional ray tracing methodology [92], [101], [102]. As mentioned earlier, the three RD s were located at $RD_1(25\text{ m}, 9\text{ m})$, $RD_2(18\text{ m}, 4\text{ m})$, $RD_3(3\text{ m}, 14\text{ m})$ with the concrete walls served as the scatterers as shown in the plot. For simplicity, the dominant path ($M=1$) are extracted from each RD and used for performance analysis. In total, there will be three paths from the RD s for each performance analysis. Fig. 5.7 traces the actual rays between the three

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RDs and MD . The following scenarios will be illustrated to examine the performance of our proposed NLOS localization scheme:

- a) Case A – all RDs are in LOS with MD ;
- b) Case B – two RDs are in LOS with MD ; and
- c) Case C – one RD is in LOS with MD .

The actual data metrics ($t_{n,m}^o, \alpha_{n,m}^o$) are obtained by correlating ray tracing methodology with the measurement data. For thorough comparison with existing conventional localization schemes, each actual data metrics will be subjected to noise effect using Gaussian random variable noise with a mean of zero, and unknown variance (variances of all devices are identical unless otherwise specified) [37], [54], [95], [96]. The RMS localization error σ_{rms} that is related to the true MD location is calculated as $\sqrt{(x - x^o)^2 + (y - y^o)^2}$. It is computed based on 10,000 independent simulation runs. MD location (x, y) is obtained from (5.11).

The conventional LOS localization schemes used for performance analysis are the TOA localization scheme [29], and the TOA/AOA localization scheme that is brought about by the modification of the TDOA/AOA localization scheme in [37]. The rationale for modifying [37] into TOA/AOA localization by extending the AOA formulation in [37] into TOA formulation in [29] is to allow stricter comparison. The TOA/AOA localization scheme will have lower localization error variance than the TDOA/AOA localization scheme because the latter sacrifices one time observation for the sake of synchronization. The conventional TOA localization scheme [29] has its

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own mitigation technique while the conventional TOA/AOA localization scheme is coupled with the LOS reference devices detection technique [54]. Furthermore as the σ_{β_n} in (5.19) is unknown, we equate it to σ_{α_n} which would render sufficient improvement in the LOS path measurement.

A. Performance probability distribution due to TOA, AOA inaccuracy

Fig. 5.8 depicts the location accuracy of the proposed NLOS localization scheme and compares with the existing localization schemes via their cumulative probability distribution (CDF). The AOA standard deviations σ_{α} for all devices are 2° [93], [104] while the distance standard deviations σ_d are 1 m [18]. In this scenario, MD is located at A (15 m , 13 m) where all RDs are in LOS with it. As shown in the plot, our proposed localization scheme's performance is equivalent to the conventional TOA/AOA localization scheme.

Fig. 5.9 depicts the CDF performance for MD location at B (20 m , 10.8 m). In this scenario, RD_2 is in NLOS with MD . The dominant path for RD_2 is a one bound scattering path arising out of the specular reflection at the wall (13 m , 6.83 m). Both the conventional LOS TOA and TOA/AOA localization schemes are coupled with their own NLOS mitigation schemes. For the LOS TOA/AOA localization scheme, this NLOS path is successfully detected and discarded in all the 10,000 runs. However, our proposed localization scheme still superiorly outperforms these conventional schemes, attaining $\sigma_{rms} \leq 2\text{ m}$ for about 70% of the time.

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Fig. 5.8 Comparison of the CDF performance using distance standard deviation $\sigma_d = 1\text{ m}$ and AOA standard deviation $\sigma_\alpha = 2^\circ$ for MD located at (15 m , 13 m). Case A- All RDs are in LOS with MD .

Fig. 5.9 Comparison of the CDF performance using distance standard deviation $\sigma_d = 1\text{ m}$ and AOA standard deviation $\sigma_\alpha = 2^\circ$ for MD located at (20 m , 10.8 m). Case B- Two RDs are in LOS with MD .

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Fig. 5.10 Comparison of the CDF performance using distance standard deviation $\sigma_d = 1\text{ m}$ and AOA standard deviation $\sigma_\alpha = 2^\circ$ for MD located at $(16\text{ m}, 8\text{ m})$. Case C- One RD is in LOS with MD .

Fig. 5.10 illustrates the case where only RD_2 is in LOS with MD that is located at $C(16\text{ m}, 8\text{ m})$. RD_1 has a dominant one bound scattering path that arises from the specular reflection at the wall $(21.14\text{ m}, 12\text{ m})$. For RD_3 , the dominant path is a triple bound scattering path that undergoes three reflection at the walls $(8\text{ m}, 16.5\text{ m})$, $(18\text{ m}, 12.5\text{ m})$ and $(13\text{ m}, 9.5\text{ m})$. As shown, both the conventional LOS schemes' NLOS mitigation schemes could not function well as the number of NLOS paths is greater than the number of LOS paths. As depicted, our proposed localization scheme outperforms the conventional schemes and is able to attain $\sigma_{rms} \leq 2\text{ m}$ for more than 90% of the time.

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B. Performance Bound Comparison

Fig. 5.11 and Fig. 5.12 illustrate the Average Location Error (ALE) performance of all the schemes with 10,000 simulated *MD* locations. These locations are uniformly distributed in the environment to demonstrate the robustness of our proposed localization scheme. Furthermore, at these uniformly distributed *MD* locations, the dominant propagation paths arriving at the *RDs* include all possible propagation paths. These propagation paths include not only the LOS, single and multiple specular reflection paths but also single edge diffraction path and path that comprises of a combination of multiple specular reflection and a single edge diffraction. The ALE is obtained by averaging the sum of the RMS location error obtained for the 10,000 *MD* location. Fig. 5.11 illustrates the ALE performance for distance standard deviation of all *RDs*, $\sigma_d = 1m$ with varying AOA standard deviation, σ_α while Fig. 5.12 depicts the ALE performance for AOA standard deviation of all *RDs*, $\sigma_\alpha = 2^\circ$ with varying distance standard deviation, σ_d . As shown in both plots, our proposed localization scheme not only outperforms the conventional localization schemes throughout the 10,000 different *MD* locations, but also robust to the ascending AOA standard deviation. Therefore, our proposed localization scheme demonstrates performance stability in relation to variations in both the location of *MD* and the AOA standard deviation.

Fig. 5.11 and Fig. 5.12 also illustrate the performance comparison between the RMS localization error of our proposed localization scheme and that of the derived analytical RMS expression (square root of the sum in (5.28)) for our proposed localization scheme. As shown in both plots, the difference between the analytical RMS expression

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Fig. 5.11 ALE comparison with distance standard deviation $\sigma_d = 1\text{ m}$ and varying AOA standard deviation σ_α .

Fig. 5.12 ALE comparison with AOA standard deviation $\sigma_\alpha = 2^\circ$ and varying distance standard deviation σ_d .

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and the actual localization scheme's RMS error is subtle, thus supporting the accuracy of our derived analytical expression.

C. Performance due to different degrees of tilted scatterer

Finally, to illustrate the robustness in performance for our proposed NLOS localization scheme in environment where some of the scatterers are not parallel or perpendicular to each other, one of the scatterers near MD in the environment is simulated to be titled to different degrees, ϕ as shown in Fig. 5.13. The scatterer is rotated in clockwise direction at an angle ϕ from 0° to 30° . As shown, the RDs' received signals can transit from a LOS to a one bound scattering path as the scatterer is rotated.

Fig. 5.14 depicts the performance of our proposed NLOS localization scheme for the titled scatterer at different degrees of clockwise rotation. As shown, our proposed localization scheme still outperforms the conventional localization schemes as the titled scatterer is rotated, demonstrating our proposed scheme's performance stability in relation to variations in the scatterers' orientation and rotation.

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Fig. 5.13 Ray tracing between the RDs and MD for different degrees of tiled scatterer for distance standard deviation $\sigma_d = 1m$ and AOA standard deviation $\sigma_\alpha = 2^\circ$.

Fig. 5.14 Performance comparison due to different degrees of tiled scatterer for distance standard deviation $\sigma_d = 1m$ and AOA standard deviation $\sigma_\alpha = 2^\circ$.

5.3 Conclusion

In conclusion, two novel approaches of NLOS localization schemes by leveraging only on the estimation of TOA/AOA at the *RD* have been proposed. The paths can be either LOS or one bound scattering paths. The proposed schemes have the key advantage of being able to work robustly in multipath environment. It has been demonstrated experimentally and coupled with simulations in a typical environment that our proposed NLOS localization scheme not only outperforms the conventional TOA and TOA/AOA localization schemes in all cases in this environment but also sustains performance stability in relation to variations in the location of *MD*, the AOA standard deviation and the scatterers' orientation. An average of $\sigma_{rms} \leq 2m$ is obtained for 90% of time for our proposed 2 step DS localization scheme without any mitigation scheme.

CHAPTER SIX

6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this thesis, we have presented novel localization approaches to overcome the detrimental effect of NLOS multipath on the localization accuracy in the multipath environment by leveraging on just one *RD* to perform the localization of the *MD*.

Chapter 3 presents two novel LOS bidirectional localization schemes that leverage on the joint estimation of TOA and AOA measurement at both the *RD* and *MD*. Only just one *RD* is sufficient to be in LOS range with the *MD* to perform localization of the *MD*. The joint LS implementations coupled with the AOA adjustment to the LOS path and the NLOS path rejection techniques have been devised. The two approaches are compared to the two conventional localization schemes in the general and typical environments and demonstrated their superiority in performances with a much higher margin over the conventional schemes for all cases of error variations.

Chapter 4 extends the novelty by devising a holistic localization approach to localize the *MD* using bidirectional estimation of the multipath TOA and AOA. Two signal paths can be either LOS or one bound scattering NLOS paths. Its robustness to multiple bound scattering paths has been demonstrated along with the superiority of its performance to that of existing localization schemes in all instances and scenarios.

CHAPTER SIX CONCLUSIONS AND FUTURE WORK

Chapter 5 provides a total breakthrough in localization methodology by introducing two novel approaches that leverage only on the estimation of TOA and AOA at the *RD* only. This removes the complexity of using bidirectional estimation at the *RD* and *MD* since the cost of having antenna array at the *MD* is expensive in terms of physical implementation (such as calibration) and computation. The proposed schemes have the key advantage of being able to work robustly in multipath environment by using paths that are either LOS or one bound scattering paths. The schemes are robust against multiple bound scattering paths and not only outperform the conventional TOA and TOA/AOA localization schemes in all cases in the NTU environment but also sustain performance stability in relation to variations in the location of *MD*, the AOA standard deviation and the scatterers' orientation.

6.2 Future Work

There are two areas of future work that can be carried out with regards to the research work that have been carried out and mentioned in this thesis. These two areas will provide completeness in the research effort to provide localization capability in multipath environments.

The first area of research effort to delve into is to provide localization capability in multipath environment where there is no existence of LOS and one bound scattering paths. Only the multiple bound scattering paths exist in this case. The conventional localization techniques and even our proposed localization schemes would not perform satisfactory in this type of multipath environment. Therefore, there exists a need to resolve and overcome the detrimental effect of multiple bound scattering paths by

CHAPTER SIX CONCLUSIONS AND FUTURE WORK

designing a robust localization mechanism to locate the *MD* using multiple bound scattering paths in the multipath environment.

The second area of the future research work is the fusion of the proposed localization techniques mentioned in this thesis into sensor network application. Proliferation of sensor network into various context such as resources optimization and identification, as discussed in the Introduction, has made localization capabilities a necessity (Table 1-1). The proposed localization schemes provide a framework to allow localization capability for sensor networks in multipath environments, ensuring correct identification of resources. Channel propagation profile of the environment can be developed and fused into the localization schemes to provide an autonomous, robust solution to localize the sensor network devices in all environments.

AUTHOR'S PUBLICATIONS

Journal Publications

1. **C. K. Seow** and S. Y. Tan, "Non-line-of-sight unidirectional mobile localisation in multipath environment," *IEE Electronics Letters*, Vol. 44, No. 2, pp. 141–143, Jan. 2008.
2. **C. K. Seow** and S. Y. Tan, "Localisation of Mobile Device in Multipath Environment using Bi-Directional Estimation," *IEE Electronics Letters*, Vol. 44, No. 7, pp. 485–486, Mar. 2008.
3. **C. K. Seow** and S. Y. Tan, "Non-Line-of-Sight Localization in Multipath Environments," *IEEE Transactions on Mobile Computing*, Vol. 7, No. 5, pp. 647-660, May. 2008
4. **C. K. Seow** and S. Y. Tan, "Localization of Omni-Directional Mobile in Multipath Environment," *Progress In Electromagnetics Research*, PIER 85, pp. 323-348, 2008

Conference Publications

1. **C. K. Seow**, S. Y. Tan and S.W. Chen, "A Localization Scheme using Bi-Directional Metrics Joint Estimation," *Progress In Electromagnetics Research Symposium(PIERS09)*, pp. 1473-1477, 23 Mar. to 27 Mar. 2009, Beijing, China.

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