Wireless channel measurement and modelling in maritime environment for USV

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Wireless Channel Measurement and Modelling in Maritime Environment for USV

DONG FENG

**School of Electrical and Electronic
Engineering**

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Summary

In this thesis, a comprehensive study on channel modelling and characterization in maritime environment for military applications such as surveillance and remote unmanned operation is investigated. The application of sea-to-land communication systems mounted on the unmanned surface vehicles requires knowledge of radio wave propagation in maritime environment at 5 GHz band. In this research work, a series of sea trials were carried out in different scenarios of maritime environment to investigate the radio wave propagation through sea-to-land paths.

Firstly, the experiment was conducted in open sea scenarios to investigate the path loss characteristic for line-of-sight propagation. Well-known pass loss models such as free space model and two-ray model are used to verify the measurement results. It is found that path loss in this open sea scenarios with line-of-sight transmission can be empirically modelled by these models especially by two-ray path loss model which considers the reflection path over the sea surface. However, the measurement results also show that the prediction accuracy of two-ray path loss model is found to be weaker, as the distance separation between transmitter and receiver becomes larger. This is due to the existence of evaporation duct which is well recognized to influence the radio wave propagation over sea surface. Therefore, a new three-ray model is proposed considering also the possible reflection path from the ducting layer. The accuracy of this model is then verified using the measurement results and

some existing published literature. The proposed three-ray path loss model is then proven to have good prediction ability in our experiment environment especially when the distance separation between transmitter and receiver goes larger.

The research study goes on by focusing on the propagation characterization on one of the selected route which is used to test the operation of the unmanned surface vehicle. Channel parameters such as the delay spread and coherence bandwidth are determined along the route through measured power delay profiles.

Finally, NLOS channel characterization is studied in the scenario that large anchored ship is in between the transmitter and receiver. It is found that the large metallic body of the obstruction ships in between the transmitter and receiver makes the transmission difficult and unreliable. Therefore, the concept of stand-off distance is proposed for the application of military surveillance purpose. The experiments are conducted in different conditions and the results are then verified by the simulation using the software “Wireless InSite”. The results show good match between the measurement data and simulation. Moreover, mitigation technique using antenna diversity is then studied to have a further understanding of the NLOS transmission.

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Chapter 1

Introduction

Wireless communication has developed rapidly ever since Guglielmo Marconi started the journey for modern wireless communication by transmitting the three-dot Morse code for the letter “S” over a distance of three kilometers through electromagnetic waves in 1895[1]. It provides greater flexibility, mobility and better cost efficiency as compared to wired communications. However, it is vulnerable to radio, weather and atmospheric interferences which are significant at high frequencies. The reliability of the wireless link is crucial for commercial applications and is particularly important for military applications. Therefore, it is important to study and characterize wireless communication links taking into consideration all possible effects that can affect the link.

Wireless communication technology has become part of our daily life, and is one of the most active areas of communication technology development research. With the rapid growth in wireless communications, many research works and experiments have been done in order to understand the characteristics of signal propagation. The main objective of these researches is to achieve a high quality of services with low power, high data rate and high reliability even in complex physical environments, such as an urban area with high-rise buildings, randomly profiled terrestrial grounds. Thus, propagation

models play a crucial role to the understanding of the wireless communication channels both indoor and outdoor. In [2-4], the signal propagation in offices, factories, and urban areas are modelled. The outdoor propagation models are relatively more complex compared to indoor propagation models since dynamic parameters such as weather effects due to rain [2], ducting effects [3], and lateral waves effects [4] has to be taken into account for the outdoor environments. The radio channel of a wireless communication system is classified into either Non-Line-of-Sight (NLOS) or Line-of-Sight (LOS). In a NLOS link, a signal is blocked and reaches the receiver through reflections, diffractions and scattering. In a LOS link, a signal goes through a direct and unobstructed path from the transmitter to the receiver. The received signals may include components coming from different paths such as the direct path, scattered energy, multiple reflections and also diffracted paths. These signals result in the constructive and destructive summations due to their differences in arrival time, attenuation, polarizations and stability relative to the direct path [5]. Most research and experiments on propagation focus on the land environment such as in urban areas. In this thesis, the focus is on radio wave propagation for sea to land links.

1.1 Motivation

In recent years, there has been a growing interest in maritime communications. Its application is of scientific and military importance, such as, Unmanned Surface Vehicle (USV) systems. In order to design a system for maritime communications, a detail understanding of the maritime propagation channel is

essential for establishing a good and reliable communication link. In such scenarios, the propagation path from transmitter to receiver is over the sea surface, and therefore, in order to understand the propagation of electromagnetic waves through the sea channel, not only the effect of the direct path needs to be considered, but also the effect of the surface reflection. Moreover, Singapore is a major sea port in South East Asia. Off the coast of Singapore, numerous large sea vessels crowd the waters. In such coastal conditions, the transmitted signal may experience multiple reflections and scattering caused by the obstacles (anchored ships) in the vicinity of the channel. Multipath fading therefore is likely to occur in such environment, which can change from one location to another and can change with the movement of the surrounding obstacles in the area. These propagation characteristics therefore require modelling and parameterization under different conditions in order to have a better understanding of the dynamic effects of the environment and the conditions on the wireless communication link. These results are important for the proper link budgeting of the maritime communication channels as well as for system design.

Furthermore, NLOS propagation also becomes crucial in coastal environment due to the crowded waters around the Singapore Island. This is because, the communication link is often blocked by the large metallic body of cargo ships anchored about 2km to 5km off the shores. The Non-Line-of-Sight transmission is made difficult due to the material and relative size of these vessels. Since the ship is a pure metallic structure, it is impossible for the

electromagnetic waves to penetrate through it as indicated in Figure 1. Diffraction, especially knife-edge diffraction [5] takes place when the propagation path is blocked by structures with sharp edges such as hills, buildings, and in our case, large metallic cargo ships. It is mathematically difficult to calculate the diffraction loss over a complex environment or irregular terrain. Therefore, it is impossible to make very precise estimation of diffraction loss due to complex structures. In this case, a complete study needs to be performed in order to investigate the NLOS behaviour of the maritime communication link. Stand-off distance would be determined for vessel surveillance usage. It is of great significance for military applications.

Figure 1: NLOS transmission for the sea to land channel

1.2 Objective

The objective of this thesis is to characterize and model the sea-to-land wireless communication links in the 5GHz band in the maritime environment. This is achieved by performing a series of channel measurements over a wide range of environment and conditions. This project aims to explore link reliability mitigation techniques, different system parameter configuration and antenna positioning. To fulfil the objectives, the focus of this project is as follow:

1. A comprehensive literature review of the channel characterization and path loss modelling, especially in maritime environment, is performed. This exercise allows one to obtain a strong foundation and background knowledge for further studies.

2. Appropriate wideband and narrowband channel sounding systems are developed to perform measurements over the sea environment. The performance of the proposed systems is evaluated experimentally. Modifications are then done to the systems in order to optimize their performance.

3. Path-loss modelling in open sea environment is conducted and a comparative study between measured data and theoretical models is performed.

4. Wideband and narrowband characterization of sea to land channel in the LOS scenario is investigated. Channel parameters such as delay spread and coherence bandwidth are determined.

5. Measurement under NLOS scenarios is carried out to study the channel performance for the application of Unmanned Surface Vehicles for vessel surveillance applications. Stand-off distance is determined and diffraction effect under NLOS conditions has been identified and verified by ray tracing simulation results.

6. Measurement with multiple transmitting and receiving antennas is conducted to study the potential for the application of MIMO technique through the investigation of the diversity gain, and some recommendation are given.

The outcome of the master degree study has produced some contributions and developments over the existing research works, and is outlined in the next section.

1.3 Major Contribution of the Thesis

In this master study on the sea to land channel modelling and characterizations over the sea surface at 5GHz bands, more than ten major measurement campaigns (lasting 3 days each) over a two year period have been carried out off the south-eastern coast of the Singapore Island. With the analysis and

modelling of the post-processed measurement data, the contribution and developments over the existing research works can be summarised. The following is the list of major contributions in this master study:

1. Path-loss model in the maritime environment off the coast of Singapore is studied and verified. Two-ray path-loss model is chosen to be compared with the measurement results in this thesis to account for the sea surface reflection. The results are found to be matched very well for the prediction of path loss over sea path at 5GHz band but only up to a certain critical distance. A new three-ray path-loss model taking into consideration the ducting layer effect is also proposed in the thesis. The model shows a good match between the measurement results and the modelled results particularly for the signal dips and enhancements.

2. Variations caused by the motion of the transmitter in the sea and the surrounding mobile environment are statistically modelled and tested. Channel parameters such as delay spread and coherence bandwidth are determined under specific route in LOS scenarios which are important for system design.

3. Channel performance under NLOS scenarios in maritime environment is investigated. Propagation mechanism such as diffraction is identified and studied. Concept of stand-off distance is proposed for the application of military

surveillance purposes. Results are then discussed in detail, and ray tracing simulation is also done and compared with experimental data.

4. The Antenna diversity technique is used to mitigate the multipath fading in order to improve the radio link reliability in the maritime environment. The diversity gain between different transmitter and received antennas combinations are studied empirically.

1.4 Organization of the Thesis

The first chapter gives an introduction to the thesis. It explains the motivation behind the project, the objective of this research and the main contributions in this thesis.

Chapter 2 gives a literature review on the channel characterization and modelling. It provides some basic concepts about radio wave propagation and summarizes the existing study on characterization of the propagation channel within the maritime environments.

In Chapter 3, two different sounding systems are introduced. The accuracy and resolution of the measurement system is detailed.

Chapter 4 describes the narrowband path loss modelling in maritime environment over the open sea surface. The results are analysed both empirically and theoretically. Two-ray path loss model is found to be a good prediction for radio propagation but only up to a critical distance. Beyond the

critical distance, the ducting layer effect has to be investigated in order to gain a better understanding of the channels' performance. A new three-ray path loss model is then proposed for path loss beyond the critical distance and the proposed model is verified using the experiment results.

In Chapter 5, both the narrowband and wideband investigations of the multipath induced effect on the radio wave propagation in maritime environment have been discussed in detail. Channel parameters such as delay spread and coherence bandwidth are determined through the power delay profiles.

Next, the NLOS channel characterization is introduced in Chapter 6. The concept of stand-off distance is proposed for the application of military surveillance purpose. Experiment results are analysed under different conditions and system settings. Besides that, simulation is also conducted and simulation results are compared with experiment results. Further investigation on the antenna diversity is also included in this part.

Finally, Chapter 7 gives a conclusion to this research work and provides recommendations for the future work.

Chapter 2

Literature Review

In this chapter, a brief introduction is given on the concepts behind channel modelling and characterization. This is the fundamental and will be useful for the further investigation of the radio wave propagation in the maritime environments. A comprehensive review on the propagation characteristics and modelling of the maritime environments are then given in detail. The existing research on the theoretical and experimental methodologies under the topic are described and summarized.

2.1 Basic Concepts of Radio Wave Propagation

Performance of the wireless communication system is primarily limited by the radio propagation channel. The transmission path from the transmitter to the receiver can be very different from direct line-of-sight to one that is blocked by buildings, mountains, and other obstructions. The radio channels are extremely random and unpredictable compared to wired channels that are stationary [5]. Thus, it is significantly important to model the radio channels, which is also the most difficult part of mobile radio system design. Accurate channel modelling is usually developed using statistics obtained from experimental measurements taken particularly in the intended communication environment for the allocated spectrum. Propagation models can be classified into large-scale models and small-scale models according to their focus on the different aspects of the radio

wave transmission. The former one emphasises on the variation trend of the mean signal strength over distance, since they characterize signal strength over large transmitter to receiver separation distance (several hundreds or thousands of meters) which is useful for predicting the radio coverage range. Meanwhile, the latter one mainly focuses on the rapid fluctuations of the received signal strength over short time period (order of microseconds) or over very short distances (a few wavelengths) [5-7]. Figure 2 illustrates the large-scale variations and small-scale fading for an outdoor communication system. The signal fades rapidly (small-scale fading) as the transmitter to receiver separation distance changes, but the local mean value changes much more gradually with distance [7].

Figure 2: Small-scale and large scale fading

2.1.1 Large-scale path loss

A. Free Space Path Loss model

The path loss is the overall mean decrease in the signal strength with an increase in the transmitter to receiver separation distance. When a clear and unobstructed line-of-sight path is between the transmitter and receiver with no obstacles nearby to cause reflection or diffraction, received signal strength could be predicted by free space propagation model [7]. Received power decays as an exponential function of the transmitter to receiver separation distance relative to the transmission power. The free space propagation loss is predicted by this model which can be express in the following equation in the decibels.

$$L_{FSL}(dB) = -147.55 + 20\log_{10}(f) + 20\log_{10}(d) \quad (2.1)$$

where d is the separation distance between the transmitter and the receiver in meter, and f is the frequency in Hz.

B. Two-ray Path Loss Model

Most radio wave propagation near the ground is seldom characterized using free space propagation model. Both the direct line-of-sight path and a ground

reflected propagation path between the transmitter and the receiver needs to be considered in order to predict the received signal strength. Thus, the two-ray path loss model is found to be more appropriate compared to free space path loss model for most of the radio systems that operate near the ground [5, 6].

The received signal in this model is the summation of the direct line-of-sight component and the ground reflected component. Not only the amplitude, but also the phase of the two components are summed together to obtain the final received signal strength. Figure 3 illustrates the simple schematic of the two-ray path loss model.

Figure 3: Two-ray ground reflection model

In Figure 3, h_t and h_r are the heights of the transmitter and receiver respectively. If E_0 is the free space Electric-field (in units of V/m) at a reference distance d_0 from the transmitter, then the Electric-field of the two waves can be express as

follows, (2.2) and (2.3), with d' representing the direct wave's travelled distance and d'' representing the reflected wave's travelled distance.

$$E_{LOS}(d', t) = \frac{E_0 d_0}{d'} \cos(\omega_c(t - \frac{d'}{c})) \quad (2.2)$$

$$E_g(d'', t) = (-1) \frac{E_0 d_0}{d''} \cos(\omega_c(t - \frac{d''}{c})) \quad (2.3)$$

Using the method of images, the path difference of the two waves can be calculated knowing the transmitter and receiver heights, and then the phase difference can be easily computed as in (2.4).

$$\theta_\Delta = \frac{4\pi h_t h_r}{\lambda d} \quad (2.4)$$

Taking the phasor sum of the two waves, the received electric field of the signal at separation distance d can be expressed as (2.5).

$$|E_{TOT}(d)| = |E_{LOS}(d) + E_g(d)| = 2 \frac{E_0 d_0}{d} \sin\left(\frac{\theta_\Delta}{2}\right) \quad (2.5)$$

E-field of the receiver signal strength at distance d can be predicted using this equation after knowing the transmitter and receiver antenna heights [7].

C. Log-distance Path Loss Model

In a realistic environment, where more than two paths are expected between the transmitter and the receiver due to the presence of the reflection, diffraction and

scattering, a popular empirical log-distance path loss model [7] is used. This model has been used extensively in the literature and can be written as (2.6).

$$L(dB) = L_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) \quad (2.6)$$

where d is the separation distance between the transmitter and the receiver, and d_0 is the reference distance. L_0 is the path loss in decibel at the reference distance d_0 . The most important parameter in this equation is the path loss exponent n which indicates the rate at which the path loss decreases with distance. Its value depends on the environment of the radio channel as well as the availability of a LOS connection between the transmitter and the receiver.

2.1.2 Small-Scale Fading and multipath

Small-scale fading describes the rapid fluctuations of a radio signal's amplitudes, phases, or multipath delays over a short period of time or over a short travel distance [7]. In the outdoor communication environment, obstacles will always exist between the transmitter and the receiver. These obstacles cause reflection, diffraction or scattering of the propagating radio waves. Thus the final received signal usually includes many different radio waves that go through different paths with different distance and time delays. These waves, called multipath waves, result in constructive or destructive summation of the signals arriving at the receiver. Signal fading occurs when the multipath are phased to attenuate each other.

A. Parameters of Mobile Multipath Channels

Power delay profile which is usually expressed as plots of relative received power as a function of excess delay with respect to a fixed time delay reference is crucial for calculating multipath channel parameters. All the plots shown in this thesis are normalized power delay profile that is an average of a few instantaneous power delay profiles over a local area in order to give a good representation of the detailed small-scale characteristics. In our case, the time resolution is 50ns which means multipath with traveling distance more than 15 m can be resolved. Figure 4 shows a typical power delay profile plot from the actual sea trial, determined from a number of closely sampled instantaneous profiles.

Figure 4: Typical example of Power Delay Profile

I. Time Dispersion Parameters

Parameters such as *mean excess delay*, *rms delay spread* and *excess delay spread* are used to characterize different multipath channels and indicate some general design guidelines for wireless systems. Mean excess delay ($\bar{\tau}$) and rms delay spread (σ_τ) are the most commonly used parameters to quantify the time dispersive properties of multipath channels and are defined below:

$$\bar{\tau} = \frac{\sum_{k=1}^N \tau_k \alpha_k^2}{\sum_{k=1}^N \alpha_k^2} = \frac{\sum_k P(\tau_k) \tau_k}{\sum_k P(\tau_k)} \quad (2.7)$$

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \quad (2.8)$$

where

$$\overline{\tau^2} = \frac{\sum_k \tau_k^2 \alpha_k^2}{\sum_k \alpha_k^2} = \frac{\sum_k P(\tau_k) \tau_k^2}{\sum_k P(\tau_k)} \quad (2.9)$$

These delays are measured relative to the first detectable signal arriving at the receiver at $\tau_0 = 0$ s [7]. Equations (2.7)-(2.9) do not rely on the absolute power level of $P(\tau)$. General values for rms delay spread are in the order of nanoseconds for indoor radio channels [7] and in the order of microseconds for outdoor radio channels [7].

A noise threshold value is defined and used in practice for calculation of delay spread. Received multipath elements and thermal noise are distinguished according to this value and it influence the value of calculated the delay spread.

II. Coherence bandwidth

Coherence bandwidth is then derived from the rms delay spread. It tells the limitation of carrier bandwidth that can be used in order to have a “flat” channel. This is of great importance for wireless system design. Any frequency components separation over the coherence bandwidth B_c would have a strong potential for amplitude correlation. If a frequency correlation function above 0.9 is used, the coherence bandwidth is calculated as below:

$$B_c \approx \frac{1}{50\sigma_\tau} \quad (2.10)$$

Otherwise, if a relaxed correlation function above 0.5 is used, the equation becomes:

$$B_c \approx \frac{1}{5\sigma_\tau} \quad (2.11)$$

B. Types of Small-Scale Fading

Different types of fading are then classified according to the relation between the channel parameters and the transmitted signal parameters. Time dispersion and frequency selective fading depends on the multipath delay spread, while frequency dispersion and time selective fading is classified according to the Doppler spread. A relationship tree for the four different types of fading is shown in Figure 5.

Figure 5: Types of small-scale fading

2.2 Propagation in Maritime Environments

In this section, existing studies on modelling and characterization of the maritime channel are described in detail. The observations and findings are from either theoretical or experimental studies over the past few decades. They help to assist the understanding of a maritime propagation channel for our current study.

2.2.1 Path Loss Modelling in Maritime Environment

Path loss models and measurements for land are readily available and discussed extensively for both indoor and outdoor scenarios [8-13]. For outdoor scenarios, many research works have been done to have a better understanding of the wireless channels in different environment [11-15]. Path loss in maritime environment is one of the interesting topics. Different models have been used to predict the path loss over a sea channel [16-21].

The two-ray path loss model can be used in open sea environment with relatively low sea state environment. In 2000, R.M Schmalenber [16] carried out a measurement campaign in the Baltic Sea near the coastal area. The measurement distance was up to 18 kilometres and results showed a good match between the theoretical two-ray path loss model and the experimental data at a carrier frequency of 2.45GHz.

However, the sea environment is usually complex and dynamic due to the effects of weather, sea state, surround obstacles. Therefore, it is not possible to

characterize the channel using a single model. In K. Yang's study [17], a sea trial was conducted in Trondheimsfjorden, Norway at 2GHz. He compared the experimental results with four classic models which includes the ITU-R model, the free space path loss model, the COST 231-Hata model and the Okumura-Hata model. It is found that the experimental results match the ITU-R P 1546 model with a 50% location time. However, the deep fading at short distances cannot be predicted by this model while they can be predicted by the two-ray path loss model.

Recently, the growing interest in the maritime communications at C band due to military and scientific applications requires a thorough and precise understanding of the propagation channel. K. N. Maliatsos [18, 19] and his group performed an extensive experimental study of different propagation environment over the Aegean Sea in Athens. They proposed a log-distance path loss model with attenuation factor n and shadowing factor s which is the root mean square error based on their experiment data under several different sea conditions. The equation is expressed as (2.12) in decibels.

$$L(dB) = L_0 + 10n \log_{10} \left(\frac{d}{d_0} \right) \quad (2.12)$$

After fitting (2.12) with the measured data, they concluded that the attenuation factor n varies between the range of 2.7 to 3.6 due to the complexity of the sea environments. The attenuation factor tends to be larger in complex sea environment especially in NLOS situation. Another study done by M. Zhou [20], in Singapore investigated the channel characteristics over the tropical sea

environment for WiMax applications. They deduced a log-distance path loss model where the path loss exponent was calculated as a function of the antenna height as shown in (2.13).

$$n = 2.358 - 0.00145h + 0.45/h \quad (2.13)$$

where h is the antenna height. Another study conducted around the coast of Singapore by J. Joe to investigate the influence of antenna heights on the path loss exponent was done in [21]. The results show that the path loss exponent approaches that of free space as the height of transmitter increases. The standard deviation decreases as the antenna height increases because the LOS is getting more dominant.

There is more work to be done in this area in order to give a comprehensive understanding of the maritime environment. The characterizations of radio wave propagation in maritime environment with climates effects, especially influence caused by the duct layers become important for the assignment of the proper path loss prediction in the radio link design. This will be studied in Chapter 4.

2.2.2 Tropospheric Ducts

A. Fundamentals of Tropospheric Ducts

Research work on the topic of radio wave propagation in maritime environment has been extensively done over the century. Studies of radio wave propagation over the sea channel play an important role for system designers trying to establish a communication link across the sea surface. Ducting, which is a well-recognized phenomenon over the water, is one of the topics that are of great interest, since it can affect the signal received strength level and can extent the transmission range for an over the sea path [22].

The troposphere is the lower region of the atmosphere which extends from the earth's surface to about 6 to 18km at different latitude [23]. Propagation mechanisms in the troposphere are all associated with abnormal vertical distribution of the refractive index with time and height [22]. Wave propagating in the atmosphere is refracted when there is different refractive index n in different layers, and the refractive index n is defined as:

$$n = \frac{c}{v_m} \quad (2.14)$$

where c is the speed of wave in vacuum and v_m is the speed of wave in the medium. Then the refractivity N is defined as:

$$N = (n - 1) * 10^6 \quad (2.15)$$

For different refractivity gradients (N/km), a radio ray traveling in the atmosphere will bend accordingly due to the refraction of waves. It consists of four types of propagation mechanisms namely, sub-refractive, standard, super-

refractive and trapping. Table 1 illustrates the conditions for the four different types of propagation mechanisms.

Condition	N-gradient (N/km)	M-gradient (M/km)
Trapping	$dN/dh \leq -157$	$dM/dh \leq 0$
Super-refractive	$-157 < dN/dh \leq -79$	$0 < dM/dh \leq 78$
Standard	$-79 < dN/dh \leq 0$	$78 < dN/dh \leq 157$
Sub-refractive	$dN/dh > 0$	$dM/dh > 157$

Table 1: Conditions for different types of refractive bending

The most dramatic effects are those that happen when there is a refractivity gradient change of less than -157N/km. This is called the trapping gradient. Under such conditions, the curvature of the radio wave bending exceeding the earth's which result in the formation of a ducting layer. The modified refractivity M is defined as:

$$M = N + 0.157h \quad (2.16)$$

where h is height in meters. According to Table 1, ducting effect happens in the trapping mechanism when $dM/dh < 0$. Thus, at the initial negative gradient point where $dM/dh = 0$, h indicates the height of the ducting layer.

In a maritime environment, three types of tropospheric ducting have been identified including surface-based ducts, elevated ducts, and evaporation ducts [22]. For low height antenna communication systems, evaporation ducts are more applicable since the other two occur up to several hundred meters in

heights above the sea level [23]. In addition, evaporation ducting is a persistent phenomenon found only over water which is created by very rapid decrease of moisture immediately above the ocean surface [22]. It is reported that the evaporation duct heights vary normally from 0m to 40m. J. R. Hampton's research [24] shows that the duct height tends to be larger in warmer climates. The mean value of evaporation duct height in the tropical region is reported to be around 30 meters [25].

B. Signal Strength Variation Due to Ducting effects

Extensive measurements have been conducted to investigate the signal strength variation due to ducting effects. In 1974, Takeo [26] conducted experiments in the area southwest of Tokyo and reported the quantitative information on fading and multipath phenomena. They concluded that the fading and multipath phenomena can be characterized as K-type fading and duct-type fading. Since then ducting effects have been an area of research interest for radio wave propagation over sea surface. P. Yue [27] has indicated in his literature that microwave propagation is significantly affected by evaporation duct, which can happen as often as 85% of the time over the sea around the world. Subsequently, signal strength variation due to ducting layers over the sea path at different frequency is extensively studied [28-32].

In 1989, H.J.M.Heamkerk and R.B.Boekema [28] conducted an experiment at Peninsula Quiberon to investigate the effects of evaporation duct.

They transmitted a wide range of signals with frequencies varying from 3 to 94 GHz over a sea path of around 27.7km in length for a period of 52 days. They then gave a statistical report of the signal strength variation at different frequencies for this link. An important finding from their literature which can be referred to in this thesis is that they observed that there was a signal strength enhancement of larger than 10dB at 5.6GHz for 48% of the time. In 2006, S.D Gunashekar and his group also did a measurement to observe the signal strength variation over a sea path [29, 30]. Different from Heamkerk, they conducted the experiment at a fix frequency of 2GHz but over 3 sea paths of different distances. They gave a conclusion on the signal enhancement phenomena during different season. Their conclusion revealed that enhancement of signal strength occurs predominantly in the late afternoon and evening during spring and summer. Recently, Y. S. Meng performed experimental studies on the effects of ducting on the air-to-ground channel over the tropical sea surface [31, 32]. In his study, it was found that around 95% of the measured channel responses can be represented by a three-ray multipath model which is caused by the reflection from the ducting layer and the propagation enhancement comparing to the 2-ray path loss model and the free space path loss model. Theoretical values also indicate to the existence of the evaporation ducts or elevated ducts.

Therefore, ducting effects have been well-recognized over the sea propagation channels. The formation and property of the troposphere ducts have been studied in detail over the years. The influence of the ducting effects

on the radio wave propagation was also investigated experimentally over different measurements conducted by different groups' of researchers all over the world. However, most of the literature focuses on the fixed channel over a large distance which is always over-the-horizon. Little work has been done on a mobile channel in maritime environment over a relatively short distance which is usually within-the-horizon. Therefore, in the thesis a further investigation is performed and the results are given in Chapter 4.

2.3 Conclusion

In this chapter, a general description to the fundamental concepts and techniques of the radio wave propagation has been introduced. Special attention is given to the channel modelling and characterization in maritime environment. Starting with a study for the path loss prediction, the different path loss models have been introduced theoretically. Large body of literature focusing on the investigation of path loss modelling over maritime environment have been summarized. The ducting effect which is a well-recognized propagation mechanism over water has been reviewed. It is understood that radio wave propagation over the sea surface can be influenced significantly by the ducting layers. However, characterization for a mobile channel with a short distance (within-the-horizon) affected by ducting layers is lacking. What's more, little literature has been done on the Non-Line-of-Sight channel modelling and characterization over a sea-to-land in maritime environment. Therefore, in the following chapters, we will mainly focus on these two areas.

Chapter 3

Channel Sounder and System Design

A literature review on the topic of channel characterization and modelling for the maritime environment was presented in the previous chapter. For most of the research work, empirical channel study is done through experimental measurement in the designated environment. In this chapter, the equipment setup used in the measurement campaign to obtain the experimental data for this research work is described, and the performance of the system is evaluated.

3.1 System Setup

3.1.1 Narrowband system

Figure 6: Narrowband channel measurement system

The equipment used for the narrowband measurement mainly consists of a signal generator and a spectrum analyzer. Details of the measurement setup are shown in Figure 6. A high power amplifier with a gain of 30dB and an omni-directional antenna are used at the transmitter. The omni-directional antennas are mounted on the top of a boat at a height of approximate 3.5m above the sea level as shown and indicated by the white circles in Figure 7(a). GPS data was logged continuously throughout the experiment so as to obtain instantaneous time, altitude, longitude, and latitude. A fluxgate compass is used to record the pitch and roll coordinates as well as the heading direction of the moving boat.

(a) Transmitter antennas

(b) Receiver antennas

Figure 7: Rx and Tx antennas of the channel sounder

At the receiver, in order to simulate the control tower and to ensure a good line of sight (LOS) condition between the transmitter and the receiver, the

antennas are mounted on the roof of a container at a height of around 10m above the sea level. Identical omni-directional antennas shown in Figure 7(b) are used to capture the transmitted signal from the boat. The received signal is then recorded through a spectrum analyzer. The peak marker readings are recorded at 1s intervals by a data logger using the Labview program connected to the spectrum analyzer via a LAN cable. All the data recorded are time stamped with the GPS time in order to synchronize the data collected at the receiver with the location, heading and orientation of the boat where the signal was transmitted.

3.1.2 Wideband System

Figure 8: Wideband channel measurement system

Figure 8 shows the setup for the wideband channel sounding system used in the measurements. PN sequence with a length of 1023-bit is used for the transmitted signal with a symbol rate of 20MSymbols/s. This setting leads to a

time resolution of 50ns which means multipath with travel distance difference more than 15 meters can be distinguished. The modulation scheme used is Binary Phase Shift Key (BPSK). The transmitted signal goes from a vector signal generator (VSG), passes through a high power amplifier (HPA) and then radiated by an omni-directional antenna. The transmitter system is placed on the boat due to its ease of use and portability. The transmitter is also equipped with a GPS system and fluxgate compass so as to obtain instantaneous altitude, longitude, latitude, pitch and roll coordinates of the moving boat. The wideband measurement receiver system is relatively complex to operate and much less portable. Identical omni-directional antenna is used to capture the signal. The captured signal is down-converted using a spectrum analyser to an intermediate frequency and then sampled at a rate of 100MSamples/s using a digitizer card controlled by a virtue instrument (VI). A GPS time-stamped data logger is used to record the signal. The following table shows the basic parameters of the wideband system,

Centre frequency	5.5GHz
Modulation	BPSK
PN length	1023-bits
Transmitting power	30dBm
Symbol rate	20Msymbols/s

Table 2: Parameters for the setting of wideband channel sounder

3.1.3 Weather information collection system

(a) Receiver side

(b) Transmitter side

Figure 9: Weather condition recording instruments

During the trials, the weather condition is recorded through a vantage pro weather station and a kestrel 14500 weather meter at both the receiver side and the transmitter side respectively. Further study will be done according to the signal strength variations due to weather effects.

3.2 System performance

In this part, the performance of the wideband system is evaluated. The designated wideband channel sounder is a spread spectrum based system which uses a Binary Phase Shift Key (BPSK) modulated at 20-Msymbols/s with 1023-bit sequence length. The theoretical system performance is discussed and some testing results are given. Next, parameters of the antennas used in the experiment are studied.

3.2.1 Performance of the Wideband sounding system

A. Dynamic Range

Dynamic range required in our measurement is the difference between the possible largest and smallest received path components in the output PDP. Every demodulator has its own dynamic range which is called Instantaneous Dynamic Range (IDR) [5]:

$$IDR = \frac{P_D^{max}}{P_D^{min}} \quad (3.1)$$

The theoretical Instantaneous Dynamic Range for the our m-sequence coded waveform channel sounding system is $20\log_{10}(L)$ in dB[5], which is 60.2dB.

To differentiate Instantaneous Dynamic Range from the receiver dynamic range, we refer to the receiver dynamic range as the Total Dynamic Range (TDR). The total dynamic range is the ratio of the ceiling of our device to the noise floor [5]:

$$TDR = \frac{P_{in}^{sat}}{MDS} \quad (3.2)$$

where P_{in}^{sat} is the saturation input power of the signal which is the ceiling of our device. MDS is the minimum detectable signal of the receiver which is also known as the noise floor. In our case the saturation input power of the signal is 23.5dBm while the noise floor of the receiver is found to be -47.6dBm. Thus, the total dynamic range (TDR) is $23.5+47.6=71.1$ dB.

B. Multipath Resolution

Multipath resolution of the wideband channel sounder is the minimum delay time between two received signals through different path. The theoretical value of multipath resolution is related to the symbol rate of the transmitted signal which is:

$$\text{Multipath Resolution} = \frac{1}{T_s} \quad (3.3)$$

where T_s is the symbol rate of the transmitted signal. In our wideband channel sounding system where the symbol rate is 20Msymbols/s, the theoretical value for multipath resolution is 50ns according to equation (3.3). That means two received signal which can be observed using our wideband channel sounding system should at least has a path difference of

$$(50\text{ns} \times 3 \times 10^8\text{m/s}) = 15\text{m} \quad (3.4)$$

where $3 \times 10^8\text{m/s}$ is the radio wave speed in free space.

A set of measurement was done in laboratory environment to investigate the accuracy of the system. In the measurement, two different RF cables with length of 1m and 50m respectively were used between the transmitter and receiver.

Figure 10: Power delay profile for signals through two RF cables with length of 1m and 50m.

In the PDP, we can observe that the time delay between the two received signals is 0.19×10^{-6} s which is equivalent to a free space distance difference of 57m. The dielectric constant ϵ_r for the RF cable is 1.21, so the path difference for the two received signal is 47.1m. The actual length difference between the two RF cables is 49m. The measured results basically show good agreement with the actual value. The error is mainly because of connectors used.

3.2.2 Parameters of the Antennas

Two types of antennas are used in the measurements for the thesis at different scenarios. In this section, some basic parameters such as gains and radiation patterns for the antennas are introduced.

A. Omni-directional antennas

The frequency range for the omni-directional antenna is 5.1GHz to 5.9GHz and the gain is about 8dBi. The antenna has a horizontal beam width of 360 degree and a vertical beam width of 16 degree. The beam pattern is shown below in Figure 11.

Figure 11: Radiation pattern

B. Directional antennas

The frequency range for the directional antenna is 5.15GHz to 5.85GHz and the gain is 16dBi. The antenna has a horizontal beam width of 90 degree and a vertical beam width of 8 degree. The beam pattern is shown below in Figure 12.

Figure 12: Radiation pattern

3.3 Conclusion

In this chapter, an introduction on the system setup for the measurement involved in the thesis is given, and system performance is evaluated before the main experiment. There are two types of channel sounders which are narrowband and wideband system. The narrowband sounding system is relatively simple to be implemented. Details on the performance of the wideband sounding system are presented and some pre-trial experiments are conducted to verify the accuracy of the system. Finally, some important parameters of the antennas used are introduced. The system setups are applied to the measurements involved in the following chapters.

Chapter 4

Line-of-Sight Path loss Modelling

Large-scale path loss characterization is investigated under maritime environment in Line-of-Sight scenarios at 5GHz band. Measurements using narrowband sound system are conducted at the open sea area in southeast of Singapore. The results are then compared with theoretical values predicted by two-ray path loss model which considers both the direct path and a reflection path from the sea surface. What's more, a new three-ray path loss model considering the ducting effects is also proposed in this chapter to achieve better prediction ability. The results and discussions are then illustrated in the following sections.

4.1 Measurement route

Figure 13: Measurement route

The first set of measurements for the channel characterization were conducted in the open sea environment with line-of-sight between the receiver onshore and the transmitter on boat, using the narrowband measurement setup mentioned above at 5GHz band. The measurement campaign was conducted at SAF yacht club located in the south-eastern of Singapore. During the campaign, the boat was driven to move away from the receiver onshore in a straight path up to approximately 10 km away as illustrated in Figure 13. The height for transmitter antennas are 3.5m and the receiver antenna heights are 20m, 10m, and 7.6m respectively.

4.2 Measurement results

4.2.1. Verification of two-ray path loss model

For the radio-wave propagation in free space, the propagation loss can be predicted by the FSL model [16] as

$$L_{\text{FSL}}(\text{dB}) = -27.56 + 20\log_{10}(f) + 20\log_{10}(d) \quad (4.1)$$

where L_{FSL} is the free space loss in dB, f is the frequency in MHz, and d is the propagation distance in meters.

When a reflected ray from the sea surface exists, besides the LoS (direct ray) component, the propagation loss could be predicted by a 2-ray path loss model. Since there is a near-grazing incidence on the sea surface in our measurements, the reflection coefficient for a vertically polarized wave approaches -1. Therefore, the 2-ray path loss model can be simplified as [5]

$$L_{2\text{-ray}}(\text{dB}) = -10\log_{10} \left\{ \left(\frac{\lambda}{4\pi d} \right)^2 \left[2\sin \left(\frac{2\pi h_t h_r}{\lambda d} \right) \right]^2 \right\} \quad (4.2)$$

where $L_{2\text{-ray}}$ is the 2-ray propagation loss in dB, λ is the wavelength in meters, and h_t , h_r are the heights of a transmitter and a receiver antennas in meters. In the following part, both the FSL model and the 2-ray path loss model will be used to predict the received signal strength under ideal conditions for the near sea-surface radio-wave propagations at 5.15 GHz.

Three typical measurement results with different receiver heights ($h_r = 7.6$ m., 10 m, and 20 m) are shown in Figure 14, together with the modelled signal

strength using the FSL model and the 2-ray path loss model (assuming an ideal case with perfect sea-surface reflection). From Figure 14, it can be observed that the FSL model is able to model the exponential decreasing trend of the received signal strength for all 3 receiver heights. The FSL model is well suited for the prediction of the local mean (large scale) propagation loss. These observations are consistent with those reported in [22, 31]. More interestingly, when the propagation distance is less than about 2000m to 3000m (from Figure 14), the measured results show a similar trend as the modelled results using the 2-ray path loss model for all measurement scenarios. That is, there are some interference nulls which are due to the destructive summation of the radio waves (the direct wave and the sea-surface reflected wave from the modelling process of 2-ray model) arriving at the receiver. It is noted that, the slight misalignments of the predicted nulls with respect to the measured ones are due to the roughness of the sea surface [33, 34] which weakens the perfect sea-surface reflection assumed in the 2-ray propagation loss modelling.

However, it is observed from Figure 14 that as the propagation distance increases beyond about 2000m to 3000m, the prediction abilities of both the FSL model and the 2-ray path loss model for the near sea-surface environments become poor. There are some nulls due to interference in the measured results beyond about 2000m to 3000m (known hereby as the critical distance) that is not predicted by both the FSL model and the 2-ray path loss model. As seen in Figure 14, both models tend to approach a stable signal level which follows a log-normal decrease. Moreover, some signal enhancements are also observed

from the measured results (e.g. in Figure 14(a) at 7000 m). These phenomena may be caused by the evaporation duct which is known to exist over the sea surface almost all of the time [35] in the tropical region. From the works reported by other researchers, the evaporation duct can trap the over-water radio-wave propagating signals [23] and can also result in a substantial increase in the received signal strength at frequencies above 3 GHz [22]. Therefore, a multi-ray path loss model which takes the signal trapped in the evaporation duct into consideration should be used. The model considered should also be able to account for the enhancement effects from the evaporation duct for the over-water radio-wave propagations for large distances beyond the critical distance.

In order to estimate this critical distance, beyond which the 2-ray path loss model ceases to provide good path loss prediction, we study the trend of the FSL model and the 2-ray path loss model. As distance increases beyond the last null predicted by the 2-ray path loss model, both models tend to level out slowly. Therefore, it can be concluded that the 2-ray path loss model will provide accurate prediction up to a distance of its last predictable null. This distance can be derived as

$$d = \left(\frac{4h_r h_t}{\lambda} \right) \quad (4.3)$$

where h_t is the height of transmitter antenna, h_r is the height of receiver antenna and λ is the wavelength of the transmission signal. The critical distance can therefore be estimated by using (4.3). For our measurement campaign, the

critical distances are found to be 4000m, 2000m and 1500m for the receiver antenna heights of 20m, 10m and 7.6m respectively.

For the path loss modelling beyond the critical distance (4.3), a multi-ray path loss model is considered. In the following section of this paper, a 3-ray path loss model, taking into consideration the reflection from the evaporation duct is proposed.

(a) Results at receiver height of 20 meters above the sea level conducted on 23 Nov 2011 17:08 to 17:50

(b) Results at receiver height of 10 meters above sea level conducted on 28-Sep 2011 17:46 to 18:06

(b) Results at receiver height of 7.6 meters above sea level conducted on 3 Apr 2012 11:21 to 11:49

Figure 14: Received signal power versus distance at different receiver heights with predicted from 2-ray model and measured values

4.2.2. Optimized model considering ducting effect

As discussed above, although the 2-ray path loss model shows a good ability to predict the propagation loss in this tropical maritime environment, its prediction ability becomes poor when the propagation distance exceeds the critical distance obtained using (4.3). According to (4.3), this critical distance is found to be dependent on the height of the transmit antenna, the height of the receive antenna, and the frequency of transmission. For example, interference nulls observed in Figure 14 (a) at around 900 m, 1100 m and 2100 m (within the critical distance of 4000m) can be predicted using the 2-ray path loss model. While the nulls at 4100 m, 5300 m and 6200 m (beyond the critical distance of

4000m) cannot be predicted by the 2-ray path loss model. These nulls could be due to the interference from the trapped waves within the evaporation duct as illustrated in Figure 15.

The trapped waves in an evaporation duct can be a single-reflected wave or multi-reflected wave between the sea surface and the upper boundary formed by the evaporation duct layer (Figure 15). As the upper boundary of the evaporation duct layer is not homogenous (or not 'solid' as described in [23]), a small amount of energy from the incident waves onto the upper boundary will be transmitted across the boundary into the free space layer immediately beyond the duct layer, shown in Figure 15.

Figure 15: Illustration of radio-wave propagations in an evaporation duct

In order to further investigate the signal nulls observed in the measured results beyond the critical distance (4.3) in Figure 14 which cannot be predicted by the 2-ray path loss model, a multi-ray path loss model is examined. Due to the leakage of the propagating energy at the upper boundary of the duct layer,

the energy level of the multi-reflected wave is significantly lower than the first-order reflection (i.e. the single reflected wave) from the upper boundary of the duct layer. Hence, the single reflected wave is expected to be one of the major contributor to the received fields, which includes the direct wave and the sea surface reflected wave. Therefore, a 3-ray path loss model (including the direct LoS ray, a reflected ray from the sea surface and also a reflected ray from the upper boundary of the duct layer) is used to predict the near sea-surface radio-wave propagation.

In order to perform the 3-ray path loss modelling, three assumptions are made; the evaporation duct layer is assumed to be horizontally homogeneous; similar to the 2-ray path loss model described earlier, a near-grazing incidence on both the sea surface and the upper boundary of the evaporation duct layer is assumed; and finally, the reflection coefficient for a vertically polarized wave for both boundaries is assumed to approach -1. With these assumptions, the 3-ray path loss model [20] can be simplified into (4.4).

$$L_{3\text{-ray}}(\text{dB}) = -10\log_{10} \left\{ \left(\frac{\lambda}{4\pi d} \right)^2 [2(1 + \Delta)]^2 \right\} \quad (4.4)$$

where

$$\Delta = 2\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right) \sin\left(\frac{2\pi(h - h_t)(h - h_r)}{\lambda d}\right) \quad (4.5)$$

where h_t and h_r are the height of the transmitter and the receiver in meters over the sea level, and h is the height of the evaporation duct layer. In order to know

the exact height of the evaporation duct layer, weather information such as air humidity, temperature, wind speed and pressure is required at regular distance intervals above the sea level up to a height of 40m or more. However, due to the limited weather measurement equipment, it is difficult to collect high resolution weather information at the location of the experimental site. This restricts the accurate estimation of the evaporation duct height h . Therefore, the single point weather information collected at both the transmitter and receiver are used to estimate the duct layer height. The theoretical duct height for all the 21 measurement campaigns can be calculated using the modified P-J formulation given in [25]. The distribution for these theoretically calculated duct heights is plotted in Figure 18 (a).

Note that the duct height calculated using the P-J formulation is very sensitive to the weather information. Therefore, a more accurate way of determining the actual ducting height is by deriving it empirically through the curve fitting technique.

In order to empirically derive the evaporation duct height, the measured signal strengths are first investigated against the calculated signal strengths using (4.4) with different evaporation duct height h , for example at 25 m, 35 m, and 45 m respectively. One sample of results under comparison is shown in Figure 16.

Figure 16: Sample of the received signal strength versus distance with the calculated values using the 3-ray model at different evaporation duct height $h = 25$ m, 35 m, and 45 m

(a) Results at receiver height of 20 meters above the sea level conducted on 23 Nov 2011 17:08 to 17:50

(b) Results at receiver height of 10 meters above sea level conducted on 28-Sep 2011 17:46 to 18:06

(c) Results at receiver height of 7.6 meters above sea level conducted on 8 Feb 2012 11:21 to 11:49

Figure 17: Received signal power versus distance at different receiver heights with predicted from 3-ray model and measured values

From Figure 16, it can be observed that the signal nulls beyond the critical distance of 1500m in the measured signal strengths which cannot be predicted by the 2-ray path loss model previously can be estimated using the 3-ray path loss model. The misalignment of the measured nulls with the modelled ones is due to the improper assignment of the values of the evaporation duct layer height h . Therefore, for the channel modelling of propagation above the tropical sea surface, a 3-ray path loss model that not only considers the direct ray and the sea reflected ray, but also the duct reflected ray, should be used.

In order to take into consideration the effect of the complex over-sea surface radio-wave propagation mechanism such as the leakage of waves from the upper boundary of the duct layer, the roughness of the sea-surface and the non-homogenous evaporation duct layer, a parameter known as the effective evaporation duct height h_{eff} is introduced in this study. A statistical analysis of this effective evaporation duct height will be presented. The empirical values for h_{eff} are evaluated by varying the value of h in (4.4) and performing curve fitting onto our measurement data (as shown in the example in Figure 13). The curve fitting of the 3-ray path loss model to the measurement results for all 3 receiver heights in order to obtain the effective duct height is presented in Figure 17. For completeness, both the FSL model and the 2-ray path loss model are also shown in Figure 17.

From Figure 17, it can be observed that the fitted 3-ray path loss model shows a good prediction ability when the propagation distance is beyond the critical distance. The effective evaporation duct height h_{eff} obtained from the

curve fitting of (4.4) to the measurement results is able to predict the signal variations of the actual measurements very well. Similarly, the effective evaporation duct height could be found for all the 21 measurements done over the tropical maritime environment (Figure 18(b)). This shows that the 3-ray path loss model which takes into consideration the contribution of the reflected wave from the upper boundary of the evaporation duct layer is more appropriate for near sea-surface propagation loss prediction as compared to the popularly used 2-ray path loss model particularly for distances beyond the critical distance. This is because the ducting effect usually becomes significant for long-range over-sea radio-wave propagations. When the propagation distance is below the critical distance, the ducting effect is almost negligible where the reflection from the sea surface and the direct line of sight waves dominate. Thus, the 2-ray path loss model is more appropriate for short-range near sea-surface propagation loss prediction whereas the 3-ray path loss model should be used for long-range near sea-surface propagation.

Next, a statistical analysis of the variation in the duct heights, both theoretically calculated and empirically obtained from all the 21 measurements (effective duct height) is performed. The distribution of the effective evaporation duct height is plotted in Figure 18 (b).

From the literature, it is found that the occurrence probability of evaporation duct around nearby marine environments such as the South China Sea is around 80%, and the annual average height of the evaporation duct layer

h is around 7 to 15m [36]. These values are similar to those calculated using the P-J formulation for the 21 measurement campaigns shown in Figure 18(a).

It is also noted that the average height of evaporation duct h can be about 25 to 40 m as reported in [36] during the months of March, April, September and November which are similar to the months in which our trials were conducted. These values are similar to those derived empirically shown in Figure 18 (b).

In Figure 18(b), results show that most (around 86%) of the estimated effective duct heights falls within the range of 20 m to 40 m, with a median value of 30.5 m. This obtained statistic is close to those reported in [36] where the average height of evaporation duct h is between 25 m to 40 m at a nearby marine environment during similar months of March, April, September and November. This result is more reliable than the calculated result for ducting height which falls mainly in the range of 10m to 18m. The theoretically calculated duct heights tend to underestimate the actual duct height. This might be due to the non-homogenous duct layer and imperfect reflection surface of the upper boundary of the duct layer. The findings therefore further prove the feasibility of applying the 3-ray propagation model in a near sea-surface microwave channel over the tropical maritime environment and that the effective duct height can be obtained empirically via curve fitting techniques.

(a) Calculated ducting height

(b) Effective ducting height

Figure 18: Distribution of the calculated and effective evaporation duct height

4.3 Conclusion

This chapter reports an experimental investigation of near sea-surface radio-wave propagations at 5 GHz through narrowband channel measurements and characterizations. The experimental results indicate that there is a good agreement between the measured results and the predicted values using the 2-

ray path loss model when the propagation distance is less than the critical distance.

However, when the propagation distance increases beyond the critical distance, the prediction ability of the 2-ray model becomes poor. Our results and analysis show that the 3-ray path loss model taking into consideration both the reflections from the upper boundary of the evaporation duct and the sea surface can well predict the trend of the signal strength variations in the tropical maritime environments. The results also show that most (around 86%) of the estimated effective duct heights falls into the range of [20 m, 40 m] with a median value of 30.5 m, which is close to reported values at a nearby marine environment. However, the theoretically calculated duct height using P-J formulation tends to underestimate the duct height due to the imperfect duct layer formed. Therefore, it can be concluded that a 2-ray path loss model should be used for distances less than the critical distance and the 3-ray path loss model should be used for distances beyond the critical distance. An accurate way for deriving the effective duct height is via curve fitting.

Chapter 5

Coherence Bandwidth Study in Open Sea Scenario

Besides large-scale path loss characteristic of the maritime communication link, the small-scale multipath fading also influences the channel performance significantly. To investigate the small-scale multipath fading effects in open sea scenario, power delay profile of the channel impulse response is presented. Parameters such as delay spread and coherence bandwidth along the specific measurement route are also indicated. Multipath fading mitigation techniques such as using directional antennas and antenna diversity are also briefly introduced and evaluated in this chapter. These are of great importance for military applications. According to the problem and observation from ST Electronics on their selected USV operating route, a set of sea trials were conducted along this route to characterize the channel. Both the narrowband and wideband measurements were taken through several trips. Different antennas setting are used in this measurement to investigate the multipath phenomenon. Same channel measurement equipment was used which is mentioned in Chapter 3. The results and discussions are then illustrated in the following sections.

5.1 Both omni-directional antennas on transmitter and receiver side

Measurements are firstly conducted using omni-directional antennas at both the transmitter and receiver sides so that detailed channel information including as much multipath as possible can be received. The settings are shown in the following table.

Receiver location	SAF yacht club (N 01°19'09", E 104°1'22")
Transmitter antenna type	Omni-directional
Transmitter height	3.5m above sea level
Receiver antenna type	Omni-directional
Receiver height	10m above sea level
Dates of measurement	April 5-7 2011

Table 3: Details of the measurement setup

5.1.1 Measurement Route

Both wideband measurements centred at 5.5GHz and narrowband measurements centred at 5.15GHz were performed to characterize the channel. The receiver was at the same position of the SAF yacht club. The transmitter boat went through the route indicated in Figure 19. The route starts from approximated 2.5km from the receiver going towards west for about 1km, then

turns back and goes the reverse direction. The route is plotted on a Google map shown below.

Figure 19: Selected operating route for USV

5.1.2 Measurement Results

A. Narrowband Results

The narrowband measurements were taken to investigate the signal strength variations along the operating route. The centre frequency was at 5.15GHz. After processing the data collected, the signal-to-noise ratio (SNR) at each different point is scattered on Google map according to the GPS location

recorded. Figure 20, 21 and 22 show three different trips along the operating route at different time during the 3-day measurement campaigns.

Figure 20: SNR plot for trial on April 5, UMT 7:17am - 7:36am

Figure 21: SNR plot for trial on April 6, UMT 4:36am - 4:53am

Figure 22: SNR plot for trial on April 6, UMT 7:25am – 7:44am

The signal strength variation can be easily observed along the route from the SNR scattering plot. The entire three diagrams indicate that the signal strength is not stable along the route. There are some points of signal dips distributed along the route which are indicated by the enclosed areas with white line on the diagrams. This observation of signal strength variation probably results from the multipath fading due to the complex environment. As shown in Figure 23, there are amounts of large ship anchored near the operating route.

Figure 23: Far view of the entire environment around operating route

The large metallic body of all the anchored ships can be considered as reflectors for the radio wave. Since the antenna used is omni-directional, the signal probably would emit to the large ship and then reflected back to the receiver. The reflected multipath together with LOS direct path from transmitter to receiver may cause constructive or destructive effect on the received signal strength depending on the phase difference. The signal dips observed on the SNR plot could be probably due to the destructive combination of the multipath. In order to further study the multipath fading effect, wideband measurements were taken for channel sounding. The results are discussed in next section.

B. Wideband Results

Wideband measurements were taken together with narrowband transmission using the other set of antennas. The centre frequency was at 5.5GHz. As mentioned in chapter 3, a direct sequence spread spectrum system is used for the wideband channel sounding. A 1023-bit PN sequence is transmitted at a rate of 20Msymbols/s. The sequence is modulated using Binary Phase Shift Key (BPSK). With these setting, a time resolution of 50ns is achieved. That is multipath separated by more than 15 meters can be distinguished in the power delay profile. From this property, details of multipath propagation can be investigated and parameters such as RMS delay spread and coherence bandwidth can be calculated.

I. Multipath

After processing the wideband measurement results, averaged power delay profile can be shown to investigate on the multipath. There are thousands of points along the entire route, so it is not meaningful to show each point's power delay profile. 10 areas are chosen indicated in Figure 24.

Figure 24: 10 areas selected along the route

The averaged power delay profile is processed for three different trips at different time and then coherence bandwidth is calculated. Trip 1 was conducted on April 5, UMT 7:17 am – 7:36 am. Trip 2 was conducted on April 6, UMT 4:36 am – 4:53 am. Trip 3 was on April 6, UMT 7: 25 am – 7:44 am. Coherence bandwidth for the 10 selected areas is shown in Table 4.

Due to multipath, coherence bandwidth for all the 10 zones are quite small. The results show that the signal strenth would go through severe fading once the operation bandwidth is larger than it. Therefore, the communication link operated by ST Electronic at 20Msymbols/s would definitely not be stable.

	Coherence Bandwidth		
	Round 1	Round 2	Round 3
Zone 1	0.2423MHz	0.2229MHz	0.3568MHz
Zone 2	0.4036MHz	0.8365MHz	0.1223MHz
Zone 3	0.6899MHz	0.2479MHz	0.2811MHz
Zone 4	0.1606MHz	0.1047MHz	0.0647MHz
Zone 5	0.1396MHz	0.9221MHz	0.2054MHz
Zone 6	0.066MHz	0.8516MHz	0.0904MHz
Zone 7	0.1640MHz	0.2628MHz	0.1550MHz
Zone 8	0.1533MHz	0.1982MHz	0.3175MHz
Zone 9	0.7139MHz	12.9078MHz	0.1617MHz
Zone 10	0.3134MHz	0.8538MHz	0.3023MHz

Table 4: Coherence Bandwidth for 10 zones

5.2 Directional antenna on receiver side

After investigating the channel information using both omni-directional antennas at the transmitter and receiver sides, cluster of multipath received are identified in the PDP. Coherence bandwidth along the route is found to be relatively small due to the influence of large amount of multipath. Therefore, directional antenna is then using at the receiver side to conduct further investigation.

Receiver location	SAF yacht club (N 01°19'09", E 104°1'22")
Transmitter antenna type	Omni-directional
Transmitter height	3.5m above sea level
Receiver antenna type	Directional with 90° beam width
Receiver height	10m above sea level

Dates of measurement	June 1-2 2011
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Table 5: Measurement set up

5.2.1 Measurement Route

Figure 25: Selected operating route for USV

Both wideband measurements centred at 5.5GHz and narrowband measurements centred at 5.15GHz are performed to characterize the channel. The receiver is on the same position at SAF yacht club. The transmitter boat went through the route indicated in Figure 25. The route starts from approximated 2.5km from the receiver going towards the west for about 1km, then turns back and goes in the reverse direction towards the east.

5.2.2 Measurement results

A. Narrowband Results

The narrowband measurements were taken to investigate the signal strength variations along the route. The centre frequency was at 5.15GHz. The results using both the omni-directional antenna on each side have been discussed in last report. So in this report, both the results from omni-directional and directional antenna on receiver are shown in Figure 26.

(a) Omni-directional antenna on both side

(b) Directional antenna on receiver side

Figure 26: SNR plot along the operating route

Figure 26 (a) is the result from 1st of June using both omni-directional antenna on each side. It is used as a reference to be compared with the results shown in Figure 26(b) which is conducted in the same day with directional antenna on receiver. As indicated in previous section, signal reflected from other large ships or land structures can cause constructive or destructive combination of the multipath and LOS path respectively. This is why the SNR reductions and enhancement seem to be random along the route. However, using the directional antenna on receiver, there seems to be less variation along the route possibly because of some of the multipath could not be received by the antenna due to its beam width. Moreover, since the directional antenna has a higher gain compare to the omni-directional one, an approximately 3-4dB enhancement on signal strength is observed. In order to further study the

multipath fading effects due to the dynamic and static reflectors, wideband measurements recorded simultaneously with the narrowband measurements are analysed. The results are discussed in next section.

B. Wideband Results

Wideband measurements are taken together with the narrowband transmission using identical antennas. The centre frequency was at 5.5GHz. As mentioned in Chapter 3, a direct sequence spread spectrum system is used for the wideband channel sounding. A 1023-bit PN sequence is transmitted at a rate of 20Msymbols/s. The sequence is modulated using Binary Phase Shift Key (BPSK). With these setting, a time resolution of 50ns is achieved. That is multipath separated by more than 15 meters can be distinguished in the power delay profile. From this property, details of multipath propagation can be investigated and parameters such as RMS delay spread and coherence bandwidth can be calculated. Coherence bandwidth for the 10 selected areas is shown in Table 6.

Figure 27: 10 areas selected along the route

	Omni	Directional
Zone 1	0.6303MHz	20.8314MHz
Zone 2	0.3033MHz	21.537MHz
Zone 3	0.1707MHz	0.5574MHz
Zone 4	0.2784MHz	0.3717MHz
Zone 5	3.2563MHz	9.7995MHz
Zone 6	0.2830MHz	11.5947MHz
Zone 7	0.1082MHz	0.4698MHz
Zone 8	0.1716MHz	0.0280MHz
Zone 9	4.4335MHz	0.0938MHz
Zone 10	0.2830MHz	0.0738MHz

Table 6: Coherence bandwidth for 10 zones

The results show that improvement for the coherence bandwidth can be seen after introducing the 90 degree beamwidth directional antenna. 7 out of 10 zone have a significant increase on the coherence bandwidth and some of them even exceed 20MHz which is the maximum bandwidth operated by ST Electronics. These results are very useful which indicating that by limiting the direction of transmission, the multipath due to the complex maritime

environment could be reduced. However, there are still many multipath and smaller coherence bandwidths existing in more than half of the zones. In order to further increase the performance of the communication link, directional antenna is then used both on transmitter and receiver side. The results would be shown in next section.

5.3 Directional antennas on both sides

The results from last section show that the coherence bandwidth along the route can be improved significantly after implementing directional antenna at the receiver side. Thus in this section, both transmitter and receiver sides are equipped with 90 degree directional antennas to have a further investigation.

Receiver location	SAF yacht club (N 01°19'09", E 104°1'22")
Transmitter antenna type	Directional with 90° beam width
Transmitter height	3.5m above sea level
Receiver antenna type	Directional with 90° beam width
Receiver height	10m above sea level
Dates of measurement	Sep 13-14 2011

Table 7: measurement set up

5.3.1 Measurement route and setup

The measurement route is the same as introduced in previous section. Both the transmitter and receiver are implemented with directional antennas to further enhance the channel performance. However, the transmitter is mounted on the boat which is mobile. Thus, beam-switching device is used to make sure the LOS transmission within the beamwidth. The setup is shown in Figure 28.

Figure 28: Beam-switching antennas setup

4 directional antennas with 90° beamwidth facing different directions are mounted on the top of the transmitter boat. A switcher is then used to control which one of the four is transmitting according to the heading direction of the boat so that the receiver antenna is always within the beamwidth of the transmitter antenna. The other parameters are kept the same. With these directional antennas, the emission angle of signal has been limited. Therefore, there should be less possibility for reflection, diffraction and scattering which

could result in multipath. The measurement is then analysed in the following section to verify it.

5.3.2 Measurement results

A. Multipath

Similar wideband measurement is taken using the beam-switching directional antennas. All the transmission parameters such as frequency, modulation and symbol rate are kept the same. After processing the measurement results, averaged power delay profile is investigated to calculate the coherence bandwidth. The results are listed in Table 8.

Four sets of trials have been done during 13-14 Sep, two with the beam-switching antennas on the highest point of the boat's top mounting and two with the beam-switching antennas on the lowest point of the boat's top mounting. There is 40cm difference on the height of the transmitter antennas between the highest point and lowest point. The coherence bandwidth is first calculated for each of the trial and then effects on the height of transmitter antennas are also reported in the following part.

Zone/CB	Highest point (14-Sep)	Lowest point (14-Sep)	Highest point (13-Sep)	Highest point (13-Sep)
1	17.08MHz	2.10MHz	4.5MHz	6.93MHz
2	7.292MHz	11.12MHz	12.78MHz	12.1667MHz
3	14.448MHz	8.43MHz	8.7MHz	7.528MHz
4	11.5428MHz	14.3116MHz	11.73MHz	10.08MHz
5	0.092MHz	14.6054MHz	13.4MHz	Inf(no multipath)
6	10.7MHz	12.1991MHz	Inf (no multipath)	Inf (no multipath)
7	Inf(no multipath)	14.8126MHz	19.32MHz	13.58MHz
8	6.4181MHz	13.7615MHz	6.9MHz	11.5MHz
9	5.89MHz	7.8042MHz	16.0328MHz	9.37MHz
10	25.68MHz	13.96MHz	18.186MHz	15.58MHz

Table 8: Coherence bandwidth for 4 different trials

As expected, the coherence bandwidths are improved quite significantly compared to the ones using either omni-directional antennas or directional antenna only on the receiver side. Most of the zones have a coherence bandwidth larger than 10MHz. A system with 10MHz bandwidth in total would experience flat fading. In summary, by introducing the parameter of coherence bandwidth, a reference on communication link performance has been set up. It is a very useful indicator to examine whether the communication link could be maintained consistently.

B. Effects on transmitter antenna height

As indicated previously, four sets of trials have been done in total with different transmitter heights. The transmitter antenna height will be 3.5m with the beam-

switching antennas mounted on the highest point and 3.1m at the lowest point. First, two sets of data conducted in 13-Sep would be analyzed with different antenna height.

Figure 29: SNR distribution for trials on 13-Sep

The two separated trials are conducted one by one closely to make sure the environment nearly keeps the same. Figure 29 shows the SNR distribution along the route for both trials. Statistically, the mean value of SNR for antennas at highest point is 23.8817dB with a standard deviation of 6.52dB, while the mean value of SNR for antennas at lowest point is 23.7793dB with a standard deviation of 5.98dB. From this point of view, it is hard to tell which one is better because that although the SNR mean value for higher antenna setting is better, it has a larger deviation. Thus, we look into the cumulative distribution function of the two sets of data.

Figure 30: CDF plot of data with different transmitter antenna height on 13-Sep

The cumulative distribution function (CDF), or just distribution function, indicates the probability that a real-valued random variable X with a given probability distribution will be found at a value less than or equal to x . In our case, for example at the probability of 0.7, the readings for antenna at high and low points are 27dB and 26dB. It means there is a probability of 70% for SNR below 27dB with higher antenna and 26dB with lower antenna. From Figure 30 we can tell that at higher probability higher antenna has better performance while at lower probability, the lower antenna seems to be better. Similar measurement has been done on 14-Sep again to further verify the result.

Figure 31: SNR distribution for trials on 14-Sep

Figure 32: CDF plot of data with different transmitter antenna height on 14-Sep

Same set of measurements have been done on 14-Sep with different antenna heights. The SNR normal distribution is plotted in Figure 31. This time, the mean value of SNR for antennas at highest point is 26.4955dB with a standard deviation of 4.9734dB, while the mean value of SNR for antennas at

lowest point is 25.7645dB with a standard deviation of 4.9946dB. The results show a little difference from it is on 13-Sep. The possible reason includes different weather condition and maritime environment. From these results on 14-Sep, it shows that with almost the same standard deviation, SNR mean value is approximately 1dB larger for higher antenna settings. This is also corresponded to the result of CDF plot on Figure 32. SNR of higher antenna setting has better performance at almost all the probability. In conclusion, different transmitter antenna setting indeed results in a slightly different channel performance. Higher antenna setting seems to be better in terms of SNR value along the route.

5.4 Antenna diversity system

To have a further investigation on the channel performance, antenna diversity system is designed and tested in this section.

Receiver location	SAF yacht club (N 01°19'09", E 104°1'22")
Transmitter antenna type	Two omni-directional antennas with 1m separation
Transmitter height	3.5m above sea level
Receiver antenna type	Two omni-directional antennas with 1m separation
Receiver height	10m above sea level

Dates of measurement	Sep 27 2011
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Table 9: Measurement setup

5.4.1 Measurement route and setup

The measurement route is still the same which is the operating route indicated in section 5.1.1. For this set of measurement, a two-by-two antenna system is introduced to investigate the effects of antenna diversity both at transmitter side and receiver side. Two identical omni-directional antennas are mounted on the top of the boat with a separation of about 1m to transmit two different set of PN sequence simultaneously. At the receiver side, another two identical omni-directional antennas are mounted on the roof top of a container also with a separation of approximate 1m. Therefore, it forms a two by two antennas combination resulting in a total number of 4 sets of data. A simple flow diagram is shown below.

Figure 33: Simple transmission schematic diagram

5.4.2 Measurement results

Calibration has been done before process the data. After careful analysis and processing, the SNR plot along the operating route for 4 different set of data from the two-by-two antenna system is shown in Figure 34.

(a) Tx 1 – Rx1

(b) Tx 2 – Rx 1

(c) Tx 1- Rx 2

(d) Tx 2 – Rx 2

Figure 34: SNR plot along the route for MIMO system

Antenna diversity which implements more than one antenna to get a better quality and reliability of the wireless channel is often used in the multipath environment. Signal may be reflected, diffracted, or scattered before finally reaching the receiver. All the multipath components are then summed up either constructively or destructively. This significantly influences the performance of the wireless link. In this case, antenna diversity is especially effective to enhance the performance through mitigating the multipath fading. Different antennas offer a different view of the same transmitted signal. While one antenna experiences a severe fading, another one may offer a sufficient signal. This can be clearly observed in Figure 34. At the same point of

transmitter, low received signal strength may be experienced in one of the links, while the others still offer relatively high signal strength.

Selection combining technique is used in our two-by-two system which means at each point, the one with highest SNR out of the 4 sets would be chosen as the final recording. A CDF plot accompanies with the selective combination is shown below.

Figure 35: CDF plot for MIMO selection

It is clearly shows that a significant diversity gain can be achieve using the two-by-two antenna system. From Figure 35, it is observed that, the selection combining can improve the communication links. For example, for the communication link, there is a probability of 50% for all the 4 sets of received signal with strength of less than 30dB SNR. However, when the selective combing is employed for the two by two antenna system, the probability

reduced to around 10%. This improvement is obtained by using a space diversity of 1m separation both for transmitter antennas and receiver antennas. These results indicate that if proper antenna diversity scheme is implemented, relative smaller power is then needed for the transmitter to maintain the communication link in terms of system design. In our case, it means that the multipath fading effect would have less influence on the channel performance. Higher diversity gain is expected to be achieved if larger antennas separation can be employed.

5.5 Conclusion

In this chapter, a detailed channel characteristic along a pre-defined route in LOS scenario is studied. Both narrowband and wideband sounding techniques are used in the measurement. Then signal strength variations along the route are investigated. Power delay profiles are also processed to get the parameters such as delay spread and coherence bandwidth. It is found that the coherence bandwidth is limited by the influence of multipath received. Therefore, two useful techniques to eliminate the multipath fading effect and to enhance the channel performance are proposed. One is using directional antenna on the transmitter and receiver, and the other is using antenna diversity design. From the measurement results, it shows that both the two method can significantly enhance the channel performance statistically. These results are valuable in the USV communication system design.

Chapter 6

NLOS communication link study

Besides the extensive measurement conducted in the operating route, plenty of trials are also done under the NLOS scenarios. Research on the channel performance of NLOS conditions when the LOS communication link is blocked by the large anchored ships off the coastal area is another important objective of this project. The non-line-of-sight transmission is made difficult due to the material and relative size of the ship. Since the ship is a pure metallic structure, it is impossible for the electromagnetic waves to penetrate through it. The scenario is illustrated as below.

Figure 36: NLOS scenarios

For some maritime environments such as around the coast of the sea port island of Singapore, large vessels (e.g. cargo ships) crowd the coast lines. In

such scenarios, the Non-line-of-sight (NLoS) propagation created by the large vessels is often encountered. The large vessels are normally anchored about 3 km to 5 km off the shores. The study of NLoS propagation therefore becomes crucial since the 5 GHz microwave link can be diffracted by the large metallic body of the large vessels anchored between the on shore control station and the moving vessel. The NLoS propagations over the maritime environment is also different from those in urban areas [12] and forested areas [15] since the blockage in the maritime environment is caused by large metallic bodies. Therefore, it is of great interest and importance to investigate the NLoS maritime mobile radio channel in the 5 GHz band.

Because the large metallic body of cargo ships could fully block the propagation paths and make the communication link almost impossible when the mobile vessel is behind the obstructing ship (Figure 36), a parameter known as the stand-off distance is introduced in this study. The stand-off distance is a parameter commonly used as in security and surveillance applications. It defines the minimum distance between a secured building or vehicle to any unauthorized intruders or surveillance vehicle. In this work that deals with maritime surveillance applications, it is defined as the shortest distance at which the unmanned surface vehicle (the surveillance ship) can approach a cargo ship (the vessel under surveillance), yet still be able to establish a reliable communication link with the control station on shore, when the cargo ship (obstruction ship) is in between the shore to sea communication path (Figure 36).

6.1 Measurement Campaign

6.1.1 Channel Sounding and Measurement Setup

Figure 37: Positions for transmitter and receiver, and measurement route

Parameters	Value
Carrier frequency	5.5GHz
PN length	1023
Modulation	BPSK
Symbol rate	20 Mchips/s
Delay resolution	50ns
Transmitter height	3.5m
Receiver height	10m
Maximum route distance	8km
Antenna type	Omni-directional
Antenna gain	8dbi

Table 10: Summary of measurement parameters

The spread-spectrum technique maximal-length pseudonoise (PN) sequence was implemented for channel sounding at the transmitter. In our measurements, a 1023-bit PN sequence was transmitted at a rate of 20 Mc/s and modulated using Binary Phase Shift Key (BPSK). This allows for a time resolution of 50 ns for the measurements [31]. For the practical channel sounding, an omnidirectional antenna was mounted on top of a speed boat as shown in Figure 38(a), at a height of approximately 3.5 meter above the sea level. The antenna was connected to a vector signal generator through a high power amplifier (housed within the boat cabin), forming a mobile transmitter. The transmitted power of the whole system was kept at 30 dBm. During the measurement, GPS data was logged continuously so as to obtain the instantaneous time, altitude, longitude and latitude coordinates. A fluxgate compass was used to log the pitch and roll of the moving boat.

For the receiver on shore as shown in Figure 38(b), an identical omnidirectional antenna was used for the signal reception. The antenna was mounted on the roof of a building at a height of about 10 m above the sea surface level regardless of tidal-wave changes. The received signal was then down-converted to a 20 MHz intermediate-frequency signal, and sampled at a rate of 100 Msamples/s. All the data recorded was time-stamped with the GPS and roll, pitch information in order to synchronize the received signal with the location, heading and orientation of the mobile transmitter (the moving boat). Weather stations were also equipped at both the transmitter and receiver to record the weather conditions such as ambient temperature, humidity and wind speed.

Table 10 gives a summarization of the main measurement parameters during the study.

(a) Transmitter on boat

(b) Receiver onshore

(c) Three classified types of blockage ships

Figure 38: Measurement setup and different types of ships

6.1.2 Measurement Plan

Measurements were carried out at the southeast coast of Singapore, where many

large cargo ships were anchored about 3 km to 5 km off the shores. These cargo ships can generally be classified into three basic types as shown in Figure 38(c); Type A ships are characterized by their low height above the sea level and their flat top structure; Type B ships are also characterized by their low height above the sea level but they have a complex periodic structure on their top; Type C ships are characterized by their high height above the sea level and their flat top structure. The reason for the choice of such a measurement plan (i.e. the transmission range and transceiver heights) are due to the maritime surveillance applications under consideration; a 2-way communication between a USV and a control station which is either on land or on a mother ship is to be established. During such scenarios, there is no line of sight transmission. The cargo ships (obstruction ship) are blocking the microwave communication link for the NLoS scenario as shown in Figure 37.

In our measurement campaigns, the boat carrying the transmitter went behind the blockage ship to form an NLoS link as shown in Figure 37. The control station was located at the coast right next to the shoreline. The maximum distance between the receiver (Rx) and the transmitter (Tx) is about 8 km during the trials with the blockage ship at a maximum distance of 5 km away from the shore. The main focus of the study is to find out the stand-off distances for the NLoS maritime surveillance applications in the 5 GHz band. The targeted blockage ship type was chosen at the beginning of each trial. The measurements were conducted both in front of the ship (LoS) and behind the ship (NLoS) repeatedly. After the transmitting boat went behind the blockage

ship, experimental data was continuously recorded while the boat moved away from the blockage ship as shown in the measurement route of Figure 37.

In this study, the dimensions and the structure of the blockage ship are the important variables that can influence the measurement results. They were obtained from the internet database using their International Maritime Organization (IMO) number. More than 10 trials were conducted with 16 different cargo ships over a period of 3 months

6.2 Ray Tracing and Verifications

6.2.1 Simulations Using Ray Tracing

Due to the nature of sea trials which requires heavy logistics, manpower and is also time-consuming, ray tracing simulation is an alternative technique for the understanding of the shadowing/diffraction effects from the three different types of obstruction ships. A ray tracing program, Wireless InSite[®] [37], is used to model the maritime environment with a cargo ship as the obstruction ship. Simplified models for the transmitter boat used for simulation is shown in Figure 39(a), the on shore receiver is shown in Figure 39(b) and the three different types of obstruction ships are shown in Figure 39(c). These models are drawn using the AutoCAD and imported into the Wireless InSite[®] software for simulation purposes.

The parameters of the models including dimensions, material and shape are all based on the actual values to the best of our knowledge. The 3-D model

of the experiment scenario is then simulated to study the effects of transmission, reflection and diffraction using the ray tracing technique. The simulation was performed using a hybrid of the shooting bouncing ray (SBR) algorithm and the uniform theory of diffraction (UTD). The SBR technique is used to find the propagation paths between the transmitter and the receiver. Once these propagation paths are determined, the UTD is implemented to evaluate the electric field for each path. One of the simulation scenarios where the signal transmitted from the boat undergoes diffraction by the periodic structure on the Type B ship and then the reflection off the sea surface before arriving at the control station on land is shown in Figure 39(d). Comparisons between the measurement and the simulation results are performed in the following.

(a) Transmitter on boat

(b) Receiver at land

(c) Three types of blockage ships

(d) Example of the simulation scenarios with a Type B blockage ship

Figure 39: Simulation models in Wireless InSite

6.2.2 Verification of propagation channels

The maritime mobile propagation channel can be modeled as a linear time-variant system, whose complex baseband equivalent channel impulse response $h(t, \tau)$ can be expressed as [7],

$$h(t, \tau) = \sum_{k=0}^N a_k(t) \exp\{j\varphi_k(t)\} \delta\{\tau - \tau_k(t)\} \quad (6.1)$$

where t and τ are the observation and application times of the impulse respectively, a_k , τ_k , and φ_k are the time-varying amplitude, propagation delay and phase shift of the k^{th} multipath component, and N is the number of multipath components of the channel of interest.

Figure 40: Examples of PDPs with the transmitter at 400-500m behind a Type A ship, a Type B ship, and a Type C ship

In this study, the empirical channel impulse response $h(t, \tau)$ of the NLoS channel at 5.5 GHz was obtained by correlating the known transmitted signal with the received signal. To evaluate the differences between the NLoS scenarios caused by different ship types, power delay profile (PDP) which is proportional to $|h(t, \tau)|^2$ is used. The PDP is a plot showing the relative power of each multipath component from reflection/diffraction versus the time delay and the measured PDPs for propagations at a distance of around 400-500 m behind each type of ship is shown in Figure 40. From Figure 40, it can be observed that the Type B ships are the only type of ship that results in significant multipath

components. These multipath components are from the diffractions caused by the complex top structures (tower-like structure) of a Type B ship as shown in Figure 39(c).

To compare the measured propagation channels with the simulated ones, both the measured and simulated PDPs are conducted as shown in Figure 41. In the following, the shadowing/diffraction from a Type B ship is presented due to the obvious multipath components which is caused by its more complex top periodic structures. One example of the measured and simulated PDPs is shown in Figure 41. The PDPs are taken when the mobile transmitter is about 320 m behind a Type B ship as illustrated in Figure 39(c).

Figure 41: Comparisons of the measured and simulated PDPs with all multipath components.

From Figure 41, it is found that the PDPs from the measurement and the simulation are qualitatively comparable. A good comparison between the measured and simulated results for other types of obstruction ships can also be

observed. It is noted that the difference in the amplitude values between the measurement and the simulation results are likely due to the inaccuracies in conductivities, permittivity's, sea surface conditions and the rough dimensions of the simplified models (as shown in Figure 39) created for the software simulation. This is expected since it is almost impossible to simulate the actual maritime environment and the obstruction ship. Similar conclusions have been reported in [38] when the Wireless InSite[®] software is used to model an outdoor environment at 5 GHz and compared to their measurements.

Moreover, the measurement results indicate that two or more multipath clusters (A cluster is a combination of many multipath components which cannot be resolved by the channel sounding technique used.) are observed around 60% of the sea trial time when Type B ships act as an obstruction ship, while multipath components are observed only around 22% of the trial time for Type A ships. It is noted that there is no multipath component observed in the PDPs for Type C obstruction ships. This is because the signal strength is extremely weak or falls into the noise floor when the mobile transmitter is behind the huge metallic body of a Type C ship since this type of ships are characterized by its high height above the sea level.

6.3 Stand-off Distance

From the above studies, it is found that the diffractions from the top structures of a ship and the shadowing due to its huge metallic body are the two main propagation mechanisms for the NLoS maritime mobile applications. When the

mobile transmitter is located behind the large metallic body of a cargo ship, the communication link can be fully blocked making communications between the mobile transmitter and the control station impossible. The unavailability of the microwave link could be disastrous for certain applications, such as control of a USV.

In order to characterize this phenomenon and provide some useful information for implementations of the maritime microwave surveillance applications (e.g. a safe distance off a blockage ship for establishment of a reliable communication link), a parameter *stand-off distance* d_{so} is introduced in this study. The stand-off distance is commonly used as a security measure that focuses on the prevention of unauthorized intruders from approaching within a certain distance to secured buildings or vehicles. In the area of maritime surveillance applications, it is defined as the shortest distance at which the transmitter on the boat can approach a cargo ship (for surveillance purposes) and yet can maintain a reliable communication link with the control station on shore, when the obstruction ship is in between the mobile transmitter and the control station.

Figure 42: Example of SNR scatter plot according to transmitter position

Types	Ship name	Length	Width	Height (above sea level)	Distance (from shore station)	Stand-off distance (Experiment)	Stand-off distance (Simulation)
Type A	Alpha	288m	45m	19m	3.5km	475m	460m
	An ho	225m	32m	9.5m	2.65km	470m	510-560m
	Formosa	289m	45m	21.7m	3.73km	725m	760-800m
	Welhero	229m	38m	13.9m	4km	610m	550m
	Aegean	224m	32.5m	9.25m	3km	380m	400-450m
	Ban Ai Hai	292m	45m	16.3m	3.95km	680m	550m
	Mckinley	292m	45m	14m	3.5km	700m	650-700m

	Kiran	292m	45m	10m	3.27km	380m	300m
Type B	Elena	186m	30m	8.75m	2.83km	300-400m	360-460m
	Genco	189m	32m	9.25m	2.48km	535m	510m
	Thalass ni	199m	34m	10m	2.6km	250-450m	410-460m
	Favorita	190m	32m	11m	3.0km	300m	320m
	Star cosmo	221m	34m	14.26 m	2.1km	346m	
	TC gold	185m	32m	8.5m	2.93km	180m	200-220m
	Malta	205m	32m	20.5m	2.41	200m	150-200m
Type C	Grand Hero	199m	32m	33m	4.13km	N.A	N.A

Table 11: Summary of Stand-off Distance

6.3.1 Tracing the Signal with Transmitter Position

In order to estimate the stand-off distance for the NLoS maritime applications blocked by a cargo ship, the signal to noise ratio (SNR) was traced against the position of a mobile transmitter. Figure 42 shows an example of the scatter plot for the SNR versus the transmitter position. Our observations show that when the transmitter boat is right behind a blockage ship at a distance of less than 200 m behind the cargo ship, the received SNR is small. This is true for all types of ships. This is because the transmitter boat has a relatively small size comparing to the cargo ships and therefore, the transmitted signal is almost fully blocked. When the transmitter boat moves away from the cargo ship, the received SNR increases (as indicated in zone 1, 2, 3 and 4 of Figure 42). The amount of

increase in SNR is dependent on the amount of diffraction from the top structures of the cargo ship. When the transmitter boat goes further beyond 1.2 km (shown in zone 7 of Figure 42), the mobile transmitter is far away from the obstruction ship such that the communication link approaches LoS condition. Therefore a good communication channel can be established again. However, due to the long range, the SNR is weak. It is noted that, there is relatively high SNR shown in zone 5 and 6 of Figure 42 due to the LoS transmission as the mobile transmitter goes beyond the shadowed areas from the cargo ship.

In this study, the transmission range is from 2km to 5km and the transmission heights are 10m and 3.5m respectively.

Both the measurement and simulation results have been carried out in order to evaluate the stand-off distances for different types of obstruction ships. A summary of the evaluated stand-off distance together with the dimensions of the ship and the distance of the blockage ship off the shore are tabulated in Table 11. From the results, it can be observed that there is no stand-off distance for Type C ships under the transmission range of consideration. This is because the Type C ship has the highest metallic body above the sea level among all the types of ships, and therefore, the communication link is fully blocked.

Figure 43: The geometry for knife-edge diffraction on ideal obstacles

Figure 44: The geometry for knife-edge diffraction on rounded obstacles

Conclusions for Type B and Type A ships are varied. Normally, the stand-off distance is shorter for Type B ships. This is because, the tower-like structures of a Type B ship is ideal for knife-edge diffractions. Another important factor to note is that, the estimated stand-off distance depends on the size of a ship. According to the knife-edge diffraction model on ideal obstacles, diffraction gain is related to ‘Fresnel diffraction parameter v ’ [7] which is expressed as (1).

$$v = h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \quad (6.2)$$

Where h is the effective height of the obstructing ship, λ is the wavelength of the transmitted signal, d_1 is the distance between transmitter and the obstructing ship and d_2 is the distance between receiver and the obstructing ship. All the parameters are labelled in Figure 43. Since the distance between transmitter and receiver is relatively large (above 2000m) compared to the receiver height (10m), the angle θ would be quite small (in the order of 10^{-5} degree) which can be ignored. Thus the effective height of the obstructing ship is approximately the difference between the height of the ship above the sea surface and the transmitter height (h_t). The relationship between the Fresnel diffraction parameter and the diffraction gain is plotted in Figure 45.

Figure 45: Knife-edge diffraction gain as a function of Fresnel diffraction parameter v .

As shown in Figure 45, higher values of the Fresnel diffraction parameter will generate a larger diffraction loss. Moreover, from equation (6.2), the value of Fresnel parameter v is proportional to the effective height of the obstructing ship. Therefore, the higher the ship body above the sea level, the longer the stand-off distances due to the larger diffraction loss. This result can be observed in our sea trial within either Type A or Type B ships. However, when we compare the results between Type A and Type B obstructing ships, the conclusion may not be applicable. Normally the diffraction happens on the periodic structure on the top of the ship body, thus a height of 10-20m of the structure should be added to the effective height. This would result in a generally higher effective height for Type B ships than Type A ships'. However, it is observed in Table 11 that the stand-off distance for Type B obstructing ship is normally shorter compared to it for Type A ship. This is because that the knife-edge diffraction model for ideal obstacles could only be applied for Type B ships which has a sharp diffraction edge which is the periodic structure on top. The diffraction happens on the body of the Type A ships which is a non-idealized obstacle. It can be assumed to be a rounded obstacle and the geometry of diffraction on Type A ship is illustrated in Figure 44. For this kind of diffraction, an excess loss needs to be added to the knife-edge loss; the value is given by [5]:

$$L_{ex} \approx 11.7 \left(\frac{\pi r}{\lambda} \right)^{\frac{1}{3}} \alpha \quad (6.3)$$

Therefore, the stand-off distance for Type A ship is normally longer than it for Type B ship due to the excess loss.

Furthermore, as shown in the last two rows in Table 11, there is a good agreement between the simulated and measured values of the stand-off distance, although there is no perfect match because the simulation model is a simplified model and not an exact representation for the actual experiment scenario. Sea surface conditions, reflection coefficient and loss tangent is not taken into consideration.

6.4 Antenna diversity

In order to enhance the performance of the NLOS communication link, three different types of obstructing ships are chosen to be investigated in the sea trials conducted in Sep. All the measurements are conducted with the two-by-two antenna system to examine the performance of antenna diversity scheme. Parameters such as height, length, width and distance from shore as listed in Table 12.

Ship	Length (m)	Width (m)	Height (m)	Distance from shore (km)	Image
Welhero	229	38	13.9	4

Favorita	190	32	11	3
Aegean	224	32.25	9.24	3

Table 12: Parameters of obstructing ships

(a) ship Aegean

(b) Ship Welhero

(c) Ship Favorita

Figure 46: CDF plot for NLOS SNR distribution

Selection combining technique is used in our two-by-two antennas system which is same as what we did in the previous section for the results on operating route. From the table, it shows that the probability to have a reliable communication link in the NLOS condition can be improved in some extends. For example, the largest probability to have reliable communication link with single channel is 35.8% for obstructing ship Welhero. However, it can be improved to 50.15% if the two-by-two antenna system is introduced and selection combining is used. The same improvement can also be observed for ship Favorita and Aegean. A 10-20% chance of improvement to have reliable communication link in NLOS conditions can be seen respectively. From the CDF plot same conclusion can be observed with a diversity gain approximately 2-4dB in every given probability. This is a good indication that antenna diversity could be a useful method to enhance the channel performance in NLOS scenarios. Therefore, further investigation to have different antenna diversity scheme such as height diversity and polarization diversity should be done.

6.5 Conclusion

In summary, NLOS channel measurement analysis is performed in this section. The concept of stand-off distance is introduction and studied to characterize the channel. It is found that the stand-off distance depends on the types of the obstructing ships. According to the classification by this report, the stand-off distance for type B ships which have periodic structures on top is the shortest. Subsequently, power delay profile is shown to have a detail

understanding of the diffraction effects in the NLOS channel. More multipath can be observed for type B obstructing ships. The periodic structure on top of the type B ships is good diffractors for the radio wave propagation that explains why they have the shortest stand-off distance compared to other 2 types. Simulation using the software Wireless InSite is also conducted, and the results from the simulation show good match with the measured ones. What' more, antenna diversity scheme is also introduced and analysed in this section and the results show that this could be a very useful method to enhance the channel performance.

Chapter 7

Conclusion and future work

In this thesis, the empirical channel characterization and modelling of the maritime environment have been conducted and reported. Special attention is given to the NLOS propagation when a transmitter and receiver direct link is blocked by large ships anchored off the coastal area. This is due to the recent interest in military application such as military surveillance, and Unmanned Surface Vehicle communication system. In order to perform a reliable research study, several measurement campaigns have been carried out in different sea and coastal scenarios. Based on the investigation and analysis, results can be summarized into 3 major categories.

Firstly, the 5GHz band LOS radio wave propagation at open sea environment can be characterized using two-ray path loss model. Experimental results and predicted values from theoretical equation show a good match. A new three-ray model which also considers the reflection from the ducting layer is proposed then to have a further investigation on this scenario. It is found that the trend of signal strength variations possibly due to evaporation ducts is well predicted by the model. It can be concluded that the two ray model together with the proposed three ray model can be used to model the large-scale channel characterization over sea surfaces.

Secondly, channel characterization for the selected USV operating route is studied. Due to the complex maritime environment near the route especially the large metallic body of the anchored ships offshore, multipath fading effect is observed. Amounts of signal dips can be found along the route both for narrowband and wideband signal transmissions. Power delay profile is then studied to investigate the multipath property. Parameter like coherence bandwidth which is important to regulate the channel is proved to be increase using the directional antennas. What's more, antenna diversity is also conducted, and the results shows that it would be a useful method to enhance the reliability of the communication link.

Then, a study of channel characterization for NLOS propagation is performed. The concept of stand-off distance is introduced for military surveillance application. Measurements using different types of blockage ship are performed. Simulation using the software Wireless InSite is also done to compare with the measured data. It provided a further understanding of the NLOS propagation channel where diffraction is the dominant propagation mechanism. The results obtained show that obstructing ships can be classified into three main types. Type B ships with periodic structure on top are a good diffractor for radio wave propagation and therefore result in shorter stand-off distance. The stand-off distance for Type A and Type C ships are related to their height above sea level. The higher the ship is above sea level, the longer is the stand-off distance. What's more, antenna diversity is also proved to be a good way to enhance the communication link in NLOS situation.

Based on the empirical studies developed in this report, there is great potential in extending the scope of the present work. Some recommendations are given below.

1. The accuracy of the path loss model needs to be further improved with more considerations. The proposed three ray model used simple assumption that the signal goes through prefect reflection over the ducting layer. Propagation mechanism such as waveguide effect may also exist in this condition.
2. Weather effects on the signal strength variation needs to be investigated. Comparative study under different weather conditions and sea surface conditions should be conducted to study the weather effect on the performance of communication link due to factors such as rain, humidity, temperature, wind speed, sea surface condition and ducting. Special attention would be given to the ducting effect which has been well recognised as an important propagation mechanism over sea surface.
3. Channel reliability optimization techniques such as MIMO and OFDM system need to be developed and tested in order to improve the reliability of communication links. MIMO and OFDM have been proven as efficient techniques to overcome multipath fading. Suitable system

should be designed to be used for measurement in this project. The performance of those systems would be evaluated. These systems can also be used to improve (reduce) the stand-off distance from big vessels thus improve military surveillance systems.

Author's Publications

Portions of the work reported in this thesis have been published previously in the following papers

Journal Papers under Review

1. F. Dong, Y. S. Meng and Y. H. Lee “Near Sea-Surface Mobile Radio-Channel at 5 GHz: Modeling the Duct Layer” submitted to *IEEE transactions on Antennas and Propagation*, in Nov. 2012, under review.
2. F. Dong, Y. S. Meng and Y. H. Lee “Stand-off Distance for Non-Line-of-Sight Maritime Mobile Applications in 5GHz Band” submitted to *IEEE transactions on Vehicular Technology*, in Jan. 2013, under review.

Conference Papers Published

1. F. Dong, C. W. Chan, and Y. H. Lee, “Channel modeling in maritime environment for USV,” in *Defence Technology Asia 2011*, Singapore, Feb. 2011.
2. F. Dong and Y. H. Lee, “Non-line-of-sight communication links over sea surface at 5.5GHz,” in *Proc. 2011 Asia-Pacific Microw. Conf.*, Melbourne, VIC, Dec. 2011, pp.1682–1685.
3. F. Dong and Y. H. Lee, “Experiment results of a two-by-two diverse antennas system over the sea surface in NLOS scenario,” in *Proc. IEEE APS Int. Symp. Antennas Propag.*, Chicago, USA, July, 2012.

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