Channel modeling and measurements in waveguide-like structures

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CHANNEL MODELING AND MEASUREMENTS IN WAVEGUIDE-LIKE STRUCTURES

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Summary

In this thesis, a detail study on channel characterization and modeling of the propagation within waveguide-like structures, namely; the lift shaft and the cargo hull of a merchant ship is performed. These channels are studied for military applications such as urban warfare and battlefield communication network onboard ships. For urban areas, although the environment can be different from one to the next, high-rise buildings with lift shafts can be commonly found. Due to the boxed shaped hollow structure of the lift shaft, guiding effect associated with the lift shaft channel can be a reliable link. The propagation mechanisms along a lift shaft in an urban area are examined based on experimental study and verified by ray-tracing simulation results. The signal variations caused by the opening/closing of the lift door and movement of the lift car are modeled in detail. On board the ship, the aim is to establish communication between two key locations, the bridge room on the top and the engine control room at the bottom. These are crucial locations in terms of trying to take control over the ship. Therefore, the knowledge of wave propagation mechanisms between these locations within the ship is required. In this study, a series of experimental work has been conducted along the lift shaft onboard a merchant ship. Waveguide-like effect and signal variations associated with the lift shaft channel is examined and compared with the results obtained from urban area. Moreover, the waveguide-like effect along the cargo hull of the merchant ship is studied based on experimental and simulation results. Small-scale channel characteristics are analyzed based on the guiding effect. Finally, besides the direct propagation in VHF band, a relay system is proposed to enable the wideband propagation between the two key locations in the military UHF band and popular ISM band. As the analogues waveguide effect of the cargo hull can ensure

the communication quality, the relay system is suggested to be deployed inside the cargo hull.

Chapter 1

Introduction

Studies of radio wave propagation in wireless channels are important for system design. This is because the performance of the wireless system can be severely affected by the characteristics of a wireless communication channel [1]-[5]. In complex environments such as indoor factories, mines, tunnels, ships, and onboard aircrafts, due to the lack of line-of-sight (LOS) propagation path, signals usually arrive at the receiver through reflection, diffraction or scattering. As multipath components arrive from different directions with different amplitudes and different time delays, the resultant signal which is a vector combination of all the multipath components can undergo significant fading depending on the phase of the wave components. This can pose severe limitations to the reliability of the signal transmission. On the other hand, the multipath components can be favorable for propagation in complex environments when multipath signals sum together constructively enhancing signals at locations where there is no LOS link [6]. Therefore, the propagation mechanism within a complex environment is a research topic of interest. In this thesis, research work is performed in order to understand

the VHF and UHF band propagation channel in complex metallic environments, namely, along the lift shaft in both the urban and the ship environment and along the cargo hull inside a merchant ship.

1.1 Motivation

The major constraint on propagation within complex structures such as the lift shaft and ship vessel is the limited reception due to high attenuation caused by metal when signal penetrates through it. With the increasing demand for wireless communication systems, both voice and video communication in complex environments becomes essential especially for military applications such as urban warfare and battlefield communication networks onboard ships. During war time in an urban city such as Singapore, it is critical for soldiers to be able to communicate with each other reliably in our urban environment. Since the lift shaft is a structure available in most if not all buildings in our urban environment, it can be exploited as a means for electromagnetic to propagate. When there is a need to take control of a ship, the bridge room on the top of the ship and the Engine Control Room (ECR) at the bottom of the ship are the two key locations that are used for the navigation and the operation of the ship. Therefore, both voice and data communication between these two points should be ensured, so that there is a reliable communication and information link between the soldiers on board the ship. However, current systems only allow for an intermittent, low reliability voice communication in such environment. To date, there is limited amount of literature on propagation along the lift shafts in the urban environment and inside the ship vessel. Instead, there is a number of works on the propagation in other similar

enclosed environments such as mines [21][53][56][73][75], tunnels [10]-[21][70]-[77] corridors [54]-[59][62]-[69] and the Heating, Ventilation and Air Conditioning (HVAC) ducts [25]-[29][91]-[97]. These enclosed environments are identified as waveguide-like structures and studies on these structures have started since 1974. Due to the similarity in geometry between the lift shaft, the cargo hull and these structures, guiding effect is also expected for electromagnetic waves propagating along the lift shaft and within the ship vessel. Due to the low propagation loss associated with the guided waves, both narrowband and wideband propagation in the studied metallic structures may become feasible. Therefore, the focus of this research is on the exploitation of the guiding effect along waveguide-like structures in order to achieve reliable voice and data communication in RF harsh environment where it is difficult to establish communication links.

1.2 Objective

In response to the aforementioned problems, the aim of this PhD thesis is to perform an empirical study and modeling of the propagation of electromagnetic waves within complex metallic structures, namely, along the lift shaft in urban area and onboard a ship vessel and along a cargo hull inside the same ship vessel. To fulfill the objective, the focus of this thesis is as follows:

1. A comprehensive literature review on channel characterization and modeling, especially for waveguide-like structures has been performed. This exercise creates a strong foundation and background for further exploration into related research topic.

2. Theoretical analysis of the feeding mechanism into the waveguide-like structure is performed and presented. After demonstrating the possibility of the coupling of EM waves into the lift shaft, channel characterization along lift shafts in different environments i.e. urban area and ship is conducted; waveguide-like effect along the lift shafts has been identified and verified by ray tracing simulation results. The guiding effects along the lift shaft in the two environments are compared. The statistical modeling of the lift motion induced signal variation is also studied and compared for the two environments.

3. Channel characteristics over the two ends of a merchant ship are studied at different frequencies. In order to achieve wideband communication between the two key locations on board the ship, two methods are recommended; one is to communicate at low frequencies such as the VHF band; the other is to deploy a relay system within the cargo hull where the waveguide-like effect is identified and studied based on both measurement and simulation results for higher frequency communications such as at 350 MHz in the military UHF band and at 2.4 GHz in ISM band.

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

1.3 Major Contribution of the Thesis

In this study on the channel modeling and characterization of complex metallic enclosures, the following is a list of major contributions:

1. The feeding mechanism into the lift shaft created by the slot between the lift doors is studied and modeled based on the theory of slot feed waveguides. Simulation results from electromagnetic (EM) simulator are used to study and verify this feeding mechanism.

2. Waveguide-like effect along the lift shaft is identified and signal variation caused by the lift motion is modeled. Propagation modes are identified based on measurement results from controlled experiments in both urban environment and ship environment. Measurement results are revealed using 3D ray tracing simulation results. Electromagnetic waves are found to be guided along the lift shaft and therefore, suffer significant temporal variations due to the motion along the lift shaft, i.e. the movement of the lift car and the opening/closing of the lift door.

3. Variations on the received signal level caused by the motion along the lift shafts in two different environments, i.e. urban area and shipboard are statistically modeled and compared using AIC based method and KS test. The Weibull distribution is identified as the best function to model signal variations along the waveguide-like structures in both environments. Comparison of the signal variation along the lift shaft in the two environments is performed using the Weibull b parameter.

4. Due to the low propagation loss within the low frequency band in RF harsh environments, use of the VHF band is proposed as one of the solutions to achieve communication link between the bridge room and the ECR within complex ship structures. The system design parameter such as maximum usable bandwidth is recommended for such environment. Moreover, it is found that the rotation of the engines can cause significant variation in the received signal strengths.

5. Guiding effect along the cargo hull is identified as the most important propagation mechanism based on measurement results along the cargo hull onboard a merchant ship. Due to the waveguide-like effect, the linear equation is found to be suitable to model the decay trend of multipath components obtained from highly reflective enclosures such as the cargo hull. Moreover, the results from the slant path measurement onboard the same ship show that guided signals are periodic and the period is proportional to the dimensions of the cargo hull. This further verifies the waveguide-like structure of the cargo hull.

6. With the help of the waveguide-like effect along the cargo hull, the solution to achieve propagation in higher frequency band between the two key locations, i.e. bridge room and ECR is to deploy a relay system inside the cargo hull. The performances of the two independent links of the relay system are examined and compared. It is found that the performance of the relay system is mainly limited by the link between the cargo hull and the ECR, due to the

significant multipath components resulted from the metallic structures along the propagation path.

1.4 Organization of the Thesis

The remaining part of the thesis is organized as follows. The literature review on the channel characterization and channel modeling is presented in Chapter 2. This chapter also provides some basic concepts on radio wave propagation. A review of the channel characteristics in complex waveguide-like structures are presented, namely, tunnels, corridors, Heating, Ventilation, Air Conditioning (HVAC) ducts, lift shafts and ship vessels. In Chapter 3, two different wideband sounding systems that are used in this project are introduced and compared based on measurement results. The accuracy and resolution of the measurement system have been studied. The ray tracing simulation software used in this research is introduced briefly.

In Chapter 4, lift shaft channels in the urban environment and within the ship vessel are modeled. Firstly, coupling of the electromagnetic waves into the lift shaft is modeled theoretically based on EM simulation results. Next, the waveguide-like effect along the lift shaft and signal variations caused by the movement along the lift shaft is identified based on several sets of controlled experiments and ray tracing simulation results in both campus and ship environments. The signal variations caused by movement of the lift door and the lift car in these two environments are then studied and compared statistically in Chapter 5.

In Chapter 6, two possible solutions are proposed to enable communication between the bridge room and the ECR, of the two key locations on board the ship. As the propagation waves suffer less attenuation at low frequency, the VHF band is suggested for use as the communication frequency in this complex metallic environment. For propagation in UHF band such as 350 MHz in military UHF band, a relay system is recommended and the location to deploy the relay is suggested to be inside the cargo hull where the waveguide-like is observed and analyzed based on measurement and simulation results shown in the same chapter. Moreover, the utilization of a relay system in the cargo hull is extended to the frequency of 2412 MHz in the ISM band; the performances of the relay system at these two different frequencies are compared.

Finally, in Chapter 7 a conclusion of this research work is presented and recommendations for future work are provided.

Chapter 2

Literature Review

In this chapter, an introduction to concepts behind channel characterization and modeling is presented. A comprehensive review on the modeling and characterization of propagation within different waveguide-like environments is presented. The latest theoretical and experimental research methodologies are reviewed.

2.1 Propagation Basic

In a complex environment, radio wave can propagate from the transmitter to the receiver via Line-of-Sight (LOS) propagation, reflection, diffraction, and/or scattering. Reflection occurs when a propagating electromagnetic wave impinges upon an object which is very large in dimensions relative to the wavelength of the propagating wave [5]. A famous model of reflection is the ground reflection (two-ray) path loss model, which will be reviewed in Section 2.1.1. Diffraction occurs when the radio path between the transmitter and the receiver is obstructed by a surface that has sharp irregularities (edges). The secondary waves resulting from

the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of the waves around the obstacle, even when the LOS path does not exist between the transmitter and the receiver [4]. Several empirical models [2] are available to predict the diffraction loss such as the knife-edge diffraction model for single edge diffraction, the Bullington's equivalent knife-edge method, the Epstein-Peterson method, the Japanese method as well as the Deygout method for multipath edge diffraction. If the received power in a mobile radio environment is predicted by reflection and diffraction models alone, the obtained value is often smaller than the actual received signal. This is because when a radio wave impinges on a rough surface such as lamp posts or trees, the reflected energy is distributed over all directions due to scattering, thereby resulting in additional radio energy at the receiver [4].

A summation of all the signals arriving at the receiver due to different propagation mechanisms can result in fading of the propagating waves. This therefore limits the performance of wireless systems [1]-[5] operating in complex environments. Generally, these fading processes can be classified as path loss, shadowing (or slow fading) and multipath fading (or fast fading).

2.1.1 Path Loss

The path loss provides information on the amount of signal attenuation experienced by the propagating signal as a function of the distance separation between the transmitter and the receiver [1]-[5]. As the distance increases, the signal attenuation increases, and therefore, the path loss is in general a positive quantity measured in dB. When the transmitter and the receiver have a clear and

unblocked LOS path, the path loss can be predicted using the Free Space Loss (FSL) model [2], [4],

$$L_{FSL}(dB) = -27.56 + 20\log_{10}(f) + 20\log_{10}(d) \quad (2.1)$$

where f is the frequency in MHz, d is the distance between the isotropic transmitting and receiving antenna in meters.

For mobile radio systems, the separation between the transmitter and the receiver is usually several kilometers and for LOS microcell systems in urban environment, the path loss can be better described by the Plane Earth (PE) or two ray path loss model in (2.2) [1]-[5] rather than the free space loss model in (2.1). This is because; the effect of ground reflection should be taken into consideration. Since the transmitter to receiver distance is less than a few tens of kilometers, it is often permissible to neglect the earth curvature and the earth surface can be assumed to be flat.

$$L_{PE}(dB) = 40\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R) \quad (2.2)$$

where d is the distance between the isotropic transmitting and receiving antenna in meters, h_T and h_R are the transmitting and receiving antenna heights, respectively, also in meters. In this model, it is assumed that d is much larger than h_T and h_R .

However, due to the complexity of propagation mechanisms in a realistic environment, the predicted path loss using (2.1) and (2.2) are not accurate. As a result, both theoretical and measurement based models have been developed in the

past decades. A popular empirical path loss modeling method called the log-distance path loss model [5] is introduced here:

$$L(dB) = L_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) \quad (2.3)$$

where n is the path loss exponent that indicates the rate at which the path loss increases with the distance. This value is highly dependent on the environment and the availability of LOS between the transmitter and the receiver. It is noted that the path loss exponent n is commonly obtained by applying the least squared curve fitting method to the measured data. d_0 is the reference distance at which a close distance reference measurement is taken. L_0 is the path loss in dB at the reference distance d_0 , and d is the distance between the transmitter and the receiver.

2.1.2 Shadowing

Shadowing is defined as the variation of the local mean value (averaged over a distance of 10λ [1], where λ is the signal wavelength) around the path loss caused by the variation of the surrounding environment. As a result, measured path loss can be different for two different environments even if they have the same transmitter to receiver separation. In the rural/suburban environment, shadowing causes significant variations in the signal strength over large distances of hundreds of meters; whereas in urban environment, shadowing causes significant variations in signal strength over small distances of a couple of meters. Furthermore, the shadowing effect is also highly frequency dependent. In general, the shadowing effect can cause a variation of up to about 20 dB as introduced in [1] for a typical

urban environment. When this shadowing effect is considered, the path loss equation in (2.3) can be rewritten as,

$$L(dB) = L_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) + X \quad (2.4)$$

where an additional parameter X is included to account for the shadowing effect. This parameter X is a Gaussian distributed random variable with zero mean and a standard deviation of σ_x .

2.1.3 Multipath Fading

Generally, in an RF harsh environment, the received signals not only consist of the direct LOS wave (if LOS exists), but also signals reflected from large surfaces (relative to wavelength), scattered from the obstacle surface and/or diffracted from edges. In practice, energy arrives via several paths simultaneously, and a multipath situation is said to exist when the various incoming radio waves arrive from different directions with different time delays [1]. The resultant signal at the receiver is a vector sum of all the multipath signals arriving at the receiving antenna. The multipath components can contribute constructively or destructively, depending on the distribution of phases among the wave components. In a static multipath situation, the resultant signal is a simple superposition of different components. When either of the transmitting antenna or the receiving antenna is moving, there is a dynamic multipath situation in which there is a continuous change in the electrical length of every propagation path and thus the relative phase shifts between them changes as a function of spatial location. Figure 2.1 shows how the received envelope of the signal varies in the simple case when there

are two incoming paths with relative phases that vary with location [4].

In practice, multipath results in rapid fading in the envelope of the received signal for narrowband transmission (an unmodulated carrier). While for wideband transmission, the existence of multipath components can cause inter-symbol-interference (ISI), and limit the maximum usable bandwidth for the communication system. In the following, both narrowband and wideband characterizations and modeling of the multipath fading are introduced. The details can be found in [1]-[5].

Figure 2.1 Envelope fades as two incoming signals combine with different phases

A) Narrowband Characterization

In narrowband channel sounding, a continuous unmodulated sine wave is transmitted and the received power or amplitude is recorded at the receiver. The narrowband characterization of the multipath fading is usually studied by modeling the received signal envelope or voltage statistically. There are several commonly

used distribution functions in the area of radio propagation [1]-[2],[5], namely, Gaussian, Rayleigh, Rician, Nakagami-m and Weibull. Their mathematical expressions are shown in the following equations.

Gaussian distribution:

$$P_r(r) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(r-\mu)^2}{2\sigma^2}} \quad (2.5)$$

where μ and σ are the mean and standard deviation of the random variable r .

Rayleigh distribution:

$$P_r(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \quad (2.6)$$

where σ is the standard deviation of random scattered components.

Rician distribution:

$$P_r(r) = \frac{r}{\sigma^2} e^{-\left(\frac{r^2+s^2}{2\sigma^2}\right)} I_0\left(\frac{sr}{\sigma^2}\right) \quad (2.7)$$

where s denotes the peak amplitude of the dominant signal, $I_0(\cdot)$ is the modified Bessel function of the first kind and zero order, and σ^2 is the variance of the random component.

The Rician distribution is often described in term of a parameter K , which is defined as the ratio between the deterministic signal power and the variance of the multipath.

$$K(dB) = 10 \log_{10} \left(\frac{s^2}{2\sigma^2} \right) \quad (2.8)$$

It is noted that as $s \rightarrow 0, K \rightarrow -\infty$, the Rician distribution degenerates to a Rayleigh distribution, where no dominant path exists. The larger the K factor, the stronger the dominant path. However, for static channels where both the transmitter and the receiver are kept stationary, all the propagation paths are predetermined theoretically. So, the Rician K factor is interpreted as the ratio of the mean power to the variance of the received power for static channels. It is used to characterize the temporal variability of the propagation channel such as human movements.

In the Nakagami distribution,

$$P_r(r) = \frac{2m^m}{\Gamma(m)\Omega^m} r^{(2m-1)} e^{-\left(\frac{mr^2}{\Omega}\right)} \quad (2.9)$$

where m and Ω are the shape and scale parameters respectively, and $\Gamma(\cdot)$ is the gamma function. If $m = 0.5$, it is reduced to the one-sided Gaussian distribution; if $m = 1$, the distribution degrades to a Rayleigh distribution; and if $m = (K+1)^2/(2K+1)$, it approximates a Rician distribution with parameter K , and if $m = +\infty$, there is no fade in the channel.

Lastly, Weibull distribution:

$$P_r(r) = \alpha \beta r^{\beta-1} e^{-\alpha r^\beta} \quad (2.10)$$

where α can be derived from the mean square value of the distribution, and the parameter β controls the spread of the distribution; if $\beta = 2$, the Weibull distribution is equivalent to the Rayleigh distribution and $\beta < 2$ implies severe fading.

B) Wideband Characterization

Figure 2.2 Tapped delay line model of a multipath channel

In a complex environment, the wideband characteristic of multipath fading can be well represented by its time-variant channel impulse response $h(\tau)$, as shown in Figure 2.2. It is noted that each pulse in Figure 2.2 represents a multipath component. The complex channel impulse response $h(\tau)$ can be expressed as:

$$h(\tau) = \sum_{k=0}^N a_k \exp(j\varphi_k) \delta(\tau - \tau_k) \quad (2.11)$$

where a_k , τ_k , and φ_k are the signal strength, propagation delay and phase shift of the

k^{th} multipath component. N is the number of multipath clusters. The instantaneous Power Delay Profile (PDP) is the envelope of the received power and is proportional to $|h(\tau)|^2$. The mean PDP obtained by averaging several instantaneous PDPs spatially or in time domain is usually used to represent the channel response.

1) Delay Spread

The Root Mean Square (RMS) delay spread which can be estimated from the PDP is an important indicator of the system performance; and is defined as the square root of the second central moment of the PDP:

$$\tau_{rms} = \sqrt{\frac{\sum_{k=1}^N (\tau_k - \bar{\tau})^2 a_k^2}{\sum_{k=1}^N a_k^2}} \quad (2.12)$$

where the mean excess delay $\bar{\tau}$ is given by

$$\bar{\tau} = \frac{\sum_{k=1}^N \tau_k a_k^2}{\sum_{k=1}^N a_k^2} \quad (2.13)$$

where a_k and τ_k are the signal strength and propagation delay of the k^{th} multipath component.

The coherence bandwidth which is a statistical measure of the range of frequencies over which the channel can pass all spectral components with approximately equal gain and linear phase can be derived from the RMS delay spread [4]. If the coherence bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.9, the coherence bandwidth is approximately

$$B_c = \frac{1}{50\tau_{rms}} \quad (2.14)$$

If the definition is relaxed to the frequency correlation function is above 0.5, then the coherence bandwidth is approximately

$$B_c = \frac{1}{5\tau_{rms}} \quad (2.15)$$

2) *Multipath Fading Distribution*

Similar to the statistical analysis on the received voltage as introduced in Section 2.1.3A, statistical study can also be performed on the tap amplitude of the obtained PDP. For channel sounding with small bandwidth, each tap on the received PDP contains a number of multipath waves; the multipath fading behavior within each tap amplitude can be modeled using an appropriate distribution function. For channel sounding with high resolution, each tap on the PDP may contain small number of multipath components; under this condition, the statistical analysis using distribution functions aims to model the channel variations. In our study, the statistical methods are used to study the signal variations in dynamic channels. Commonly used methods for the selection of the most suitable distribution functions are used. These methods include the maximum likelihood fits, the chi-squared test, the Kolmogorov-Smirnov (KS) test [90], and the Akaike Information Criteria (AIC) [8] method. In this research, KS test and AIC based methods are used.

The KS test [90] is designed to test the hypothesis that a given distribution could be drawn from a given data set. Given a sample set $x = [x_1 \ x_2 \dots x_N]$ with some unknown distribution P , the KS test can be used to decide if the hypothesis of P being equal to a particular distribution P_0 is acceptable at certain significance

level.

$$H_0: P = P_0 \quad (2.16)$$

The KS test statistic is defined as:

$$D = \max_{1 \leq i \leq N} (F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i)) \quad (2.17)$$

where F is the theoretical cumulative distribution of the data set under test which must be continuous and fully specified. For the significance level of α (it is 0.05 in our test), the hypothesis regarding the distributional form is rejected if the test statistic, D , which evaluates the distance between the empirical distribution function of the sample and the cumulative distribution function of the given distribution is greater than the critical value obtained from the KS table.

Besides the KS test, the other statistical method used in this research work is the AIC based method. It is a good criterion that can be applied to model signal variations in wireless communication [7] initially developed by Akaike [8] in 1974. Compared to the popular goodness-of-fit (GOF) approach used to characterize the tapped amplitude distribution of measurement data, such as the KS test, besides being able to identify the best fit distribution function within the candidate set, AIC based method is also able to provide information on the candidates' relative fitting quality based on the Akaike weights, as defined in (2.18).

$$\omega_j = \frac{e^{-0.5\varphi_j}}{\sum_{i=1}^J e^{-0.5\varphi_j}} \quad (2.18)$$

where the AIC difference $\varphi_j = aic_j - \min(aic_j)$, and the operating model aic_j is determined by

$$aic_j = -2 \sum_{n=1}^N \log g_{\hat{s}_j}(x_n) + 2U \quad (2.19)$$

which denotes the minimum AIC value over all the J candidate families (in this case, the lognormal, Rayleigh, Rician, Nakagami, and Weibull distributions). g is the probability density function of the examined channel model; $\hat{s}_j$ is the estimated parameter vector for the candidate family from the experiment data set; U is the dimension of vector and N is the size of the sample set $\mathbf{x} = [x_1 \ x_2 \dots x_N]^T$. In AIC method, ω_j can be interpreted as an estimate of the probability that the cumulative density function of the j^{th} model shows the best fit within the candidate set [9]. Therefore, the model with the highest Akaike weights is the best distribution to describe the data set. As a rule of thumb, useful AIC values can only be obtained when $N/U \geq 40$ [7].

2.2 Propagation in Waveguide-like Structures

This research concentrates on radio propagation along a lift shaft (waveguide-like structure) in the campus environment and within a metallic ship structure (another waveguide-like structure). Therefore, in this section, theoretical and experimental methodologies on the modeling and characterization of propagation in waveguide-like structures are described in detail. Identification and study of waveguide effect in waveguide-like structures such as tunnels, LOS corridors, Heating, Ventilation, Air Conditioning (HVAC) ducts and lift shafts are introduced. A review on propagation inside metallic ship vessels is also performed.

2.2.1 Theoretical Approach of Waveguide Effect in Different Structures

Among the theoretical work that model the radio wave propagation in waveguide-like environments, the most common methods used are; the modal analysis method and the geometrical optics or ray optical method. Comparing these two approaches, the waveguide effect along box-shaped structure is best described and modeled by the modal approach. Therefore, the modal approach is reviewed in detail while the other approach will briefly be introduced.

A) Modal approach

Due to the analogy between the waveguide-like structure such as tunnel, LOS corridor and HVAC duct and a common electromagnetic waveguide, modal approach is the most popular theoretical method to study the propagation along such structures. As the purpose of studying the propagation along tunnels is to enable communications, most research works in this area concentrates on the important parameter, the attenuation constant. The first work that theoretically modeled the rectangular tunnel was reported in 1974 by Emslie *et al.* [10]. The focus of their work was on providing wireless telecommunications for the mining industry. They modeled the attenuation constant associated with dominant waveguide modes in lossy tunnels by assuming the height and the width of the tunnel to be much greater than the wavelength. In 1982, the same attenuation constant was modeled for a lossy rectangular tunnel by Jacard *et al.* [11] without any constraint on the dimensions of the tunnel. Besides the rectangular tunnels, theoretical modeling of a ‘realistic waveguide’ focusing on attenuation constant or

received signal level along circular tunnels [12]-[14] and tunnels with arched cross-section [15] – [17] and elliptical cross-section [18] have also been done.

Tunnels such as railway tunnel is not always empty, the effect of the trains and other objects inside the tunnel on the waveguide modes and attenuation constant is therefore examined by researchers. Chiba *et al.* [19] theoretically studied the effects of trains in the railway tunnel on the cutoff frequency for waveguide modes and field distribution based on the finite element method. They assumed that the tunnels and the trains were infinitely long and fully conductive. Subsequently, in 1998, Zhang and Hwang [20] proposed an oversized imperfect periodically loaded waveguide model to study the effect of the train on propagation by using a partially conductive train. Attenuation constant for dominant modes were calculated and it was concluded that the density of passengers considerably affected the dominant mode propagation. Recently, Zhang *et al.* [21] used the same method to formulate the field distribution in a non-empty mine tunnel which was filled with vertical metallic supports. Propagation attenuation constant α (dB/m) of the dominate mode TE_{10} was calculated and compared for a scaled model.

Besides the tunnels, modal approach is also applied to study the propagation along LOS corridors theoretically. In [22], the trend of path loss with respect to the distance within the corridor from the theoretical results was compared with that from experimental results. It was concluded that the LOS corridor can be modeled as an oversized waveguide for frequencies in the order of or greater than 1 GHz. In [23], the physical waveguide model for radio propagation

along the indoor corridor was examined. By examining the relationship between the pass loss and the number of guiding modes, it was concluded that only the first two main waveguide modes were important for distances above ten meters. Contrary to [23], Tsalolihin *et al.* [24] conducted both theoretical and experimental study on the path loss along the corridor in the joint angle-of-arrive (AOA) and time-of-arrival (TOA) domain. In their proposed model, the waveguide mode number used to estimate the maximum waveguide effect was found to be closely related to the path loss.

HVAC ducts that can be easily found in buildings have also been identified as waveguide structure based on waveguide modal approach. The researchers believe that the HVAC duct is a wave guiding channel with multiple TE and TM modes. In [25][26], the concept of ‘multimode waveguide’ was used to describe the physical mechanisms (probe coupling, attenuation along the guide, and dispersion) that affected the propagation in a HVAC channel. In [27], the frequency response of the channel between two probes coupled into a straight HVAC duct system was derived based on multi-mode waveguide theory. Mode coefficients for all the possible TE and TM modes were calculated using standard microwave technique for probe-waveguide coupling. Subsequently, Nikitin *et al.* [28][29] developed a technique which was able to determine waveguide mode contents (TE and TM) propagating in a multimode waveguide structure such as HVAC duct based on the measured frequency response. The TE and TM modes extracted from measurement results were identified and compared with theoretical results.

From the literature, it is obtained that waveguide theory can be applied to model the propagation in box-shaped structures, i.e. tunnels, LOS corridor and HVAC ducts. Similar to waveguide, multiple modes can propagate along the waveguide-like structures depending on the dimensions of the cross-section of the structure and the operating frequency. Among these modes, dominant mode can propagate most easily and its attenuation is lowest.

B) Ray optical approach

Ray optical modeling of radio propagation channels in waveguide-like structures can be traced back to 1974 when Mahmoud and Wait [30] derived a geometrical ray model for straight rectangular tunnels. In the literature, different approaches of ray optics were reported. Ray summing taking into consideration only reflected ray, was reported by Lienard and Degauque [31][32]. Zhang and Hwang [33][34] extended this ray optics approach to branched tunnels by using ray summing that not only considered the reflected waves but also the diffracted waves whose amplitude were evaluated based on the Uniform Theory of Diffraction (UTD). This ray launching together with UTD model was used in [35] and [36] in tunnel environments. Didascalou *et al.* [37][38] modeled arbitrarily shaped tunnel by introducing a ray tracing method where bundles of rays were used to represent each “physical” wave. Each bundle of rays was traced to a receiver position where the reception spheres determined which rays have intercepted with the receiver. This shooting and bouncing ray (SBR) image method was then applied to model the wave propagation in road tunnels for scenarios with and without traffic in [39]. It was found that the traffic can cause fast fading to the received signal due to the reflections/obstruction of the vehicles. The same ray tracing method was also

applied to simulate the propagation in LOS corridors in different frequency bands [40]-[44]. Image theory of ray optics was also used to study tunnels covered by a distributed antenna system by Zhang and Hong [45]. In [46], a semi-deterministic propagation model for various shaped tunnels was developed by combining the deterministic ray-launching approach and the stochastic approach, which was used to avoid complex calculation. In [47][48], ray launching approach with the Monte Carlo method was used to model curved tunnels. Another approach in the literature that uses ray optics was the ray-tube tracing method proposed by Yang's team [49][50]. The proposed method includes multiple reflections and transmissions for structures with both flat and curved surfaces, as well as diffractions from wedges of the tunnels. Zhang in [51] proposed a novel model based on analytical ray optical (waveguide) model to distinguish between near and far regions in the tunnel and to predict propagation loss in these two regions.

2.2.2 Experimental Approach of Waveguide Effect in Different Structures

In the literature, the empirical study on propagation along waveguide-like structures covers both the narrowband characteristics and the wideband characteristics. However, the waveguide-like effect was mainly identified through path loss model. Therefore, experimental work on the modeling of path loss or attenuation in the three structures i.e. tunnel; LOS corridor and HVAC duct are reviewed. Tunnels and corridors are not always empty and hollow; blockage and movement inside the tunnels and corridors can affect the wave propagation along the waveguide-like structures. The signal variation caused by movement inside

these waveguide structures can be examined experimentally. Furthermore, researchers have explored several applications of the waveguide-like effect in HVAC ducts based on experimental results; these interesting works are also reviewed in the following.

A) Path Loss Modeling

Similar to theoretical works, attenuation constant is an important indicator of the waveguide-like effect. In 1978, the feasibility of using radio communication in tunnels was proven experimentally in the frequency band of 40 MHz – 4 GHz by Chiba *et al.* [52]. The attenuation constant along a 1470 m straight railway tunnel was found to increase monotonically with the inverse of the frequency. In the same year, Deryck [53] studied the attenuation constant experimentally along different road tunnels and mine tunnels with various cross sectional shapes and sizes at frequencies between 1 MHz to 1 GHz. It was shown that at frequencies above the cutoff frequency, attenuation depended on both the conductivity and the transverse dimensions of the tunnel. In 2004, Tonguz *et al.* [54][55] proposed an approximate path loss prediction model for link budget analysis in indoor wireless local area networks that used HVAC ducts in 2.4-2.5 GHz based on measurement results. Besides the attenuation rate of multimode propagation, the path loss model considered the impact of bends, tees, and wyes in the network. These results can be applied to the prediction of power level at any point along the HVAC duct network.

Besides the attenuation constant, the path loss obtained from the waveguide-like structures is often compared with the value calculated based on free space propagation. In [56], the study of path loss showed that for long

corridors in the mines, the waveguide effect in general resulted in better propagation compared to the free space propagation. In other LOS corridors such as in commercial buildings and office buildings [57]-[59], the path loss was also found to be less than free space path loss; therefore the guiding effect along the corridor was claimed to be the dominant propagation mechanism. The path loss exponent which is an important parameter for the propagation quality is another popular indicator of waveguide-like effect.

$$PL \propto d^n \quad (2.20)$$

In [60] and [61], the path loss exponent n that indicates the increase rate of the path loss PL with respect to the distance d was found to be less than 2 based on wideband channel measurements at different frequency in different types of tunnels. The same observation was made based on measurements along LOS corridors in different frequency band range from 450 MHz to 90 GHz [40],[62]-[69]. However, in [70]-[73], the obtained path loss exponent in various tunnels were found to be larger than 2 although the waveguide-like effect was concluded to be still an important propagation mechanism along the tunnels. In [73], the path loss exponents obtained in five different tunnels at 900 MHz and 1800 MHz in the GSM band ranges from 1.87 to 4.49, with only one of them below 2. It was claimed that the variation on the path loss exponent from tunnel to tunnel is a result of the tunnel conditions including the pedestrians, vehicles and curvature. From the study, it can be concluded that the waveguide effect along the waveguide-like structures contributes to the propagation if the frequency is above the cutoff. However, due to the complex variation in the tunnel conditions, conventional one-slope path loss or attenuation model may not be good enough for studying the waveguide effect.

The dual-sloped path loss trend is a common phenomenon that has been observed from waveguide propagation since 1975 [74]. In [74], the waveguide-like propagation along two wet granite tunnels was modeled by Gillette *et al.* in the frequency band of 1 to 1000 MHz. It was shown that waveguide-like propagation (low attenuation constant) occurred at higher frequency (above cutoff). Moreover, the relationship between the attenuation constant and the distance was modeled by two slopes. One associated with the shorter distances and the other associated with the longer distances. The slope for shorter distances is much larger than the slope for longer distances. This dual-sloped decay was further explained by a hybrid tunnel propagation model proposed by Zhang *et al.* [75] based on measurement results at 900 MHz in underground coal mines in 2001. The hybrid tunnel propagation model consists of the free-space propagation model, the modified waveguide propagation model, and the break point model. The region before the break point was called the near region, while the region after the break point was called the far region. In the near region, the guided propagation by the tunnel waveguide structure has not been well established due to the multiple modes propagation and the intermodal dispersion. With the first Fresnel zone clearance, the propagation behaves as in free space. In the far region, the guided single mode propagation by the tunnel waveguide structure has been stabilized; the propagation occurred as in an oversized imperfect waveguide. Subsequently, dual-sloped path loss model was used to model path loss obtained from different tunnels [37],[74]-[77] and LOS corridors [40], [78]-[81]. The attenuation factor from the near region and far region are calculated separately; it is common that the decaying of received power is very low in the far region. Therefore, long distance propagation in tunnels and LOS corridors is feasible.

Besides the one-sloped and dual-sloped path loss trends, path loss prediction in tunnels at 400 MHz with four slopes was proposed by Hrovat *et al.* [82]. Based on the measurement results inside road and railway tunnels, the path loss can be modeled as four segments: the free space segment (close to transmitting antenna), the high path loss segment, the waveguide segment and the free space propagation segment (close to receiving antenna). Compared to the dual-slope model, the four-slope model is more detailed. The first region and the fourth region are added on top of the near region and the far region of the dual-slope model. Authors stated that this four-slope model can be applied for distances over 500 m, while the dual-slope model used in [74]-[77][82][83] was mainly applicable to distances less than 500 m.

From the review on wireless propagation in different waveguide-like structures, it has been shown both theoretically and experimentally that tunnels, LOS corridors and HVAC ducts can behave as oversized waveguides, and the waveguide-like effect is the main propagation mode. Due to the low attenuation for dominant waveguide modes, the attenuation factor or path loss is an important parameter and widely studied in the literature.

B) Signal Variations in Waveguide-like Structures

Among the three types of reviewed waveguide-like structure, only HVAC ducts are hollow most of the time. The obstacles such as vehicles inside the tunnels, and human activities in the corridors can cause addition attenuation to the received signal. The experimental study on the signal variations in these two structures are reviewed in the following.

For propagation in tunnels, besides the frequency, the distance, the dimensions and shape of the cross section, other parameters such as the traffic condition (vehicles such as van, truck and train) and the pedestrians in the tunnel have impact on the received signal. In the literature, the signal variation due to vehicles in road tunnels was reported in [73][84]-[86]. In [73], Zhang and Hwang have examined the effect of the car and truck in a road tunnel environment in UHF band. It was shown that the shadowing caused by a car was negligible while the truck can cause an additional loss of 6 – 10 dB. Klemenschits *et al.* [84] provided a cheap and efficient method to obtain measurement data for mobile radio in or around road tunnels by using a scaled environment. The traffic influence has been simulated by putting metal boxes to represent vans and trucks. It was reported that a single obstacle will simply result in addition loss. In [85], measurements were performed in several road tunnels with various traffic conditions at 900 and 1800 MHz. The additional loss due to the van and truck passing was listed for these two frequencies. It was found that the medium value for the additional loss was less than 1.5 dB regardless of frequency and type of vehicle. In [86], the effect of the vehicles in the tunnels on the radio wave propagation was tested in the frequency range from VHF to microwaves. It was found that the propagation loss due to the vehicle was determined by the size and the number of vehicles. The location of the vehicle in the tunnel did not have a significant effect.

As trains in the subway tunnel and railway tunnel have much larger size compared to vans and trucks in road tunnels, the signal attenuation caused by the trains is expected to be more severe. In [87], Lienard *et al.* studied the influence on the received power at 2.45 GHz by the “*masking effect*” which was caused by the

stationary train in the subway tunnel. It was reported that the masking effect was not significant if the train was situated in one track of a two-tracked tunnel while the additional loss can reach up to 15 dB if the subway tunnel is a one-tracked tunnel. In [83], Guan *et al.* defined the term “*near shadowing*” as the additional attenuation on the received power when the train was in front of the transmitter. The maximum variation of the signal level can reach up to 21.4 dB and 32.1 dB at 2.4 GHz in a narrow subway tunnel and wide subway tunnel respectively. Rodriguez *et al.* [76] examined the effect of train passing from outside to inside and two trains passing on the received signal quality in the GSM planning in railway tunnel in 900 MHz band. Three transmitters were installed at the edge of the 4000 m tunnel at the distance of 1000, 2300, and 3500 m respectively; the receiver was installed on the top of a train locomotive. It was shown that the signal transmitted at the edges of the tunnel was attenuated by 15 to 20 dB when the train is either moving from outside to inside and from inside to outside. An identical stationary train stopped at different position was used to study the blocking effect when two trains are passing each other. The maximum signal variation was observed when the stationary train was located at the midpoint between the two transmitters. The maximum variation in the received power was found to be up to 20 dB. Besides the subway train and railway train, the coal-mine train [73] can cause a shadowing loss of 13 dB at 900 MHz.

In general, human activities are kept to a minimum in any road tunnel or railway tunnel, therefore, the effects of human activities in such environment are not considered. Instead, the effect of pedestrian density can be examined in underground market tunnel by Zhang and Hwang [73] and along an underground

street and corridors by Yamaguchi *et al.* [88]. In [73], the power distance factor or attenuation constant (dB/m) in an almost vacant to fully occupied underground market tunnel was found to increase from 2.96 and 3.71 to 3.17 and 5.49 for horizontal and vertical polarization respectively. This study indicated the pedestrians constituted to an additional loss. In [88], in order to study the effect of the pedestrian, the attenuation constants obtained in a crowded underground street during day time and night time were compared. It was concluded that pedestrian had a significant impact on the waveguide-like propagation; the maximum variation in the attenuation constant was found to be 20 dB/m at the frequency of 5.5 GHz. From the review, it can be obtained that obstacles inside the waveguide-like effect can result in additional loss to the received signals. The significance of the shadowing effect caused by the obstacles depends on the size, location and the material property of the obstacles.

C) Application of the Waveguide-like Effect

Based on the models derived from both theoretical and experimental approach, the guiding effect along the HVAC duct was proved to be an effective propagation mechanism due to its much lower signal attenuation. In the literature, several works have explored the application of this guiding channel. The capacity limits of HVAC duct channel for the application of high speed internet access at the 2.4 GHz ISM band were estimated based on measurement results from [89][91]-[93]. It was reported that the data rate over 2 Gb/s was achievable for a distance up to 22 m by using the HVAC duct channel. The findings in this work suggested a new distribution technique for indoor high data rate wireless networks using waveguide effect. The possibility of solving the handover problem by utilizing the HVAC

guiding channel has been explored by Xhafa *et al.* [94][95]. From the experimental results published, the mean number of handovers that a call in progress experienced can be reduced by up to a factor of 9 as compared to traditional indoor wireless network. In [96], the HVAC duct was also used for signal distribution for the WCDMA indoor solution. Measurement results from a real installation were used as input to a simulation work using Matlab. The performances in terms of coverage, macro network off-load, cost and capacity were compared for the HVAC solution and the distributed antenna system. It was reported that, the HVAC solution performed almost as good as a distributed antenna system, but the cost was only a fraction. Recently, there has been significant interest in the design and implementation of the UHF Radio-Frequency Identification (RFID) system. In 2010, Nikitin *et al.* [97] proposed the use of HVAC ducts as a low loss propagation medium and power grid to enable powering up and communicating with passive UHF RFID tags that can be located far away from the reader. It was found that as the HVAC ducts behaved as electromagnetic waveguides with much lower signal attenuation compared to free space propagation, the reader range achieved by the HVAC duct is 5 times longer than that in the free space.

2.2.3 Summary

In summary, waveguide propagation inside different types of box-shaped structures is reviewed theoretically and experimentally. In order to achieve a realistic communication model, signal variations caused by obstacles inside the structures (tunnels and LOS corridors) are reviewed. It is shown that waveguide-like effect along tunnels, LOS corridors and HVAC ducts is an effective communication means due to the single mode propagation with low attenuation

constant. Because of that, the HVAC ducts can be used for many popular applications such as WCDMA and RFID. The HVAC duct works well as a waveguide as reported in numerous literature. Another commonly found waveguide like structure that is less reported in the literature is the lift shaft. Therefore, in this thesis, the lift shaft together with its moving lift car is considered as a means for communication improvement. Therefore, such structures will be reviewed next.

2.3 Propagation along the Lift Shafts

In the literature, limited work [98]–[101] is done on the propagation effect within the lift shaft. In [98], Blackard *et al.* conducted impulsive noise measurements for indoor buildings at UHF (918 and 2440 MHz) and microwave (4 GHz) frequencies. The elevator has been identified as one of the significant sources of impulsive noise. The study showed that as the frequency increases, the impulse noise amplitude and duration decreases. Subsequently, narrowband measurement has been conducted, with the aim of studying the variation in signal strength due to the moving elevator [99]–[100]. In 1998, Meskanen *et al.* examined the propagation along the lift shaft through both simulations [99] and field measurements [100]. In [99], the effect of placement and orientation of antenna has been examined for propagation along the lift shaft through FDTD simulations. They concluded that the main mechanism for signal propagation within the lift shaft is independent of polarization. In the following year, they studied the propagation of GSM signals in a lift shaft for network planning purposes [100]. It was concluded that, at the higher GSM frequency band of 1800 MHz, although signal propagation is believed

to be worse than that at the lower GSM frequency band of 900 MHz, it was found to be approximately 5 dB better. The authors attributed this to the lower energy absorption by the lift car and the people in the lift car in the higher GSM band. It was also shown that the vertical lift shaft was an over-sized waveguide and therefore, has a lower attenuation factor in the higher GSM band. In [101], application focused research works have studied the effect of the moving elevator on the number of handoffs required for effective cell planning purposes.

In summary, it is found that lift shaft channel has not been well explored in the literature. Although the guiding effect along the lift shaft has been initially stated, no detailed study focusing on either propagation mechanism or multipath fading has been conducted. In this research work, the propagation modes and signal variations along lift shafts will be studied in details in Chapter 4 and Chapter 5.

2.4 Propagation onboard the Ship Vessels

As is known, the material and set-up are two key elements affecting the indoor propagation. It is because; for indoor propagation, the existence of multipath components and the amount of multipath components propagating in this environment depends on the location of the transmitter and receiver in the experimental setup. The location of the furniture relative to the transmitter and receiver, the amount of furniture within the environment, the reflectivity of this furniture, materials within the environment affects the propagation channel characteristics. The ship environment definitely displays significant different

characteristics compared to the common indoor channel due to its metallic and enclosed structure where there is a high possibility of signal guiding. Besides, some sub-structures such as the lift shaft and the cargo hull onboard the merchant ship is box-shaped; guiding effect along these structure can be one of the primary propagation mechanism. Therefore, works that focus on propagation inside ship vessels are reviewed in this section.

From literature, it is found that most of the reported work focuses on short-distance propagation on board ships in UHF band. In these works, discussion on both narrowband characteristics (such path loss and multipath fading) and wideband channel characteristics (delay dispersion) are available; however, little effort has been devoted to exploring the propagation modes (such as reflection, diffraction, scattering, waveguide effect and others) within the ship environment. Therefore, reviews in this section are concentrated on the channel characteristics.

2.4.1 Narrowband Characterization

A) Path Loss Modeling

The radio frequency coverage test was taken at both cellular band (824-894.4MHz) and unlicensed ISM band (2.4 GHz) by Simth *et al.* [102]. The path loss has been analyzed to verify the feasibility of operating a personal communication service (PCS) system at four locations (island structure, gallery deck, hanger deck and the mess decks) inside a ship. It was found that a single base station can provide a coverage range with a diameter of up to several hundred feet. Furthermore, the electromagnetic interference (EMI) was evaluated for the application of PCS. Results indicate that there is no EMI problem. However, only four locations were

included in the test, and the worst case – engine room where maximum EMI problem is expected was not tested, therefore, the conclusions drawn may not be concise. Lately in [103], the EMI was observed for frequency range 800 MHz to 1000 MHz, this contradicts the findings in [102].

Mokole *et al.* [104] characterized the underlying radiation and propagation mechanisms of signal sources at frequencies between 800 MHz and 3 GHz by collecting the received power level for open-closed door configuration, for selected transmitter-receiver locations (up to 5 meters) and for different signal polarization. By studying the path loss, it was concluded that signal level was sufficient to achieve inter-deck and intra-deck communication. In [6], path loss was obtained by ultra-wideband (UWB) measurements over 0.8-2.5 GHz across a closed hatch. The path loss exponent was found to be less than 2 due to the rich multipath signals resulted from the metallic structure of the ship. Based on the received signal level, it was also concluded that communication was possible from one compartment to another (separation less than 5 meters) on board the ship. The propagation was achieved through energy passing by the non-conductive structures in the bulkheads such as hatch seals and insulation around the pipes. In [105], the path loss model for propagation in a restaurant hall and along a cabin corridor onboard a cruise ship was reported. It was claimed that path loss in the restaurant hall almost followed the free space law of propagation, while a non-power law of propagation has been found for the corridor due to the complex reflections.

B) Multipath Fading

In [103], the complex channel response measured by wideband channel sounding

using Vector Network Analyzer (VNA) in three different naval vessels was studied. It was found that the received signal was Rayleigh distributed. Estes *et al.* [6] have characterized the wireless channel aboard naval ships using narrowband measurement technique inside a compartment. Multipath effect or fading was analyzed by plotting the received power when varying transmitter-receiver separation. The Rician distribution was found to be the best fit and Rician- K factor is presented. However, the experiment site was a compartment, where the maximum separation between the transmitter and the receiver is only 4 ft, so the narrowband results are only applicable for short distance RF transmission.

2.4.2 Wideband Characterization

Balboni *et al.* [103] conducted wideband channel measurements from 800 to 2600 MHz onboard 3 different naval vessels. The RMS delay spread was found to be independent of frequency. In [6], ultra-wideband (UWB) measurements over 0.8-2.5 GHz were applied to study the attenuation across one closed hatch. Moreover, the time dispersion parameter's RMS delay spread was found to be relatively large due to the rich multipath components. In [106], channel impulse responses and plots of received power versus distance were obtained for transmission within several compartments and passageways at 2 GHz and 5 GHz using VNA. The deployment of wireless local area network on board warships was investigated over a bandwidth of 500 MHz. It was concluded that the received power levels would support the use of wireless LAN, but the high RMS delay spread would restrict the maximum utilizable data rate. In [107], the received power and coherence bandwidth of the commercial off the shelf WiFi system was tested. Throughput and latency were studied based on measured results. It was concluded

that the wireless relay system may be useful and effective in a shipboard environment.

From the review, it is noticed that the study for propagation on board ship is not complete and more effort should be devoted to the derivation of the system performance over a long distance within the ship environment. Due to the unique complexity of the ship structure and its substructures, waveguide-like effect can be studied. Methods to exploit or to avoid the waveguide effects will be explored in order to enhance system performance such as the received power and the maximum data rate. Therefore, characterizations of radio wave propagation over a long distance onboard a merchant ship is studied in this thesis. Specifically, modeling of the guiding effect along the lift shaft onboard the ship is presented in Chapter 4; study of propagation along the cargo hull of the merchant ship and exploiting the application of this guiding effect are presented in Chapter 6.

2.5 Conclusions

This chapter provides a general introduction to channel modeling and characterization in RF complex environments. Starting with a brief introduction to the interested channel information, the RF-harsh environments have been classified into two categories: waveguide-like structures (direct guides) and metallic ship vessels (metallic enclosure with sub-guides). In the category of waveguide-like structures, both the theoretical and experimental characterization and modeling of tunnels, LOS corridors, HVAC ducts and lift shafts have been

reviewed in detail. The channel characteristics onboard ship vessels have also been reviewed.

It is understood that waveguide-like effect which has been well studied in some of the structures such as tunnels, LOS corridors and HVAC ducts is an effective communication channel. However, study of other similar structures such as the lift shaft and the ship vessel is lacking. A proper modeling of waveguide-like effect in these structures is necessary. Moreover, due to motions along the lift shaft and onboard the ship, signal variation can be significant and worth studying. Therefore, in the following chapters, we will focus our researches in this area.

Chapter 3

Experiments and Simulations Setup

In the previous chapter, a literature review on the channel modeling of the propagation in waveguide-like structures was presented. It is shown that channel performance can be well modeled and evaluated both theoretically and experimentally. In this chapter, the wideband channel sounding techniques used for this research work is presented. The ray tracing simulation used for verification of experimental results is also introduced.

3.1 Wideband Channel Sounding Techniques

For wideband channel sounding, three techniques are often used; the direct RF pulse system; the spread spectrum sliding correlator channel sounding system; and the frequency domain channel sounding system using the Vector Network Analyzer (VNA). Details of these three sounding techniques can be found in [1] and [4]. Amongst these three techniques, the spread spectrum sliding correlator channel sounding system and the frequency domain channel sounding system are used for our measurement campaigns. On the other hand, the direct RF pulse

system was not suitable for channel modeling in complex environments where LOS is usually not available. It is because; the direct RF pulse system relies on the first arrival signal to trigger the oscilloscope if no external trigger is used. If the first arriving signal is blocked or faded, the system may not be triggered properly [4]. Furthermore, the direct RF pulse system is highly susceptible to interference and noise. The width of the sounding pulse determines the resolution of such a system, and this is found to be another severe limitation. Due to all these limitations, this system is now rarely used in channel characterization measurements. A brief introduction to the two selected wideband channel sounders will be presented in subsections 3.1.1 and 3.1.2.

3.1.1 Spread Spectrum Based System

The spread spectrum based measurement is a time domain technique which is pioneered by Cox [108]. This sounding system has the advantage of low power-spectral density operation, controllable processing gain, controllable multipath resolution, ability to provide bit error rate (BER) information and immunity to noise. A disadvantage of the spread spectrum system is that the measurement results are not obtained in real time. Depending on the system parameters and measurement objectives, the time required for the post processing of channel impulse response $h(\tau)$ detection may be excessive [4]. For a spread spectrum based sounding system, a carrier signal is *spread* over a larger bandwidth by mixing it with a binary PN sequence. At the receiver, both sliding correlator [108] and matched filter detector [109] can be used as correlation detectors. A comparative study between the sliding correlator and the matched filter detector at the receiver for the determination of the channel impulse response with the spread spectrum

technique: maximal-length pseudo-noise (PN) sequence (“*m*-sequence”) was conducted by Kivinen *et al.* [110]. From their study, it was concluded that the sliding correlator-based sounder is popular due to its simplicity because it eliminates the need for rapid sampling and digital processing. However, stationary requirement of the channel between consecutive impulse response measurements limit the usefulness of this receiver because of the inherent slowness of it. In this study, sliding correlator is implemented due to its simplicity; the received spread spectrum signal is filtered and *despread* using a PN sequence identical to that used at the transmitter.

Figure 3.1 shows the basic block diagram of the spread spectrum based system used in the measurement. The transmitter consists of a vector signal generator, a high power amplifier and an Omni-directional antenna. An identical antenna is used to receive the signal. After been amplified by a low noise amplifier, the RF signal is down-converted to an Intermediate Frequency (IF) signal. This captured IF signal is then stored into a hard disk for post-processing. Important parameters in a spread spectrum based sounding system are introduced in the following.

Figure 3.1 Block diagram of the spread spectrum based wideband measurement system

A) Processing gain

The processing gain (PG) is the ratio between the output and input Signal-to-Noise Ratios (SNR) of a system. For a m -sequence coded sounding system which is modulated by BPSK, PG in dB can be expressed [110] as

$$PG \cong 10\log_{10}(L) \quad (3.1)$$

where L is the code length of the m -sequence.

B) Dynamic range

The required dynamic range of the measurement system depends on the difference between the peaks with the largest and the smallest amplitude in the obtained power delay profile and also the noise floor. Theoretically, the dynamic range for any m -sequence coded waveform with a length L is $20\log_{10}(L)$ in dB.

C) Spatial resolution

The spatial resolution capability of a sounder is the minimum time delay between two consecutive resolvable impulses. The study in [1] and [110] shows that the resolution in time-domain is equivalent to the reciprocal of the PN code bit rate R_c . Based on Nyquist sampling theory, the maximum bit rate transmitted is limited by the sampling rate of the system, and so is the multipath resolution.

3.1.2 VNA Based System

The VNA based measurement technique is a wideband coherent frequency response measurement technique that performs coherent amplitude/phase

measurements. It is widely used in short-range wideband channel measurements, and is reported in many literatures [1][2][5][111]. The VNA based measurement system is an attractive measurement solution because it is simple to use and implement. Besides its simplicity, the generic VNA based system is relatively flexible since the frequency of operation, multipath resolution and maximum measurable delay can be configured by adjusting the operating parameters of the VNA. Moreover, it is able to track system error and to provide absolute delay to output time domain channel impulse responses. However, the VNA based system can only be used for short distance measurements if a single VNA is used because it requires a wired link to carry the transmitted reference [111]. Sarabandi *et al* [112] made the effort to extend the sounding distance to 1000 m by using two VNAs. These VNAs have to be synchronized through two rubidium atomic clocks. Then the whole sounding system became very costly. Due to the extremely fine resolution which can be achieved by the VNA based channel sounder, it is used in our measurements when the distance between the transmitter and receiver is separated by less than 50 meters.

Figure 3.2 shows a basic block diagram of a VNA based measurement system used in our study. The data acquisition/logging system is internally built inside the VNA. Continuous data logging is controlled by a computer through the General Purpose Interface Bus (GPIB). Besides the VNA, cables and antennas are also required for measurement. Other RF components such as appropriate amplifiers can also be included depending on the received power level.

Figure 3.2 Block diagram of the VNA based system

In the VNA based system, uniformly distributed continuous waves are transmitted over a pre-set bandwidth from port 1 (transmitting port). The complex frequency channel response S_{21} is recorded as it is directly correlated to the channel transfer function $H(f)$. The frequency response $H(f)$ of the multipath radio channel can be converted into the time domain impulse response $h(\tau)$ by taking the Inverse Fast Fourier Transform (IFFT) process. The important measurement parameters for the VNA based system are described as follows.

A) *Spatial resolution*

The measurement bandwidth BW determines the spatial resolution T_{res} that can be achieved in the time domain. The relationship between the BW and T_{res} is given as,

$$T_{res} \approx \frac{1}{BW} \quad (3.2)$$

B) *Maximum echo-path time delay resolution*

From the frequency step Δf_m which is determined by the bandwidth BW and the number of points N , the maximum measurable delay in time domain can be

obtained [113]. The maximum measurable delay d_m of a measurement is the range or delay over which the received energy can be unambiguously related to a certain transmitted pulse. For distances larger than d_m , aliasing due to under-sampling in the frequency domain will occur. The maximum measurable delay in terms of distance is given in (3.4).

$$\Delta f_m = \frac{BW}{N} \quad (3.3)$$

$$d_m = \frac{3 \times 10^8}{\Delta f_m} \quad (3.4)$$

C) Processing window

Before being converted to the impulse response in time domain, the frequency domain channel response can be processed using a filter in order to suppress the undesired sidelobes. Figures 3.3(a) and (b) show the effect of the Hanning window function which has been chosen in our study. It is shown that sidelobes due to the default rectangular window is suppressed; this will improve the accuracy of multipath identification although at the cost of a slightly decreased resolution (a widening of the peak width). The Hanning window function is chosen for study due to its ability to provide a good compromise between the suppression of sidelobes and the widening of the main peak width.

(a) Default rectangular window

(b) After applying Hanning window

Figure 3.3 Analysis of the effect of processing window

3.2 Comparison of Spread Spectrum Based System and VNA Based System

In this section, the time-domain and frequency-domain wideband channel sounding techniques are compared by using measurement results along a lift shaft in the campus environment. The received power, multipath resolution, as well as RMS delay spread are studied and compared in detail. It is shown that similar conclusions can be drawn for both techniques for this particular measurement

environment. In general, both systems have advantages and constrains; the choice of sounding technique heavily depends on the experimental environment.

3.2.1 Measurement Campaign

In this measurement campaign, both spread spectrum based system (time-domain technique) and VNA based system (frequency-domain technique) are used along a lift shaft (as shown in Figure 3.4) in a university environment. The transmitter level varies from level 5 to level 2, while both the receiver and the lift car are fixed at level 6. The center frequency is fixed at 255.6 MHz in the military UHF band which covers from 225 to 400 MHz. For spread spectrum based sounding, a 1023-bit PN sequence is transmitted at a symbol rate of 20 Msym/s (PN Sounding), while 1601 tones are transmitted over a 300 MHz bandwidth using the VNA for the frequency domain channel sounding (VNA Sounding). The performances of these two channel sounding techniques are compared in terms of multipath resolution, received power, as well as RMS delay spread.

Figure 3.4 The schematic diagram of the measurement setup

3.2.2 Results and Discussions

Figure 3.5 PDPs obtained at different transmitter levels (PN sounding)

Figure 3.6 PDPs obtained at different transmitter levels (VNA sounding)

Figure 3.5 shows the mean power delay profiles (PDPs) averaged over 50 frames obtained by the PN sounding. As shown, the 1st peak in the PDP of transmitter level 5 contains 2 or 3 peaks in PDPs of other transmitter levels, and the common

area (0-0.25 μ s) is identified as the 1st cluster. The same cluster is also identified in Figure 3.6, which shows time-averaged PDPs averaged over 50 files obtained by the VNA sounding. It is noted that the noise floor for these two figures are aligned to the same level for the comparison of Signal-to-Noise Ratio (SNR).

A) Multipath Resolution

The multipath resolution capabilities include two types: spatial resolution and maximum echo-path time delay resolution. For both the PN and VNA sounding techniques, a larger spread bandwidth provides a finer spatial resolution. In this measurement, the spatial resolution of PN sounding (20 Msym/s) is 15 m while that of VNA sounding (300 MHz bandwidth) is 1 m. The resolution difference can be observed from Figure 3.7, which is obtained when the transmitter is fixed at level 5. It can be observed that one peak in PDP from the PN sounder contains several peaks in the PDP from the VNA sounder. This is due to the different spatial resolution. In general, the VNA sounding technique can provide a good spatial resolution, and it is often used for ultra-wideband application. The maximum echo-path time delays in this measurement are 51.15 μ s and 5.34 μ s for PN sounding and VNA sounding respectively. This time delay resolution can be improved by using more bits in the PN sounding technique and by sending more tones for the VNA sounding technique.

Figure 3.7 Comparison of PDPs obtained from the two sounding techniques

B) SNR Difference in 1st Cluster

It is shown in both Figure 3.5 and Figure 3.6 that the amplitude of the peaks in the 1st cluster decreases as the transmitter to receiver separation is increased. However, the amplitude of other peaks nearly remains constant even when the transmitter moves away from the receiver. The peaks in the 1st cluster come from reflection from nearby objects, and therefore, the 1st cluster is affected by the transmitter to receiver separation. Since we are only interested in the effects of nearby objects, only the power within the 1st cluster is studied. The average power in the 1st cluster is obtained by integrating PDP over the time 0 to 0.25 μ s. And the SNR differences between two consecutive transmitter levels are listed in Table 3.1. From Table 3.1, it is observed that the decrease in power difference when the transmitter moves away from the receiver are nearly the same for both techniques. Moreover, they follow the same trend that the power difference decreases as the transmitter to receiver separation increases.

Table 3.1 SNR difference between consecutive levels for the 1st cluster

Transmitter Levels	Power difference (PN)	Power difference (VNA)
level 5 to level 4	20.9dB	20.6dB
level 4 to level 3	9.8dB	6.5dB
level 3 to level 2	5.3dB	4.5dB

C) RMS Delay Spread

The RMS delay spread listed in Table 3.2 is calculated for PDPs in Figure 3.5 and Figure 3.6. In each of these two figures, the common peaks among PDPs are identified as signals and accounted for in the calculation of the RMS delay spread. It is shown in Table 3.2 that the RMS delay spreads obtained from different sounding techniques do not have significant difference even when a different spread bandwidth was used for the different sounding techniques. Moreover, the finding that RMS delay spread increases as the transmitter to receiver separation increases is consistent for both techniques.

Table 3.2 RMS delay spread for different transmitter levels

Transmitter Level	RMS Delay Spread (PN)	RMS Delay Spread (VNA)
5	11.8ns	16.7ns
4	52.2ns	80.6ns
3	123.8ns	128.6ns
2	138.9ns	176.0ns

3.2.3 Summary

This section has compared wideband measurement results obtained along a lift shaft in military UHF band in a university environment by using different sounding techniques. For the two sounding techniques, the rate of decrease in power difference with an increase in transmitter to receiver separation is

similar and follows the same trend. It is also concluded that the RMS delay spread increases as the transmitter to receiver separation increases. The RMS delay spread values calculated from measurement data collected using these two sounding techniques are close. Therefore, it can be concluded that both techniques provide similar channel information about the propagation in the military UHF band for this particular environment. Therefore, both sounding techniques can be used. In general, for transmission in clean frequency band such as the military UHF band in a relatively complex environment, the frequency domain channel sounding is recommended. For transmission in popular frequency bands such as WiFi frequency at 2.4 GHz in a relatively simple environment with big obstacles, the spread spectrum based sounding technique is recommended.

3.3 Simulation Setup

In this work, the commercial ray-tracing simulator “Wireless Insite [114]” is used to obtain detailed channel information via simulation. The simulated scenarios in Chapters 4 and 6 are simplified models of the actual environments. The simulation results obtained from this software are used to provide qualitative explanations of the phenomena observed from the measurement results. The quantitative comparison between the simulation results and the measurement results may not be meaningful since the actual sounding environment during measurement is bound to be more complex than the modeled environment for simulation. The applied simulation model is developed based on a hybrid shooting bouncing ray (SBR) algorithm and geometrical theory of diffraction (GTD). The SBR method is

implemented with robust ray tracing techniques where once the propagation paths are found, the field is evaluated by far-field transmission and reflection coefficients. The amplitudes of the diffracted fields are evaluated by GTD [114]. In the basic form of the SBR technique, it is assumed that the incident electromagnetic wave is planar and is partitioned perpendicularly into a large number of ray tubes such that any particular ray tube will initially intersect with a small area of the whole target. The ray tubes are required to be spaced sufficiently fine so that other simplifying assumptions i.e. ray remaining planar and the shape remaining circular, can remain valid throughout the full ray path. For this simulator, the ray spacing can be specified by the user based on the application. However, fine ray spacing can lead to long computation time. The advantage of the SBR algorithm is its simplicity, but the model is less effective when the target features are complex and there are multiple scatters in more than one direction [115][116]. The transmitter power, maximum number of reflection, maximum number of transmission, maximum number of diffraction as well as the maximum number of the output path can be set based on the complexity of the simulated scenarios. For each simulation, Wireless Insite will generate a list of propagation paths and the amplitudes associated with the paths.

3.4 Conclusions

This chapter presents a general introduction to the wideband sounding system and simulation software used for channel characterization. Both time domain channel sounder and frequency domain channel sounder are introduced and their performances are compared based on measurement results. It is found that, for

short-range measurements in a clean frequency band such as the military UHF band, the VNA based system is the best choice for channel sounding since it has the advantage of extremely fine resolution, which enables the detail study of different propagation modes. For long-range measurement in a popular band such as 2.4 GHz in the ISM band, the spread spectrum based system is preferred since it is less susceptible to interference. In our measurement campaigns, different frequency bands and RF complex environments are studied. The selection of the sounding system heavily depends on the realistic condition including the frequency; location of the antennas as well as the focus of the research work. The simulation software introduced in this chapter is a 3D ray tracing simulator, which is used to validate the propagation mechanisms obtained from the measurement results.

Chapter 4

Modeling of Propagation along the Lift Shaft

The propagation mechanisms and signal variations along the lift shaft located in different environments are studied in detail in this chapter. First, the feeding mechanism of the lift shaft channel is modeled based on a slot feed into a waveguide structure. After demonstrating the possibility of the coupling of EM waves into the lift shaft, the propagation mechanisms along the lift shaft are studied based on measurement results in a campus environment and onboard a merchant ship. These propagation mechanisms are then verified using 3D ray tracing simulation results. It is found that, regardless of the location of the lift shaft, the electromagnetic waves can be guided along the lift shaft and these guided waves along the lift shaft are subjected to signal variations caused by the movement along the lift shaft including the opening/closing of the lift door and the movement of the lift car.

4.1 Modeling of the Slot Feed along the Lift Shaft

Before studying the waveguide-like propagation along the lift shaft, the ‘feeding’ mechanism or the coupling of EM waves into the lift shaft structure should be examined. The coupling loss at the feeding point of the waveguide can be significant, especially when the opening of the waveguide structure is small. In this section, the feeding mechanism of a waveguide-like structure is discussed. More particularly, the slot feed at the door slot of a lift shaft is modeled.

4.1.1 Simulation Setup

Table 4.1 Dimensions of the simulation model

Structure	Dimensions		
	X (m)	Y (m)	Z (m)
Lift Shaft	1.5	1.5	1.5
Air Box	1.3	1.4	1.3
Door Slot	0.1	1.5	0.01
Dipole	1.8×10^{-3} (radius)	0.6	1.8×10^{-3} (radius)

The behavior of the coupled electric field on the door slot is simulated using the High Frequency Structure Simulator (HFSS). This simulator is able to perform 3D full-wave electromagnetic field simulation. The simulated lift shaft model with the transmitting dipole antenna placed 1 m away from the center of the door slot is shown in Figure 4.1. The dimensions of the structures included in this 3D model are detailed in Table 4.1. The length of the dipole is 0.6 m, which is half of the wavelength of the sinusoidal waves at 250 MHz. The transmit power at the dipole antenna is set to 1W. It is noted that the simulation was done according to the actual measurement setup. The lift doors can only be opened on the floor where the

lift car is. The simulated model is done for one level of the lift shaft (with a gap of 1 cm in the middle of the two closed lift doors) with height of 1.5 m since the effective coupling of EM waves into the lift shaft is through the door slot at that level, where the transmitting antenna is placed. Moreover, the size of 1.5m x 1.5m x 1.5m is the largest dimensions that can be simulated in HFSS at the frequency of 250 MHz. (close to the frequency 255.6 MHz used in measurements). From the simulation results, the radiation pattern of the dipole is extracted for comparison purpose. More importantly, both the amplitude and the direction of the electric field along the door slot can be modeled.

Figure 4.1 The simulation model.

4.1.2 Results and Discussions

Figures 4.2 (a) and (b) show the radiation patterns of the dipole with a length of 0.6 m at 250 MHz in free space and near the lift shaft respectively. Comparing the two graphs, it is observed that the radiation pattern in both the vertical plane (grazing angle equal to 90°) and the horizontal plane (grazing angle equal to 0°) are affected by the presence of the lift shaft. However, the antenna gain in the horizontal plane is more significantly affected by the metallic lift shaft. Therefore,

it can be deduced that the most of the electromagnetic field are coupled into the lift shaft in the horizontal direction along the x axis as indicated in Figure 4.1.

Figure 4.2 Radiation pattern of a dipole antenna (a) in free space (b) near the lift shaft.

(a)

(b)

(c)

(d)

Figure 4.3 Distribution of electric field for phase of (a) 0° (b) 90° (c) 180° (d) 270° at the dipole.

The coupled electric field along the door slot at different time is analyzed and shown in Figure 4.3. Figure 4.3 (a) is obtained when the phase of the transmitted sinusoidal wave from the dipole equals to 0 degree. Figures 4.3(b), (c) and (d) are obtained when the phase equals to 90 degrees, 180 degrees and 270 degrees respectively. From Figure 4.3, it is observed that electric field along the door slot is dominantly in the horizontal direction along the x axis except at the two extreme ends of the door slot. Based on the theory of waveguide excitation, the aperture on a conductive wall with tangential magnetic field nearby can be replaced by two magnetic polarization current located parallel to the conducting wall. In this case, the coupled H field at the slot is along the z direction, the couple E field is along the x direction as shown from simulation results; therefore, the propagation of the waves is in y direction along the height of the lift shaft. It is also shown in Figure 4.3 that the amplitude of the effective electric field is varying periodically with a period of 360 degrees. Both the maximum amplitude and the initial phase depends on the location of the point along the door slot. Therefore the electric field along the y direction can be expressed as (4.1).

$$E_x(y) = A(y) * \sin (2\pi t + \theta(y)) \quad (4.1)$$

where $A(y)$ is the maximum amplitude of the electric field while $\theta(y)$ is the initial phase relative to the transmitted sinusoidal wave from the dipole antenna (phase of E field when the phase of the transmitted sinusoidal wave from the dipole equals to 0).

A) Modeling of the Maximum Amplitude

The maximum amplitude for each point along the door slot in the y direction are plotted and fitted in Figure 4.4. It is observed that the maximum amplitude is linearly distributed along the door slot when the examined point is at least 0.25 m (approximately 0.2λ) away from the two extreme ends at $y = -0.75$ and $y = 0.75$. The maximum amplitude increases when the distance between the point and the center of the slot ($y = 0$) increases. Beyond the distance of 0.5 m, the maximum amplitude can be fitted using a 2nd order polynomial function. The fitted models are given in (4.2a) to (4.2d), where $A(y)$ is the maximum amplitude of the coupled E field in V/m, y is the distance between the examined point and the center of the slot in m.

$$A(y) = -130y^2 - 170y - 46 \quad 0.75 < y \leq -0.5 \quad (4.2a)$$

$$A(y) = -9.4y + 0.2 \quad -0.5 \leq y \leq 0 \quad (4.2b)$$

$$A(y) = 9.4y + 0.2 \quad 0 \leq y \leq 0.5 \quad (4.2c)$$

$$A(y) = -110y^2 + 150y - 40 \quad 0.5 \leq y < 0.75 \quad (4.2d)$$

Figure 4.4 Modeling of the maximum amplitude of the E_x .

B) Modeling of the Relative Initial Phase

The initial phase relative to the phase of the dipole for the electric field along the y axis is plotted in Figure 4.5. It can be seen that the initial phase along the slot can best be described by a 2nd order polynomial function which is shown in (4.3). In (4.3), y is in meters while θ is in degrees. Since the modeled initial phase is the relative phase to the transmitted wave from the dipole antenna, it will be larger when the distance between the dipole antenna and the point increases. The shortest distance between the transmitting dipole antenna and the door slot occurs when $y = 0$ along the door slot. Therefore, as the examined point moves away from $y = 0$, the distance increases, so does the initial phase relative to the dipole antenna.

$$\theta(y) = 190y^2 - 0.24y + 170 \quad -0.75 < y < 0.75 \quad (4.3)$$

Figure 4.5 Modeling of the relative initial phase of the E_x .

4.1.3 Summary

In this section, the feeding mechanism of a lift shaft is studied based on EM simulation results. The incident magnetic field along the door slot of the lift shaft is found to be tangential to the slot, and therefore, can be represented by two magnetic dipoles with opposite direction. Furthermore, the electric field is modeled as a sinusoidal function with the same period as the transmitted wave from the antenna outside the lift door. The maximum amplitude of the electric field and its initial phase relative to the transmitting antenna are modeled with respect to the distance between the examined point and the antenna. After demonstrating the possibility of the coupling of EM waves into the lift shaft, experimental study focusing on the lift shaft propagation and signal variations due to the movement along the lift shaft is conducted in the following sections.

4.2 Propagation Modes and Signal Variations along a Lift Shaft in Complex Urban Areas

In this section, propagation along the lift shaft channel in an urban area is studied based on measurement results. Ray tracing simulation results are then applied to verify the conclusions. Besides the propagation mechanisms, signal variations caused by the movement along the lift shaft such as opening/closing of the lift door and movement of the lift car are also discussed in detail.

4.2.1 Measurement Campaign

The measurements in urban environment were performed along a lift shaft in an education building in Nanyang Technological University, Singapore. This education building is 7-storey high and is known as block S2. Each level (except level 7) in block S2 is about 3.9 m in height and it consists of three main blocks. Inside each block are laboratories, except for level 6 where there are offices. There are open walk ways that runs along all the 3 blocks on both sides of the building as seen in Figure 4.6(a). These open walk ways have concrete railings. The walls of the 3 main blocks are made of concrete and on the side walls facing the two walk ways are glass windows. All doors in the building are made of heavy wood. The ceilings along the walk ways are lined with thin aluminium plates. The lift shaft under study has concrete walls that spans 7 levels and with a dimension of 2.5 x 2.5 x 27 m (W x D x H). It is situated between the middle block and the last block in the building S2. On the opposite side of the lift shaft, there is a stairwell of the same height. Throughout the experiment, the location of the transmitter and the receiver are fixed at level 3 and level 6, respectively. The levels on which the antennas are placed, are chosen to maximize the propagation path, yet include as many case studies as possible. All levels along the lift shaft are similar except for levels 1 and 2 as shown in Figure 4.6(b). Antennas are placed at levels 3 and 6 for large separation distance. One level up and one level down are used for creating the case study where the lift shaft is out of the propagation channel. The antennas are placed directly outside of the lift door as shown in Figure 4.6(a). From Figure 4.6(b) it can be seen that there is a building in the surrounding environment known as block S1 which is identical and in parallel to block S2 (the experimental site) at a distance of 78 m away. There is also another group of education buildings known

as the Communication School (CS) which is situated between block S1 and block S2 as seen in Figure 4.6(b). The material of the blocks CS and S1 are similar to that of block S2.

(a)

(b)

Figure 4.6 Experimental environment. (a) Location of antenna. (b) Surrounding environment of the experimental site.

Wideband channel sounding at 255.6 MHz was performed in frequency domain. The measurement system consists of an Agilent Vector Network Analyser (VNA) and two identical omni-directional Discone antennas AX-71C (Figure 4.6 (a)) with a gain of 4.7 dBi at 255.6 MHz. Figure 4.7 shows the schematic diagram of the experiment setup. 1601 uniformly distributed continuous waves were

transmitted over a bandwidth of 300 MHz. With this specification, the highest resolvable path difference is 1 m and the maximum excess delay is 5.33 μ s. To ensure that the channel is static during a single sweep of the measurement, the minimum sweep time of 111.56 ms was used. For each measurement, a set of 50 sweeps were taken and logged onto a laptop. The pre-calibration using VNA's build-in calibration routings has been performed to compensate for amplitude and phase distortion up to the point where the cables attach to the antennas

Figure 4.7 The schematic diagram of the measurement setup.

4.2.2 Simulation Setup

Figure 4.8 3D simulation scenario for propagation in campus.

Figure 4.8 shows the simulation scenario with the lift shaft under investigation in block S2, and the surrounding blocks S1 and CS. The material of the walls of all

the buildings is modeled using layered drywall, while the floors and ceilings are modeled using concrete. For each level, two railings with a height of 1 m are added. The lift shaft and the stairwell are modeled as a series of empty rooms which spans 7 levels, and the lift car is modeled as a hollow metallic box. Vertically polarized omni-directional dipoles are used as the transmitting and receiving antennas. The simulated power differences between the different rays/multipaths are compared to the measured ones. The maximum reflection is set to 2 and the maximum transmission is set to 10. For each simulation, Wireless Insite is able to generate a list of propagation paths (up to 250 rays) and the amplitudes associated with the paths.

4.2.3 Results and Discussions

A) Overview of the Power Delay Profiles

Figure 4.9(a) shows the measured time domain channel response when the transmitter is at level 3 and the receiver is at level 6 while the lift car is kept stationary at level 3. The power delay profile can be classified into three regions indicated by the vertical lines. Region 1 ranges from 0 to 0.14 μs on the time axis, region 2 ranges from 0.14 to 0.5 μs while region 3 is for a time of 0.5 μs and above. Figure 4.9 (b) shows the simulated power delay profile (PDP) with the different rays identified by the simulator. Similarly, the simulated rays are classified into 3 regions according to their time of arrival. It is noted that all the PDPs from measurements and simulations have been normalized to the local maximum for the ease of comparison. Comparing the two figures, the propagation mechanism associated with each region can be analyzed with the help of the ray visualization

shown in Figure 4.9 (c). It is identified that rays in region 3 and region 2 are a result of signals being reflected off obstacles in the far region (block S1) and the intermediate region (block CS and far ends of block S2). The loss-distance relationship in region 1 indicates the possible sources of signals; they are the direct signal that penetrates through the ceilings and floors; the signal that are reflected and/or diffracted by nearby objects; and more importantly, the EM waves induced into the lift shaft, and propagate within the lift shaft to the receiver. The propagation within each region is further analyzed in the Sections 4.2.3B to 4.2.3E. In Section 4.2.3B, the far and intermediate reflectors are identified through measurements and simulations. In Section 4.2.3C, the nearby environment especially the signal variations associated with the lift shaft is examined in detail. In Section 4.2.3D, a comparison of the average channel gain for different measurement scenarios are presented. Finally in Section 4.2.3E, the root-mean-square (rms) delay spread for all measurement scenarios are discussed.

(a)

(b)

(c)

Figure 4.9 (a) Normalized measured power delay profile (b) Normalized simulated ray tracing power delay profile (c) 3D visualization from simulation in campus environment.

B) Propagation Mechanism of Signals in Region 3 & 2

By examining the time of arrival of the signals within region 3 and region 2, it can be concluded that signals in these two regions are a result of reflections by large static obstacles in far and intermediate regions. In this measurement campaign, there are two clusters of buildings (block S1 and block CS) situated on the left-hand side of the building block S2. In order to identify the reflections from these buildings, a set of controlled measurements are conducted by placing a metallic plate on the left-hand side of the corridor at the level of the transmitter. This metallic plate serves to reduce the number of signals propagating out of the corridor towards the far and intermediate reflectors.

Figure 4.10(a) shows a comparison of measured channel response with and without the metallic plate. It can be observed that when the metallic plate is present, the strength of signals in region 2 (except the first two clusters of peaks) and region 3 decreases by up to 7.7 dB. This verifies that region 3 and region 2 contain signals reflected from the far region of block S1 and the intermediate region of block CS. The unchanged amplitude of the first two clusters of peaks in region 2 is due to the reflections of intermediate reflectors within block S2 and the incomplete blocking caused by the limited size of the metallic plate.

A perfect electric conductor board is used to block the same side of the corridor in the simulation. Figure 4.10(b) shows the simulated power delay profile. The dotted impulses indicate the rays that are absent when the metallic plate is placed in the corridor. The red dotted impulse represents signal reflected from the block CS whereas the blue dotted impulse represents the signal reflected off the block S1. Comparing Figure 4.10(c) and Figure 4.10(c), it is observed that rays

reflected from block CS and block S1 are missing when the metallic plate is placed in the corridor in the simulation. As shown in Figure 4.10(b), there are three remaining multipath rays in region 2 when the metallic plate is placed in the corridor. These three rays are a result of reflections from the wall partitions within block S2. This can also be seen in Figure 4.10(c).

(a)

(b)

Figure 4.10 Metallic plate at transmitter level (a) Normalized measured power delay profile (b) Normalized simulated ray tracing power delay profile (c) 3D visualization from simulator.

C) Propagation Mechanism of Signals in Region 1

In order to verify the existence of induced EM waves through the lift door gap, a set of controlled measurements are conducted by placing a metallic plate outside a closed lift door at the level of the transmitting antenna. This metallic plate serves to block the transmission from the antenna towards the lift door. Figure 4.11 shows the comparison of the normalized power delay profiles with and without the metallic plate outside the lift door. It is observed that the first two peaks in region 1 have lower amplitudes when the metallic plate is placed outside the lift door. The maximum difference caused by the plate is approximately 15 dB. It is verified that EM waves can be induced via the gap between the lift doors. Due to the blockage between the transmitting antenna and the lift door, less EM waves with lower amplitude are coupled into the lift shaft, a lower received power is observed for region 1 signals. Moreover, the variation on the amplitudes of signals within regions 2 and 3 are insignificant; as it is shown in Section 4.2.3 B, signals arrival

within regions 2 and 3 are mainly reflected signals from static structures in intermediate and far regions. Therefore, the metal plate outside the lift door does not affect these signals a lot. In order to further study the waveguide effect of the lift shaft, controlled experiments are conducted by keeping the lift door opened and closed at the transmitter level and the receiver level; and by varying the position of the lift car from level 1 to level 7 (with the lift door closed). For all of the three sets of experiments, the transmitter and the receiver are fixed at level 3 and level 6, respectively.

Figure 4.11 Normalized measured power delay profile with and without a metallic plate outside the lift door at the transmitter level.

1) Lift Door Effect

The effect of opening/closing of the lift door is examined at the transmitter level (level 3) and the receiver level (level 5) since the signal variation is expected to be more significant if the lift door is opened at the antenna level as compared to other levels. Figure 4.12 shows the measurement result obtained when the lift door is opened and when the lift door is closed at the transmitter level. It is observed that

almost all the resolvable signals within region 1 are affected by the opening and closing of the lift door and the strength of these signals are approximately 14 dB higher when the lift door is opened. This indicates that EM waves are induced into the lift shaft via the gap of the lift door and then propagate along the lift to the receiver. When the lift door is opened, there is a larger opening for signals to be coupled into the lift shaft and therefore, higher amplitude is associated with the guided waves in region 1.

Figure 4.12 Normalized power delay profile obtained when lift door is opened and closed at transmitter level.

A similar analysis has been performed in order to examine the effect of the lift door (opened and closed) at the receiver level (level 6). Figure 4.13 shows the power delay profile obtained through experiments by opening and closing lift door at the receiver level. As expected, EM waves coupled out from the lift shaft are with higher signal strengths due to the open door at the receiver level. From the measured results, the maximum difference is approximately 7.6 dB. This is significantly less than that obtained by opening and closing the lift door at the transmitter level (14 dB) due to the asymmetrical of the experiment setup.

Figure 4.13 Normalized power delay profile when the lift door is opened and closed at the receiver level.

As shown from the sets of controlled experiments, the status of the lift door can cause signal variations to the guided waves. A closed lift door at the transmitter level can result in a signal strength variation as much as 14 dB, whereas that at the receiver level results in a much lower signal strength variation of 7.6 dB.

2) Attenuation Induced by Lift Car

Figure 4.14 shows the signal variation of the signals guided by the lift shaft when the lift car is moving. These plots are obtained by averaging data files over different period of times. The data files are recorded when the lift is in use and moving along the lift shaft. As can be seen in Figure 4.14, the signal variations caused by small movement of the lift car within the propagation path can lead to significant small-scale fading. Therefore, a series of controlled experiments are conducted to examine the effect of the lift car on the lift-shaft guided waves. Figure 4.15(a) shows the measurement results when the transmitter is at level 3 and the receiver is at level 6, and the position of the lift car is varied from level 1

to level 7, one level at a time and the lift door is closed at all times. In order to get a close view of signal variations of region 1 signals, the maximum delay of $0.4 \mu\text{s}$ (regions 1 and 2) is shown on the power delay profiles. No obvious variation on the amplitude of region 3 signals is observed.

Figure 4.14 Measured power delay profile when the lift car is moving.

From Figure 4.15(a), it can be seen that the channel gain for the signals in region 1 is the lowest when the lift car is at level 4 and level 5, while the channel gain is the highest when the lift car is at level 1, level 2 and level 7. This is because, when the lift car is at level 1, level 2 or level 7, it is not within the propagation path, therefore, leaving the wave guiding channel empty. Thus, there is no attenuation due to the obstruction of the guided waves by the lift car within the channel. This leads to the high channel gain. When the lift car is at level 4 and level 5, it is in the middle of the propagation path, and therefore, induces significant attenuation to the guided signal. Figure 4.15(b) shows the power delay profile of the two extreme cases when the lift car is outside the propagation path at level 7 and in the middle of the propagation path at level 5. It is clearly shown that signals within region 1 is

greatly affected by the lift car position, while the effect of the lift car position is minimum on the signals reflected from static structures arriving within regions 2 and 3. This result further demonstrates both the guiding effect of the lift shaft and the signal variation to the guided waves due to the movement of the lift car.

(a)

(b)

Figure 4.15 Variation of lift car position. (a) Normalized power delay profile. (b) Normalized power delay profiles when lift car is at level 5 and at level 7.

D) Channel Gain

From the previous sections *A*, *B*, and *C*, it can be concluded that region 1 mainly consists of signals coupled into the lift shaft and then guided through the lift shaft to the receiver. The status of the lift door and the position of the lift car will affect the propagation of the signals within region 1. Besides being guided along the lift shaft in the near region (region 1), signals can be reflected by objects in the intermediate and further regions, shown in region 2 and 3 respectively. In this section, the average channel gain in the three different regions are compared and analyzed. Different measurement scenarios are considered in order to study the effect of the lift door and the effect of the position of the lift car. Table 4.2 summarizes the normalized average channel gain within different regions when the lift door is opened/closed at the transmitter and the receiver level (corresponding PDPs shown in Figure 4.12& Figure 4.13. It is observed that the average channel gain in regions 2 and 3 are not affected by the status of the lift door, whereas the channel gain in region 1 depends a lot on the status of lift door as discussed in section *C1*. By comparing the channel gains in the three regions in Table 4.2, it can be concluded that, signals in region 1 has the highest channel gain (at least 4.8 dB above that of region 2) and the signals in region 3 have the lowest channel gain due to the longest propagation distance.

Table 4.2 Normalized average channel gain for opening/closing lift door (a) at transmitter level (level 3) (b) at receiver level (level 6)

(a)			
Normalized average channel gain (dB)	Region 1	Region 2	Region 3
Door opened	0	-14.6	-19.2
Door closed	-9.9	-14.7	-19.4

(b)

Normalized average channel gain (dB)	Region 1	Region 2	Region 3
Door opened	0	-16.3	-21.8
Door closed	-8.1	-16.4	-22.1

The variation of average channel gain in the three regions as the position of the lift car is varied is shown in Figure 4.16 (corresponding PDP shown in Figure 4.15(a)). It is observed that the channel gain of region 1 is the highest amongst the 3 regions regardless of the position of the lift car. The standard deviations of the average gain for the 3 regions are 4.3, 0.6, and 0.3, respectively. This shows that the channel gain of region 2 and 3 are independent of the position of the lift car, whereas the channel gain of region 1 varies a lot depending on the position of lift car. From this analysis it can be concluded that since the channel gain in region 1 is always high, the wave-guiding effect of the lift shaft is an important propagation mechanism in this complex environment. And it is important to understand the signal variations induced by the lift door and the lift car.

Figure 4.16 Average channel gain for different lift car level.

E) RMS Delay Spread

Table 4.3 RMS delay spread for opening/closing lift door

RMS delay spread (ns)	At transmitter level (level 3)	At receiver level (level 6)
Door opened	80.5	73.4
Door closed	159.2	127.3

The rms delay spread values (τ_{rms}) for the scenario when the lift door is opened/closed at the transmitter level and the receiver level are tabulated in Table 4.3. The time-averaged PDPs used for delay spread calculation are obtained by taking an average in the time domain of 50 continuous sweeps at a single position. All signals in the time-averaged PDP with amplitude of at least 5 dB above the noise floor (a threshold of 5 dB signal-to-noise ratio) are considered to be significant peaks. These significant peaks will then be accounted for towards the calculation of the rms delay spread. In Table 4.3, it can be seen that the status of the lift door has significant effect on the rms delay spread as it is determined by the signals' amplitudes and their corresponding time delays. When the lift door is closed, the strength and number of rays guided along the lift shaft decreases, while the signals in regions 2 and 3 arriving with a longer delay remain unchanged, therefore, resulting in a longer delay spread. The rms delay spread for different position of the lift car is plotted in Figure 4.17 (blue solid line). The delay spread varies with the position of the lift car. When the lift car is in the middle of the propagation path (level 3, 4 and 5), the guided waves are attenuated by the lift car. Therefore, a high rms delay spread of 159 ns is obtained. When the lift car is out of the wave guide (lift shaft), the rms delay spread is smaller.

Figure 4.17 RMS delay spread for different lift car level.

Taking all the measurement results into consideration, the mean rms delay spread is 122.3 ns. For propagation in typical urban environment, the delay spread is in order of μ s, which is larger than the value obtained in this environment. It is mainly due to the small separation between the antennas in the setup, i.e. the two antennas are within the same building and separated by a distance of less than 20 meters. However, the obtained delay spread is larger than those reported in the literature for propagation along analogues-waveguide structures [118][32]. In [118], it is reported that the rms delay spread is less than 32 ns for about 50% of the measurement results in an underground mine at 2.4 GHz. In [32], delay spread for propagation in a mine environment in the frequency band of 400 to 500 MHz is within the range of 5-42 ns. The larger delay spread reported here is because this calculation has taken into consideration multi-paths in all 3 regions (the wave guided along the lift shaft in region 1 and the open space propagation in regions 2 and 3). If only the delay spread of region 1 is considered, the delay spread for different lift car level is presented in Figure 4.17 by the red dotted line. As can be

seen, the average value is approximately 31 ns, which is similar to those reported in the literature for waveguide-like structures [118][32].

4.2.4 Summary

In this section, channel responses from wideband measurements along a lift shaft in a complex university environment have been studied. The corresponding ray tracing simulations have been performed to verify the measurement results and to identify and visualize the propagation mechanisms. The lift shaft is shown to function as a waveguide, and is the primary propagation channel in this complex urban environment. In an environment where propagation is difficult, the waveguide effect of the lift shaft makes it an important communication channel. Moreover, it is found that guided waves along the lift shaft are subjected to signal variations caused by the movement along the lift shaft including opening/closing of the lift door and movement of the lift car. In next section, propagation mechanisms and signal variations along a lift shaft channel onboard a merchant ship is studied based on experimental and simulation results.

4.3 Propagation Modes and Signal Variations along a Lift Shaft onboard a Ship

As presented in Section 4.2, the waveguide-like effect along the lift shaft is an important channel in a complex urban environment. A ship is mainly made of metal; non LOS propagation is therefore difficult to achieve because the propagation is mainly achieved via reflections and/or diffractions. The lift shaft connecting the ship from the top to the bottom becomes a useful channel for

propagation over the two ends of the ship. In this section, the propagation along the lift shaft on board a merchant ship including the propagation mechanisms and signal variations is examined.

4.3.1 Measurement Campaign

Similar experiments as introduced in Section 4.2.1 were conducted along the lift shaft on board a docked merchant ship. The 8-level ship is a metallic enclosure with many substructures. The bridge room used for navigation is at the top level (level 7), while the engine control room used for controlling the ship is located at the bottom level (level B1). The lift shaft which connects the ship from bottom to the top spans level 1 to level 7 with a dimension of 0.85 x 0.85 x 17.5m (W x D x H). Figure 4.18 shows the schematic diagram of the studied ship. Throughout the experiments, the antennas are placed directly outside of the lift door and the locations of the transmitter and the receiver are fixed at level 2 and level 6, respectively.

Frequency domain measurement technique was applied; the system setup including the center frequency, bandwidth, number of points per sweep, sweep time as well as number of sweeps was the same as that presented in Section 4.2.1.

Figure 4.18 The schematic diagram of the merchant ship.

4.3.2 Simulation Setup

Figure 4.19 3D simulation scenarios for propagation onboard ship.

Figure 4.19 shows the simulation scenario with the lift shaft under investigation inside a merchant ship. It is noted that this is a simplified model which only includes the large structures, i.e. the lift shaft, the ship enclosure and the cargo hull. All the material in the ship structure is modeled using Perfect Electrical Conductor (PEC). The lift shaft is modeled as a series of empty rooms which spans 7 levels, and the lift car is modeled as a hollow metallic box. The ship enclosure and the cargo hull are modeled as empty metal boxes. Vertically polarized omnidirectional dipoles are used as the transmitting and receiving antennas. For ease of comparison, the received powers from the simulation results are normalized to the local maximum. The maximum reflection is set to 5 and, the maximum transmission is set to 2. For each simulation, Wireless Insite is able to generate a list of propagation paths (up to 250 rays) and the amplitudes associated with the paths.

4.3.3 Results and Discussion

A) Overview of the Power Delay Profiles

(a)

(b)

Figure 4.20 (a) Normalized measured power delay profile (b) Normalized simulated ray tracing power delay profile (c) 3D visualization from simulator in ship environment.

Figure 4.20(a) shows the normalized time-averaged PDP when the transmitter is at level 2 and the receiver is at level 6 while the lift car is at level 6. Figures 4.20(b) and 4.20(c) show the simulated PDP and ray visualizations for the impulses respectively. In the PDP shown in Figure 4.20(a), two regions are be classified. Region 1 ranges from 0 to $0.09 \mu\text{s}$ on the time axis, region 2 is for a time of $0.09 \mu\text{s}$ and above. It is noted that the separation point of the two regions is at $0.09 \mu\text{s}$ instead of $0.14 \mu\text{s}$ for the lift shaft on campus. Since the PDP in this region consists of guided waves by the lift shaft, the time period in region 1 for the lift shaft channel in both environments are defined based on the ratio of the heights of the two lift shafts, i.e. $H_{\text{lift onboard the ship}}/H_{\text{lift in campus}} = 0.09/0.14$. Besides the guided waves along the lift shaft, region 1 also consist signals penetrating through the floors and ceilings and signals reflected and/or diffracted by nearby objects in the ship enclosure. Signals in region 2 are mainly multiple reflected signals by the

substructures within the enclosed ship structure. From the simulated results, the reflected signals in region 1 are mainly from the bouncing between the lift door and the nearby walls; while regions 2 signals with longer time delay are mainly multiple-reflected signals or guided signals by the ship enclosure. In the ship environment, the ship and its substructures form an enclosure and thus another waveguide. This results in a structure of ‘waveguide within waveguide’, where the inner guide refers to the lift shaft, and the outer guide refers to the ship enclosure. Therefore, any movement within the inner wave guide such as opening/closing of the lift door and moving of the lift car may not only affect guided signals along the inner waveguide, but also the signals guided by the outer waveguide. In Section 4.3.3B, signal variations caused by movement of lift door and lift car in the two regions are studied based on measurement results from two sets of controlled experiments. In Section 4.3.3C, the root-mean-square (rms) delay spread for all measurement scenarios are discussed.

B) Signal Variation along the Lift Shaft

As presented in Section 4.2, signal variations along the lift shaft are mainly caused by the opening/closing of the lift door and the movement of the lift car. The effect of these two movements on the guided signals by the inner wave guide (lift shaft) and the outer wave guide (ship enclosure) is studied based on experimental results from controlled experiments in the following.

1) Lift Door Effect

Figure 4.21 shows time-averaged PDPs obtained when the lift door is opened and closed at the transmitter level. It is shown that that both regions are significantly affected by the lift door status; the difference in the average channel gain is 6.1 dB

and 3.8 dB for region 1 and region 2 respectively. This is because; region 1 contains signals propagating along the lift shaft before arriving at the receiver for both environments. When the lift door is open, the opening into the lift shaft is larger; more waves are allowed to be coupled into the lift shaft. Signals arriving within region 2 consist of multiple reflected or guided signals within the ship enclosure, the outer waveguide. Therefore, the opening/closing of the lift door affects the multiple reflected signals, causing significant variations. This conclusion differs from the results shown in Figure 4.12 when the lift shaft is situated in a campus environment. In the campus environment, only the region 1 signals are affected by the opening/closing of the lift door, because signals arriving in the other two regions are reflected from static structures in a semi-opened environment. However, the ship environment is a complete enclosed environment with a lift shaft inside; the movement of the metallic lift door also affects the signals bounced within the outer guide.

Figure 4.21 Normalized time-averaged PDPs for Open-close lift door at transmitter level along the lift shaft on board ship.

2) Lift Car Effect

(a)

(b)

Figure 4.22 Time-averaged PDPs for (a) all lift car levels (b) lift car at level 4 and level 7.

Figure 4.22(a) shows the measurement results when the transmitter is at level 2 and the receiver is at level 6, while the position of the lift car is varied from level 1 to level 7. The lift door is closed for this set of controlled experiments. From

Figures 4.22(a), it can be observed that signals in both regions are affected by the movement of the lift car. The maximum variation in average channel gain caused by the movement of the lift car is 4.7 dB and 4.9 dB for region 1 and 2 respectively. For the same reason given before, the movement of the lift car within the lift shaft can affect signals in both regions because of the ‘waveguide within waveguide’ structure of the ship environment.

In order to examine the effect of the lift car position on the guided waves, the PDPs for the two extreme cases are plotted in Figure 4.22(b). The two extreme cases are; when the lift car is out of the propagation channel at level 7; and when the lift car is in the middle of the propagation channel at level 4. The channel gain is lower when the lift car is in the middle of the propagation path i.e. level 4. The channel gain is higher when the lift car is out of the propagation channel i.e. level 7. This is because when the lift car is in at level 4, the guided waves are significantly attenuated by the lift car since it is in between the transmitter (level 2) and the receiver (level 6). In Figure 4.22(b), part of the region 2 signals is affected by the movement of the lift car because the propagation of signals only reflected by the outer waveguide is independent of the lift car position as expected. Again, comparing the results obtained from the lift shaft in the campus environment presented in Figure 4.15, when the lift shaft is in the campus environment, the movement of the lift car only affects the waves guided by the lift shaft. Signals in region 2, out of the lift shaft is not affected. However, in this waveguide within waveguide structure, both the signals in region 1 guided along the lift shaft and the signals in region 2 guided by the ship enclosure are affected. This again verifies the waveguide within waveguide structure explained earlier.

C) RMS Delay Spread

Figure 4.23 RMS delay spread for different lift car level.

The rms delay spread values (τ_{rms}) for the scenarios when the lift door is opened/closed at the transmitter level are found to be 84.8 ns and 85.9 ns respectively. A threshold of 5 dB Signal to Noise Ratio (SNR) is used to calculate the delay spread from the time-averaged PDPs. It can be concluded that the status of the lift door does not have significant effect due to the opening/closing of the lift door for propagation along the lift shaft inside the shipboard. This is because; the rms delay spread value is calculated based on both the relative amplitude of the multipath components and their corresponding time delays with respect to the first arrival. For the propagation along the lift shaft inside the shipboard, signal strength for most of the peaks decreases when the lift door status changes from open to closed. Therefore, the delay spread which evaluates the significance of multipath signals with respect to the first arriver does not vary much. The rms delay spread values for different lift car positions are plotted in Figure 4.23. It can be observed that the variation in the rms delay spread due to the lift car movement is not

significant and do not follow any obvious trend because of the complex metallic environment of the ship board. The average value is approximately 89 ns.

Taking all the measurement scenarios into consideration, the average rms delay spread is approximately 88 ns. Compared to the value of 161.3 ns obtained from propagation along the lift shaft in the campus, the value from the campus environment is about twice that of the ship environment. This can be accounted for by the existence of the strong reflected signals from the large static buildings in the intermediate and far regions of the semi-open campus environment. For the average delay spread value of 88 ns obtained in the ship environment, it is comparable to the value obtained from an obstructed and heavily cluttered channel within a multi-floor structured factory [129]. The heavily cluttered factory environment forms a similar propagation channel to that of the ‘waveguide within waveguide’ environment on board the ship.

4.3.4 Summary

In this section, propagation modes and signal variations associated with the lift shaft channel onboard a ship has been presented. The wave guiding effect along the lift shaft and multiple reflections within the ship enclosure are the main propagation mechanisms. The opening/closing of the lift door and the movement of the lift car will not only induce signal variations to the guided waves along the lift shaft (inner waveguide), but will also induce signal variation to the guided signals by the ship enclosure (outer waveguide). This is due to the ‘waveguide within waveguide’ structure of this complex environment. Because of this,

obtained delay spread values are not closely related to the status of the lift door or the position of the lift car.

4.4 Conclusions

In this chapter, propagation along two lift shafts located in two different environments, i.e. campus environment and ship environment is modeled in detail. Following the modeling of feeding mechanism of the door slot into the lift shaft, propagation modes along the lift shaft are identified based on wideband channel measurement results in these two environments. The waveguide-like effect along the lift shaft is significant and is a common and important propagation mechanism for both environments. Besides the guiding effect, other propagation modes associated with the sounding environments are also discussed.

Signal variations on the guided waves caused by different components of the lift shaft such as the lift door and the lift car have also been studied. It can be concluded that lift shaft can function as a guiding channel which is subjected to temporal variations in both urban area and ship enclosure. Due to the difference in the surrounding environment of the lift shafts, movement along the lift shaft has little effect on reflected signals by the nearby static buildings in the campus environment, while the same movement can significantly affect the reflected signals within the ship enclosure due to the ‘waveguide within waveguide’ structure in the ship environment. The signal variations in these two environments will be analyzed and compared statistically in next chapter.

Chapter 5

Statistical Comparison of Signal Variation along the Lift Shaft in Two Complex Environments

As presented in Chapter 4, the lift shaft channel can perform as a waveguide-like structure regardless its surrounding environment. However, the signal variation due to the movement along the lift shaft such as opening/closing of the lift door and moment of the lift car is different depending on the surrounding of the lift shaft. In this chapter, signal variations along the lift shaft in the campus environment and on board the merchant ship are modeled statistically using the AIC based method. These results are then verified using the KS test results. The selection of the most suitable distribution function that best describes the amplitude variations in the received signals is compared for these two environments.

5.1 Measurement Campaign

Measurements have been conducted along the same lift shaft in an education building as introduced in Section 4.2. The lift shaft in the campus spans level 1 to level 7 with a dimension of $2.5 \times 2.5 \times 27$ m (W x D x H). During the experiment, the transmitter and the receiver are positioned outside of the lift doors at level 3 and level 6 respectively. Details of the experimental site can be found in Section 4.2. Similar measurements are conducted along the lift shaft on board a docked merchant ship as introduced in Section 4.3. The lift shaft which connects the ship from bottom to the top spans level 1 to level 7 with a dimension of $0.85 \times 0.85 \times 17.5$ m (W x D x H). Throughout the experiment, the antennas are placed directly outside of the lift door and the locations of the transmitter and the receiver are fixed at level 2 and level 6, respectively. It is noted that both the transmitting antenna and the receiving antenna are stationary; while the lift shafts are operated in normal condition, therefore, the distributions here accounts for the dynamic channel rather than the dynamic transmitter and receiver.

For this measurement, the frequency domain channel sounding technique is used. The measurement system consists of a Vector Network Analyser (VNA) and two identical omni-directional Discone antennas. The centre operating frequency is fixed at 255.6 MHz and 1601 uniformly distributed frequency steps over a bandwidth of 300 MHz are transmitted. In order to ensure that the channel is static over a single sweep of the measurement, the minimum sweep time of 111.56 ms is used. To study the signal variation on the signal strength, continuous measurements are conducted. 10000 data files (two-port frequency response S_{21}) have been recorded in campus environment and 5000 data files have been recorded

on board ship due to time constraint. It is noted that the lift shaft is operating in real conditions when the data was recorded, e.g. with people entering and leaving the lift shafts, lift door opened and closed at different levels and the lift car moving up and down the real time needs of the lift users.

5.2 Results and Discussions

According to the analysis in Section 4.2, the time-averaged PDP obtained along the lift shaft in the campus can be classified into three regions. Region 1 ranges from 0 to 0.14 μs . Signals arriving within this time range are mainly signals guided along the lift shaft. For this reason, significant signal variations are observed when the lift door opens and closes or when the lift car moves along the lift shaft. Region 2 (0.14 μs to 0.5 μs) and region 3 (0.5 μs onwards) mainly consist of reflected signals by the surrounding structures, i.e. static buildings in the intermediate and far regions of the campus environment. In this campus environment, there are no significant signal variations in region 2 and 3 when the lift is in use. The main focus in this chapter is the signal variation due to the movement along the lift shaft channel. Therefore, regions 2 and 3 are combined as one region (region 2) for analysis purposes. In Figure 5.1(a), the boundary for the new region classification is indicated by a vertical line. For the time-averaged PDP obtained along the lift shaft in the ship environment as shown in Section 4.3, the classification is already into two regions. Region 1 ranges from 0 to 0.09 μs , while region 2 is for a time of 0.09 μs and above. The time-averaged PDP with a vertical line to separate these two regions is shown in Figure 5.1(b). For both environments, guided waves along the lift shaft, signals penetrating through the floors and ceilings, signal reflected

and/or diffracted by nearby objects are included in region 1 due to the short propagation delay. In Figure 5.1(a), region 2 includes multiple reflected signals by static buildings. In Figure 5.1(b), signals in region 2 are mainly from multiple reflections by the substructures within the enclosed ship.

Figure 5.1 Normalized time-averaged PDPs (a) along the lift shaft in campus. (b) along the lift shaft on board ship.

In Figure 5.2, examples of 2000 copies of instantaneous PDPs are shown. The vertical lines indicate the separate between region 1 and region 2. Signal variations can easily be identified through the color variation, indicating a variation in multipath amplitude in dB. It is noted that, there is no significant multipath arriving after the time delay of 0.65 μ s. Therefore, the focus of this statistical analysis is from 0 to 0.65 μ s on the time axis. From Figure 5.2 (a), it can be observed that signals arriving in the region 1 are varying over the time, while signals in the region 2 have constant amplitudes. In Figure 5.2 (b), signals in both

Figure 5.2 Instantaneous PDPs obtained from (a) campus environment; (b) ship environment.

regions are subjected to amplitude variations. This observation agrees well with the findings in Chapter 4. In the following, the amplitude variations are studied statistically.

5.2.1 Channel Model Selection Based on Akaike Weights

In this section, five functions, namely the lognormal, Rayleigh, Rician, Nakagami, and Weibull distributions are the candidate members. The size of the data set, N , is equal to 10000 and 5000 for campus environment and ship environment respectively. AIC based method is applied to statistically model the signal effect associated with the time-averaged PDPs. Figure 5.3 show the plots of the Akaike weights for different candidate members as well as the normalized time-averaged PDP (blue curve) obtained from the experiment results in campus. Similar plots for the ship environment are shown in Figure 5.4. The maximum received power of the time-averaged PDPs in Figure 5.3(f) and Figure 5.4(f) has been normalized to 0 dB for ease of analysis. It is noted that the arrows in the two time-averaged PDPs indicate peaks whose normalized signal strength are larger than -20 dB and these peaks are considered significant and indicate the existence of a multipath component. All the significant peaks are at least 40 dB above the noise floor of the time-averaged PDP.

Figure 5.3 (a)-(e) AIC weights for different functions; (f) Weibull b parameter obtained from campus environment.

Figure 5.4 (a)-(e) AIC weights for different functions; (f) Weibull b parameter obtained from ship environment.

By examining the Akaike weights for significant peaks in region 1 of Figure 5.3, it can be observed that, for most of signals arriving within this region, the Akaike weights of the Weibull distribution function is 1. In Figure 5.4, the Akaike weight of Weibull function in region 1 is also found to be the highest. Therefore the Weibull function is able to best describe the tapped amplitude distributions within region 1 for the lift shaft propagation in both campus and ship environment. This is because the guided waves that are subject to signal variations caused by the opening and closing of the lift door and the movement of the lift car are included in region 1 regardless of the environment. Therefore, for both environments, there is severe signal variation within this region when the lift is in use. Since the Weibull function is the best function to describe channel with severe signal variations, it is found to have the highest Akaike weights from Figure 5.3 and Figure 5.4.

By examining the Akaike weights for the significant signals or peaks in region 2, it can be seen from Figure 5.3(c) that the Rician function has the highest

Akaike weights (around 1) for campus environment. This is as expected since these signals are the result of reflection from static buildings in the intermediate and far surrounding as presented in Section 4.2, there is little or no signal variation on these signals. The Rician distribution is commonly used to describe propagation channels with a dominant signal, therefore, for the channel with static reflectors in region 2 in campus environment, this distribution is found to best describe the significant peaks. In Figure 5.4(f), region 2 includes the signals bouncing within the ship enclosure, the outer waveguide as introduced in Section 4.3. Therefore, signals in this region are subjected to severe signal variations. Thus, again, the Weibull probability density function has the overall highest Akaike weights in region 2. The amplitude of these signals guided by the outer waveguide is randomly affected by the motion in the inner guide. Therefore shows severe signal variations. Insignificant peaks in both Figure 5.3(f) and Figure 5.4(f) are best described by the Rayleigh distribution. This distribution is commonly used to describe signals arriving from multiple random directions.

If the overall Akaike weight is examined, it can be found that lognormal distribution has the lowest overall weights while the Weibull function is the best function for describing the overall channel for both the campus environment and the ship environment. In order to verify this result, the KS test is applied to all the above candidate families. The passing rate for different distribution functions in the two environments is tabulated in Table 5.1. It is noted that since the distribution parameters required by the KS test are estimated from the data, the validity of the fitting has been checked and ensured during the process of parameter estimation. In both environments, the passing rate of the Weibull

distribution function is the highest, whereas that of the lognormal distribution function is the lowest. The other three distribution functions have similar performances. This agrees with the conclusions drawn from the AIC based method.

Table 5.1 KS test results for signal variations in the two environments

Distribution Function	Passing Rate (%) in Campus	Passing Rate (%) onboard Ship
Lognormal	0	0.5
Rayleigh	48.3	33.7
Rician	54.2	43.4
Nakagami	55.2	45.4
Weibull	69.2	52.5

From both the AIC based method and the KS test, the Weibull function is found to be the best distribution to describe the signal variation for the overall propagation channel. If channels are grouped based on its stability, static channels such as regions 2 in the campus environment is best described by Rician function; dynamic channels subjected to signal variations, i.e. lift shaft guiding channel (region 1) in both environments and outer waveguide (regions 2) in the ship environment can best be described by the Weibull distribution. In next section, the indicators of the Rician function, i.e. the Rician K factor and the Weibull function, i.e. the Weibull b parameter is further studied.

5.2.2 Rician K -factor

The Rician K -factor is an important indicator used to study the static channel. A higher K -factor indicates a relatively static channel with less signal variations. For the campus environment, the maximum K -factors are 3.2 dB and 11.1 dB for regions 1 and 2 respectively. If cumulative density function is used, 90% of K -factors in region 1 are below 2.8 dB, while those in regions 2 is below 5.8 dB. The

low K -factor (even falls below 0 dB) in region 1 indicates a multipath varying region due to the movement along the lift shaft while the high K -factor for region 2 indicates relatively static regions from the intermediate and far static reflectors. For the ship environment, the maximum K -factors are found to be 4.8 dB and 4.1 dB for regions 1 and 2 respectively. 90% of the K -factors in region 1 are below 3.2 dB, while those in region 2 are below 3.1 dB. The value of K -factors in these two regions are very similar because signal in both regions experience amplitude variation when the lift is in use. Compared to the campus environment, the obtained Rician K value for region 1 of PDP from ship environment is larger. This indicates that the signal variation associated with lift shaft in the campus is more significant due to its larger size. The K -factors of region 2 obtained from the campus environment is larger because significant signals in region 2 are reflected signals from static buildings while in the ship environment, significant signals in region 2 are multiple reflected signals bouncing inside the ship enclosure. These signals are affected by the motion along the lift shaft due to the ‘waveguide within waveguide’ structure.

5.2.3 Weibull b Parameter

As introduced in Chapter 2, the Weibull probability density function (PDF) is defined as:

$$p_{a,b}(x) = a \cdot b \cdot x^{b-1} \cdot \exp(-a \cdot x^b) \quad x \geq 0 \quad (5.1)$$

The parameter a can be derived from the parameter b and the distribution mean square value. The parameter b controls the spread of the distribution; a lower value of parameter b corresponds to a larger dispersion. If the parameter b is equal to 2,

the Weibull distribution is similar to the Rayleigh distribution, and $b < 2$ implies severe fading. The plot of b parameter together with the time-averaged PDP is shown in Figure 5.3(f) and Figure 5.4(f) for campus environment and ship environment respectively.

From Figures 5.3(f) and 5.4(f), it is observed that the parameter b is below 2 for most of the tapped amplitudes arriving within region 1 for both environments. This indicates that signals arriving within region 1 experience significant signal variation. For significant peaks arriving within region 2 shown in Figure 5.3(f), the b parameters are found to be larger than 2 and can reach up to 5.8. This indicates a dominant path (Rician distributed) from the intermediate and far regions. In Figure 5.4(f), the corresponding Weibull b parameter for significant peaks in region 2 varies within the range of 1.5 to 2.4. Over 60% of the b parameters in region 2 are below 2. This indicates that Weibull distribution is again able to describe the signal variation associated with the guided signals by the outer waveguide. For non-significant peaks in region 2 shown in both Figure 5.3(f) and Figure 5.4(f), the parameter b is nearly equal to 2. Therefore, they are best described by the Rayleigh probability density function since the signal strength is near to the noise floor. The conclusions drawn from the Weibull b parameter analysis is found to agree well with those drawn from the AIC based method. The Weibull distribution is the most suitable function to describe signal variations in the guided channels such as the lift shaft and the ship enclosure.

5.2.4 Summary

In this section, statistical modeling of the signal variation for the channel along a lift shaft in two different complex environments, i.e. inside the campus and on board the ship at UHF frequency is performed. When the signal variation is studied based on the signals' propagation mechanism (region by region), it is found that Weibull function is the best-fit model for analyzing the wave guiding effect of the lift shaft regardless of the surrounding environment of the lift shaft. This is because the lift shaft experiences a significant amount of amplitude variation due to the change in the status of the lift door and the movement of the lift car. The Rician function is found to be the most suitable model to describe the tapped amplitude variation for signals reflected by large static buildings and walls in the intermediate and far regions for the campus environment. For the ship environment, the Weibull function is again the most suitable function to describe signal variation in region 2. This is because signals reflected within the outer waveguide (the ship enclosure) are also affected by the motion inside the inner waveguide (the lift shaft). The selection of distribution functions are then verified using the KS test results. The Rician K -factor and the Weibull b parameter are then used to study the characteristics of the EM waves in all regions. It is found that the conclusions drawn from the Akaike weights agree well with those obtained from the Rician K -factor and the Weibull b parameter.

5.3 Conclusions

In this chapter, signal variation along the lift shaft in the two complex environments is statistically modeled and compared. It is concluded that,

regardless of the surrounding environment, the Weibull function is an appropriate model to model the signal variation along waveguide-like structures. The Rician function is found to be the most suitable model to describe the tapped amplitude variation for signals reflected by static structures. The Rician K -factor obtained from the static channel is therefore higher than that obtained from the waveguide channels. Furthermore, it is concluded that the Weibull distribution function is also the most suitable function to model the overall channel characteristics. This is because the Weibull b parameter can be used to identify and study the signal variation. This model can be extrapolated to model other waveguide-like structures in different environments and used for the simulation of a realistic waveguide-like structure with signal variations.

Chapter 6

Propagation between Two Extreme Ends of a Ship

On a ship vessel, the two key locations for controlling and navigating the vessel are the engine control room (ECR) and the bridge room respectively. The two rooms are generally located at the bottom and top of the ship; the direct propagation between the two locations is thus hindered as most parts of the ship are made of metal. Current communication devices used on board ships are narrow band devices such as the walkie-talkies. These devices can work well in the VHF band due to the low attenuation at the low frequencies. However, the feasibility of using wideband propagation between the two key locations is unknown. Therefore, this will be examined in Section 6.1. At a higher frequency such as in the military UHF band and ISM band, wideband communication via direct propagation is almost impossible. Therefore, a relay system is required. Since the cargo hull has a waveguide-like effect, examined in Section 6.2, a relay system is proposed to be deployed within the cargo hull. The application of the waveguide-like effect, i.e.

deployment of relay systems in both military UHF band and ISM band inside the cargo hull is then studied in Section 6.3.

6.1 Propagation between Two Ends of a Ship in VHF Band

In this section, channel characteristics and temporal variations associated with VHF wave propagation between the two key locations, i.e. ECR and bridge room on board a vessel is presented. By using Kolmogorov-Smirnov (KS) test, the received signal level from narrowband measurements are found to be Rician distributed with a temporal variation of below 3.5 dB for 90% of the time. Moreover, based on wideband channel measurement results, variation on the signal-to-noise ratio (SNR), Rician K -factor as well as the root-mean-square (RMS) delay spread are studied and compared for two different transmitter positions.

6.1.1 Measurement Campaign

The measurement campaign was carried out onboard a merchant ship in Singapore in 2008. The ship docked alongside a wharf throughout the entire period of the experiment. The ECR is near the lowest level (level B1) of the ship while the bridge room is at the top most level (level 7) of the ship. The vertical distance between the two points is equal to the height of the vessel which is approximately 20 m and the horizontal separation between the doors of the two locations is around 1.5 m. It is noted that the engine room is only a slight distance away from the ECR. There is a lift shaft that links the cargo hull to the bridge room; it is one of the important paths for signal to propagation from bottom to the top of the ship.

Two positions inside the ECR have been chosen for transmission; Position 1 is located near to the door of the ECR; Position 2 is located in the center of the ECR (around 2 m away from the door). The receiver is placed near the door of the bridge room. The schematic sketch of the relative positions of the two transmitters and the receiver is shown in Figure 6.1(a). Figure 6.1(b) shows the photograph of the antenna positions inside the ECR. It is noted that the door of the ECR is on the right hand side of the antenna as indicated by the arrow. It can be seen that most of the structures inside the ECR, e.g. floor, walls, and cabinets are metallic. Therefore, strong reflections are expected. Compared to the experiments conducted along the lift shaft onboard the ship (presented in Chapter 4 and 5), the vertical distance between the bridge room and the ECR is larger. More importantly, from the deck level downwards, most of structures within the ship are metallic; the propagation is expected to be more difficult as compared to along the lift shaft. On the other hand, the large pieces of metal can reflect and/or diffract electromagnetic waves, thus creating a rich multipath environment which limits the channel performance.

For this channel sounding, the VHF frequency of 79.125 MHz was used. Both narrowband and wideband measurements were performed at this frequency. For narrowband measurements, the transmitter consists of a vector signal generator, which produces a continuous sinusoid wave at 79.125 MHz. This signal was transmitted through an omni-directional discone antenna with a typical gain of 2.4 dBi. The same antenna together with a low noise amplifier (LNA) was used to receive the signal. This received signal was then sampled by a spectrum analyzer and logged via a data logging computer. For each set of experiment, 2000 copies of continuous sinusoidal wave were recorded for post processing. For wideband

measurements, the vector signal generator produces a Binary Phase Shift Keying (BPSK) modulated broadband signal at a carrier frequency of 79.125 MHz. The carrier frequency was spread using a 1023-bit Pseudo random Noise (PN) sequence and transmitted at a data rate of 10 Msymbol/s. The antennas used for wideband sounding are the same as those used for the narrowband measurements. At the receiver end, the captured signal passed through a low noise and it was down-converted to an intermediate frequency (IF) of 24 MHz. This IF signal was then sampled at a rate of 100 MSamples/s and stored in a data logger for offline data processing.

(a)

(b)

Figure 6.1 (a) Schematic diagram of the vessel. (b) Photographs of the Engine Control Room (ECR)

6.1.2 Results and Discussions

A) Narrowband Measurement Results

From the 2000 copies of received power, it is obtained that the mean signal levels at position 1 and 2 are -51 dBm and -52 dBm respectively. The variation with reference to the mean signal level can be studied by the cumulative-distribution-function (CDF) as shown in Figure 6.2. From Figure 6.2, it is shown that the signal variation for transmitter position 1 is always higher than that of transmitter position 2. It can also be obtained that 90% of the signal variations for position 1 and 2 are below 3.5 dB and 2.8 dB respectively. In order to examine the distribution of the signal variation on the received amplitude, the KS test is used. Five commonly known distribution functions are tested: Rician, Weibull, Nakagami, Rayleigh and Lognormal. The results of the fitness of these functions are tabulated in Table 6.1. It can be seen that the Rician function shows the best-fit for the amplitude fading for both transmitter positions; while the Weibull distribution is the second best fit with a slightly lower KS passing rate. The Rician distribution with a Rician K -factor of 11.1 dB (position 1) and 8.7 dB (position 2) indicates that there is a dominant path which is possibly the guiding effect of the lift shaft [119] between the transmitter and the receiver. It means that the lift shaft creates a reliable propagation path for the link between the bridge room and the engine control room. On the other hand, as presented in Table 5.1, signal variation associated with the lift shaft channel and ship enclosure can be best described by Weibull distribution; the use of the lift shaft, people entering/leaving the room create signal variations. Therefore, Weibull distribution is the 2nd best distribution in this environment. From the study of signal variation in narrowband communication, it can be concluded that narrowband communication is feasible

between the ECR and the bridge room. Although the transmitter position 1 has a slightly better reception (1 dB), it is however subjected to severer signal variation. This is due to the difference in nearby environment between the two transmitter positions. Position 1 is near the engine room and the door of ECR, where signal variations are significant due to the presence of the rotating engines in engine room and human activities near the door of the ECR.

Table 6.1 KS test results for signal variation in two TX positions

Distribution Function	Tx Position 1 Passing Rate (%)	Tx Position 2 Passing Rate (%)
Rician	74.4	84.4
Weibull	70.8	82.0
Nakagami	64.4	82.4
Rayleigh	34.4	52.2
Lognormal	7.6	8.8

Figure 6.2 CDF plot of variation of received power.

B) Wideband Measurement Results

The mean power delay profiles (PDPs) from different time segments for transmitter position 1 and 2 are plotted in Figure 6.3. The arrival time of the 1st peak has been normalized to 0 for both figures to ease comparison and analysis. For each time segment, 333 frames are recorded and processed to obtain the time-averaged PDP. In Figures 6.3(a) and (b), it can be seen that the signal variation affects the second, third and subsequent multipath signals but not the 1st arrival peak. This indicates that there is a dominant signal propagating between the two locations and this explains the good fit of the Rician distribution obtained from the CW results. Comparing Figure 6.3(a) and Figure 6.3(b), it is found that the power level of the 1st peak is approximately 5 dB higher for transmitter position 1 due to its closer position to the receiver and the guiding path, i.e. lift shaft. In Figure 6.3(a), there is a cluster of multipaths that are not well resolved due to complex multiple reflections from the metallic engines and structures near the transmitter position 1. Due to the engine rotation and other movements around the antennas (i.e. the opening/closing of the door to the ECR and movement of human) near the transmitting antenna, severer temporal fading of up to 8 dB is associated with the multipath components as shown in Figure 6.3(a). In Figure 6.3(b), distinct multipath components are also observed. However, there is smaller signal variations (maximum value 5.2 dB) associated with the transmitter position 2 as compared to that of position 1. It is noted that difference between the narrowband results and the wideband results is mainly due to the fact that the spectrum analyzer records the average power in time domain while arriving signals are resolved and analyzed individually for wideband measurement results. Next, the SNR, Rician K -factor, RMS delay spread are studied and compared for these two transmitter positions.

(a)

(b)

Figure 6.3 Mean power delay profiles from different time segments at (a) transmitter position 1 (b) transmitter position 2.

1) SNR

Any signal with a SNR higher than 10 dB is considered as a significant peak and accounts for mean power calculation. The mean SNR refers to the ratio between

the mean power and the noise power level. The 999 instantaneous files used to obtain the time-averaged PDPs in Figure 6.3 are used for the calculation of the mean SNR. The scatter plots of the SNR for the two positions are shown in Figure 6.4. It can be seen that SNR is higher for majority of the data obtained at position 1. The difference between the average values of the two sets of mean SNRs is approximately 2.5 dB. From Figure 6.4, the variation of the SNR is found to be more significant for position 1. This is again verified by the CDF plot of the variation in SNR in Figure 6.5. From Figure 6.5, 90% of the variation in the SNR for transmitter position 1 is 1.8 dB, while that for position 2 is 1.5 dB. This confirms that position 2 is a relatively more static channel as compared to position 1.

Figure 6.4 Scatter plot of SNR.

Figure 6.5 CDF plot of variation of SNR.

2) Rician K -factor

As shown in Table 6.1, the received signal level can be best described by the Rician function. The Rician K -factor which serves as a good indicator for the significance of the dominant signal can be calculated for the study of the temporal variations.

Figure 6.6 CDF plot of Rician K -factor

From Figure 6.6, the medium value of the K -factor is found to be 14 dB and 10 dB for positions 1 and 2 respectively. As reported in section B, the power level of the dominant signal for position 1 is 5 dB higher than that for position 2. The higher K -factor obtained for position 1 verifies that the channel between the transmitter position 1 in the ECR and the bridge room has a dominant path with higher received power level as compared to position 2. However, the link suffers from more signal variations. The variation in the Rician K -factor for the two different transmitter positions is plotted in Figure 6.7. As expected, position 1 has a higher variation on the K -factor and the maximum difference between the two variations is 1.4 dB at 99.3% of time.

Figure 6.7 CDF plot of variation on Rician K -factor.

3) RMS Delay Spread

The RMS delay spread values for the 10 dB SNR threshold are calculated based on equations (2.15) and (2.16) for the two transmitter positions are shown in Figure 6.8. Most of the delay spread for position 1 is higher than that of position 2. This

again shows that there are many multipath components induced by the engine and human activities near position 1. It is also

Figure 6.8 Plot of RMS delay spread.

Figure 6.9 PDPs with the maximum and minimum RMS delay spread.

observed that there is severer variation on the RMS delay spread for position 1, and the maximum difference is approximately 258 ns. PDPs for the corresponding maximum and the minimum delay spread values are plotted in Figure 6.9. From

Figure 6.9, it is clearly shown that there is large variation of up to approximately 14 dB in signal strength of the multipath components. This difference in strength and number of multipaths causes the significant variation in the delay spread as shown in Figure 6.8. The mean RMS delay spread values obtained are 238.7 ns and 183.6 ns for positions 1 and 2 respectively. If the coherence bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.5, the maximum usable data rates (BPSK is assumed) are 0.8 and 1.1 Mbps for the two measured links.

6.1.3 Summary

Both narrowband and wideband channel characteristics for the link between the ECR and the bridge room in VHF band are presented in this section. Variations on the received narrowband power level can reach up to 5.7 dB for this direct link and the received amplitude is found to be Rician distributed. Variations on the SNR, Rician K -factor as well as the RMS delay spread are studied in detail based on the wideband measurement results. When the transmitter position is closer to the door of the ECR, a higher received power, SNR as well as Rician K -factor is obtained since the distance between the transmitter and the receiver is slightly shorter and it is closer to the lift shaft. However, there is a significantly higher variation at this position due to its close proximity to the engine room and the entrance/exit door of the ECR. Due to the non-static nature of the channels, the maximum usable bandwidth for the link between the ECR and the bridge room is found to be 0.8 Mbps if no equalizer is used. Therefore, it can be concluded that both voice and data communication is feasible for the link between the ECR and the bridge room if the transmission is operated in VHF band. However, the channel performance is

intermitted as the signal variations due to the movement near the antenna can be severe; the antenna position becomes a critical factor for the propagation quality. In emergency situation, it is impossible to impose restrictions on the position of the antenna and its surroundings. At higher frequency such as in the military UHF band and popular ISM band, the direct propagation is not possible. Therefore, the waveguide-like effect of the cargo hull is studied and the cargo hull is proposed as a possible location for a relay system. The guiding effect that dominates the channel characteristics along the cargo hull are studied in following section.

6.2 Waveguide Propagation along the Cargo Hull in UHF Band

In a merchant ship, the cargo hull is possible location for the deployment of a relay system in order to achieve communication between the two extreme ends of the ship. This is because; the waveguide-like effect along the cargo hull can ensure the propagation to and from every point within the cargo hull. Besides the application of the relay system, the guiding effect can ensure the propagation between any two points within the cargo hull. Therefore, wireless sensor networks can be implemented in the cargo hull. For example, an unmanned loading and unloading system can be implemented in the cargo hull using wireless sensor networks. Remote sensing is also required for the monitoring of highly explosive/toxic goods or perishable goods during transportation. Currently, wireless sensor network based monitoring system is proposed for the monitoring of dangerous goods during transportation [120]. This is done by installing a number of sensor nodes on the inside walls of the container ship. If the channel within the cargo hull is well-

understood, sensor networks can be efficiently deployed as monitoring systems during transportation.

In this section, experimental characterization of Line of Sight (LOS) and Non-Line of Sight (NLOS) links within the military ultra high frequency band (225 to 450 MHz) inside the cargo hull of a merchant ship is presented. The guiding effect associated with the cargo hull and its sub-structures is identified as an important propagation mechanism for both the LOS and NLOS scenarios. This propagation mechanism is then verified through 3D ray tracing simulations. Both large-scale channel characteristics such as path loss and small-scale channel characteristics such as the number of multipath components, decay factor of the multipath components and Root-Mean-Square (RMS) delay spread are studied and compared for the LOS and NLOS scenarios.

6.2.1 Measurement Campaign

The measurement campaign was performed inside a cargo hull of a docked merchant ship. The metallic cargo hull is located at the bottom of the ship and has dimensions, 130m by 22m by 5m (Length x Width x Height). Two sets of measurements were conducted. The first set was the LOS measurement which was conducted along one side of the cargo hull. The second set was the NLOS measurement where the LOS path is obstructed by a metallic door structure. An important application of channel characterization inside the cargo hull is the implementation of wireless sensor network inside the cargo hull for monitoring purposes. Usually, sensor nodes are installed on the walls of the cargo hull, and therefore, the experiment for the LOS measurements is executed along one side of

the cargo hull instead of in the center of the cargo hull. For NLOS scenario, the position of the metal door and the application of wireless sensor network determine the receiver position to be at the side of the cargo hull. In order to achieve large separation, the transmitter route follows the route along the other side of the cargo hull. In this measurement environment, most if not all structures within the cargo hull including the walls of the cargo hull are made of metal. Figure 6.10 shows the two dimensional layout of the measurement set up for both the LOS and NLOS scenarios. As shown in Figure 6.10, substructures inside the cargo hull includes: four metallic compartments, four pillars and a metal wall. There is no cargo within the cargo hull during the experiment. All the compartments, pillars and walls are made of metal and extend from the top to the bottom of the cargo hull. Compartments 1, 2 and 4 are service compartments and contain lighting cables and power sockets. Their dimensions (length by width) are 24.7 m by 7.8 m, 9.1 m by 2 m, and 8.1 m by 12 m respectively. Compartment 3 is the power generator compartment. Its dimension (length by width) is 4.7 m by 3 m. The four metallic pillars are identical, with dimensions (length by width) 0.8 m by 0.8 m. The metal wall used in the NLOS setup is part of the ship's deck that opens downwards into the cargo hull for loading and unloading purposes. The length of this wall is approximately 12.6 m and the width is 1 m. For the setup of the LOS scenario, the transmitting antenna moves away from the receiving antenna; the transmitter to receiver distance varies from 5.7 to 41.5 m with 48 separation steps along a straight line. For the NLOS layout, there is no direct propagation path between the transmitter and receiver due to the presence of the metal wall. Note that in the LOS experimental setup, the metal wall was not present. For this experimental setup, 20 transmitter to receiver positions are examined. The

transmitter was shifted along a straight line as indicated in Fig. 1 with increasing distance between the transmitter and the receiver. The distance between the transmitter and the receiver ranges from 21.6 m to 37.9 m for the NLOS set up.

A step frequency sweep was performed at the centre frequency 370 MHz. The measurement system consists of an Agilent VNA and two identical vertical polarized omni-directional discone antennas, AX-71C with a gain of 4.7 dBi at 370 MHz. The height of the antennas is 2.5 meters. For both LOS and NLOS measurements, 1601 uniformly distributed frequency steps of continuous waves are transmitted over a bandwidth of 5 MHz. To ensure that the channel is static during a single sweep of the measurement, the minimum sweep time of 111.56 ms was used. With these settings, the minimum resolvable delay is 0.2 μ s and the maximum measurable delay is 320.2 μ s. For each transmitter to receiver separation, a set of 50 sweeps are taken and logged via a GPIB card onto a laptop. In order to obtain the time domain channel response, the Inverse Fast Fourier Transform (IFFT) of the recorded frequency domain transfer function S_{21} as shown in (2) and (3) was performed during post processing. The averaging PDP in time domain is obtained by taking the average over 50 continuous instantaneous impulse responses. Pre-calibration was performed using the VNA's build-in calibration routine in order to compensate for amplitude and phase distortion. This calibration was done to the point where the cables connect to the antennas. According to [121], if the test environment is rich with scatterers, the physical multipath components will arrive from all possible directions and each resolvable multipath component includes many physical multipath components. The measured channel response will be equivalent to the propagation channel response.

Figure 6.10 LOS and NLOS measurement setup inside the cargo hull.

6.2.2 Simulation Setup

The ray-tracing scenario presented is a simplified model of the actual environment. In order to match the measurement scenarios, the simulation scenarios for LOS and NLOS consist of four compartments, six pillars and a movable metallic door (for NLOS only) as shown in Figure 6.10. The material of all the objects is Perfect Electric Conductor (PEC). The cargo hull, compartments and pillars are modeled as a series of hollow metallic boxes while the door is modeled as a metallic plate. Vertically polarized omni-directional dipoles are used as the transmitting and receiving antennas. The maximum reflection is set to 10, the maximum transmission is set to 2 and the maximum diffraction is set to 2. For each simulation, Wireless Insite is able to generate a list of propagation paths (up to 250 rays) and the amplitudes associated with each path.

6.2.3 Results and Discussions

A) Propagation Modes for LOS and NLOS Topology

Figure 6.11 shows the obtained average PDPs for the shortest and the longest transmitter to receiver distances in both LOS and NLOS tests. For ease of comparison, the arrival times of the first peaks for the shown PDPs have been

Figure 6.11 Power delay profiles from LOS and NLOS measurements

normalized to 0 μs . It is found that the difference in power level between the two first peaks in the LOS PDPs is around 10.4 dB. If free space path loss is assumed, the difference in received signal power level should be 17.2 dB. The power difference obtained from measurement is significantly smaller than that calculated from free space path loss. This is because, based on the geometry of the cargo hull, signals are guided along the cargo hull and reflected by the metallic substructures. These signals arrive within the first peak and sum up constructively to result in a higher received power as compared to free space path loss. The guided rays that

are contained in the first peak (delay less than $0.2 \mu\text{s}$) are simulated and the visualization of these simulated rays is provided in Figure 6.12. Figure 6.12 (a) shows all the guided signals arriving within the first peak of the LOS PDP in Figure 6.11 for the shortest transmitter to receiver distance. Figure 6.12(b) shows the guided waves arriving within the first peak of the PDP of LOS measurements shown in Figure 6.11 for the longest transmitter to receiver distance. It can be observed that when the transmitter and receiver are separated far apart (41.5m), although the propagation path is longer, due to the large amount of reflected and diffracted waves, the number of waves arriving at the receiver is similar to those at the shorter propagation path (5.7m).

For PDPs obtained from NLOS tests shown in Figure 6.11, it can be observed that the signal strength does not drop when the transmitter to receiver distance varies from shortest (21.6 m) to longest (38 m). This is due to the shadow regions and the diffraction in the NLOS experimental setup. When the transmitting antenna moves from the 1st to the 20th position, although the distance between the transmitter and the receiver is increased, the transmitting antenna is moved out of the shadow region. Therefore, diffraction loss reduces and a higher channel gain is obtained. In the NLOS measurement setup, due to the presence of the metallic door, a waveguide analogous structure is formed as shown from the simulation in Figure 6.13. This guiding structure is similar to an indoor hallway that has been studied and modelled as a waveguide structure in [122]. Therefore, besides the propagation mode of diffraction, electromagnetic waves are guided through the structure before being reflected and/or diffracted to the receiver. Due to the small dimensions of the waveguide like structure, the guided signals obtained from the simulations have a

short propagating delay. Therefore, these numerous multiple paths that are guided towards the receiver arrive at the receiver with a short time delay and are within the first peak.

Figure 6.12 Visualization for guided signals in the first peak in LOS setup (a) for the shortest distance. (b) for the longest distance.

(a)

(b)

Figure 6.13 Visualization for guided signals along the corridor in NLOS setup (a) for the shortest distance. (b) for the longest distance.

B) Path Loss for LOS and NLOS Topology

The distant dependent path gain is obtained by taking the average of 50 continuous channel gains. The channel gain is obtained by taking the mean value of the magnitude of the measured 1601 complex frequency response $H(\omega, d)$ over the bandwidth of 5 MHz. The path loss is obtained by adding the antenna gains to the absolute value of the path gain.

$$PL = abs(\frac{1}{M \times N} \sum_{j=1}^N \sum_{i=1}^M |H_{i,j}(\omega)|^2) \quad (6.1)$$

where M is the number of frequency steps for each sweep, and N is the number of continuous sweeps. For this particular experimental setup, $M = 1601$ and $N = 50$. Assuming a classical Log-normal shadowing path loss model, the path loss PL (in dB) at a distance d (in m) can therefore be expressed as:

$$PL(d) = PL(d_0) + 10n \times \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma} \quad (6.2)$$

where $PL(d_0)$ refers to the path loss in dB at a close range ($d_0 = 1$ m), n is the path loss exponent, and X_{σ} is a zero-mean Gaussian distributed random variable (in dB) representing shadowing with standard deviation σ (in dB).

Figure 6.14 Propagation loss versus distance and the fitted lines.

For the measured results of the LOS scenario shown in Figure 6.14, a linear fitting with Minimum Mean Squared Error (MMSE) for the path loss is used. The linear fitting model is given in (6.3a) where the path loss exponent is found to be

1.7 and the standard deviation (σ) of shadowing is 2.6 dB. The path loss exponent of 1.7 verifies that the cargo hull environment is heavily cluttered. Due to the highly reflective and diffractive nature of the structures in the cargo hull, a multipath rich environment is created. Therefore, a path loss exponent of less than 2, for free space path loss, is obtained. Similar results were reported in [123]-[125], where path loss exponents of less than 2 were obtained from LOS measurements in different factory halls at different frequencies due to the cluttered nature of the environment. The small standard deviation (σ) of shadowing (2.6 dB) indicates that shadowing does not play an important role in the LOS propagation within the cargo hull environment. As reported in [124], severe shadowing (> 10 dB) occurs when the receiver is situated a few meters behind a metal obstacle that is much taller than the receiving antenna.

$$LOS: PL = 17 \times \log_{10}(d) + 70 \quad (6.3a)$$

$$NLOS: PL = 34 \times \log_{10}(d) + 23 + \text{diffraction loss} \quad (6.3b)$$

As shown in Section A, diffraction by the edge of the metallic door is the primary propagation mode for NLOS propagation in this particular setup. As the position of the transmitting antenna is varied, the diffraction loss is varied, therefore resulting in a non-homogenous NLOS environment over the 20 measured positions. To compensate for this diffraction loss, the knife-edge diffraction model is used to calculate the diffraction loss which is then subtracted from the measured path loss. This obtained path loss for the NLOS scenario together with its linear fitting with MMSE is then plotted in Figure 6.14. The linear fit for the NLOS scenario is given in (6.3b), where the “*diffraction loss*” is the calculated knife edge diffraction loss. The path loss exponent for the NLOS scenario is 3.4 and the

standard deviation (σ) of shadowing is 1.7 dB. This path loss exponent for the NLOS topology is expected to be larger than 2. The path loss exponent of 3.4 indicates that the environment is highly complex and cluttered. In [123], the path loss exponent for lightly cluttered NLOS links is found to range from 2.2 to 3.2, and the path loss exponent for heavily cluttered NLOS links is found to range from 3.7 to 4.5. In [124], the path loss exponent for obstructed links with light clutter and heavy clutter derived from measurement data in five different factories are 2.4 and 2.8 respectively.

C) Small-scale Multipath Effect for LOS and NLOS Topology

In Section A and B, LOS and NLOS measurement and simulation results have been studied and the propagation modes have been examined. It has been shown that besides the direct path in LOS topology and diffraction in NLOS topology, the bulk of the received power is a summation of numerous multipath components resulting from multiple reflections by the metallic cargo hull and its substructures. In this section, small-scale channel characteristics for both LOS and NLOS scenarios are presented and compared. In part 1, the number of multipath components is examined.

1) Number of Multipath Components

Table 6.2 lists the mean values of the number of multipath components obtained from the set of 48 LOS measurement locations and the set of 20 NLOS measurement locations for four threshold levels. The four threshold levels are 10 dB, 13 dB, 15 dB and 20 dB above the noise floor. The minimum threshold used is 10 dB above the noise floor (10 dB SNR). This is because the standard deviation

of the noise floor is about 6 dB for both sets of measurement. From Table 6.2, it can be seen that the number of multipath components decreases gradually as the threshold increases from 10 dB SNR to 20 dB SNR for both the LOS and NLOS results. This is mainly due to the diffusive nature of the multipath components.

Table 6.2 Number of multipath components

Threshold	10 dB	13 dB	15 dB	20 dB
LOS	17.3	15.5	15.0	13.4
NLOS	19.7	18.1	17.3	15.8

Comparing the mean number of multipath components for the LOS scenario and the NLOS scenario, although there are more multipath signals for the NLOS measurement scenario for all the four threshold levels, the difference in the number of multipath components is insignificant. This is because most of the multipath components are due to waves reflected and guided by the cargo hull and its substructures which are common to both LOS and NLOS scenarios. Therefore, it can be deduced that the number of multipath components is independent of the availability of the LOS.

$$LOS: N = 0.013 \times d + 17 \quad (6.4a)$$

$$NLOS: N = -0.037 \times d + 21 \quad (6.4b)$$

The following analysis is done based on a threshold of 10 dB SNR since it captures the most channel information. The number of multipath components, N , is fitted using a linear relationship with the transmitter to receiver separation distance, d (in m). Therefore, two linear equations (6.4a) and (6.4b) are obtained for the LOS and the NLOS scenarios respectively. From the small slopes, with absolute value of less than 0.05, in (6.4a) and (6.4b), it can be concluded that the number of

multipath components is almost independent of the transmitter to receiver separation, d . This is not surprising, since it was reported in [126] that the statistics of the measured number of multipath components is comparable in LOS and NLOS topographies for the spacious, open plan industrial area. The cargo hull environment is similar to the environment reported in [126]. The average number of multipath components is also found to be similar to those obtained in [126].

Due to the waveguide-like structure of this environment, the amount of multipath components is found to be independent of the transmitter to receiver distance. In order to study the behavior of these multipath components, the rate of decay of these multipath components will be modeled next.

2) *Multipath Strength vs. Delay*

In the literature, PDPs are commonly modeled using the exponential function [127]-[130]. For example, in [127], the shape of the average PDPs obtained from LOS channels in a passengers' cabin of an aircraft is modeled using a simple exponential decay function (6.5), where γ is the exponential decay constant, a_k and τ_k are defined as the amplitude and the arrival time of the k^{th} arrival signal respectively. The random significant impulses within the first 30 ns in the PDPs were reported to be due to specular reflection from the cabin bulkhead or floor.

$$E\{|a_k|^2\} \propto \exp\left(\frac{-\tau_k}{\gamma}\right) \quad (6.5)$$

Besides the exponential function, PDP for propagation along a street at 2.6 GHz was calculated based on the waveguide theory in [131]. The structure of the PDP matches the empirical power law model (power is linearly proportionate to

$10 \cdot \log_{10}(d)$, where d is the arrival time of signals) in [132]. In this report, linear equation is proposed to model the structure of the average PDPs obtained in a waveguide-like environment. The linear model with MMSE is used to fit the average PDPs given in Figure 6.11 for both scenarios. It is shown in Figure 6.15 that the proposed linear equation can describe the trend of the PDPs well. The corresponding linear fits for the shortest and the furthest distance in LOS and NLOS scenarios are provided in (6.6a) to (6.6d) where P represents the average channel gain in dB and t represents the time delay in μs . The slope of the linear models for the average PDPs from the shortest distance and the furthest distance in LOS scenarios are $-7.7 \text{ dB}/\mu\text{s}$ and $-7.1 \text{ dB}/\mu\text{s}$ respectively; while those in NLOS scenarios are $-5.9 \text{ dB}/\mu\text{s}$ and $-6.5 \text{ dB}/\mu\text{s}$ respectively. It is found that the slope is higher when the first arrival signals have higher amplitudes, i.e. at shortest distance in the LOS scenario since the reflected signals with long delays are of similar amplitudes in all scenarios. Comparing the LOS and the NLOS results, although the difference in slope is not significant, the slopes from LOS scenarios are higher since the amplitude of the first arrival signals are generally higher for LOS scenarios as compared to the NLOS scenarios. The guiding effect/multiple reflection from the cargo hull and its substructures is a significant propagation mode and is common to both the LOS and the NLOS measurement scenarios.

$$\text{LOS with } D_{min}: P = -7.7 \times \tau - 68 \quad (6.6a)$$

$$\text{LOS with } D_{max}: P = -7.1 \times \tau - 77 \quad (6.6b)$$

$$\text{NLOS with } D_{min}: P = -5.9 \times \tau - 79 \quad (6.6c)$$

$$\text{NLOS with } D_{max}: P = -6.5 \times \tau - 73 \quad (6.6d)$$

In such cluttered environment, the linear equation is capable of describing the structure of the average PDPs. The passengers' cabin described in [127] filled with seats and baggage holder can also be regarded as a cluttered environment. In the passengers' cabin, signals also arrived at the receiver through multiple reflections via the corridor and the walls of the cabin. The cabin in [127] and the cargo hull structure in this report are both waveguide-like structures with highly reflective substructures. Therefore, the proposed linear model should also be suitable for the PDPs obtained from the passengers' cabin as well. The average PDPs obtained from propagation inside the passengers' cabin presented in [127] is shown in Figure 6.16. A linear fitting is used to fit the average PDPs for 3 different scenarios within the passengers' cabin. As shown in Figure 6.16, the linear equation is sufficient to describe the structure of the PDPs since the multipath signals resulting from multiple reflections within the passengers' cabin are mainly diffusive. This verifies that the linear equation is suitable for the modeling of multipath components in a confined cluttered environment with reflective materials.

Figure 6.15 Measured average PDPs and associated linear fittings for LOS and NLOS scenarios.

Figure 6.16 Extracted average PDPs and associated linear fittings from when receiving antenna is mounted at row 19 on headrest (PDP1), on the outboard armrest (PDP2) and on the footrest (PDP3) in Boeing 737 from [127].

The linear equation is proposed to model the decay of the average PDPs obtained in confined cluttered environments of the cargo hull. This is verified by

using results from another cluttered environment reported in the literature [127], i.e. passengers' cabin in an aircraft. Another important small-scale fading parameter, the RMS delay spread that takes into consideration both the amplitude and delay time of the multipath components from average PDPs is studied.

3) RMS Delay Spread

The RMS delay spread is defined as the square root of the second central moment of the average PDP. The calculated RMS delay spread values for a threshold level of 10 dB above noise floor (10 dB SNR) are plotted against the distance between the transmitter and the receiver in Figure 6.17. For the LOS measurements, the delay spread increases as distance increases. This is because although there is minimum increase in the number of multipath components with an increase in distance, the signal strength of the multipath components decreases with an increase in distance. After a distance of about 38 m, the delay spread tapers off since the signal strength of the multipath components also tapers off and becomes a constant. However, because of the random appearance of multipath components at large distances, the delay spread appears random. For NLOS measurements, the delay spread does not follow any obvious trend with the increase in distance. Comparing the delay spread obtained from LOS and NLOS measurements in Figure 6.17, it can be seen that the delay spread is generally higher for the NLOS measurements. This is because multipath signals strengths are relatively high compared to the obstructed line of sight signal strength (first arrival signal) in the NLOS scenario. Therefore, the NLOS scenario has a higher delay spread as compare to the LOS scenario. The difference in the number of multipath

components and their corresponding signal strengths for both scenarios is shown in the measurement PDP results in Figure 6.11.

Figure 6.17 RMS delay spread versus distance.

Amongst the 48 LOS links, 50% of them have RMS delay spread below 355 ns and amongst the 20 NLOS links, 50% of them have RMS delay spread below 577 ns. In the literature, the RMS delay spread for a factory environment is reported to be between 30 ns and 300 ns [142]. The larger delay spread obtained from the measurements in this cargo hull is due to the rich multipath environment as a result of the box-shaped and the pure metallic structure of the cargo hull within a smaller volume space. This metallic box-shaped environment creates a waveguide like structure allowing the effective guiding of multiple waves along the structure. Taking the coherence bandwidth as the bandwidth over which the frequency correlation function is above 0.5, the maximum usable data rates (BPSK is assumed) for LOS and NLOS channel are 0.56 and 0.35 Mbps respectively. Therefore, the maximum usable symbol rate for the link between two ends of the ship is 350 Kbps if no equalizer is used. The achieved data rate is enough for voice

communication and data communication; for example, voice encoded with GSM 6.10 codec requires about 15 Kbps and moderate frame-rate, low resolution colour video typically requires about 256 Kbps [107].

6.2.4 Summary

In this section, propagation mechanisms inside a cargo hull of a merchant ship are studied for both LOS and NLOS topologies. 3-*D* ray-tracing simulations are used to verify the propagation modes obtained from the measurement results. It is found that the guiding effect and the multiple reflections via the cargo hull and its substructures is an important propagation mechanism for both LOS and NLOS communication within the cargo hull. Path loss model using linear regression have been derived for the cargo hull environment. Furthermore, it is found that although the 1st signal arrival has higher received power for LOS propagation, both the LOS and the NLOS propagation paths experience similar multipath fading due to the complex guiding structure of the cargo hull. However, since the presented results are for an empty cargo hold, further research needs to be performed for a partially loaded or completely loaded cargo hold. With the help of this waveguide-like effect of the cargo hull, a relay system is proposed to be deployed inside the cargo hull to achieve both narrowband and wideband communication between the ECR and the bridge room in UHF band; the performance of the proposed relay system is studied in next section.

6.3 Performance of a Relay System between Two ends of a Ship in UHF Band

Due to the complex metallic environment on board a vessel, it is difficult to establish a direct communication link in the military UHF band ranging from 225 MHz to 400 MHz and the popular ISM frequency band of 2.4 GHz, especially when the two locations are far apart at the two extreme ends of the vessel, i.e. the bridge room and the engine control room (ECR). Therefore, a relay system is proposed to overcome the difficulty in establishing a long distance link within a complex metallic environment. Based on experimental study at 370 MHz in Section 6.2, waveguide-like effect is a dominant propagation mode inside the cargo hull which can be found on most of the merchant ships. The guiding effect ensures the communication is reliable at any position inside the cargo hull. Therefore, the cargo hull is a good location for the deployment of relay system. In this section, a relay system working at a similar frequency of 350 MHz by utilizing the waveguide-like effect of the cargo hull in military UHF band is tested. The application of the relay can be extended to the popular WiFi frequency of 2.4 GHz in ISM. Wideband channel characteristics for the two independent links of a relay system; from the bridge room to the cargo hull; and from the cargo hull to the ECR are discussed and compared for these two frequencies.

6.3.1 Measurement Campaign

A measurement campaign was carried out over three days onboard a docked merchant ship in Singapore in February 2010. Propagation between two key locations, namely, the bridge room and the ECR was examined. The bridge room

is at the top most level (level 7) while the ECR is near the lowest level (level B1) of the ship. The vertical separation between the two locations is equal to the height of the ship. The vertical separation between the two locations is equal to the height of the vessel (approximately 20 m). There is no line-of-sight between the two locations. Instead, there are five levels (level 7 to level 3) of wooden cabins, a metallic deck at level 2 and a cargo hull at level 1 with dimensions, 130m by 22m by 5m (Length x Width x Height) separating the two locations. Note that the engine room where all the engines are housed is very close to the ECR. The relative positions of the four locations are labeled in Figure 6.18. Therefore, a relay system located in the cargo hull was proposed. Link 1 refers to the propagation channel from the bridge room (Tx) to the cargo hull (RS) and link 2 refers to the channel between the cargo hull (RS) and the ECR (Rx).

Figure 6.18 Schematic drawing of antenna locations.

The spread spectrum sliding correlator sounding method is implemented in this measurement. A vector signal generator produces a Binary Phase Shift Keying (BPSK) modulated broadband signal at the carrier frequency of 350 MHz and 2412 MHz. The carrier frequency is spread using a 1023-bit Pseudorandom Noise (PN) sequence. A high power amplifier is used to amplify the signal before it is transmitted through an omni-directional antenna at a data rate of 10 Msymbol/s. The same antenna is used to receive the signal. It is noted that the gain of the discone antenna at 350 MHz is 3.7 dBi, while that of the Wifi antenna at 2412

MHz is -1 dBi. The received signal passes through a low noise amplifier, before being down-converted to an intermediate frequency (IF) of 42 MHz where it is sampled at 200 MSamples/s and stored for offline data processing.

6.3.2 Results and Discussions

A) Proposing of the Relay System

There are two advantages of implementing the relay system in the cargo hull of a merchant ship. Firstly, the guiding effect of the cargo hull structure in the UHF band as studied in Section 6.2 ensures that both the link from bridge room at level 7 to the cargo hull at level 1 and the link from the cargo hull at level 1 to the engine control room at level B1 are achievable at any position within the cargo hull. Therefore, the relay station can function well anywhere within the cargo hull. Secondly, the retransmission of a relay system can overcome the high attenuation induced by the metallic structures between level 1(cargo hull) and level B1 (ECR). Figures 6.19(a) and (b) show the time-averaged PDPs (taking an average of 50 consecutive frames) obtained at 350 MHz for the link 1 between the bridge room and the cargo hull and the link 2 between the cargo hull and the ECR respectively. The similar results obtained at 2412 MHz are shown in Figures 6.20(a) and (b). It is noted that the arrival time of the 1st peak has been normalized to zero for ease of analysis.

Figure 6.19 Power delay profile for (a) link 1 (b) link 2 at 350 MHz

Figure 6.20 Power delay profile for (a) link 1 (b) link 2 at 2412 MHz.

Comparing Figure 6.19 and Figure 6.20, it is obtained that there are more significant multipath components with SNR larger than 5 dB at the lower frequency of 350 MHz in both link1 and link 2 due to the lower propagation loss at the lower frequency. In the PDPs of link 1, it is common for both frequencies that the PDP is a single cluster due to the slant path propagation into the waveguide-like structure (cargo hull). In the PDPs of link 2, there are three clusters of multipath signals from the PDP obtained at 350 MHz while there are two clusters of multipath signals observed from the PDP obtained at 2412 MHz due to the lower SNR at the higher frequency. Comparing the PDP of link 1 and the PDP of link 2, more significant multipath peaks (indicated by arrows) are observed in the PDP of link 2, and the amplitude of these multipath components are more significant (relative to the 1st arrival) compared to those in the PDP of link 1 regardless of the centre frequency. The finding that multipath components from the link 2 have similar power levels indicates a strong waveguide effect from the cargo hull. Signal variation caused by human activities on the deck or inside the cargo hull will not cause significant performance degradation to the two proposed links since propagation over the links are mainly via multipath propagation.

B) RMS Delay Spread

The RMS delay spread values for a 5 dB SNR threshold are calculated for the two links at different centre frequencies and listed in Table 6.3. As expected, the RMS delay spread is higher for link 2 for both frequencies due to the significant reflected signals caused by the guiding effect along the cargo hull and the pure metallic environment associated with link 2. In the literature, the RMS delay spread for similar environment such as the factory environment is reported to be between 30 and 300 ns [133]. The delay spread value obtained for link 2 is beyond this reported range. This is due to the complex metallic environment on board the ship and the waveguide-like effect induced by the cargo hull. It can also be concluded that the delay spread decreases as the frequency increases from 350 MHz to 2412 MHz. This is because; at the lower frequency, more significant multipath components with longer arrival time are included in the PDP as shown in Figure 6.19, and therefore a higher delay spread value is obtained.

Taking the coherence bandwidth as the bandwidth over which the frequency correlation function is above 0.5, the maximum usable data rates (BPSK is assumed) for the two links are 0.4 and 0.3 Mbps for military UHF band and 0.9 and 0.5 Mbps for WiFi frequency respectively. Therefore, the maximum usable symbol rate for the link between two ends of the ship is 300 and 500 Kbps for 300 MHz and 2412 MHz respectively if no equalizer is used. The achievable symbol rate for WiFi frequency is significantly higher. However, the maximum data rate for both frequencies is enough for voice communication and data communication; for example, voice encoded with GSM 6.10 codec which requires about 15 Kbps;

moderate frame-rate, low resolution colour video which typically requires about 256 Kbps [127].

Table 6.3 Delay spread for the two independent links

Frequency (MHz)	Link	RMS delay spread (ns)	Coherence bandwidth (MHz)
350	1	552.2	0.4
	2	701.3	0.3
2412	1	215.7	0.9
	2	392.0	0.5

C) Ray Decay Factor

The intra-cluster decay time constant [134] or the ray decay factor for single cluster in the Saleh - Valenzuela (SV) model and the inter-cluster decay time constant for multiple clusters are studied through linear fitting for the two links. The significant peaks and their fitted lines with respect to the arrival time are shown in Figure 6.21 and Figure 6.22 for the centre frequency of 350 MHz and 2412 MHz respectively. The corresponding linear equations for 350 MHz of intra-cluster decaying are given in (6.7a) for link 1, (6.7b), (6.7c) and (6.7d) for the three clusters in link 2. The inter-cluster decaying model for link 2 at 350 MHz is given in (6.7e) and (6.7f). The corresponding linear equations for 2412 MHz of intra-cluster decaying are given in (6.8a) for link 1, (6.8b) and (6.8c) for link 2. The inter-cluster decaying model for link 2 at 2412 MHz is given in (6.8d). In (6.7a) to (6.8d), p is the amplitude of the peak in dBm while t is the delay time of the peak in μ s.

Figure 6.21 Decay factor for both channels at 350 MHz.

$$p = -5.7t - 30 \quad (6.7a)$$

$$p = -1.6t - 22 \quad (6.7b)$$

$$p = -12t - 11 \quad (6.7c)$$

$$p = -7.3t - 15 \quad (6.7d)$$

$$p = 0.57t - 21 \quad (6.7e)$$

$$p = -0.068t - 20 \quad (6.7f)$$

Figure 6.22 Decay factor for both channels at 2412 MHz.

$$p = -8.8t - 44 \quad (6.8a)$$

$$p = -4.7t - 45 \quad (6.8b)$$

$$p = -15t - 32 \quad (6.8c)$$

$$p = 0.49t - 45 \quad (6.8d)$$

It is common for both frequency that, the decay rate of cluster 1 in link 2 (1.6 dB/ μ s and 4.7 dB/ μ s for 350 MHz and 2412 MHz respectively) is much smaller than that of link 1 (5.7 dB/ μ s and 8.8 dB/ μ s for 350 MHz and 2412 MHz respectively). The lower decay factor is a result of the waveguide-like effect induced by the metallic cargo hull. The significantly higher decay rate of clusters 2 and cluster 3 (for 350 MHz only) in link 2 at both frequencies is due to the multiple reflections by metallic structures within the cargo hull. Due to the strong resonance inside the cargo hull, the inter-cluster decay rate for link 2 at both frequencies are with a absolute value less than one when the transmitting antenna is placed in the complex metallic cargo hull. In the literature, the values of the decay factor for indoor office building are between 2 to 14.1 dB/ns for line-of-sight (LOS) tests and between 1.06 to 84.1 dB/ns for non line-of-sight (NLOS) tests [135]; this shows that decay factor is heavily dependent on environment. The decay factor obtained is much lower due to the highly metallic and complex environment.

If the frequency dependency of the decay factor is studied, it can found that both the intra-cluster decay factor and the inter-cluster decay factor are smaller at the lower frequency of 350 MHz as compared to those at 2412 MHz due to the smaller reflection loss experienced at the lower frequency in the metallic complex environment; the multipath components at the lower frequency is then ‘diffusive’

rather than ‘impulsive’. It can be inferred that the propagation via multipath is more reliable at the lower frequency of 350 MHz although the maximum usable bandwidth is smaller as compared to 2412 MHz.

6.3.3 Summary

A relay system is proposed to be deployed within the cargo hull in order to achieve broadband communication between two extreme ends of a vessel at both 350 MHz in the military UHF band and at 2412 MHz in the ISM band. It is found that regardless of the centre frequency, the average power and delay spread is higher for link 2, while its associated decay factor is lower. Therefore, by performing relay within the cargo hull, the performance of the relay system is mainly limited by link 2 due to the significant multipath components caused by the metallic structures and the guiding effect of the cargo hull. If no equalizer is used, the maximum usable data rate is 300 Kbps and 500 Kbps for 350 MHz and 2412 MHz. This is sufficient for real time voice or low resolution video communication applications and the performance can be improved by using equalization technique and diversity schemes. By comparing the performances at these two frequencies, it is found that the lower frequency has a higher link reliability in terms of receive power. However, the usable bandwidth is smaller. In summary, the relay system can function well in both military UHF band and ISM band.

6.4 Conclusions

In this chapter, two solutions are proposed to achieve communication between the two key locations: ECR and the bridge room onboard a merchant ship. One is to

communicate in the VHF band which is used for the current communication devices onboard ship since the propagation loss in VHF frequency band is low. From the experimental results, it is found that, narrowband communication and wideband communication with a maximum bandwidth of 0.8 MHz can be achieved at 79.125 MHz. However, variation on the received signal level, Rician K -factor as well as the delay spread is severe when the antenna is placed near the engine rooms and therefore this channel is not reliable.

The direct propagation is not possible at higher frequencies. Therefore, a relay system is proposed to be deployed inside the cargo hull with the help of the waveguide-like effect along the cargo hull. The study of propagation inside the cargo hull at 370 MHz shows that the guiding effect of the cargo hull is the most important propagation mechanisms along the cargo hull for both LOS and NLOS topologies. Because of the waveguide-like effect, both LOS and NLOS links within the cargo hull experience similar small-scale channel characteristics. Since the waveguide-like ensures the propagation is achievable at any position inside the cargo hull, it is a good location for the deployment of the relay system. The performance of a relay system operating at 350 MHz and 2412 MHz is analyzed and compared. It is found that, due to the guiding effect of the cargo hull, the reception within the cargo hull is good enough to provide both narrowband and wideband communication for both frequencies although the usable bandwidth is only 300 Kbps and 500 Kbps for 350 MHz and 2412 MHz respectively.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

In this thesis, the channel characterization and modeling in different waveguide-like structures including the lift shaft in an urban area and on board a ship vessel have been conducted and reported. Special attention is given to the waveguide-like effect along these complex metallic structures in UHF band. The presented results are useful for establishing a reliable wireless communication link for military applications such as urban warfare, and battlefield communication networks on board vessels. Based on the empirical studies, the results and contributions of this thesis can be summarized into two major categories.

Waveguide-like effect in UHF band along the lift shaft is emphasized in this research work. This waveguide-like structure is useful for establishing a reliable communication channel in RF harsh environments. Experimental studies were conducted along two different lift shafts; one situated in an education building

within the campus environment; while the other is situated inside a merchant ship. In both environments, the guiding effect is identified as one of the significant propagation mechanisms that aid the establishing of a reliable communication link. Besides the guided signals along the lift shaft, signals can arrive at the receiver via reflections from static buildings in the campus environment; while in the ship environment, signals can propagate through multiple reflections by the local metallic substructures inside the ship. Signal variations caused by the movement along the lift shaft, i.e. opening/closing of the lift door and movement of the lift car are studied and compared for these two environments. It is found that the opening/closing of the lift door and the movement of the lift car induces signal variations to the lift shaft guided signals in both environments. The signal variation is more significant for the larger lift shaft in the campus environment. For reflected signals from the static buildings in the campus environment, movement along the lift has the least effect. However, the multiple reflected signals propagating inside the ship enclosure are severely affected by the status of the lift door and the position of the lift car as the lift shaft inside the ship board forms a ‘waveguide within waveguide’ structure. Therefore, movement along the lift shaft in the inner guide, the lift shaft, can significantly affect the waves bouncing within the outer guide, the ship enclosure.

Next, the signal variation caused by the movement along the lift shaft is studied statistically using AIC-based method and verified by KS test results. Regardless of the environment, the Weibull probability density function is the most suitable model to describe the signal variation along the lift shaft channel. For static signals reflected from nearby buildings in the campus environment,

Rician function is the best-fit model. The variation of multiple reflected signals or guided signals by the ship enclosure (outer waveguide) again can be best modeled by Weibull function. Therefore, the Weibull function is concluded to be the best function to model signal variations in an waveguide-like channel where signal variations are significant.

Channel characteristics of another waveguide-like structure, the cargo hull onboard the merchant ship is studied based on experimental and simulation results obtained in military UHF band. Based on the experimental results, guiding effect is identified as the dominant propagation mechanism for both LOS and NLOS scenarios. Due to this dominant guiding effect along the cargo hull, LOS and NLOS scenarios have similar small-scale channel characteristics and linear functions are found to be able to model the decay trend of multipath components resulted from this complex metallic enclosure.

The aim of study on RF propagation onboard ship is to establish a *reliable communication link* in the metallic complex environment. In such environment, extremely large attenuation is the main constrain for long distance propagation. In this thesis, two solutions are proposed to enable communication over the two extreme ends of the merchant ship, i.e. the bridge room on the top and the engine control room at the bottom.

i) One solution is to utilize the low frequency band such as VHF band. In this thesis, experimental study is carried out in VHF band at 79.125 MHz. It is

found that wideband propagation with a maximum data rate of 800 Kbps (BPSK) is possible when operating at 79.125 MHz in VHF band. Moreover, if the antenna position is closer to the door of the engine control room, the reception in terms of SNR and Rician K -factor is better as the antenna is closer to the guiding channel, i.e. the lift shaft. However, a significantly higher signal variation is associated with this link due to its close proximity to the engine room and the entrance/exit door of the engine control room.

ii) A relay system is proposed to be deployed within the cargo hull if operating in a high frequency band such as at 350 MHz in military UHF band and at 2.4 GHz in ISM band. With the help of the waveguide-like effect along the cargo hull, the reception within the cargo hull is satisfactory. The performances of the relay system at these two different frequencies are compared as well.

In summary, propagation in waveguide-like structures including lift shafts and cargo hull onboard a merchant ship are modeled and studied in detail in this research work. With the help of waveguide-like effect, two methods are proposed to achieve the propagation between the bridge room and the engine control room onboard the ship vessel. That is, either to transmit at low frequency or to form a relay system using the wave guiding structure of the cargo hull.

This work on waveguide-like structures although substantial, is by no means complete. Some recommendations for future works are listed in the next section.

7.2 Recommendations for Future Work

Based on the studies developed in this thesis, it is found that there is great potential to extend the current research work. Some recommendations are given below.

1. Waveguide-like effect can be further studied by conducting experiments along lift shafts with different size and structures in different environments. By examining the path loss, empirical path loss model for waveguide-like structures can be derived and compared to that derived from propagation in tunnels and mines reported in the literature.

2. Application of the mitigation technique such as spatial diversity (MIMO) techniques in waveguide-like structures for the improvement in the reliability of the propagation need to be explored. Other mitigation techniques such as polarization diversity and frequency diversity (OFDM) should also be considered.

3. Empirical models of large scale channel parameter such as path loss and small scale channel parameter such as delay dispersion for same level and inter-level propagation onboard ship can be derived by collecting more data in different ships. This will complement the existing study on indoor propagation and provide guidelines for system design onboard ships.

4. For the spread spectrum sliding correlator sounding technique, besides the modulation scheme of BPSK, the performance of QPSK can be tested and

compared with that from BPSK. Moreover, Bit Error Rate (BER) can be obtained from the sampled bits and used to evaluate the link performance. This will allow us to relate the derived channel model with practical values such as BER of a system.

Author's Publications

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

Journal Papers

1. X. H. Mao, and Y. H. Lee, "UHF propagation along a cargo hull on board a merchant ship," accepted for publication in *IEEE Transactions on Wireless Communication* in Sep. 2012.
2. X. H. Mao, and Y. H. Lee, "Comparison of temporal variations along a lift shaft in two complex environments," *Progress in Electromagnetics Research B*, vol. 36, pp. 337-355, 2012.
3. X. H. Mao, and Y. H. Lee, "Performance of a relay system for two extreme ends of a vessel at 2.4 GHz," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 686-689, 2011.
4. X. H. Mao, Y. H. Lee, and B. C. Ng, "Statistically modeling of signal variation for propagation along a lift shaft," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 752-755, 2010.

5. X. H. Mao, Y. H. Lee, and B. C. Ng, "Propagation modes and temporal variations along a lift shaft in UHF band," *IEEE Transactions on Antennas and Propagation*, vol. 58, pp. 2700-2709, 2010.

Conference Papers

1. X. H. Mao, and Y. H. Lee, "Frequency Dependence of Propagation along a Lift Shaft on board a Merchant Ship," in *Proc. 8th International Conference on Information, Communications and Signal Processing (ICICS)*, Singapore, Dec. 2011.
2. X. H. Mao, and Y. H. Lee, "Study of Guiding Effect along the Cargo Hull of a Ship by Measurements and Simulations," in *Proc. 2011 Symposium on Antennas and Propagation*, Spokane, USA, Jul. 2011, pp. 2809-2812.
3. X. H. Mao, Y. H. Lee, and B. C. Ng, "Study of propagation over two ends of a vessel in VHF band," in *Proc. 2010 Asia-Pacific Microwave Conference (APMC 2010)*, Yokohama, Japan, Dec. 2010, pp. 1946-1949.
4. X. H. Mao, Y. H. Lee, and B. C. Ng, "Wideband channel characterization along a lift shaft on board a ship," in *Proc. 2010 Symposium on Antennas and Propagation*, Toronto, Canada, Jul. 2010, pp. 1-4.
5. X. H. Mao, Y. H. Lee, and B. C. Ng, "Waveguide Propagation Effect along the Cargo Hull on Board a Ship," in *Proc. 2009 Symposium on Antennas and Propagation*, Charleston, USA, Jun. 2009, pp. 1-4.
6. X. H. Mao, Y. H. Lee, and B. C. Ng, "Study of propagation along a lift shaft in UHF band by measurements and 3-D simulations," in *Proc. 7th International Conference on Information, Communications and Signal Processing (ICICS)*, Macao, Dec. 2009, pp. 1-5.
7. X. H. Mao, Y. H. Lee, and B. C. Ng, "Comparison of Wideband Channel Sounding Techniques," in *Progress In Electromagnetics Research Symposium (PIERS 2009)*, Moscow, Russia, Aug. 2009, pp. 400-404.
8. X. H. Mao, Y. H. Lee, and B. C. Ng, "Wideband channel modeling in UHF

band for urban area,” in *Proc. 2008 International Symposium on Wireless Communication Systems (ISWCS 2008)*, Reykjavik, Iceland, Dec. 2008, pp. 240-244.

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