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COMPARISON OF PROPAGATION ALONG A LIFT SHAFT IN TWO COMPLEX ENVIRONMENTS

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Abstract—Signal variation caused by motions along the lift shaft in a campus environment and on board a ship is compared. The guiding effect is common for both lift shafts, and the variation in amplitude of the guided signals is more significant for the lift shaft with larger dimensions. Unlike the lift shaft within the campus, the ship with its lift shaft forms a 'waveguide within waveguide' structure. Therefore, the reflected signals within the ship enclosure outside the lift shaft are significantly affected by the motion along the lift shaft. Due to the difference in the degree of the signal variations in these two environments, the rms delay spread is found to be closely related to the lift door status and the lift car position in the campus environment, whereas it is not significantly affected by the motions along the lift shaft in the ship environment. From the statistical study and comparison of the signal variations in the two environments, the Weibull probability density function is found to be the most suitable model to describe analogous waveguide channels such as the lift shaft and the ship enclosure.

1. INTRODUCTION

In the field of indoor propagation, lift shaft and its associated lift car have been identified as a radio frequency (RF) harsh propagation environment for communication system planning [1]. In the literature, there is not much research work on propagation along a lift shaft [1–3]. In [1], it was concluded based on finite difference time domain simulation results that the distribution of electrical field in the lift car is independent of the placement and the orientation of the dipoles outside of the lift shaft. In [2, 3], narrowband measurement has been

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conducted to study the variation in signal strength along a lift shaft. The group of researcher from [1] also studied the propagation of GSM signals along the lift shaft for network planning purposes in [2]. They concluded that, at the higher GSM frequency band of 1800 MHz, the signal propagation is approximately 5 dB better compared to that of 900 MHz. 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. Application focused research work has studied the effect of the moving elevator on the number of handoffs required for effective cell planning purposes [3]. Wideband channel characteristics were analyzed in order to identify different propagation mechanisms and to study the signal variations in [4–6]. In [4], the propagation mechanisms associated with the lift shaft in a campus have been studied through wideband channel measurements and simulations. It was shown that the guiding effect of the lift shaft in the military UHF band of 225 to 400 MHz [5] is important for urban warfare. The statistical modelling of the signal variation along the lift shaft is reported in [6]. The Weibull distribution is found to be the best function for describing the signal variation associated with the signals guided by the lift shaft. The signal variation associated with signals reflected by static buildings in the nearby environment can best be described by the Rician distribution.

A ship vessel consisting of mainly metallic structures creates a RF harsh environment and its channel characteristics can be significantly different from other common indoor environments. It is because the material and the layout of an indoor structure have great impact on the signal propagation [7]. Due to the large amount of highly reflective objects in the ship environment, numerous multipath signals are generated. Multiple copies of the transmitted signal with different phase are received resulting in possible multipath fading. Moreover, signals suffer from attenuation when penetrating through metallic structures. Therefore, communication within the ship is difficult to achieve. In the literature, majority of the research done on propagation on board ships focuses on same-level and short distance communication links [8–12]. In [8–10], narrowband channel measurement results are presented. In [8], received power level of signals transmitted in the frequency band of 800 MHz to 2500 MHz between two adjacent compartments within a naval ship was examined. It was concluded that the source of bulkhead penetration are the rubber door gaskets and other non-conductive structures, such as hatch seals and insulation around pipes. In [9], the opened/closed door effect and polarization effect on the received power level for different transmitter to receiver locations was modeled. This was performed for a maximum distance of 5 m in the frequency range of 800 MHz to 3 GHz. It was found that the closing of a watertight door can result in an attenuation of 5 to 30 dB. In [10], the relationship between path loss and distance for a restaurant hall and along the corridor of cabins on board a cruise ship was studied using two slopes linear fitting around the 2.4 GHz frequency band. In [11, 12], wideband channel measurements were conducted in the frequency domain using a vector network analyzer. In [11], channel impulse responses for transmission within compartments and along passageways at 2 GHz and 5 GHz were studied. Based on the received power level, it was concluded that the usage of wireless LAN with a limited bandwidth on board a warship is possible. Path loss exponent and root-mean-square (rms) delay spread were studied for channels inside rooms and along the starboard hallway in [12]. It was reported that neither of the studied parameter is dependent on frequency within the range of 800 MHz to 2.6 GHz. For the design of any practical wireless systems, inter-level channel characteristic on board a ship is important. In [13], the propagation mechanisms at 255.6 MHz associated with the channel along a lift shaft connecting the top and the bottom levels of the ship were examined. The guiding effect of the lift shaft was identified. A large delay spread was obtained due to the metallic multipath rich environment. From previous experiments, wideband communication between the two key locations of the ship, i.e., the bridge room and the ECR is found to be possible at 79.125 MHz due to the guiding effect of the lift shaft and the low propagation attenuation in the VHF band [14]. From [13, 14], the guiding effect of the lift shaft is the key mechanism that enables communication between the top and bottom of a ship.

In this paper, the guiding effect and the associated signal variations along the lift shaft for the campus environment and the shipboard environment are studied and compared. Frequency domain wideband channel sounding is performed at 255.6 MHz along a lift shaft in both environments. Controlled experiments are performed to study and isolate the different propagation mechanisms in the two environments. The signal variation on the signals and the statistical fitting of the signal variation in the two environments are compared. It is found that guided signals along the lift shaft and within the ship enclosure are subjected to signal variation caused by the motion along the lift shaft and this signal variation can best be described by the Weibull probability density function.

This paper consists of three sections. Section 2 describes the measurement environment and the measurement setup in both environments. In Section 3, results obtained from measurement in the two environments are compared and analysed. Based on the analysis, propagation modes and signal variations are discussed. This is followed by the conclusions of the findings in Section 4.

2. CHANNEL MEASUREMENT

Measurements have been conducted along a lift shaft in an education building in Nanyang Technological University, Singapore. The lift shaft in the campus spans level 1 to level 7 with a dimension of $2.5 \times 2.5 \times 27\,\text{m}$ ($W \times D \times H$). Details of the experimental site can be found in [4]. Similar measurements are conducted along a 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 $0.85 \times 0.85 \times 17.5\,\text{m}$ ($W \times D \times H$). For both sets of 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. The dimension of the lift shaft in the campus is larger than the dimension of the lift shaft on board the ship. As the dimension of the analogous waveguide structure increases, the number of TE and TM modes being excited at the frequency of 255.6 MHz increases. Therefore, the signal variation of the guided waves is expected to be more significant for the larger lift shaft.

Frequency domain channel sounding [15] is used for both experiments due to its ability to achieve high resolution channel information. The measurement system consists of an Agilent Vector Network Analyser (VNA) and two identical omni-directional Discone antennas, AX-71C. The centre frequency is fixed at 255.6 MHz and 1601 uniformly distributed continuous waves are transmitted over a bandwidth of 300 MHz. With this specification, the smallest resolvable path difference is 1 m and the maximum excess delay is 5.33 µs. The minimum sweep time of 111.56 msec is used. In order to study the signal variations in Section 3.2, a set of 50 continuous sweeps are taken for every test case. In order to study the signal variation statistics in Section 3.3, 5000 continuous sweeps are taken. All data are logged via the general purpose interface bus (GPIB) and stored onto a laptop. In order to obtain the time domain channel response as expressed in (1). Hanning windowing is applied in frequency domain to suppress the side-lobes before transferring the frequency domain channel response to the time domain impulse response by taking the Inverse Fast Fourier Transform (IFFT) as shown in (2) and (3). The averaging process is done in time domain, i.e., the mean power delay profiles (PDPs) are obtained by taking average over the continuous instantaneous impulse responses. The difference between the signal variations along the two lift shafts in the two different environments is then compared and analyzed based on the mean PDPs. 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 connect to the antennas.

$$h_b(n,\tau) = \sum_{i=0}^{N-1} a_i \exp(j\theta_i)\delta(\tau-\tau_i) \tag{1}$$

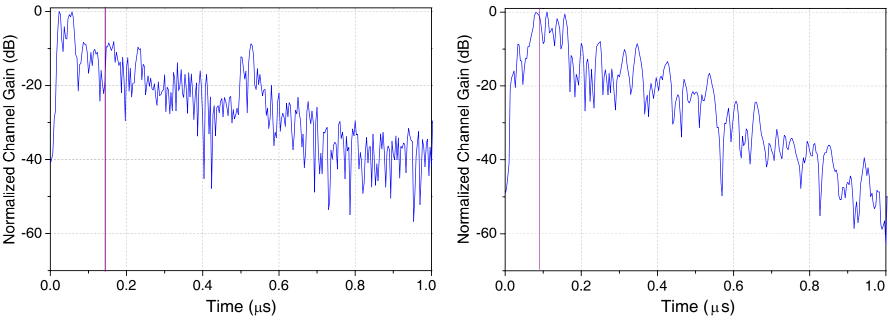
$$S_{21}(\omega) \propto H(\omega) = \frac{Rx(\omega)}{Tx(\omega)} \tag{2}$$

$$h(t) = FT^{-1}[H(\omega)] \tag{3}$$

3. RESULTS AND DISCUSSION

3.1. Overview of Power Delay Profile

Figures 1(a) and (b) show the normalized mean PDPs when the transmitter is at level 2 and the receiver is at level 6 while the lift is in use for campus environment and ship environment respectively. According to the analysis in [4], the mean PDP obtained along the lift shaft in the campus shown in Fig. 1(a) can be classified into three regions. Region 1 is from 0 to 0.14 μs on the time axis. During this period of time, signals guided by the lift shaft are received. Region 2 is from 0.14 to 0.5 μs while region 3 is for a time of 0.5 μs and above. Signals arriving in regions 2 and 3 are a result of reflections by large static obstacles, i.e., education buildings in the intermediate and far



(a) (b)

Figure 1. Normalized mean PDPs (a) along the lift shaft in campus. (b) along the lift shaft on board ship.

regions in the campus environment. No significant signal variation was observed in regions 2 and 3 in [4]. The main focus in this paper is the signal variation within the propagation channel. Therefore, the relatively static regions 2 and 3 are combined as one region (region 2) for analysis purposes. In Fig. 1(a), the boundary for these two regions is indicated by a vertical line. For comparison purposes, the mean PDP obtained along the lift shaft on board the ship is also classified into two regions. Region 1 in the mean PDP obtained along the lift shaft on board the ship is from 0 to 0.09 µs, instead of from 0 to 0.14 µs for the lift shaft on campus. Since the PDP in this region consists of signals guided 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., $H_{liftonboardtheship}/H_{liftincampus} = 0.09/0.14$. The time period above 0.09 µs in time shown in Fig. 1(b) is region 2 for the lift shaft within the ship. 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 Fig. 1(a), region 2 includes multiple reflected signals by static buildings. In Fig. 1(b), signals in region 2 are mainly from multiple reflections by the substructures within the enclosed ship.

The difference in propagation mechanism of region 2 between the two environments is a resulted from the difference in the surrounding of the two lift shafts. In the campus environment, the lift shaft is in a relatively open environment with intermediate and far reflectors in an outdoor environment. Therefore, obvious 'impulsive' multipath components can be identified in Fig. 1(a). In the ship environment, the ship and its substructures form an enclosure and thus another waveguide. This results in an inner guide, the lift shaft, within an outer guide, the ship enclosure. In Fig. 1(b), the multipath components in region 2 are 'diffusive' and decaying linearly due to the bouncing effect in the outer guide. Due to this difference in surroundings of the lift shaft between the two environments, the signal variations caused by the motion along the lift shaft for the two environments in region 2 of Fig. 1 are expected to be different. This will be examined in detail in Section 3.2. The signal variation along the lift shaft in both environments are analyzed and compared statistically in Section 3.3. Finally in Section 3.4, a comparison of the rms delay spread for different measurement scenarios are presented.

3.2. Signal Variations along the Lift Shaft

As reported in [4], signal variations along the lift shaft are mainly caused by the opening/closing of the lift door and the movement of the lift car. It was also reported that these variations are mainly within region 1 of Fig. 1(a) for the lift shaft in the campus environment. For the ship environment, due to the 'waveguide within waveguide' channel, the motion along the lift shaft in the inner guide, the lift shaft, affects not only signals within region 1 of Fig. 1(b) but also signals within region 2 of Fig. 1(b), that is, signals guided by the outer waveguide, the ship structure. Signal variation caused by the lift door status and the lift car movement in these two environments will be compared in this section.

3.2.1. Lift Door Effect

Figures 2(a) and (b) are the normalized mean PDPs obtained when the lift door is opened and closed at the transmitter level for the campus environment and the ship environment respectively. From Fig. 2(a), it can be observed that most of the signals in region 1 are affected by the opening and closing of the lift door. There is no significant variation to the signals arriving within region 2 of Fig. 2(a) caused by the change in lift door status. The variation in average channel gain for region 1 and 2 is 8.9 dB and 0.83 dB respectively. In Fig. 2(b), it can be seen that both regions are significantly affected by the lift door status. The variation in average channel gain for the 2 regions is 6.1 dB, and 3.8 dB respectively.

For both environments, signals arriving within region 1 are significantly affected by the change in lift door status. This is because; region 1 contains signals that enter the lift shaft from the lift door, propagate along the lift shaft before arriving at the receiver for both

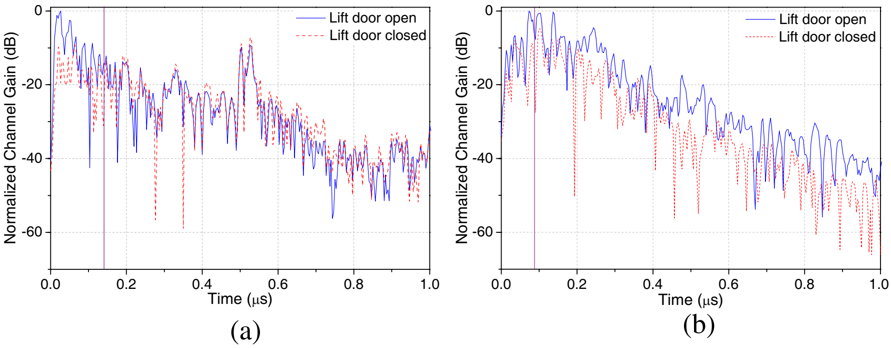


Figure 2. Normalized mean PDPs for Open-close lift door at transmitter level. (a) along the lift shaft in campus. (b) along the lift shaft on board ship.

environments. When the lift door is open, the opening into the lift shaft is larger than one wavelength, whereas, when the lift door is closed, waves can only propagate into the lift shaft via diffraction through the rubber seal. The degree to which the guided waves are affected is dependent on the size of the lift shaft. For region 2, the variation in average channel gain in the campus environment is negligible compared to that in the ship environment. This is because signals arriving within region 2 in the campus environment consist of signals reflected from buildings in the intermediate and far regions, thus not affected by the status of the lift door. Signals arriving within region 2 in the ship environment consist of multiple reflected signals within the ship enclosure, the outer waveguide. Therefore, the opening/closing of the lift door affects the multiple reflected signals, causing significant variations in signals within region 2.

3.2.2. Lift Car Effect

Figures 3(a) and (b) show 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 in both the campus environment and the ship environment respectively. The lift door is closed for this set of controlled experiments. Based on the location of the lift car, the PDPs for the two extreme cases are plotted in Fig. 4. The two extreme cases are; when the lift car is out of the propagation channel at level 1; and when the lift car is in the middle of the propagation channel at level 4. It can be observed from Fig. 3(a) and Fig. 4(a) that in the campus environment only signals arriving within region 1 are affected by the movement of the lift car. The

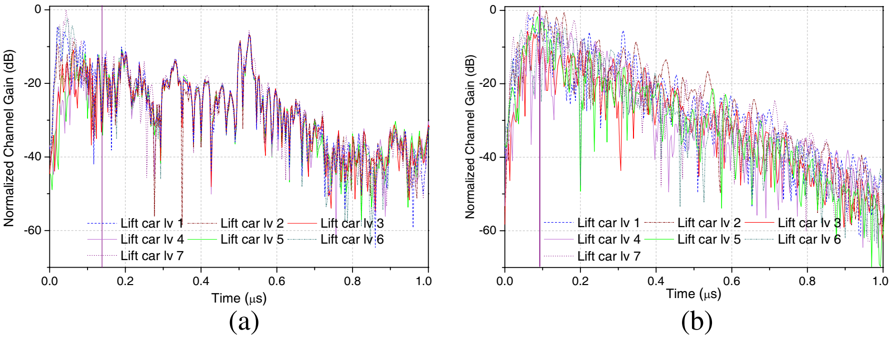
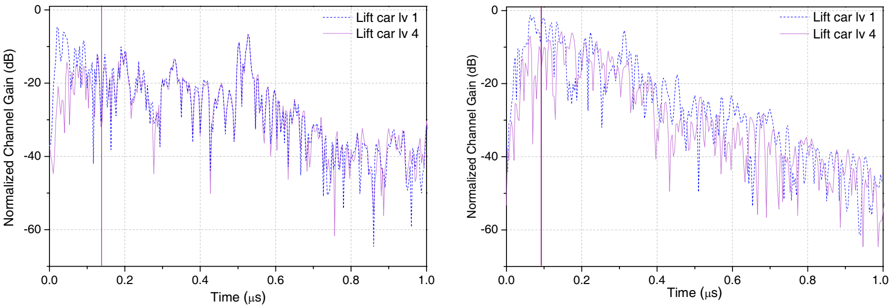


Figure 3. Mean PDPs for 7 lift car levels (a) in campus. (b) on board ship.

maximum variation in average channel gain caused by the movement of the lift car is 9.8 dB and 0.58 dB for region 1 and 2 respectively. From Fig. 3(b) and Fig. 4(b), for the lift shaft in the ship environment, 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. Comparing the signal variation in both regions in Fig. 4, the same trend as that of the opening/closing of the lift door is obtained. For the same reason given before, the movement of the lift car within the lift shaft in the open space of the campus only affects signals in the immediate vicinity, i.e., region 1. The movement of the lift car within the lift shaft affects 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 in the lift shaft, signals arriving within region 1 of Figs. 3(a) and (b) are examined. The channel gain is lower when the lift car is in the middle of the propagation path, i.e., level 3 and level 4. The channel gain is higher when the lift car is out of the propagation channel, i.e., level 1 and level 7. This is because when the lift car is in at level 3 or 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).

From Section 3.2, the signal variation on the guided waves in region 1 caused by the motion of the lift door and the lift car is found to be more significant when the size of the lift shaft is larger in the campus environment. Signals reflected by static buildings (region 2) in campus are not affected by the motion along the lift shaft. However, because of the structure of 'waveguide within waveguide' in the ship environment, motion along the lift shaft in the inner guide, the lift



(a) (b)

Figure 4. Mean PDPs for lift car level at level 1 and level 4 (a) in campus. (b) on board ship.

shaft, can significantly affect the waves bouncing within the outer guide, the ship enclosure. In the following section, the signal variations caused by motion along the lift shaft will be modeled statistically and compared for the two environments.

3.3. Statistically Modeling of the Signal Variations

The Akaike's Information Criterion (AIC) which was initially developed by Akaike in 1973 is a good criterion to model signal variations in wireless communication channels [16]. Compared to the goodness-of-fit (GOF) test such as maximum likelihood estimator used in [21], AIC based methods are able to identify the best distributions in the candidate set, and also able to provide information on the candidates' relative fitness quality. The fitness can be studied using the Akaike weights ω_j, defined in (4).

$$\omega_j = \frac{e^{-\frac{1}{2}\varphi_j}}{\sum\limits_{i=1}^{J} e^{-\frac{1}{2}\varphi_i}} \tag{4}$$

where AIC differences $\varphi_j = AIC_j - \min_i AIC_i$, and the operating model AIC_j is given in (5).

$$AIC_j = -2\sum_{n=1}^{N} \log g_{\hat{s}_j}(x_n) + 2U \tag{5}$$

where $\min_i AIC_i$ denotes the minimum AIC value over all the J candidate families (in this paper, 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 and U is the dimension of vector $\hat{s}_j$. N is the size of sample set $x = [x_1\ x_2\ \ldots\ x_N]^T$. For AIC based method, ω_j can be interpreted as an estimate of the probability that the cumulative density function of the jth model shows the best fit within the candidate set [16]. The statistical 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 $N/U \geq 40$ [17]. In this paper, the size of the data set, N, is equal to 5000. The AIC based method is applied to statistically model the signal effect along the lift shaft for both the campus environment [6] and the ship environment.

In order to statistically model the signal variations, continuous measurements are conducted by fixing the transmitter and receiver positions at level 2 and level 6 respectively, while the lift is in use and moving along the lift shaft. In Fig. 5, 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 μs. Therefore, the focus of this statistical analysis is from 0 to 0.65 μs on the time axis. From Fig. 5(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 Fig. 5(b), signals in both regions are subjected to amplitude variations. This observation agrees well with the findings in Section 3.2. In the following, the amplitude variations are studied statistically.

Figure 6 show the plots of the Akaike weights for different candidate members as well as the normalized mean PDP (blue curve) obtained from the experiment results in campus [6]. Similar plots for the ship environment are shown in Fig. 7. The arrows in Figs. 6(f)

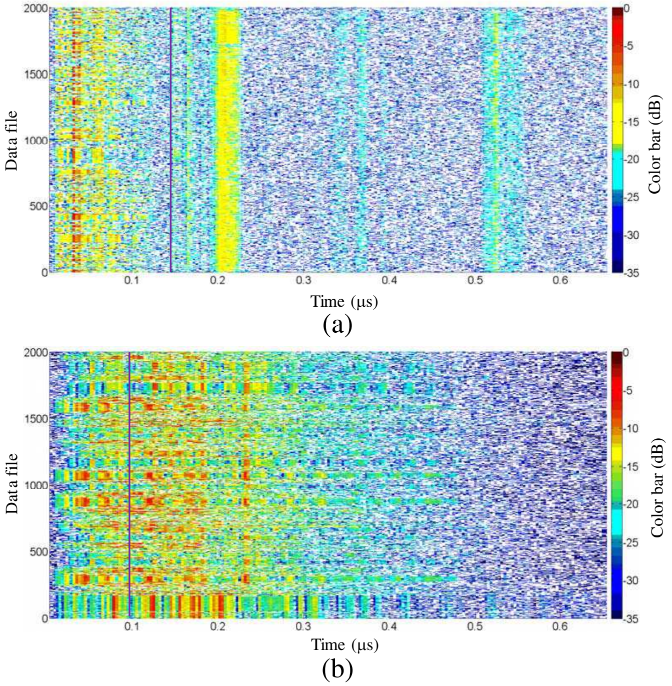
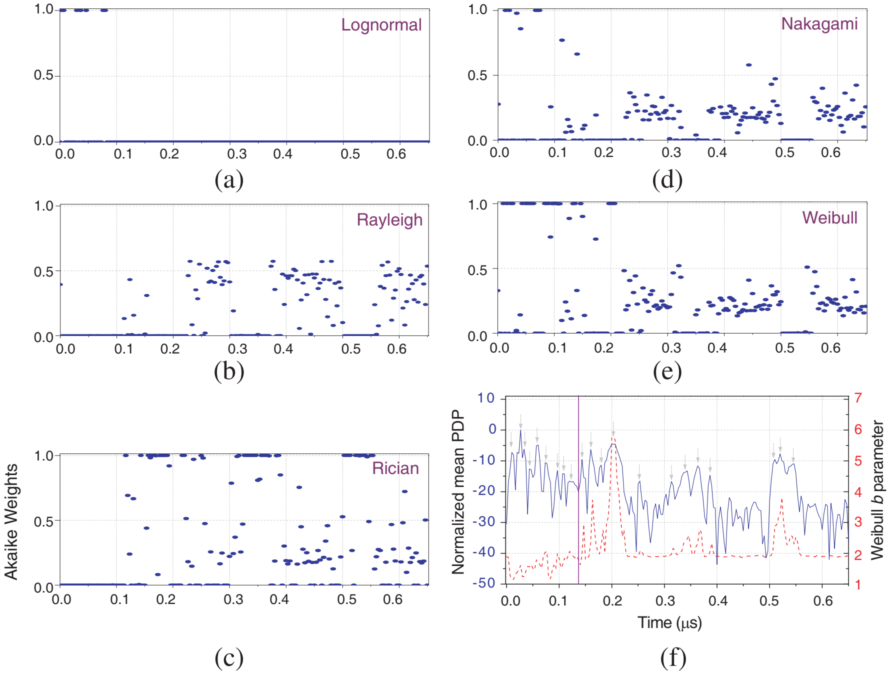


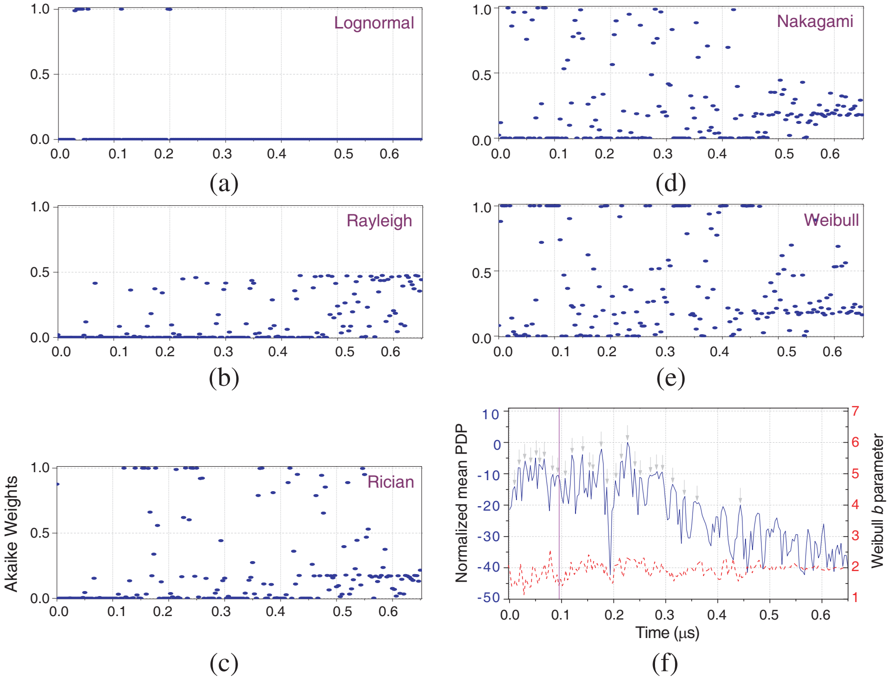
Figure 5. Instantaneous PDPs obtained from (a) campus environment [6]; (b) ship environment.



(a) (d) (b) (e) (c) (f)

Figure 6. (a)–(e) AIC weights for different functions; (f) Weibull b parameter from campus measurements [6].

and 7(f) indicate peaks whose normalized signal strength are larger than −20 dB, these peaks are considered significant and indicate the existence of multipath components. All the significant peaks are at least 40 dB above the noise floor of the mean PDP. From Fig. 6 and Fig. 7, it is observed that Weibull probability density function has the highest Akaike weights within region 1 (0 to 0.14 μs) for both environments. 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. Since the Weibull probability density function is the best function to describe channel with severe signal variations, it is found to have the highest Akaike weights from Fig. 6 and Fig. 7. In Fig. 6(f), the significant peaks included in region 2 are found to be Rician distributed with high Akaike weights. These significant peaks in region 2 are reflected signals from static buildings. Since the Rician probability density function is



(a) (d)

(b) (e)

(c) (f)

Figure 7. (a)–(e) AIC weights for different functions; (f) Weibull b parameter from ship measurements.

used to describe dominant paths, these peaks can best be described by the Rician probability density function. In Fig. 7(f), region 2 includes all the signals bouncing within the ship enclosure, outer waveguide. Therefore, signals from region 2 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 Fig. 6(f) and Fig. 7(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 weights are examined, it is found that the lognormal distribution has the lowest overall weights while the Weibull distribution has the highest overall weights 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 members. The passing rates for the different distribution functions in the two environments

Table 1. KS test results for signal variations.

Distribution Function	Passing Rate (%) in campus environment	Passing Rate (%) in ship environment
Lognormal	0	0.5
Rayleigh	48.3	33.7
Rician	54.2	43.4
Nakagami	55.2	45.4
Weibull	69.2	52.5

are tabulated in Table 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. This agrees with the conclusions drawn from the AIC based method. 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 in the two complex environments.

Therefore, the Weibull b parameter (red curve in Figs. 6(f) and 7(f)) which is an indicator of the degree of the signal variation is used for further analysis. The Weibull probability density function is defined as:

$$p_{a,b}(x) = a \cdot b \cdot x^{b-1} \cdot \exp\left(-a \cdot x^{b}\right) \quad x \geq 0 \tag{6}$$

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 low value of parameter b corresponds to a large dispersion. If the parameter b is equal to 2, the Weibull distribution is similar to the Rayleigh distribution. For $b < 2$, the signal suffers severe fading.

From Figs. 6(f) and 7(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 regions 2 and 3 shown in Fig. 6(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 Fig. 7(f), the corresponding Weibull b parameter for significant peaks in regions 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 Fig. 6(f) and Fig. 7(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 where propagating signals are subjected to temporal variations such as the lift shaft and the ship enclosure.

3.4. RMS Delay Spread

The rms delay spread values (τ_{rms}) for the scenarios when the lift door is opened/closed at the transmitter level are tabulated in Table 2. A threshold of 5 dB SNR is used to calculate the delay spread from the mean PDPs. In Table 2, it can be seen that the status of the lift door has significant effect on the rms delay spread for propagation along the lift shaft inside the campus. However, there is no obvious 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 in the campus, the signal strength and number of rays guided along the lift shaft decreases when the lift door status changes from open to closed. However, the signals in region 2 arriving with a longer delay remain unchanged. Therefore, a larger delay spread is obtained when the lift door is closed. When the lift door status changes from open to closed inside the shipboard, most of the signals are approximately equally attenuated as shown in Section 3.2.2, hence leaving the rms delay spread unchanged.

The rms delay spread values for different lift car positions are plotted in Fig. 8. The squares are the delay spread values obtained from

Table 2. RMS delay spread for opening/closing lift door at level 2.

RMS delay spread (ns)	Door closed	Door opened	Door closed	Door opened
	Campus test		Ship test	
	151.8	93.9	85.9	84.8

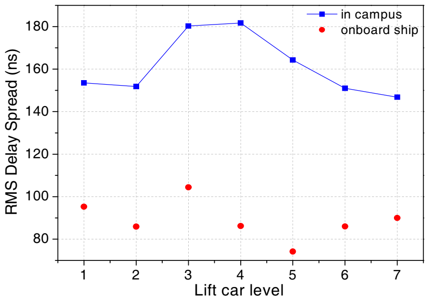


Figure 8. RMS delay spread for different lift car level.

the campus environment, while the dots are those obtained from the ship environment. Two different trends can be observed from Fig. 7. For results from the campus environment, a higher delay spread value is obtained when the lift car is within the propagation channel at level 3, 4, and 5. This is because the guided signals are attenuated by the lift car when it is in the propagation path between the transmitter and the receiver. For the ship environment, the delay spread does not vary significantly when the lift car level is varied. As explained in Section 3.2.3, the variation of the guided signals within the ship enclosure varies is not directly correlated with the lift car position. Therefore, the obtained delay spread values in Fig. 7 do not follow any obvious trend.

Taking all the measurement scenarios into consideration, the average rms delay spread is 161.3 ns and 88.0 ns for propagation along the lift shaft in the campus and on board the ship respectively. 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 campus environment. In [18], delay spread for propagation along an analogous waveguide structure-mine environment in the frequency band of 400 to 500 MHz is within the range of 5–42 ns. Delay spreads for both environments in this paper are larger than those reported in [18]. In this paper, besides the guided signals by the lift shaft, reflected signals from buildings in the intermediate and far regions in the campus environment and guided signals by the ship enclosure are included. The delay spread value of 161.3 ns from the campus environment (urban area) is similar to those found in a suburban environment [19] due to the semi-indoor locations of the antennas. In [19], 80% of the rms delay spreads values obtained from channel characterization in the 788–794 MHz band in suburban areas is below 200 ns. 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 [20]. The heavily cluttered factory environment forms a similar propagation channel to that of the 'waveguide within waveguide' environment on board the ship.

4. CONCLUSION

In this paper, signal variation associated with a lift shaft in a complex campus environment and on board a ship has been presented and compared. The wave guided along the lift shaft is one of the main propagation modes in both the urban environment and metallic ship environment. Besides the guided signals along the lift shaft, signals arriving at the receiver via reflection from intermediate to far static buildings in the campus; and signals propagating through multiple reflections by the local metallic substructures inside the ship are also considered. The effect of the lift door and the effect of the position of the lift car are examined and compared via two sets of controlled experiments. It is found that the opening/closing of the lift door and the movement of the lift car induce signal variation to the guided signals for both lift shafts. This signal variation is more significant for the larger lift shaft in the campus. Due to the different propagation mechanisms associated with signals with longer arrival times, region 2 signals in the mean PDPs obtained from the show little or no signal variation. However, the multiple reflected signals propagating inside the ship (outer waveguide) are severely affected by the status of the lift door and the position of the lift car. Due to the same reason, the delay spread obtained from the campus environment is closely related to the motion along the lift shaft while that from the ship environment varies around a constant value. Moreover, the average rms delay spread from the campus environment is about twice of that from the ship environment. Through the statistical analysis of the signal variation in the two environments, it is found that, regardless of the environment, the Weibull probability density function is the best-fit model for analysing the signal variation along analogous waveguide structures such as the lift shaft in both the campus and the ship environments and the metallic ship enclosure. It is the most suitable function to model the overall channel as well, since its b parameter can be used to identify and study the signal variation. This model can be extrapolated to model other analogous waveguide structures in different environments and used for simulation of realistic analogous waveguide structures as well.

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