Statistical Modeling of Signal Variation for Propagation Along a Lift Shaft

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***Abstract*—Temporal variation on the tapped amplitude of propagating waves along a lift shaft in a complex campus environment is presented and modeled statistically in this letter. By using the Akaike's Information Criterion (AIC)-based method, distributions of amplitude of signals from different propagation mechanisms are studied separately. If the channel is considered as a whole, the Weibull function is identified as the best model for describing the temporal variation. The Kolmogorov–Smirnov (KS) test is applied to verify the selection of the Weibull model. Through the analysis of the Weibull *b*-parameter, the severe temporal variations caused by the opening and closing of the lift door and the movement of the lift car within the lift shaft can clearly be identified. Signals reflected from buildings and walls in the intermediate and far regions do not suffer from much temporal variations. The Weibull function is ideal for the statistical modeling of channel propagation along the lift shaft. Using the Weibull *b*-parameter, the dynamic channel along the lift shaft and the static channel from the intermediate and far regions can easily be classified.**

***Index Terms*—Akaike's Information Criterion (AIC)-based method, lift shaft, temporal variation, UHF band, Weibull distribution.**

I. Introduction

IN THE FIELD of indoor propagation, the lift shaft and its associated lift car have been identified as a RF-harsh propagation environment for communication system planning inside buildings [1]. However, it can be a useful and reliable link, especially when the nearby environment makes radio wave propagation difficult or impossible, such as in a ship and factory environment, where structures within the environment are mainly metallic and are likely to block transmission. In the literature, there is not much research work on propagation along a lift shaft. In [1]–[3], narrowband measurement has been conducted. The main focus of their studies is on the variation in signal strength. In [4], the propagation mechanisms associated with the lift shaft in a campus have been studied through wideband channel measurements and simulations. For a channel where both transmitting and receiving antennas are kept stationary, any movements within the channel—i.e., motion along the propagation path and movements around the antennas—will result in multipath variance and fading effects. For example, it is reported in [5] that the average received signal power obtained from wideband measurement at 5.2 GHz in a laboratory environment will decrease by 2–3 dB in the presence of human shadowing. In [4], it has been concluded that in the VHF and UHF range, when the transmitter and receiver are near a lift shaft in a complex campus environment, the main propagation mechanism is the guiding effect along the lift shaft, whereas multipath components are caused by reflection from the surrounding buildings and walls. In the wireless communication link in [4], there are relatively more moving metallic objects in the channel compared to the laboratory environment in [5]. It is concluded in [4] that the opening and closing of the metallic lift door and the movement of the metallic lift car causes significant temporal effects along the propagation path. Since the main propagation mechanism in the complex campus environment is via the lift shaft [4], it is important to be able to statistically model and analyze the channel. The statistical model and analysis can provide system designers with information on the requirements for a practical system design.

The temporal variation obtained through measurements in common indoor environments such as offices, laboratories, and homes in the UHF band has been investigated by researchers in [6]–[10]. From the wideband measurements at 1.1 GHz within two office buildings [6], the amplitudes of the multipath components are found to be lognormal-distributed. In [7], the Rayleigh function is proposed for the modeling of the temporal variation of signals obtained from wideband measurements at 5 GHz inside 23 homes. Narrowband measurements at 900, 2400, and 5200 MHz in four modern factories by Tanghe and *et al.* [8] have shown that the temporal fading statistics can be well described by the Rician distribution. In [9], based on the statistical analysis of ultrawideband (UWB) measurements in a modern office building, the Nakagami function is identified as the best model to describe the amplitude distribution. In [10], the Weibull function shows the best fit for the amplitude fading in an office environment at 1.1 GHz.

In this letter, as a continuation of the research work in [4], the temporal variation for communications in UHF band along a lift shaft is analyzed and modeled statistically. The Weibull function is identified as the best model for this propagation channel, especially since the Weibull b-parameter can be used to identify both the static and dynamic channels.

II. Channel Measurement

A. Measurement Campaign

A measurement campaign has been performed along a lift shaft in an education building S2 that spans seven levels and

Manuscript received April 07, 2010; revised June 29, 2010; accepted July 21, 2010. Date of publication July 29, 2010; date of current version August 09, 2010. This work was supported by the Advanced Communications Research Program DSOCL06271, a research grant from the Directorate of Research and Technology (DRTech), Ministry of Defence, Singapore.

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Digital Object Identifier 10.1109/LAWP.2010.2061831

is approximately 27 m in height. The lift shaft, which is as high as the building S2, is made of concrete walls, while the lift doors and its associated lift car are made of metal. On the opposite side of the lift shaft, there is a stairwell of the same height. The floor of block S2 is made of enforced concrete of approximate thickness 0.8 m, and the ceiling of block S2 is lined with metal plates. During the experiment, the transmitter and the receiver are positioned outside of the lift doors at level 3 and level 6, respectively. In the surrounding, there is a building known as block S1 parallel to block S2 at a distance of 78 m away. Another group of education buildings known as the Communication School (CS) is situated between blocks S1 and S2. The detailed environment can be viewed in [4].

B. System Setup and Sounding Technique

For this measurement, the frequency-domain channel sounding technique is used. The measurement system consists of an Agilent vector network analyzer (VNA) and two identical omnidirectional Discone antennas AX-71C. The center 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 temporal variation on the signal strength, continuous measurements are conducted over a period of 8 h, and 10 000 data files [two-port response S_{21} as expressed in (1)] have been recorded. The time-domain channel response can be obtained during post-processing by taking the inverse fast Fourier transform (IFFT) of the recorded frequency-domain transfer function (2). The instantaneous power delay profile (PDP) is the envelope of the received power, and it is proportional to $|h(t)|^2$

$$\mathrm{S}_{21}(\omega) \propto H(\omega) = \frac{\mathrm{Rx}(\omega)}{\mathrm{Tx}(\omega)} \quad (1)$$

$$h(t) = \mathrm{FT}^{-1}\left[H(\omega)\right]. \quad (2)$$

III. Results and Discussion

A. Overview of the Power Delay Profile

From continuous measurements, an example of instantaneous time-domain channel responses or PDPs from different time segments is shown in Fig. 1. The power delay profiles can be classified into three regions based on the signals' arrival time, which indicates the distance of the obstacles. Region 1 ranges from 0 to 0.14 μs on the time axis. Region 2 ranges from 0.14 to 0.5 μs. Region 3 ranges from 0.5 μs and above. In [4], measurements have been conducted in the same environment. The origin of each multipath cluster within all three regions has been identified through sets of controlled experiments and verified through ray-tracing simulation results. Based on the time of arrival for different regions, region-1 signals are identified to be signals penetrating through the floors and ceilings; signal reflected and/or diffracted by nearby objects such as the lift door, walls, and railings; and, most importantly, signals guided by the stairwell and the lift shaft. Signals arriving within regions 2 and 3 are identified to be signals reflected from intermediate and far-away static structures such as surrounding buildings (block S1 and CS) and partitioning walls in block S2 [4]. Comparing the received power of signals in the PDPs over different time segments shown in Fig. 1, it can be seen that there is significant amplitude variation of up to 10 dB for signals arriving within region 1, whereas signals in regions 2 and 3 are relatively static. The large amplitude variation within region 1 is mainly due to the temporal variation of signals guided by the lift shaft. The guided signals are severely affected by the opening and closing of the lift door and the movement of the lift car when the lift is in use [4].

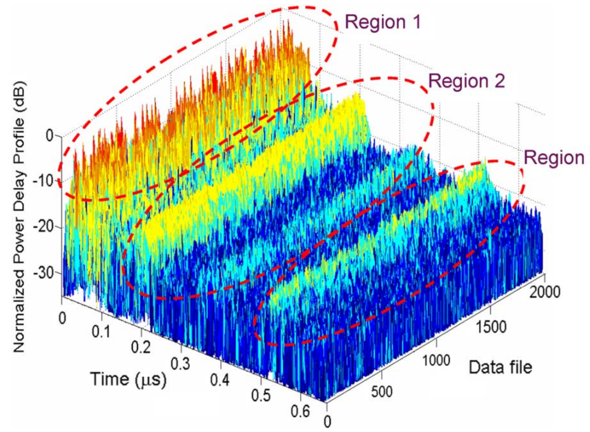

Fig. 1. Instantaneous PDPs with temporal effect.

B. Channel Model Selection Based on Akaike Weights

The Akaike's Information Criterion (AIC) was initially developed by Akaike in 1973. It is a good criterion that can be applied to model temporal variations in wireless communication [11]. In fact, the most popular approach to characterize the tapped amplitude distribution based on measurement data is through goodness-of-fit (GOF) tests. Compared to the GOF test, the AIC-based method will not only identify the good distributions in the candidate set, but also provide information on the candidates' relative fitting quality based on the Akaike weights ω_j, defined as

$$\omega_j = \frac{e^{-\frac{1}{2}\varphi_j}}{\sum_{i=1}^{J} e^{-\frac{1}{2}\varphi_j}} \quad (3)$$

where AIC differences $\varphi_j = \mathrm{AIC}_j - \min_i \mathrm{AIC}_i$, and the operating model AIC_j is given as

$$\mathrm{AIC}_j = -2\sum_{n=1}^{N} \log g_{\hat{s}_j}(x_n) + 2U \quad (4)$$

where $\min_i \mathrm{AIC}_i$ denotes the minimum AIC value over all the j candidate families (in this letter, the lognormal, Rayleigh, Rician, Nakagami, and Weibull distributions), g is the probability density function (pdf) 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 the 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 [12]. 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 $N/U \geqslant 40$ [11]. In this work, the size of the data set N is equal to 10 000, and the AIC-based method is applied to statistically model the temporal effect associated with the mean PDP obtained by taking the average over the 10 000 data files. Another selection criterion, the Kolmogorov–Smirnov (KS) test [13] is then used to verify the model selected by the AIC-based method. The models selected by both the AIC-based method and the KS test are then used to examine the temporal variation of the channel.

Fig. 2 shows the plots of the Akaike weights for different candidate members as well as the mean PDP. The maximum received power of the mean PDP in Fig. 2(f) has been normalized to 0 dB for ease of analysis. It is noted that the arrows in Fig. 2(f) 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. It is noted that all the significant peaks are at least 40 dB above the noise floor of the mean PDP. By examining the Akaike weights for significant peaks in the three regions, it can be observed that, for most signals arriving within region 1, the Akaike weights of the Weibull distribution function are 1. Therefore, the Weibull function is able to best describe the tapped amplitude distributions within region 1 (0–0.14 μs) compared to the other four functions. This is because there is severe temporal variation caused by the opening and closing of the lift door and the movement of the lift car on the guided waves along the lift shaft, and the Weibull distribution is the best for describing severe fading.

For the significant signals or peaks in regions 2 and 3 (0.14 μs and above), by examining the Akaike weights in Fig. 2, it can be seen from Fig. 2(c) that the Rician function has the highest Akaike weights (around 1). This is as expected since these signals are the result of reflection from static buildings in the intermediate and far surrounding [4], and there is little or no temporal variation on these signals (as seen in Fig. 1). The Rician distribution is commonly used to describe propagation channels with a dominant signal. Therefore, for the channel with static reflectors in regions 2 and 3, this distribution is found to best describe the significant peaks. For the nonsignificant peaks with normalized tapped amplitudes less than -20 dB, they are close to the noise floor and therefore, as seen in Fig. 2(b), are best described by the Rayleigh distribution, which is a distribution commonly used to describe signals arriving from multiple random directions.

For strong signals in Fig. 2(f), the Weibull function that indicates severe temporal variation associated with region 1 is the best-fit function for the guiding effect of the lift shaft. The Weibull b-parameter is an important indicator that will be studied in Section III-C. Static signals reflected from surrounding buildings and walls (regions 2 and 3) can best be modeled by the Rician function. The Rician K-factor is an important indicator used to study the static channel. A higher K-factor indicates a relatively static channel with a significant dominant component. The maximum K-factors are 3.2, 11.1, and 7.7 for regions 1, 2, and 3, respectively. If cumulative density function is used, 90% of K-factors in region 1 are below 2.8 dB, while those in regions 2 and 3 are below 5.9 and 5.8 dB, respectively. The low K-factor (even falls below 0) in region 1 indicates a multipath-rich region due to the movement along the lift shaft, while the high K-factor for regions 2 and 3 indicates relatively static regions from the intermediate and far static reflectors.

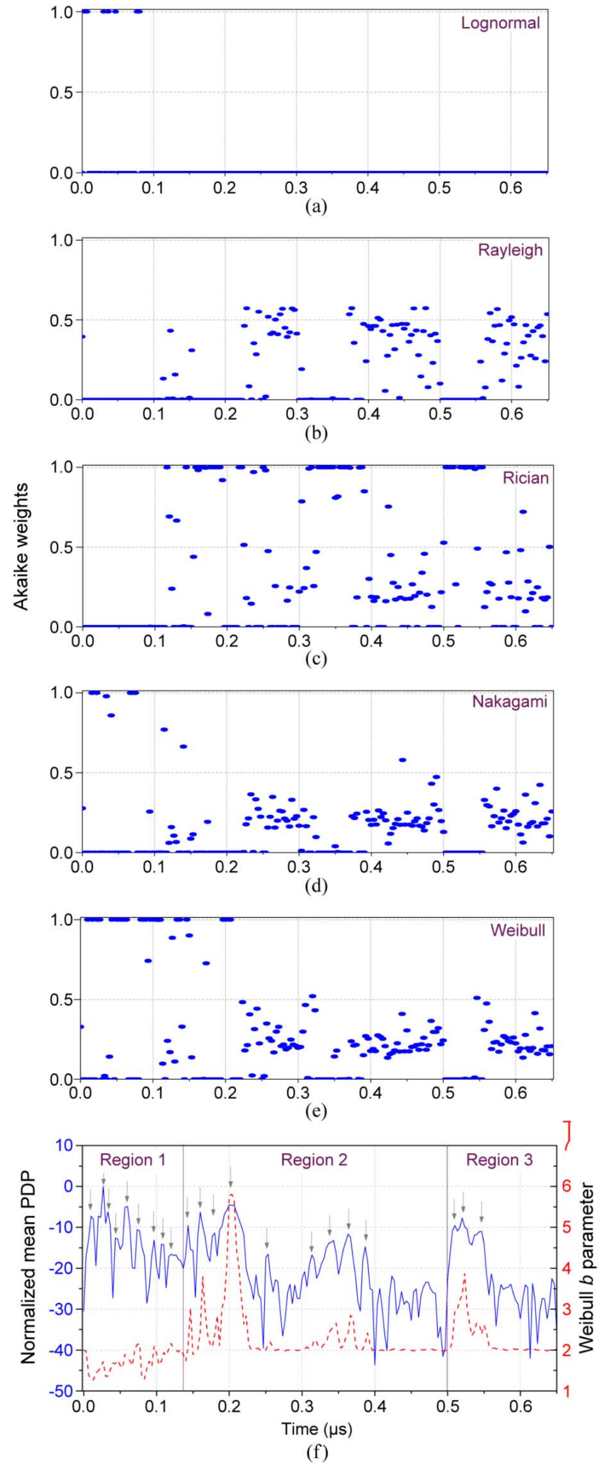

Fig. 2. (a) AIC weights for lognormal function. (b) AIC weights for Rayleigh function. (c) AIC weights for Rician function. (d) AIC weights for Nakagami function. (e) AIC weights for Weibull function. (f) Analysis of Weibull b-parameter.

From the Aikaike weights plotted in Fig. 2(a)–(e), the Weibull function is found to have the highest overall Akaike weights,

TABLE I
KS TEST RESULTS FOR TEMPORAL VARIATION

Distribution Function	Passing Rate (%)
Lognormal	0
Rayleigh	48.3
Rician	54.2
Nakagami	55.2
Weibull	69.2

while the lognormal function is found to have the lowest overall Akaike weights. In order to verify this result, the KS test is applied to all the candidate families. The passing rate for different distribution functions are tabulated in Table I. The Weibull function has the highest passing rate, whereas the lognormal function has the lowest passing rate. This agrees well with the conclusions drawn from the AIC-based method. The other three distribution functions have similar performances. From both the AIC-based method and the KS test, the Weibull function is found to be the best distribution to describe the temporal variation for the overall propagation channel. Furthermore, since the focus of this letter is to study and model the channel associated with the lift shaft, the modeling of region 1 is of the highest importance. Therefore, the Weibull function is chosen as the statistic model to describe the temporal variation associated with the lift shaft, and the Weibull b-parameter is studied in Section III-C.

C. Weibull b-Parameter

The Weibull pdf is defined as

$$p_{a,b}(x) = a \cdot b \cdot x^{b-1} \cdot \exp(-a \cdot x^{b}), \qquad x \geq 0. \tag{5}$$

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. Therefore, the Weibull b-parameter (dashed curve) is used to analyze the temporal variation in different regions of the PDP (solid curve) in Fig. 2(f).

From Fig. 2(f), it is observed that, the parameter b is below 2 for most of the tapped amplitudes arriving within region 1. This indicates that signals arriving within region 1 experience significant temporal variation. For significant peaks (reflected by buildings and walls in the intermediate and far region) arriving within regions 2 and 3, the b-parameters are found to be larger than 2. This indicates a dominant path within these peaks (Rician-distributed). For nonsignificant peaks (near noise floor), the parameter b is nearly equal to 2 and is therefore best described by the Rayleigh distribution as shown in Fig. 2(b). Conclusions drawn from the Weibull b-parameter are similar to those drawn from the AIC-based method. This indicates that the Weibull distribution provides the best description of the tapped amplitudes in this complex campus environment with lift-shaft wave guiding effects. Its b-parameter is a good candidate for studying the temporal variation and identifying propagation modes. The Weibull model is found to be able to model the lift shaft environment. This model can be extrapolated to model other lift shafts in different environments.

IV. CONCLUSION

In this letter, statistical modeling of the temporal variation for the channel along a lift shaft in a campus environment at UHF frequency is performed. AIC-based method has been applied to select the distribution function that best describes the channel variation. KS test is then applied to verify the selected model. From both the AIC-based method and the KS test, the Weibull function is identified to be the most suitable model to describe the temporal variations for the overall channel. When the temporal effect 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, which 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 environment. For a general lift shaft where the static environment is different, Weibull function is recommended for the propagation along lift shaft itself.

Further study on the lift shaft channel by examining the path loss exponent and delay dependence of power of multipath components (decay factor) [14] and proposing a model for general building by using clustering model should also be performed.

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