Propagation Path Loss Modeling in Stacked Containers Environments

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ABSTRACT

The container terminals and carriers are regarded as a challenging wireless communication enviroment, caused by the metalic walls of container and the corners with the resulting multipath and shadow effect. Accurate propagation modeling of it is helpful for node deployment and channel estimation. However, existing researches mostly focus on obstacles on the macro-scale, and rarely analyze the small-scale propagation characteristics, such as the propagation characteristics along the gaps between containers. Thus there is also a lack of engineering practical path loss model. In this paper, we first study the propagation environment of the stacked containers. Then we propose a path loss model for gaps between containers based on geometric analysis. The proposed path loss model matches well with ground truth value.

Keywords: wireless communication, stacked containers, path loss model

1. INTRODUCTION

With the rapid development of logistics industry in the globalization context, the scale of container freight as its main form is also expanding gradually. In order to cope with the rapid growth of the number of orders and containers, as well as the security, management, transportation efficiency and service quality problems brought by them, one of the effective ways is to establish an Internet of Things (IoT) system. The IoT applications acquires more efficient communication systems and green energy strategies. Nowadays, based on the available radiocommunication standards, various wireless communication systems with operating frequencies ranging from 0.4GHz to 5GHz have been applied in almost all major container ports[1]. However, the radio wave propagation characteristics in densely packed and stacked containers have not been studied clearly, which is important for deployment of IoT nodes. Radio wave propagation characteristics are critical knowledge for reliability in the design of wireless systems, which can improve the service quality in industrial environments such as personnel communication, M2M communication, etc. The storage yard environment where containers are densely placed is considered to be a difficult wireless transmission scene. In this scenario, containers made of alloy steel constantly reflect wireless signals, making the receiver affected by multipath effect. Secondly, the densely placed containers form many obstacles on the propagation path, resulting in shadow fading at the receiver end. In addition, the stacking scheme of containers in the yard and the climate will change over time, thereby the channel characteristics will change accordingly.

In recent years, some researches based on actual measurement were conducted on radio propagation characteristic in container terminal environment. Katulski et al.[2] and Ambroziak et al.[1] carried out a series of measurements and proposed a novel empirical model in DCT Gdansk Container Terminal (Poland). Ambroziak[3] fitted the same data with several generic models and then statistically tuned the Walfisch-Ikegami model[4]. Finally they proposed a new empirical model considering more parameters[5].Ferreira et al.[6] further studied the characteristic of slow and fast fading components in the case of mobile communicationw which shows that the slow and fast fading component subjects to Lognormal and Nakagami Distribution respectively. The works above has gained the knowledge of basic propagation characteristics of the overall container terminal. However, it is more necessary to consider the environment within stacked containers.

Tanghe et al.[7] and Ruckebusch et al.[8] analyzed the intra-,inter- and extra-container links. They then proposed the propagation model for two different stack scenario,i.e. row stacking and block stacking.Their works still did not consider the case of containers in the middle of container stacks. Considering various requirement of the measurements brings practical difficults, computer simulation software is a solution with many advantages. In container environment, Jarma et al.[9]used a wireless LAN design tool to study the metal shielding and waveguide effect. They provided a lot of information for understanding the characteristics of inter-container communication inside the stacks,while no specific analytical model is proposed.

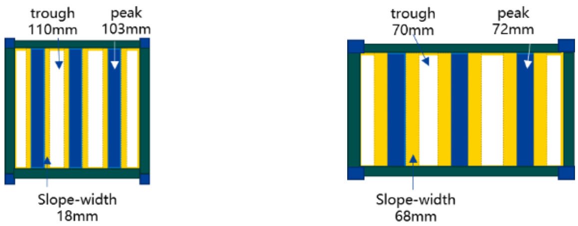
In this paper, the propagation characteristics of radio waves in stacked containers are studied when the transmitters are located at the midpoint of width side, the top corner point and the midpoint of height side. Based on the propagation model recommended by the International Telecommunication Union (ITU), a path loss model in gaps (it will be called as Gap Path Loss Model between Containers in this paper) is proposed by utilizing linear regression method. This paper is organized as follows. In Section 2, analysis of the transmittion environment is illustrated. Section 3 give the analytical Gap Path Loss Model and evaluation of its performance. Finally, the conclusions are drawn in Section 4.

2. PROPAGATION ANALYSIS AND ANALYTICAL MODEL

2.1 Geometric and Physical Properties

HFSS is a commercial simulation software developed by ANSYS. It aims at solving problems of electromagnetic fields based on finite element method. In order to make our simulation environments more authentic, parameters reflecting the container stacks are set and a certain degrees of simplifications to the simulation model, considering the computing complexity, are also needed.

20-ft container with code of *1CC* is selected according to the relevant specifications[10] released by the International Organization of Standardization.It is the most widely used type with size of $6058 \times 2438 \times 2591mm$, which is also the baseline of container stacking. Containers are not a regular cuboid, but ones with landmark periodic Trapezoidal corrugated steel plate. Parameters of the steel plates are shown in Figure 1, according to the size of corrugated panels on the market and size regulated by [11]. Furthermore, physical properties of the materials are considered to fit the real environment. According to[12], weathering or Cor-Ten steels with grades of Q355GNHJ (corresponding to S355J2WP in European Norm). Thus the conductivity and relative permeability of the container surface are set to be $7.6\%\,IACS$ and 850 respectively.

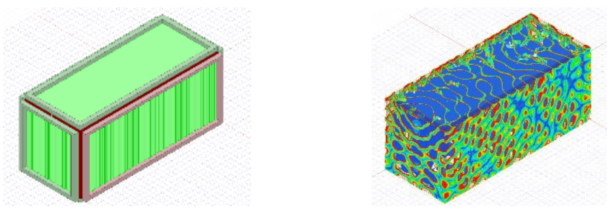


(a) Front panel of a container (b) Side panel of a container

Figure 1. Geometric sizes of steel panels

2.2 Analysis of the Propagation path

Containers will be densely placed with certain space in the direction of length, width and height. A central container within the stack surrounded by others endures the worst propagation environment. In order to study how tough the communication channel is for the central container, a simulation model of stacked containers is required.



(a) Overall view of the model (b) E field in the gaps

Figure 2. Model of the simplified container stack

According to [13]-[16], a standard gap of $76mm$ called ISO Gap in the length direction is adopted. Considering the height of possible securing fittings and the corner fittings, a gap of $30mm$ is selected in the direction of height. In the direction of width, the gap could reach $400mm$ in heavy (containers) area , while it may smaller than $100mm$ in empty area. 80mm is selected in this research, which refers to the relevant documents released by MacGregor Company cosidering the case of densely stacked containers. Furthermore, the overall stack is modeled as only one complete model of container where the adjacent containers are replaced relatively with one of their six surfaces since the target area is confined to the scope of container gaps, as is shown in Figure 2, which also shows distribution diagrams of electric field in the gaps.

Propagation links through gaps between adjacent containers, As is shown in Figure 3, can be divided into line-of-sight (LoS) and non-line-of-sight (NLoS) paths depending on the installation location of the transmitter. Path 1 and 2 in the figure represent LoS paths along the side and end panels respectively. It can be deduced that LoS paths exist in cases of coplanar transmitters and receivers. Path 3 and 4 represent two kinds of NLoS paths. NLoS paths only pass around one corner (1-Turn NLoS) at most. In addition, some receivers at different positions may have equivalent paths, which are represented by the same number (e.g. two paths of the same number 2). Hence, almost all of the different paths in container stacks can be studied by only focusing on area around the central container, and thereby the model could be simplified as mentioned above. Figure 4 shows the distribution of adjacent containers with LoS and NLoS paths under different transceivers deployments.

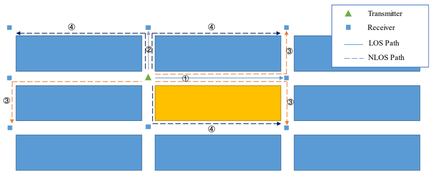
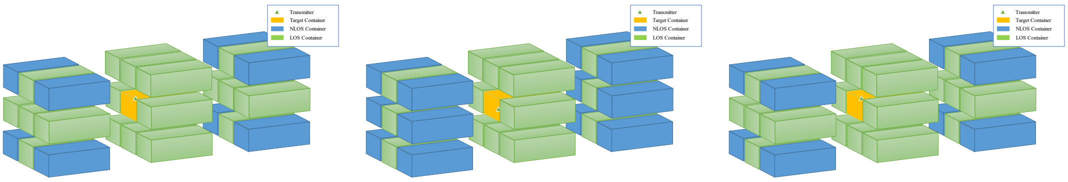


Figure 3. Side view of one containers stack



(a) Antenna on the width edge (b) Antenna on the height edge (c) Antenna the on corner

Figure 4. Reachable containers in different deploy location of transceivers

2.3 Gap Path Loss Model Between Containers

Propagation loss of a wireless link between a transmitter and receiver may depend on many different factors, such as losses from antenna and feeder or brought by impedance or polarization mismatches, and attenuation caused by physical transmission environments. This paper focuses on propagation characteristics in gaps of the stacked containers, and the data of interests are the energy flow density vector of the electromagnetic fields. Assuming that both transmitting and receiving antennas are isotropic, that is, the directional gain for all θ and ϕ satisfies $g(\theta,\phi)=1$, where θ and ϕ refers respectively to the pitch angle and the azimuth angle. Average Poynting vector could be represented as $\left|\overrightarrow{P_{av}}\right| = \frac{1}{2}Re[E \times H^*]$, thus the relationship between Poynting vector and transmitted or received power can be derived as below according to [17],[18].

$$P_t \approx \frac{\pi L^2 \left|\overrightarrow{P_{av0}}\right|}{16\delta} \tag{3.1}$$

$$P_r = \left|\overrightarrow{P_{av}}\right| \cdot A_e = \left|\overrightarrow{P_{av}}\right| \cdot \frac{\lambda^2}{4\pi} \cdot g(\theta,\phi) = \left|\overrightarrow{P_{av}}\right| \cdot \frac{\lambda^2}{4\pi} \tag{3.2}$$

$\overrightarrow{P_{av0}}$ is the maximum average Poynting vector at axis of the dipole antenna in the near field, while $\overrightarrow{P_{av}}$ is average Poynting vector at the receiving point. L and δ refers to the maximum size and aperture efficiency of the antenna respectively. Then path loss can be represented via Poynting vectors since it is the ratio of transmitted power to the power available at the point of receiver, as is shown by (3.3).

$$L = \frac{P_t}{P_r} = \frac{\left|\overrightarrow{P_{av0}}\right| \cdot \pi L^2}{\left|\overrightarrow{P_{av}}\right| \frac{\lambda^2}{4\pi} \cdot 16\delta} = \frac{\pi^2 L^2}{4\delta\lambda^2} \cdot \frac{\left|\overrightarrow{P_{av0}}\right|}{\left|\overrightarrow{P_{av}}\right|} \tag{3.3}$$

$$L_b = P_t[dB] - P_r[dB] = 10\log_{10}\left(\frac{p_t}{p_r}\right) \approx \left|\overrightarrow{P_{av0}}\right|[dB] - \left|\overrightarrow{P_{av}}\right|[dB] = L_{bf} + L_m \tag{3.4}$$

It can be derived that path loss represented by Poynting vector differs from the usual path loss only in a constant coefficient. Therefore, the logarithmic path loss can be represented by (3.4). The right side of (3.4) corresponds to the basic transmission loss defined by [19] where L_{bf} represents the propagation loss in free space and L_m represents the additional loss, including the loss caused by diffraction, reflection and other effects. Acquired Path loss data at different points are set to be ground truth value, which is regarded as the truth value for the fitting process.

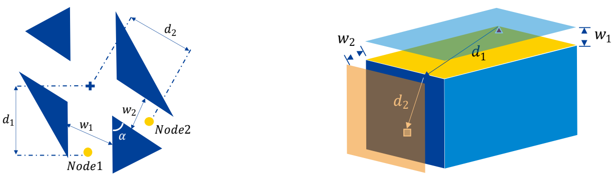
In stacked containers environment, gaps around the container are very similar to the streets in cities. The propagation wave is reflected and propagated continuously in the container gaps, which leads to waveguide effects. And diffraction phenomenon occurs at the intersections. This propagation pattern is usually called as *Street Canyon*, which suits the scenario of this paper.The difference is that radio waves can travel through the plane thoroughly where the gap is located because of the ignored reflected wave from the earth in our simulation model. Thus Gap Path Loss Model of two cases (i.e. LoS and NLoS) in container gaps is derived, based on the *street canyon* model in Section 4.1 of [20]. The model for LoS paths such as Path 1 and Path 2 in Figure 3 is then represented as (3.5), model for NLoS paths such as Path3 and Path 4 is represented as (3.6).

$$L_b(d) = 10 \cdot \alpha_0 \cdot \log_{10}(d) + \alpha_1 \tag{3.5}$$

$$L_b(d_1, d_2) = -10 \cdot \alpha_0 \cdot \log_{10}\left(10^{-\frac{\alpha_1 L_r}{10}} + 10^{-\frac{\alpha_2 L_d}{10}}\right) \tag{3.6}$$

$$where \begin{cases} L_r = 20 \cdot \beta_0 \cdot \log_{10}(d_1 + d_2) + \frac{\beta_1 d_1 d_2}{\left(\frac{\pi}{2}\right)^{\beta_2}} + \beta_3 \\ L_d = 10 \cdot \beta_4 \cdot \log_{10}[d_1 d_2 (d_1 + d_2)] \\ \quad + \beta_5 \left[\arctan\left(\frac{d_1}{w_1}\right) + \arctan\left(\frac{d_2}{w_2}\right) - \frac{\pi}{2}\right] + \beta_6 \end{cases} \tag{3.7}$$

In (3.7), L_r and L_d refers to the reflection and diffraction components respectively. d_1 and d_2 refers to the distance traveled along two gaps respectively. Meanwhile, w_1 and w_2 refers to the width of two gaps, as is shown in Figure 5. Parameters are obtained by utilizing multiple linear regression to fit the simulation data in the corresponding gap of each surface at different frequencies[1]. To evaluate whether the proposed model could reflect the propagation characteristics, a performance evaluation based on the parameters calculated during fitting process is illustrated in the next subsection.



(a) Digram of *Street Canyon* (b) Digram of NloS path

Figure 5. Diagram of the *Street Canyon* model

3. PERFORMANCE EVALUATION

In this paper, several metrics representing performance of the model are calculated, the most important of which is Deterministic Coefficient ($R^2 \in (-\infty, 1]$). It indicates the adaptability of proposed model to our simulation data. A deterministic coefficient with a value more close to one means a better performance of matching data for our model. R^2 is used to determine the fitting performance combined with Root Mean Square Error (RMSE), since a model only with a small RMSE value may not be able to represent details of the data.

3.1 Performance of model with LoS Path

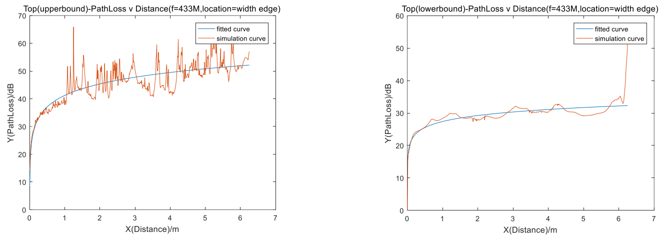
Table 1 shows the performance of proposed model in stacked container with antenna mounted at midpoint of the width edge of the top panel. It can be seen that performance of model with LoS path, which is assumed to contain direct and reflection components only, is relatively stable. Reflection component can be represented as a waveguide effect parameter in the model of LoS path. This simple form of model with LoS path just leads to a more stable performance. The fitting figure of one LoS path is shown by Figure 6.

Table 1. Performance of proposed model [f = 433MHz, Upperbound (Lowerbound)]

Panel	Path Type	R^2	RMSE
Top	LoS	**0.6934(0.6212)**	3.918 (2.066)
Left	NLoS	**0.3350 (0.7586)**	4.568 (1.26)

[1] The table of parameters and source codes are availabe on https://github.com/Heinriciro/stacksContainerPathLossModel.git.

Front	NLoS	**0.5016 (0.5626)**	4.481 (0.822)
Door	LoS	**0.7358 (0.8537)**	4.328 (1.487)
Bottom	NLoS	**0.1554 (0.5624)**	5.338 (1.501)

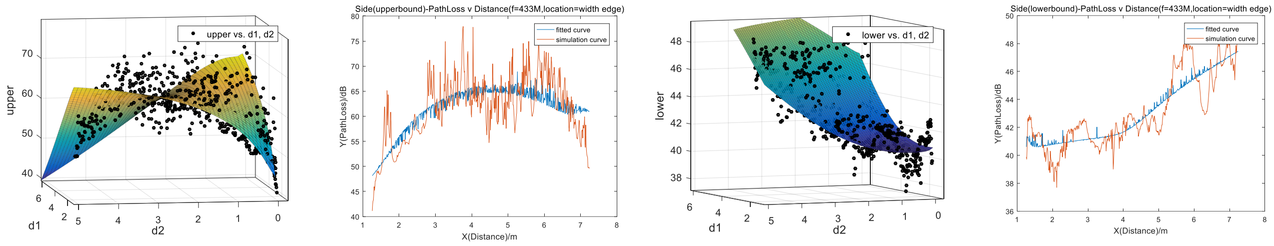


(a) upperbound curve (b) lowerbound curve

Figure 6. Fitting figure for LoS path corresponding to the top panel

3.2 Performance of model with NLoS Path

In contrast, performance of model with NLoS paths varies a lot in gaps corresponding to different panels. As is shown by Table 1, NLoS model in gap corresponding to front-side panel shows the best performance with R^2 only equals to about 0.5. This may be attributed to the short distance between left-side panel and the transmitter antenna, since the radio wave would diffract at the edge after traveling a short distance. For gaps corresponding to other panels, the energy of signal would be small after experiencing a long distance propagation and diffraction loss at edges, which influence the performance since that NLoS model mainly considering diffraction and reflection loss. Another important factor leading to the unstable performance is the reflection effect caused by corrugated side panels, which is considered insufficiently in proposed model. However, overall trend of the data with NLoS paths could be shown by our proposed model as is shown by Figure 7, which proves that the model based on *Street Canyon* is capable to represent the overall propagation characteristic.



(a) 3d upperbound curve (b) 2d upperbound curve (c) 3d lowerbound curve (d) 2d lowerbound curve

Figure 7. Fitting figure for NLoS path corresponding to the left panel

In addition, performance for lower-bound curves are generally better than those for upper-bound curves, as is shown in Table 1. From perspective of data characteristics, this can be explained as that the lower bound curve is relatively more gentle compared with the upper-bound curve with strong fluctuation, which makes it easier to be predicted. In terms of transmission characteristics, the fluctuation is brought by the superposition of reflection and diffraction component.These two components then depend on the geometric shapes and antenna positions. Thus, the general *Street Canyon* model is hardly cover all details of the propagation process especially for such a specific scenario. In general, the improved *street canyon* model performs well on lower-bound curve. Its R^2 is generally above 0.6 and even can reach 0.8 and 0.9 for some cases. The relatively accurate prediction to the lower-bound curve is helpful for supervision of the wireless system design.

In this section, evaluations on the performance of proposed model are illustrated. The results show that the model can reflect the overall propagation characteristic since it performs well in fitting curves of LoS paths and the lower-bound of NLoS paths. However, the performance for upper-bound curves of NLoS paths are unstable. Hence, the model failed to take all details in the reflection and diffraction process into account , which indicates that a more accurate model with geometric optics theory are needed for later researches.

4. CONCLUSIONS

In this paper, a container stack is simplified and modeled utilizing computer simulation technology. A Gap Path Loss Model between Containers based on urban propagation model is then proposed at frequency 433M and 868M, which are usually used in Internet-of-Things applications. Propagation links through gaps around the container are divided into LoS and NLoS link, and multiple linear regression method is applied to fit the upper-bound and lower-bound of simulation data. The proposed model shows a good performance on LoS paths whose deteministic coefficient is more stable. In addition, the fitting performance for the lower-bound curve is better than that fot the upper-bound curve. It should be noted that the proposed model can still be improved by applying theory of geometrical optics since the unsatisfied performance on NloS path.

In general, the proposed model can reflect the radio propagation characteristics of inter-container communications and provide relevant guidance for the application of IoT in stacked container environment.

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