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Channel Impulse Response Analysis of the Indoor Propagation Based on Auto-Regressive Modeling

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Abstract. A novel statistical channel impulse response model at 2.6 GHz is proposed for the indoor stairs and corridor environment. The model is based on the frequency domain auto-regressive (AR) process. The samples of the complex frequency response can be described as the output of the AR transfer function driven by a Gaussian white-noise process. In this model, the number of poles of the AR transfer function is determined by the significant paths of radio propagation. The paths depend on the reflectors of different propagation environment. The accuracy of the AR modeling has been verified by utilizing the root-mean-square error and root-mean-square delay spread as metrics. The model is also compared with the conventional tapped delay line model. The proposed model can be useful for the development and design of future communication.

Keywords: Channel impulse response · Stairs and corridor
Auto-regressive process · Radio propagation

1 Introduction

The stairs and corridor are not only an entrance/exit in our daily lives, but also an integral part of communication integration in future intelligent buildings. Furthermore, these areas can be utilized for deploying emergency communications and monitoring systems. Therefore, it is necessary to design a communication system that satisfies the requirements of data transmission in terms of quantity, quality and speed. Also, understanding the comprehensive and complex characteristics of channel in the stairs and corridors is very important for the communication system design [1–4].

The propagation characteristics of stairs and corridors are researched in [5–7] by using image-based ray tracing methods. In fact, the wireless propagation channel can be modeled by channel impulse responses (CIRs), which can be described as a time-varying linear filter. The CIR is an important characteristic of the channel. It can be

J. Zheng et al. (Eds.): ADHOCNETS 2018, LNICST 258, pp. 282–291, 2019.
https://doi.org/10.1007/978-3-030-05888-3_26

used to predict and compare the performance of different communication systems, and provide many important channel parameters, such as root-mean-square (RMS) delay spread and coherent bandwidth. In general, researchers tend to describe the CIRs as a tapped delay line (TDL) in time domain [8, 9]. Some researchers successfully applied the concept of clusters to the multipath arrival of channels [10, 11], and suggested that the formation of clusters is related to the spatial structure of buildings. However, in order to accurately describe the original channel of measured environment, a large number of delay taps and complex parameters are needed. For ray tracing methods, the deterministic modeling method requires a very accurate input database, which includes many details and parameters of the measured site.

In this paper, we put forward a novel frequency domain autoregressive statistical model at 2.6 GHz. The selected band is intended to mimic the band 41 in the time division duplexing-long term evolution (TDD-LTE) system. This model is based on three different indoor conditions: the line-of-sight (LOS) stairs environment, the non-line-of-sight (NLOS) stairs environment and the corridor environment. In the auto-regressive (AR) modeling process, it is found that the distribution of poles is related to the structure and reflectors of the indoor environment. At the same time, we will also use the traditional TDL model to verify the accuracy and superiority of the proposed model.

In Sect. 2, the measurement environment and the frequency domain measurement system are described. Section 3 proposes a frequency domain autoregressive model for the indoor stairs and corridor environment. In Sect. 4, the results of AR modeling are compared with the TDL model, and the relationships between the poles of AR transfer function and reflectors of measurement environments are analyzed. The conclusions of the study are summarized in Sect. 5.

2 Measurement Environment and Settings

The selected stairs in our measurement campaign is located in a typical office building. The structure of the stairs measurement is shown in Fig. 1(a). We select two consecutive stairs for measurement in the building. There are 14 and 9 stair steps in the down direction and up direction, respectively. The size of each stair step is 120×28 15 cm, as shown in Fig. 1(a). What calls for special attention is that there is a crossbeam made of concrete over the second stair step in the up direction. The height of transmitting (Tx) antenna is 1.9 m. Further, the height of receiving (Rx) antenna under LOS circumstance (Rx1–Rx14) is 1 m, while the NLOS measurement is operated on the eighth and ninth stair steps in the up direction (Rx21 and Rx22) and the height of receiving antenna is 1.9 m. As shown in the Fig. 1(b), the position of corridor is at the exit of the stairs. The transmitter is fixed on the corridor while the receiver is moved along the corridor with the interval of 2 m at each receiving point (indicated as Rx31–Rx35) among the measurement campaign. The ceiling made of plaster is 3.2 m above the floor and the floor is made of marble. Both of the measurements for the transmitting and receiving antennas in the corridor are 1.5 m. What's more, there is no movement during all the measurements to make sure the channel can be considered to be time-invariant.

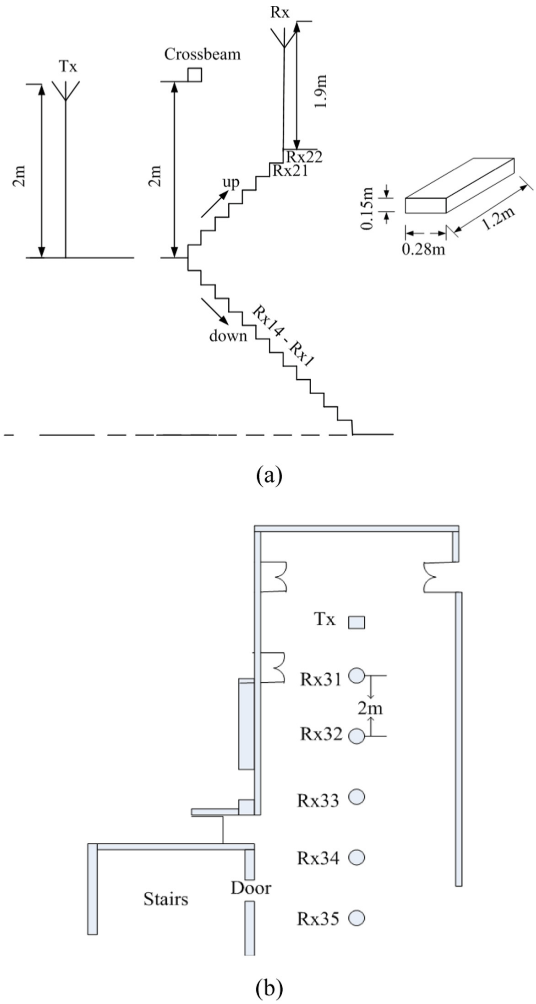

Fig. 1. The experimental environment. (a) The structure of the measured stairs environment. (b) The geometry of the measured corridor environment.

Figure 2 displays a rough diagram of the measurement system. The core equipment of the entire system is an Agilent 8720ET vector network analyzer (VNA). The detailed information of the frequency domain measurement system can be referred to in [12]. For convenience, the experiments were divided into two groups: stairs measurement and corridor experiment. The stairs measurement is conducted at 2.5–2.69 GHz with 201 frequency domain sweep points, while the corridor experiment has 801 sweep points in 2.35–2.85 GHz band.

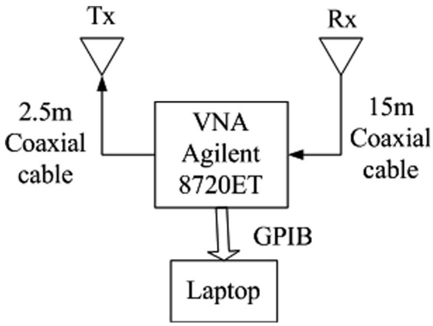

Fig. 2. The diagram of the measurement system.

3 Frequency Domain Autoregressive Modeling

The frequency response of stairs channel at frequency $H(f_n)$ measured in Sect. 2 can be considered as a random process, which is described by an AR process. The frequency domain AR model of order P is given by the following:

$$H(f_n) + \sum_{k=1}^{P} a_k H(f_{n-k}) = W(f_n),\ n = 1, 2, \ldots, N \tag{1}$$

where $H(f_n)$ is the sample of the complex frequency response at frequency f_n, $n = 1, 2\ldots, N$, N represents the number of sweep points of the measurement system. The symbol a_k, $k = 1, 2\ldots, P$ signifies the complex coefficients of AR model. $W(f_n)$ is a zero-mean complex Gaussian white-noise process.

In general, the frequency response can be regarded as the output of a linear filter with transfer function $G(z)$ driven by the excitation signal $W(f_n)$. The AR transfer function can be obtained from the z-transformation of Eq. (1).

$$G(z) = \frac{1}{1 + \sum\limits_{k=1}^{P} a_k z^{-k}} = \frac{1}{\prod\limits_{k=1}^{P} (1 - p_k z^{-1})} \tag{2}$$

The AR model can be seen as an all-poles model with parameters p_k in Eq. (2). To characterize the complex model, the P parameters and the variance of excitation signal need to be identified. Many algorithms can be used to achieve the coefficients a_k, for instance, the Levinson algorithm, Burg algorithm, and so on. The coefficients are the result of the Yule-Walker equations in this paper:

$$\sum_{k=1}^{P} a_k R(k - l) = -R(l),\ l = 1, 2, \ldots, P \tag{3}$$

where $R(k)$ is the frequency autocorrelation function defined as follows:

$$R(k) = \begin{cases} \frac{1}{N}\sum_{n=1}^{N-k} H(f_{n+k})H^*(f_n), & k \geq 0 \\ R^*(-k), & k < 0 \end{cases} \quad (4)$$

The autocorrelation function is vital in this process. The average received power can be calculated by using the function in Eq. (4). The variance of the zero-mean white noise can be calculated through the minimum mean square error criteria (MSE).

$$\sigma_v^2 = R(0) + \sum_{k=1}^{P} a_k R(k) \quad (5)$$

In the paper, there are many methods to determine the order of AR model. Specifically, the Akaike information criterion (AIC) and Final Prediction Error (FPE) methods are currently the most widely used methods. The AICs [13] of different frequency responses are calculated by:

$$AIC = 2L - 2\ln(K) \quad (6)$$

where L represents the number of estimated parameters, and K is the maximum likelihood function in this model. The minimum AIC is selected as the order of AR model.

4 Statistical Result and Analysis

The results of power delay profile (PDP) of stair step 1 (Rx1) from AR modeling, the conventional TDL model [8], and the measured data are shown in Fig. 3. The goodness-of-fit of AR modeling and the TDL model are verified by the root-mean-square error (RMSE) evaluation criterion between simulated value and measured data. The algorithm of RMSE is provided as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(X_{simu,i} - X_{meas,i}\right)^2}{\sum_{i=1}^{n} X_{meas,i}^2}} \quad (7)$$

The RMSE of PDP of AR modeling and the TDL model for stair step 1 is 0.037 and 0.108. The graph of the cumulative distribution functions (CDFs) of the RMS delay spread for measured data, AR modeling, and TDL model is shown in Fig. 4. The number of delay taps of TDL model is set to be the same as the order of AR model for the LOS stairs measurement. Both the RMSE and the RMS delay spread prove that AR modeling is in better agreement with the measured data than the TDL model. In addition, the frequency selectivity can be observed from the simulated channel, which is a characteristic that the TDL model does not have. High delay resolution is responsible for the AR model being better than the TDL model.

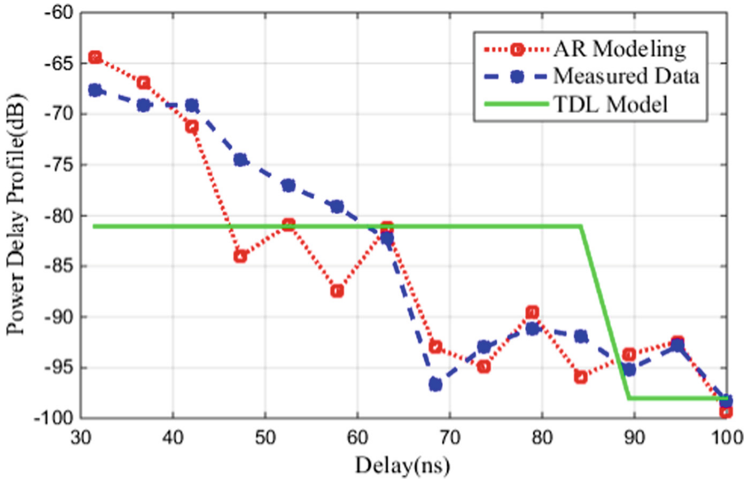

Fig. 3. The time response of the measured data, AR modeling, and TDL model for stair step 1 (Rx1) in the first 100 ns.

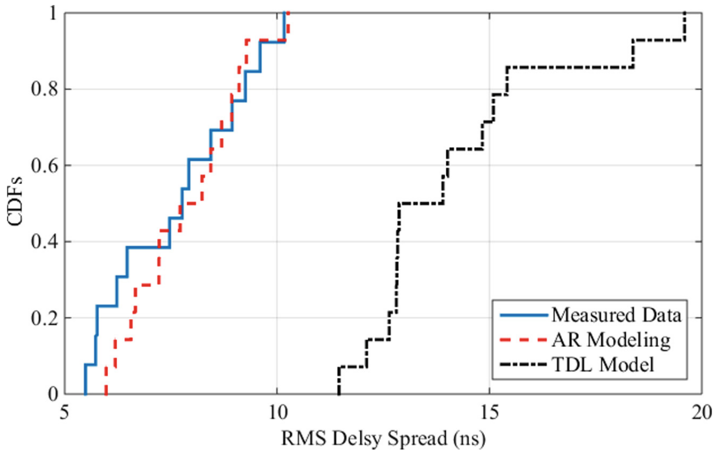

Fig. 4. The distributions of the RMS delay spread for measured data, AR modeling, and TDL modeling in the LOS stairs environment.

The scatter plot of the poles of the fourth quadrant from the transfer function in the stairs measurement is shown in Fig. 5. In this paper, the delay of the significant paths in the time domain is related to the angle of p_k and the arrival time can be calculated by Eq. (8):

$$\tau = \frac{-\arg(p_k)}{2\pi f_s} \tag{8}$$

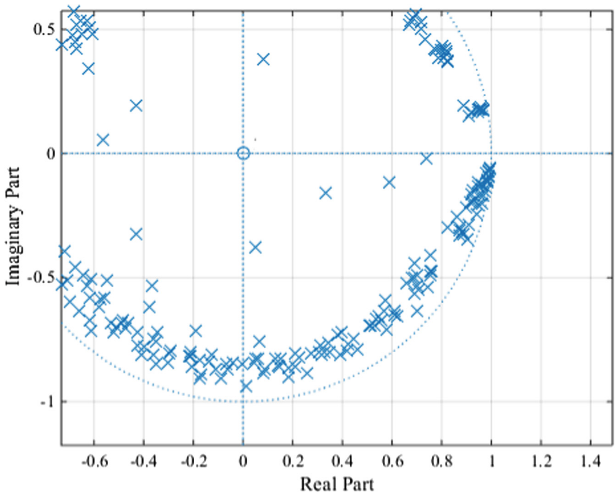

Fig. 5. The scatter plot of poles of AR transfer function in the fourth quadrant for the LOS stairs measurement.

where f_s is the frequency resolution. In the stairs measurement, the resolution in the frequency response is 0.95 MHz. Then the observation window of maximum delay is 1052.6 ns. However, too much redundant information (e.g., the noise and weak signals) is included in the channel impulse response. It is found that the obvious multipath components are unable to be observed when the delay surpasses a certain value. In the LOS stairs measurement, the specific value is determined to be 100 ns in order to reduce the complexity of data. At the same time, we only analyze the distribution of poles in the fourth quadrant of the unit circle. For the 14 stairs steps in the case of LOS, most of stairs have 3 poles in the first 100 ns and there are 5 steps with 4 poles. Pole 4 can be ignored because it is relatively small. Based on the above analysis, there are three, one, and two poles, respectively, for the stairs of LOS, the stairs of NLOS, and the corridor.

Figure 6 shows a graph of the delay of the first three poles in the first 100 ns for the LOS stairs environment. For the analysis reported in [14], the poles close the unit circle can be seen as the significant clusters in multipath propagation. The delay of the first pole is proportional to the distance of the direct path. The time required for the signal to reach the receiving antenna is almost the same as the time for the rays to propagate in free space. However, errors due to the measurement system may have an effect on this result.

Electromagnetic wave propagation in the indoor stairs environment is a fairly complex problem, but the mechanism of signal propagation is of interest for some researchers [7, 15]. In the LOS stairs measurement, the reflectors that cause the paths of signal propagation change are the wall on the left side (on the right of the Rx is the stair handrail), the stairs oblique beam above the Rx, the steps of stairs, and the wall behind the Rx. The delay of the second pole is between 21.74 ns and 42.57 ns, and it increases with the distance of the receiving antenna. The trend caused by the last 4 steps (11, 12,

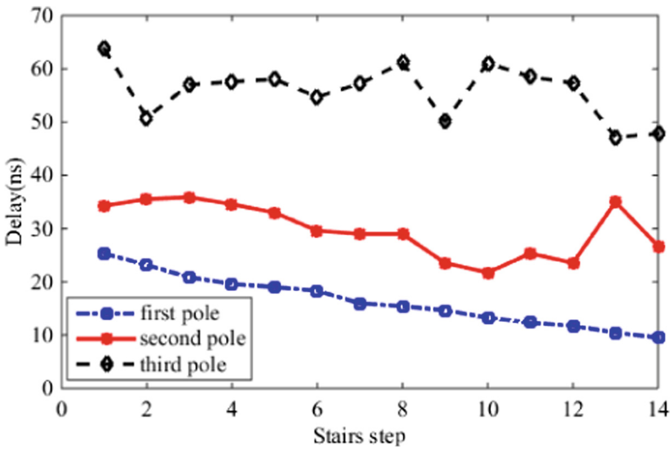

Fig. 6. The graph of the delay of the first three poles in the first 100 ns.

13, and 14) is because of the rays from both of the walls on the left and right sides. Thus, this indicates that the rays reflected from the wall on the left side mainly contribute to the received power. Those rays are unable to directly reach the receiver after one reflection from the steps because of the geometry of measurement environment, unless they are reflected multiple times. However, the final signal to the receiver will be weak and the delay will increase. For pole 3, longer delays (50–60 ns) and smaller modules relative to the first two poles indicate the signals experience at least two or three reflections. The result of the LOS stairs measurement is in disagreement with the observations of other researchers [14, 16]. A two-pole model is applied to describe the indoor radio channel in their research work. The difference can be explained as that even after multiple reflections, the attenuated signal can still reach the receiving antenna because of the special structure of the stairs environment, and it contributes to the received power.

For the NLOS stairs (Rx21, Rx22) measurement, it is reasonable that there exists only one pole within the first 100 ns because there is no direct path. The most obvious path is reflected from the floor in front of the steps to the receiver. In the corridor measurement, there exists two obvious paths: a direct ray similar to the propagation in free space and rays reflected from surrounding walls, ceiling, and floor (wave-guide effect). Accordingly, two significant poles can be seen in the first 200 ns, which is in agreement with the conclusion from [5, 6].

5 Conclusion

The CIR of indoor stairs and corridor at 2.6 GHz is described as a novel frequency domain auto-regressive model, which has higher accuracy than the traditional TDL model and lower complexity compared to ray-tracing methods. The RMSE evaluation criterion and the CDFs of the RMS delay spread are utilized to verify the results. The measured channel frequency response can be interpreted by the location of P poles of transfer function. The locations and magnitude of the poles are related to the reflectors of measurement environment and the mechanism of signal propagation. The number of poles representing the significant paths (clusters) depends on different measurement environments (the LOS stairs, the NLOS stairs and the corridor). The first pole in the LOS case can determine the formation of the first cluster caused by the direct ray. The determination of the second and third cluster depends on single reflected and double reflected (or higher order reflected) rays. These studies are expected to be applied in the development and design of the indoor communication system for stairs and corridor.

Acknowledgments. This work was supported by the National Natural Science Foundation of China under Grant No. 61701197 and 61571108, the Open Foundation of Key Laboratory of Wireless Communication, Nanjing University of Posts and Telecommunication, Jiangsu Province, under Grant No. 2017WICOM01, the Open Research Fund of National Mobile Communications Research Laboratory, Southeast University, under Grant No. 2018D15, the Open Foundation of State Key Laboratory of Networking and Switching Technology, the Fundamental Research Funds for the Central Universities under Grant No. JUSRP11742 and JUSRP11738, the Postgraduate Research & Practice Innovation Program of Jiangsu Provence under Grant No. SJCX18_0646.

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