Modeling of Radio Channels With Leaky Coaxial Cable for LTE-M Based CBTC Systems

Hongwei Wang, F. Richard Yu, and Hailin Jiang

***Abstract*—Due to some disadvantages of wireless local area networks (WLANs) in communication-based train control (CBTC) systems, long term evolution for metro (LTE-M) has been proposed to be the main communication method for future urban rail transit systems. In this letter, we model the channel of LTE-M with leaky coaxial cable for CBTC systems. Specifically, the proposed model is based on real field CBTC channel measurement results. Both path loss and small-scale fading are studied. The Akaike information criterion (AIC) is applied to determine the model of small-scale fading. We show that lognormal distribution is suitable for small-scale fading, and the corresponding parameters of lognormal distribution are also determined from the measurement results.**

***Index Terms*—LTE-M, CBTC, channel modeling.**

I. Introduction

URBAN rail transit systems are developing rapidly around the world. Being a key subsystem of urban rail transit systems, communications-based train control (CBTC) is an automated train control system using bidirectional train-ground communications to ensure the safe operation of rail vehicles [1]. It can enhance the level of safety and service offered to customers and improve the utilization of railway network infrastructure. CBTC is a modern successor to the traditional railway signalling system using interlockings, track circuits, and signals [2].

Due to the commercial off the shelves (COTS) technologies, wireless local area networks (WLANs) are usually adopted as the main method of CBTC systems, which work at the frequency band $[2.4GHz, 2.4835GHz]$. As there are many devices working at the same frequency band, interference is inevitable. In addition, as WLANs are not originally designed for high-mobility environments, there are some problems for WLAN-based CBTC systems, such as handoff and quality of service (QoS) issues [3].

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Recently, long term evolution for metro (LTE-M) has been proposed as the communication method in urban rail transit systems [4]. In fact, Zhengzhou metro Line 1 in China has used LTE as the communication method for the passenger information system (PIS), which works at 1,795 MHz to 1,805 MHz frequency band [5]. The PIS is built to help the operators monitor the situation related with passengers and trains, and video is transmitted in the PIS train-ground communication system. As CBTC systems are safety-critical, they have much higher QoS requirements for the train-ground communications (e.g., handoff latency, packet loss, capacity and security) compared with the PIS.

Radio channels play an important role in QoS provisioning of wireless communication systems. Therefore, there is strong motivation to study the propagation characteristics in the application environment. The finite markov channel model is applied to model the wireless tunnel channels for CBTC systems [6], where the large scale fading and the small scale fading are both illustrated. The propagation mechanism is proposed for tunnel channel in [7], [8], where the tunnel is divided intro several sections. Leaky waveguide and leaky coaxial cable (LCX) are also gradually used to increase the reliability of transmission and decrease the impact from the interference. The characteristics of large scale fading and small scale fading are summarized from measurement results at the Beijing Subway Line [9].

Although some works have been done on applying LTE in railways, *channel modeling* of LTE in urban rail transit systems has been largely ignored in the literature. In this letter, we will fill this gap by modeling both the large scale fading and the small scale fading of LTE-M for CBTC systems. According to measurement results, the path loss model is proposed based on the polynomial fittings with confidence probability 95%. With the Akaike Information Criterion (AIC), the characteristics of small scale fading are described after removing the effects of large scale fading. We will show that Lognormal distribution is the best fit model. In addition, the relationship between the parameters of Lognormal distributions and the location of the receiving antenna is summarized.

The rest of the letter is organized as follows. Section II describes the measurement campaign. The measurement results are shown in Section III, where the characteristics of large scale fading and small scale fading are demonstrated. Finally, in Section IV, we conclude the study.

II. Measurement Campaign

Measurements were performed at the inner circle railway of the loop track test base in Beijing. The map of the inner circle railway is shown in Fig. 1, and the perimeter is 8.5 km.

Fig. 1. The map of the real field measurements.

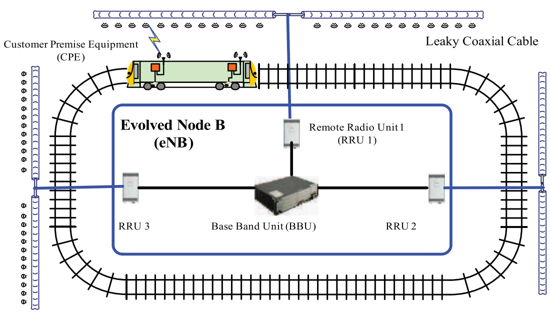

Fig. 2. The measurement principle.

TABLE I
THE PARAMETERS OF MEASUREMENTS

Frequency	$1.447GHz$—$1.452GHz$
eNodeB Power	$47dBm$
Scanning Step	$5MHz$
The RES bandwidth	$1000KHz$
Sampling interval	$0.0001s$

The goal of measurements is to assess the propagation performance of LTE-M at the CBTC scenarios and develop a channel model. The structure of LTE-M networks is demonstrated in Fig. 2. The evolved-NodeB (eNodeB) is a network node, which is composed of a base band unit (BBU) and several remote radio units (RRU), where a RRU could be treated as an access point (AP) of WLAN-based CBTC systems. The RRU can communicate with the customer premise equipment (CPE) located in the train, which builds the train-ground wireless link. During the measurements, the R&S ESPI is used to capture the channel samples. The sample interval is set as 0.0001 s, and the average velocity of the train is 60 km/h. The detailed information of measurements is shown in Tab. I.

As shown in Fig. 1, there are nine RRUs deployed. In order to increase the reliability and availability of LTE-M, leaky coaxial cables are adopted in CBTC systems. Before the measurement, the GPS device and the ESPI should synchronize time. When the train is running, the GPS can record the velocity, the latitude and the longitude of the train, and the ESPI can capture the channel samples. Therefore, we can map the channel sample with the corresponding location, which can help us build a more accurate channel model.

TABLE II
THE COEFFICIENTS OF POLYNOMIAL FITTINGS

Test Time	Degree 1		Degree 2		
	$c_1x + c_0$		$c_2x^2 + c_1x + c_0$		
	c_1	c_0	c_2	c_1	c_0
1	-0.0358	-53.5685	8.0279×10^{-5}	-0.0713	-51.3087
2	-0.0442	-51.3745	5.2776×10^{-5}	-0.0702	-49.2619
3	-0.0353	-52.3951	4.0951×10^{-5}	-0.0590	-50.0995
4	-0.0300	-54.5792	4.1723×10^{-5}	-0.0588	-51.2187
5	-0.0405	-52.0726	5.7691×10^{-5}	-0.0732	-48.9734
6	-0.0480	-50.3775	1.2254×10^{-5}	-0.0538	-49.9195

x : The location of the receiving antenna (m)

III. MODELING THE CBTC CHANNEL WITH LCX

A. *The Large Scale Fading*

We have performed several measurements to obtain the statistical characteristics of the channel with LCX. In the measurements, there are three different environments installing LCX, including free space, tunnel and viaduct. In this letter, we focus on the performance of LTE-M with LCX in the free space and the channel samples of RRU1, RRU2 and RRU3 should be processed.

Generally, the expression of a channel model is shown as follows [10].

$$PL(d) = PL(d_0) + 10Nlg\left(\frac{d}{d_0}\right) + X_\sigma \tag{1}$$

where d_0 is the reference point, X_σ is the distribution model of small scale fading, N is the path loss exponent. From (1), we find there is an exponential relationship between the path loss and the distance. However, the structure of LCX is almost the same as leaky waveguide, where the large scale fading of channel is linear [9]. Therefore, it is possible that the channel with LCX is also linear. As a result, the polynomial fittings are applied to analyze the large scale fading of the channel with LCX.

Without loss of generality, we use the polynomial fittings of degree 1 and degree 2 with the confidence probability 95% to process the experimental data, and the coefficients are shown in Table II. Obviously, the magnitude of the second order coefficient of the polynomial fittings of degree 2 is 10^{-5}, which is much smaller than the first order. As a result, the second order coefficient could be ignored and the channel with leaky coaxial cable of LTE-M at CBTC application scenarios could be approximated as a linear model, which is the same as the fading channel with leaky waveguide.

The measurement results and the fitting lines are illustrated in Fig. 3. The upper bound and the lower bound of the confidence interval with 95% confidence probability are demonstrated. Although there are some bigger bias close to the location of RRU, 95% of the experimental results are still at the confident interval (the space between the upper bound line and the lower bound line), which proves that the fitting results are reasonable. From Fig. 3, we can see that the received power is high when the location of the receiving antenna is near the RRU. The minimum of the received power is -75 dBm and the maximum is -40 dBm. Therefore, we can find there is large overlapping between the adjacent RRUs with LCX, and the distance

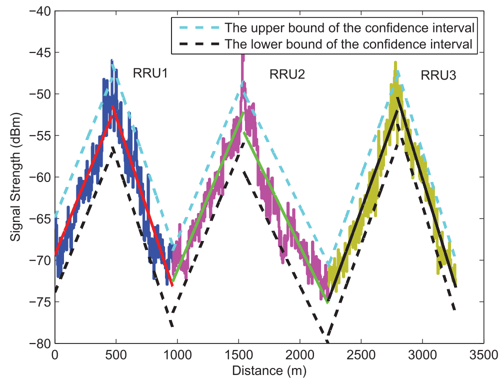

Fig. 3. The measurement results and the fitting lines.

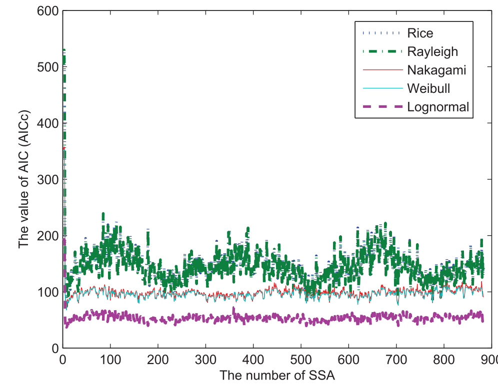

Fig. 4. The AIC or AICc value of each candidate model for each SSA channel sample.

between RRUs should be increased when LCX is applied. With the proposed channel model (2), we can give some guidance for the deployment of RRUs when the LTE-M is adopted in CBTC systems.

According to (1), the model of the LTE-M channel with LCX is proposed as follows:

$$PL(d) = PL(0) + nd + X_\sigma \tag{2}$$

where n is the path loss exponent, whose unit is dB/m, d is the distance between the receiving antenna and the beginning of LCX. Parameter n could be determined through the experimental results.

According to the slopes of the polynomial fitting results, we can get the average value of the path loss exponent $n = \frac{1}{t}\sum_{m=1}^{t} n_m$, where t is the number of measurements, n_m is the slope for the mth fitting. The path loss exponent $n = 0.039$.

B. Determination of the Small Scale Fading

The small scale fading of wireless channels directly affects the performance of communication systems. Generally, the statistical model of the small scale fading should be determined, which can show the variance of the signal level on the basis of the large scale fading. There are several distribution models for small scale fading, including Rice, Rayleigh, Nakagami, Weibull and Log-normal, which could be taken as the candidate model for the LTE-M with LCX in the letter. Therefore, we apply Akaike Information Criteria (AIC) to select the best fitting model compared with the measurement results. AIC criteria is defined in [11] as follows.

$$AIC_{i,j} = -2\sum_{n=1}^{S_i} \log_e(l(\widehat{\theta}_{i,j}|x_{i,n})) + 2k_j \tag{3}$$

where i the number of small scale fading areas (SSAs), j is the number of the candidate distribution models, S_i is the number of channel samples for the ith SSA, $\widehat{\theta}_{i,j}$ is the estimated parameters of the jth candidate model at the ith SSA, $x_{i,n}$ is the nth sample at the ith SSA, and k_j is the number of the parameters of the jth model.

However, according to the relationship between the number of channel samples S_i and the number of distribution models k_j, the AIC should be converted into AIC with correction (AICc) shown as formula (4) when $\frac{S_i}{k_j} \le 40$.

$$AICc_{i,j} = AIC_{i,j} + \frac{2k_j(k_j+1)}{S_i - k_j - 1} \tag{4}$$

Before the AIC criteria is used, the measurement data should be processed and the small scale fading data should be abstracted, which means we need to remove the effects of the large scale fading and determine the length of small scale area (SSA). Based on the results in [12], the small-scale fading can be separated from the received power by averaging samples at intervals of 20—40 wavelengths, where the shadowing fading is also removed. The SSA is defined as 20λ, which can keep the model estimation with enough data [13]. When we get the statistical feature of small scale fading, the channel samples should be spatial independent (uncorrelated). As the empirical decorrelation distance is $\lambda/2$, we could select one sample from the measurement results in each $\lambda/2$ [9]. Therefore, the SSA is 20λ, the decorrelation distance is $\lambda/2$, and the maximum total number of uncorrelated channel samples is $\frac{20\lambda}{\lambda/2} = 40$. Based on the AICc application conditions, when the number of distribution models is larger than 1, AICc criteria should be applied, otherwise, we should use AIC criteria.

For each SSA, the value of AICc or AIC is computed for each candidate model, and the best fit model is selected with the lowest value. The AIC (AICc) value of Rice distribution and Rayleigh distribution is basically consistent. The same conclusion could be made for Nakagami model and Weibull model. However, as shown in Fig. 4, for each SSA, the AIC (AICc) value of Lognormal is the smallest compared with other candidate models. Therefore, the best fit model of small scale fading could be determined as the Lognormal distribution. The expression of Lognormal distribution is

$$p(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{(-\frac{\ln x - \mu}{2\sigma^2})}, x > 0, \tag{5}$$

where μ and σ are the mean and standard deviation of the variable's natural logarithm, respectively.

According to (3) and (4), for each SSA, when the value of AIC (AICc) is calculated, the MLE should applied. As a result, the parameters of distribution models could be obtained.

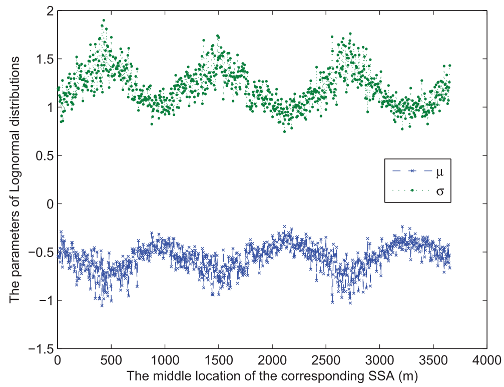

Fig. 5. The parameters of Lognormal distributions versus the location of SSA

TABLE III
THE FITTING RESULTS OF LOGNORMAL DISTRIBUTION PARAMETERS

Test Time	μ		σ	
	c_1x+c_0		c_1x+c_0	
	c_1	c_0	c_1	c_0
1	0.0007	-0.7492	-0.0011	1.4986
2	0.0008	-0.8095	-0.0012	1.5579
3	0.0005	-0.7082	-0.0007	1.4290
4	0.0006	-0.7536	-0.0009	1.4641
5	0.0007	-0.7777	-0.0010	1.4974
6	0.0008	-0.7469	-0.0011	1.4626

x : The location of the SSA (m)

Due to the SSA mapping with a location, the relationship of the Lognormal distribution parameter and the location can be built. As shown in Fig. 5, the parameters σ and μ change with the location of the corresponding SSA. Compared with the measurement results in Fig. 3, we find the variance of the Lognormal distribution parameters shows the same features as the signal strength. Therefore, the polynomial fitting of degree 1 could be used, and the coefficients are demonstrated in Table III. The mean of the variable's (x) natural logarithm μ increases when the receiver is closer to the RRU while σ decreases. According to the processed data, we can get the small scale fading data that includes the minimum and the maximum values. Therefore, the method to compute μ and σ is proposed as follows:

$$\begin{aligned}\mu(d) &= N_\mu d + \mu_0\\ \sigma(d) &= N_\sigma d + \sigma_0\end{aligned} \tag{6}$$

where N_μ and σ could be obtained through averaging the slopes in Table III, μ_0 and σ_0 are the average intercepts of fitting results.

According to the processed data, we can get the small scale fading data that includes the minimum and the maximum values. Based on the Lognormal distribution and the corresponding parameters proposed in (6), the small scale fading could be obtained at the specified location. With the path loss model, we can determine the channel variance, which is helpful to the performance evaluation of wireless communication systems.

IV. CONCLUSIONS AND FUTURE WORK

In the letter, we modeled the channel of LTE-M for CBTC systems based on real field CBTC channel measurement results. We found that the large scale fading for the channel with LCX is linear. With the AICc method, the distribution model of small scale fading was showed to be Lognormal. The parameters of Lognormal distribution are also determined. Future work is in progress to study the effects of wireless channels on the control performance of CBTC systems based on the proposed channel model.

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