An Experimental Study of 2.4GHz Frequency Band Leaky Coaxial Cable in CBTC Train Ground Communication

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***Abstract*—Leaky Coaxial Cables (LCXs) are widely used in tunnels and underpasses for smoother electric field coverage in wireless communication systems. But there are very few studies on LCXs working in 2.4GHz, which are the frequency bands used in 802.11b/g. The paper shows characteristics of 2.4GHz LCX through simulations and field tests. The results show that the communication through 2.4GHz frequency band LCX can provide stronger radio signals and thus better throughput compared with free space in tunnels. What's more, the handover interruption time between APs can be reduced because the Ping-Pong handover is avoided through LCX.**

I. INTRODUCTION

Communication-Based Train Control (CBTC) is an automatic control system for railways that ensures the safe operation of rail vehicles through data communication between various control entities of the system [1]. The train ground communication scheme is one of the key technologies in CBTC systems. For urban mass transit systems, wireless local area networks (WLANs) which work at the frequency range from 2.4GHz to 2.4835GHz are widely used due to available commercial-off-the-shelf equipment, open standards and interoperability. However, most of the current IEEE 802.11 WLANs standards are not originally designed for high speed and tunnel environments. The performance of WLAN links in tunnels must be carefully studied.

Substantial work has been done for the radio communication in tunnel environments. Authors of [2]measure the radio channel frequency response; the large scale and small scale fading in tunnel are investigated through field experiments. Statistical characteristics of the propagation channels are suggested in [3]. Both [2] and [3] indicate that WLAN cannot achieve good performance when used in tunnel environments.

As a result, leaky waveguide and leaky coaxial cable are used in wireless communication due to their stability and robustness from the interference. The availability of train ground communication in subway systems by waveguide is analyzed in [4] and [5]. Meanwhile, leaky coaxial cable is also studied. H. Cao [7] introduces the way to calculate frequency range of LCX and shows experimental results about LCX performance at 1.8GHz. Authors of [11] introduce the propagation at 2GHz in an enclosed area using a leaky coaxial cable. Authors of [12] study the theory of leaky coaxial cable with periodic slots, and frequency band of the studied LCXs is from 450MHz to 900MHz. However, few people specialize in the performance of leaky coaxial cable at 2.4GHz band, especially the application in tunnels.

In this paper, we study the availability issue and advantages of 2.4GHz LCX used in train ground communication in CBTC systems. The contributions of this paper are as follows.

1). We introduce a kind of low attenuation 2.4GHz LCX and some methods to calculate three important parameters.

2). Based on illustration of [13], a method to measure transmission performance of LCX is introduced. And the reliability of test methodology is proved through the comparison between calculated parameters from experimental results and normal values of these parameters of LCX.

3). The availability of LCX used in tunnels is analyzed through experimental results according to the basic need of CBTC train-ground communication. Advantages of LCX are also introduced compared with free space.

The rest of this paper is organized as follows. Section II briefly introduces principles of LCX and in section III the field tests and the results of the experiments of LCX in tunnels are introduced. The conclusions and some future work are shown in section IV.

II. PRINCIPLES OF LEAKY COAXIAL CABLE

As Figure 1 shows, it is a typical leaky coaxial cable with periodic slots (the interval is d). Generally it consists of three parts: inner conductor, dielectric material and outer conductor. There are three important parameters needed to be studied.

- Frequency range is defined by an inequality [7]

$$\frac{c}{\sqrt{\varepsilon_r}-1)d} \le f \le \frac{c}{\sqrt{\varepsilon_r}+1)d} \quad (1)$$

Where, d is the interval distance between two adjacent slots; ε_r is the relative permittivity of the dielectric

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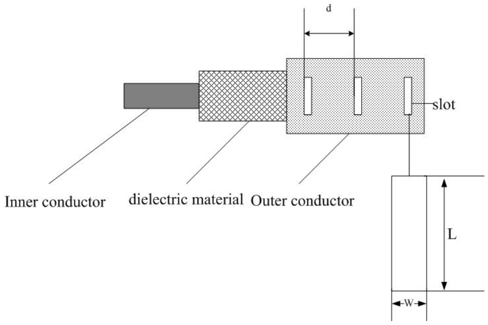

Fig. 1. The Structure of LCX

Fig. 2. typical LCX installation in tunnels

material inside the cable; c is speed of light and f means the operational frequency.

- Transmission Loss is mainly determined by conductor loss and dielectric loss as follows

$$\alpha = \alpha_1 \sqrt{f} + \alpha_2 f + \alpha_R \tag{2}$$

Where, α is the transmission loss coefficient; α_1 means the conductor loss coefficient; α_2 is dielectric loss coefficient; α_R is the radiating loss coefficient.

- From the definition of coupling loss [13], coupling loss can be defined based on experiments as follows:

$$\alpha_0 = P_r - P_t - \alpha z \tag{3}$$

Where, P_r is the received power at the antenna; P_t is the input power of LCX; z is the distance from the cable input end to the projective point of antenna located in the LCX.

However, many people have done much work to study coupling loss in theory such as [12] and [14]. A theoretical expression is shown as follows:

$$\alpha_0 = 53.2 - 10\lg(\frac{\lambda^2}{r}) - \alpha_R(dB/km) \tag{4}$$

Where, λ is the operational wavelength; r is the distance between the location of antenna and LCX; α_R is the radiating loss coefficient just the same as formula (2).

III. THE FIELD TESTS AND RESULTS

A. Description of the environment

The experiment is operated in a 2000-m-long, 5045-mm-wide and 4442-mm-high empty arch tunnel in one of the Beijing subway lines. LCXs are located 3.75m above the ground and 0.15m off the wall, which are made for 2.4GHz, and four pieces of 100-m-long LCX are connected by three pieces of feeder line. The LCX typical installation is shown in Figure 2. The parameters and traverse section of tunnel are shown in Table I.

1) Testing Methodology: The experiment measurements are consisted of three parts: signal strength test, data rate test and handover test.

- The methodology of signal strength test is the same as mentioned in [13]. As shown in Figure 3, a panel antenna is put on a trolley moving parallel along the cable. The height of the antenna center is the same as the cable and its horizontal distance from the cable which is denoted as s (1.4m) is fixed.

AP(Access Point) at 2.4GHz is injected into the beginning end of LCX, when WGB (Work-group Bridge) connected with the panel antenna is located on the trolley as the receiving terminal. Using corresponding software running in the computer, real-time experimental datas can be collected every 200ms. The location of trolley varies from 0m to 400m, with a 10m step shown in Figure 3. At every testing point, it takes 3 minutes to collect datas in order to avoid signal strength sharp jumps. The real signal strength measurement scenarios are shown as Figure 4.

TABLE I
PARAMETERS OF LCX

Width of slot (W in figure 1)	3.5mm
Length of slot (L in figure 1)	77mm
Radius of outer conductor	43.5mm
Radius of inner conductor	17.5mm
relative permittivity ε_r	1.32
Out conductor resistance k_D	2.5/km
Inner conductor resistance k_d	1.5/km
α (transmission loss coefficient for 2.4GHz)	58 (dB/km)
α_R (Coupling loss for 2.4GHz 95%)	69(dB)$\pm$5
Period (d in figure 1)	100mm

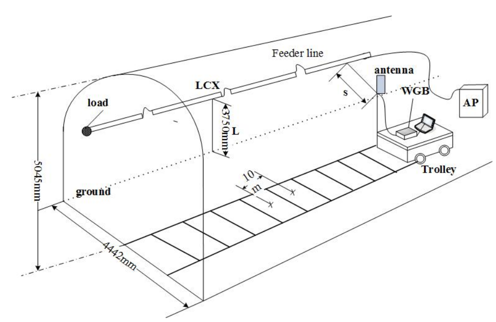

Fig. 3. measurement scenarios of signal strength

By contrast, the measurements about the propagation of electromagnetic wave in free space are also performed at the same section of tunnel. Yagi antennas are used for emitting and receiving 2.4GHz signals, which means one is located on the trolly and the other is used as the transmitting antenna of the same AP. Natural propagation results are collected in the same places.

- Data rate is an important performance index of communication system. And the test is operated in the running train with the speed of $60km/h$. The whole LCX section is 1000m long, which is composed of five 200m-long LCXs. And each LCX is injected by an AP with the power set as 27dBm. The panel antenna is installed on the top of the train to receive signal with the same height as LCXs; for free space, in the same section of the tunnel the same trackside APs are deployed every 200m with Yagi antennas, when a Yagi antenna is installed on the train. Using corresponding software, the real-time data rate can be computed.

Fig. 4. Real signal strength measurement scenarios

- Handover is also important for wireless communication. In the same scenario as the data rate test, another software compiled by VC 6.0 is used to record the handover results, such as AP names of each handover, handover time delay and packets loss caused by handover.

The schematic diagram of data rate test and handover test is shown in Figure 5.

2) Configuration information: At the transmitter, the power of AP is set to 27dBm (0.5W). And considering the loss of connecting line, filter, duplexer and 1×4 power divider, the transmitting power is decreased to 13.7dBm. At the receiving end, the gain of panel antenna, splicing loss and feeder line loss are shown in Table II.

B. Results Analysis

1) Basic Parameters: The transmission loss can be obtained as follows:

$$\hat{\alpha} = \frac{\sum_1^N (P_{i+1} - Pi)}{10N} (dB/m) \quad (5)$$

where, P_i means the average receiving power in the i^{th} testing point; N is the number of testing points.

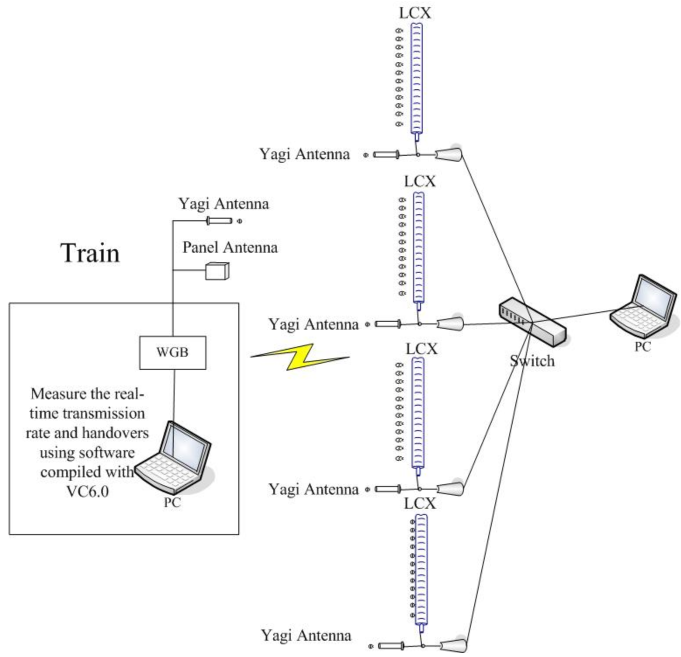

Fig. 5. measurement scenarios of handover and data rate

TABLE II
THE CONFIGURATION INFORMATION

Gain of the panel antenna: G_R	11.5dB
Loss in receiving end splicing loss and feeder line loss: L_R	Feeder line: 0.8dB Splicing loss: 3dB
Transmitting power: P_T	13.7dB

As a result, the experimental transmission loss $\hat{\alpha}$ can be obtained as $0.05237dB/m$ i.e. $\hat{\alpha} = 52.37dB/km$, which is approximate to the normal value of transmission loss listed in Table 1. To get the experimental value of coupling loss, the received power P_R should subtract the gain of antenna and the loss of line.

$$P_r = P_R - L_R - G_R \quad (6)$$

where, P_R is the received power; L_R, G_R are shown in Table 2. Substitute these parameters into formula(3), so the experimental coupling loss $\hat{\alpha_0}$ is $66.64dB$. According to formula(4), the theoretical coupling loss can be obtained as $66.36dB$.

Both theoretical and experimental results are in accordance with the normal values of parameters listed in Table I.

2) Electric field distributions: The electric field distributions are given by simulation and verified by signal strength tests as follows.

a) Simulated Results: As the special structure of LCX, every slot is considered as a magnetic dipole. [7] proposes a method to calculate the total signal strength without considering the transmission loss in a separate way, which is helpful to calculate the electric field distributions. As transmission loss

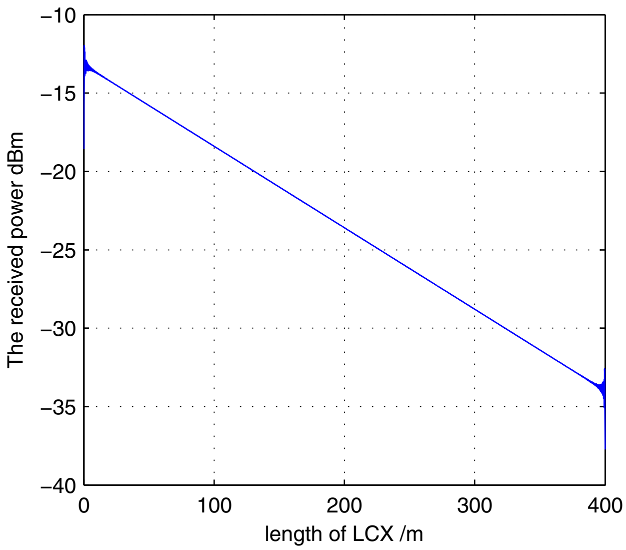

Fig. 6. simulated results of LCX

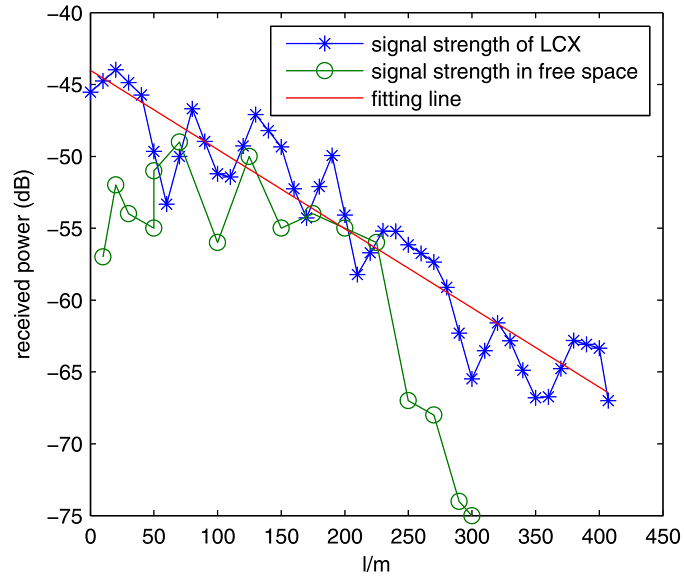

Fig. 7. the fitting line, the experimental results in free space and the processed experimental data of LCX

is important for us, we update the calculation formula [10] as follows.

$$|E| = |\sum_{i=1}^{N} E_0 e^{-j\beta(i-1)d} \sin\theta_i \frac{e^{-j\beta_0 r_i}}{r_i}| \quad (7)$$

$$E = 20\lg(|E(V/m)|^2 \times 10^6)(dB\mu V) \quad (8)$$

$$P = 20\lg(\frac{1.76^{-4}}{f(MHz)} \times 10^{E(dB\mu V)/20}) \quad (9)$$

Where, N is the number of slots, β is the propagation constant in free space; θ_i is the angle between the direction of the i_{th} slot to the test point and the long direction of LCX; β_0 is the propagation constant in LCX; r_i is the distance between the i_{th} slot and the test point. E_0 is the electric field amplitude of the beginning slot of LCX, normalized as 1V/m. (7) and (8) are for unit conversion from V/m to dBm.

Simulation results in Figure 6 show that distributions of electric field are impacted a lot by the transmission loss which makes distributions approximate to be linear, and the slope of the simulated curve is the same as transmission loss.

b) Experiments Results: Figure 7 shows the signal strength test results of LCX and free space . There are three curves, including a fitting line, signal strength of LCX and free space. And the x axis is the distance from the trolley to the AP location, whose unit is m; the y axis is the signal strength whose unit is dBm. The experimental datas of LCX fluctuate around the straight line which is a fitting one and it shows that the electric field along LCX is an approximately linear attenuation which is the same as the simulated results in Figure 6. As the slope of the fitting line shown in Figure 7 is -0.0551. And the value is close to transmission loss which is -0.05237. So electric field distribution of LCX is determined by the transmission loss. The experimental datas of free space seriously fluctuate with high attenuation.

It is obvious that power radiated from LCX is stronger than that propagating in free space except few testing points. From Figure 7, when the distance is longer than 250m, the power received from LCX is much stronger than that in free space. As general urban systems deploy one AP every 200-300m, once LCX is applied as the main propagation medium, intervals of APs can be longer, e.g. 400m. Therefore, fewer trackside devices are needed, which can improve the reliability of the system and save a lot of costs.

Figure 8 shows the real-time transmitting rate of LCX and free space. The x axis is time and the y axis is the data rate whose unit is $Mbps$. For LCX, the range of data rate is (12.5628 36.7720), while it is (1.6124 27.2748) for free space. Considering the basic need of CBTC is hard to determine, we can get an approximate value. As the size of packet transmitted is 100-300Byte and the period of transmitting is 200ms, the maximum basic traffic need is 12kbps. We can make sure the application of LCX can meet needs of CBTC traffic.

Table III presents the statistical results of signal strength and transmitting rate. From the comparison of means and variances of two propagation mediums, we can conclude that LCX can supply more stable signals besides stronger signal strength, which is important for subway systems. In the terms of throughput, advantages of LCX are more obvious, especially the stability.

In the train ground communication system the interruption time of handover is the key factor which impacts the performance of wireless communication systems. Figure 9 shows handover tests of LCX and free space, where x axis is time and y axis is the AP name marked as number for convenience. It indicates that in free space Ping-Pong handovers are common, while there is no Ping-Pong handover if LCX is applied. Since

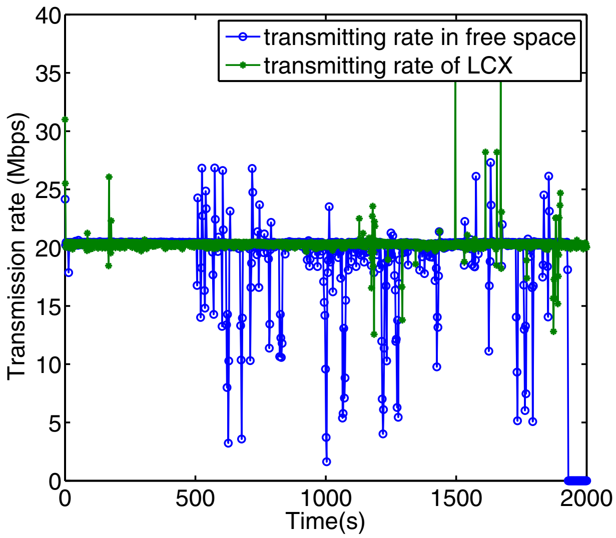

Fig. 8. The Transmitting Rate of LCX and In Free Space

TABLE III
THE STATISTICAL RESULTS

test item	statistics	LCX	Free Space
Signal Strength	mean(dBm)	-55.2994	-58
	variance	51.1474	68.2667
	maximum(dBm)	-43.9736	-49
	minimum (dBm)	-67.0066	-75
Data Rate	mean($Mbps$)	20.3274	18.8985
	variance	1.0218	21.4594
	maximum($Mbps$)	36.7720	27.2748
	minimum ($Mbps$)	12.5628	1.6124

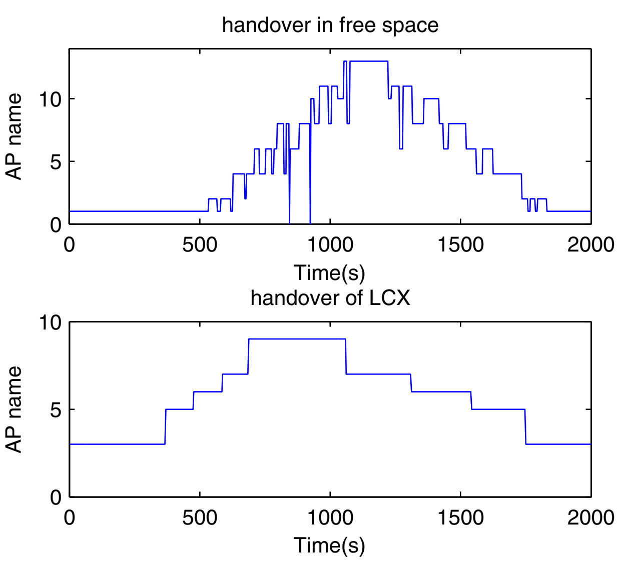

Fig. 9. handover test of LCX and free space

fewer Ping-Pong handovers mean shorter delay and less packet loss, LCX is an ideal propagation medium of WLAN used in CBTC in tunnels.

IV. Conclusion and Future Work

In this paper, availability of 2.4GHz frequency band LCX in tunnels is studied and proved through the simulations and field tests. And we get the key characteristic of electric field distributions of LCX that the electric field along LCX is an approximately linear attenuation and the approximate slope is equal to the transmission loss of LCX. The results show that by using LCX more stable and stronger radio signals can be acquired by the receiver and the throughput of the system can be improved. The interruption time due to handover between APs is also reduced compared with free space transmission.

For future work, we plan to study radiation principles of LCX to design more suitable products for CBTC systems.

References

[1] IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements *IEEE Standard 1474.2-2003*

[2] Molina-Garcia-Pardo. J.-M., Lienard. M.,Nasr, A., Degauque, P., "Wideband Analysis of Large Scale and Small Scale Fading in Tunnels", *8th International Conference*, pp. 270–273, Oct. 2008

[3] Martine Lienard, Pierre Degauque, "Propagation in Wide Tunnels at 2GHz: A Statistical Analysis", *IEEE Transaction on Vehicular Technology*, Vol. 47. No. 4. Nov 1998

[4] Marc Heddebaout,"Leaky Waveguide for Train-to-wayside Communication-based Train Control", *IEEE Trans.Veh.Technol*, vol. 58, No. 3, pp. 1068-1076, Mar. 2009.

[5] Li Zhu, Hongwei Wang, Bin Ning , "An Experimental Study of Rectangular Leaky Waveguide in CBTC", *Intelligent Vehicles Symposium*, 2009

[6] Masayuki Nakamura, Hideaki Takagi, Kiyoshi Einaga, Toshiyuki Nishikawa, Naoshi Moriyama, Katsumi Wasaki, "Development of a 300 m 2.4 GHz Frequency Band Leaky Coaxial Cable for Wireless Network Access", *Radio and Wireless Symposium*, 2008 IEEE

[7] Cao, H., Zhang, Y.P., "Radio Propagation along a Radiated Mode Leaky Coaxial Cable in Tunnels", *Asia Pacific Microwave Conference*,vol. 2, pp. 270–272, Dec 1999

[8] YAO Shan-hua, ZHU Zong-jiu, "Performance analysis of leakage cable and its application", *Coal Mine Machinery*, vol. 7, 2003

[9] John D. Kraus, Ronald J. Marhefka, "Antennas: For All Applications Third Edition", *Publishing House of Electronics Industry*

[10] Shu Lin, Shi Hua, Wang Junhong, "Calculation of the electrical field distributions of a leaky coaxial cable in a railway tunnel", *Journal of the China Railway Society*, VOL. 24, NO. 2, April 2002

[11] Zhang Wen-wei, Zhang Yue-ping, Zheng Guo-xin, Sheng Jian-huan, "Propagation at 2GHz in a enclosed area suing a coaxial cable with leaky sections as the transmitting antenna", *Journal of China Institute of Communicaiton*,Vol. 22,No. 7,July 2001

[12] Junhong Wang, Kenneth K. Mei, "Theory and Analysis of Leaky Coaxial Cables with Periodic Slots", *IEEE Transactions on Antennas and Propagation*,Vol. 49, NO. 12. Dec 2001

[13] "Coaxial communication cables - Part 4: Sectional specification for radiating cables"*IEC 61196-4*

[14] KOICHI MIKOSHIBA, YOSHIHIRO NURITA, "Guided radiation by coaxial cable for train wireless systems in tunnels", *IEEE Transactions On Vehicular Technology*, Vol. 18, No. 2,Aug 1969

[15] Zhao Zixin, "Research on Electrical Characteristic of Leaky Coaxial Cable (LCX) Used for Radio Communication in Confined Areas", *Harbin Engineering University*

[16] Zhang Jie, Jiang Yao-peng,Gu Yu-cui, "Research Of Type SLYFY(N)-50-42 Leaky Coaxial Cable", *Optical Fiber and Electric Cable*,No. 1,2005