Research on Transmission Performance of Double Leakage Cable Based on LTE-M System under Tunnel Simulation Environment

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Abstract. With the improvement and maturity of LTE technology, the vehicle-ground wireless communication system based on it has become a new technical direction of rail-vehicle-ground communication in recent years. Based on an LTE-M vehicle-to-ground wireless communication system covered by double leaky coaxial cables, load simulation service tests were carried out to test the transmission performance of leakage coaxial cables. This study found out that when two leakage cables are HV: one is horizontally polarized and another vertically polarized, the average transmission rate of the vehicle-ground communication system of the same polarization mode increased by about 50%. At the same time, there was no significant decrease with the system transmission rate when the space between them reduced from 1 m to 0.3 m. Thus, an optimized leakage cable deployment scheme was obtained. When the horizontally polarized and vertically polarized leakage cable was used and the space between the two leakage cables was 0.3 m, the optimum transmission rate has been achieved.

Keywords. Vehicle-ground communication; double leaky cable coverage; transmission rate; tunnel environment.

1. Introduction
With the development and maturity of LTE technology, rail transit has already had related applications based on LTE technology in both China and overseas. In December 2010, LTE-R was first proposed as a high-speed railway mobile communication solution at the 7th World High-Speed Railway Conference organized by the International Union of Railways (UIC). In 2011, Europe, Japan, North America, etc. successively carried out research on technologies related to passenger broadband wireless access, such as channel modeling, QoS analysis and assurance technology, interference analysis and suppression. At the same time, China has also established a major special topic of “Key Technology and Application Verification of High-Speed Railway Broadband Communication Based on TD-LTE” [1]. In November 2012, the first Hangzhou Metro Line 1 entirely covered by TD-LTE network, was officially opened, and it became the first metro line in the world to cover the 4G network. In August 2013, Huawei announced that it would provide the Polish Zmigrod Railway Bureau with an LTE-based vehicle-ground wireless communication system for train control bearers, vehicle-ground communication, video communication, and railway value-added services. This project became the first rail transit line in Europe based on LTE wireless communication technology. In March 2015, the Ministry of Industry and Information Technology officially confirmed the 1.785-1.805 GHz frequency range as a dedicated communication network frequency range for transportation, power, petroleum and other industries. In December 2016, the phase I of Wuhan Metro Line 6 was opened and put into operation. It uses LTE-M technology to build a vehicle-ground wireless communication system to carry CBTC services, becoming the first
urban rail transit line in China that uses LTE technology to carry train control information [2].

Leakage cables have been widely used as a transmission medium for vehicle-ground wireless communication systems in urban rail transit vehicle-ground. The concept of a leakage cable was first proposed by Monk in 1956. So far, many scholars have studied the radiation characteristics of leakage cables. Ref. [3] studied the radiation field characteristics of the leaky cable using the magnetic dipole equivalent method. Ref. [4] used the finite-difference time-domain (FDTD) method to study the slot radiation characteristics of leakage cables. Ref. [5] used the transmission line theory to study the transmission loss of the leakage cable in the tunnel and the influence of other factors on its performance. Ref. [6] used mode matching and Fourier transform to theoretically study the near-field and far-field coupling characteristics of the leakage cable.

As an emerging communication technology, LTE is far different from WLAN technology that has been widely used in coverage and network structure. The relevant units have also conducted research on the application of LTE in the field of urban rail transit. Beijing Metro Construction Administration Co., Ltd. and the National Key Laboratory of Traffic Operation Control and Safety of Beijing Jiaotong University used the LTE-M standard to build and test a vehicle-ground wireless communication system applied to urban rail transit integrated bearing [7]. The test verified that the leakage cables as transmission media to build a vehicle-ground wireless communication system based on the LTE-M standard can meet the basic needs of urban rail transit services in terms of overall bearing and transmission rate. Ref. [8] verified the anti-interference of the vehicle-ground wireless communication system by adjusting the time slot ratio, leakage cable directional coverage, and optimizing the location of the vehicle antenna. Beijing Subway Co., Ltd. conducted an on-site test of the LTE-M vehicle-ground wireless communication system using directional antennas as the transmission medium on the Beijing Metro Line 5. The test results showed that there was a risk of interference in the networking method using wireless free waves as the transmission medium. In the case of strong interference, the transmission rate of the car-ground wireless communication system would be affected, and the minimum standard of comprehensive carrying of CBTC, PIS and CCTV services would be barely achieved. Ref. [9] shows that in the actual operation line, the wireless communication system based on LTE-M can realize the comprehensive bearing under the operating state.

In the above research, the radiation and coupling characteristics of the leakage cable have been studied. At the same time, the vehicle-ground wireless communication system using the leakage cable has also been applied. However, there are few studies on the effects of three different forms of single leakage cables, double leakage cables with the same polarization direction and double leakage cables with different polarization directions on the LTE transmission rate and the effect of different leakage cable spacing on the transmission rate. When using a leakage cable as the transmission medium for a vehicle-ground wireless communication system based on LTE-M, the system can basically meet the comprehensive carrying requirements for CBTC, SD PIS, and SD CCTV, but it also exposes the shortcomings of low data transmission rate, poor MIMO effect, etc. under limited spectrum bandwidth.

2. Experimental Design in Simulated Environment

The purpose of this experiment is to build an LTE-M vehicle-ground wireless communication system covering double leakage cable in a tunnel simulation environment, and to test it with different polarization modes and cable spacing. The simulated tunnel is a reinforced concrete structure with a length of 100 m and a width of 5 m. Corresponding fixtures are installed on the tunnel wall according to the different leakage cable spacing for placing leakage coaxial cables. The vehicle-ground wireless communication system consists of two LTE-M systems consisting of two BBUs, two RRUs, one EPC, and one switch. By increasing the attenuation between the RRU and the leakage coaxial cable, the terminal environment is simulated with cell coverage. The system is connected to a laptop computer to run software for testing. The dual-polarized directional antenna is used on the mobile station side to connect to the mobile station and notebook computer [10].

Simulated tests collect field strength and transmission rate data. The field strength data is read by the software that comes with the mobile station to reflect it most veritably by the LTE device, while the
location information is recorded. The transmission rate data is obtained by streaming through Ixchariot software. The software clients on the network side and the mobile station are installed respectively, and the transmission rate data is obtained by using the transmission rate script.

A wireless channel propagation model for double leakage coaxial cables is established using statistical methods and minimum information criteria for the collected data in a tunnel environment. In this simulation experiment, a tunnel with a length of 100 m and a width of 5 m was built to simulate the real tunnel environment. The tunnel is a reinforced concrete structure. Corresponding fixtures are installed on the tunnel wall according to different leakage cable spacing for placing leakage coaxial cables. The leakage cables are installed on the same side wall of the tunnel as the actual line at the spacing required by the test. Because the length of simulated tunnel environment is only about 100 m, and the switching between the two cells needs to be tested, the leakage coaxial cable coverage of each cell is only 50 m. In order to simulate the actual operating environment as realistic as possible, the signal strength of the two cells needs to be adjusted to the signal strength level of the last 50 m covered by the real cell. Under normal circumstances, RSRP is less than -85 dBm, it can be considered as a far point, so the RSRP measured at the beginning of the leakage coaxial cable is controlled at -85 dBm during the test. Within the coverage of the leakage coaxial cable of 50 m length in a single cell, the signal intensity varies between -85 dBm~ -88 dBm. The vehicle-ground wireless communication system is composed of two BBUs, two RRU's, and one EPC, and one switch consists of an LTE-M system consisting of two cells. The test system structure is shown in figure 1.

![Figure 1. The test system structure diagram.](image)

Due to environmental constraints, the simulated tunnel test can only run at a low speed. The simulated tunnel test is mainly used to compare the performance and transmission rate of double leakage cables with different polarization modes and leakage cable spacing, which provides a basis for the best leakage cable coverage plan. The system performance under high-speed movement will be further tested and verified in the operation line test.

3. Experiment Result and Analysis

In this test, three types of double leakage cable coverage were set: two leakage cables both are horizontally polarized (HH), two leakage cables both are vertical polarized (VV), and one leakage cable is horizontally polarized and one is vertical polarized (HV). In three cases, the signal field strength, signal-to-noise ratio and transmission rate were tested at the cable spacing of 0.3 m, 0.6 m and 1 m. In the test, the LTE system used a frequency range of 1790 MHz-1800 MHz with a total bandwidth of 10 MHz. The system used a subframe ratio of 1, that is, an uplink and downlink ratio of 2: 2, and a special subframe ratio of 10: 2: 2. The simulated tunnel test was completed and preliminary statistics was...
conducted on the test data. The preliminary statistical results are shown in tables 1-3.

It can be seen from tables 2 and 3 that there is no significant change in the field strength and signal-to-noise ratio of the received signal of UE as the receiving end is reduced from 1 m to 0.3 m under three different polarization modes. It is proved that when the transmission signal frequency in the 1.8 GHz frequency range is reduced from 1 m to 0.3 m, the coupling loss between the double leakage cables does not increase evidently, and the reduction in cable spacing does not significantly affect the signal field strength and signal-to-noise ratio.

It can be seen from table 3 that when the two leakage cables are HV, that is, one is horizontally polarized and one is vertically polarized, the average transmission rate of the vehicle-ground communication system with the same polarization mode is increased by about 50%. Compared with the double leakage cable deployment method that uses the same polarization method, the method that a double leakage cable is formed of horizontally polarized and a vertically polarized deployment has lower channel correlation for the two signals at the same spacing. In addition, when the transmission rates under different leakage cable spacing is compared longitudinally, it can be seen that the system transmission rate does not decrease significantly when the leakage cable spacing is reduced from 1 m to 0.3 m, indicating that there is no evident impact on the channel correlation when the cable spacing is reduced to 0.3 m.

Table 1. Field strength test result.

| Cable spacing (m) | Field strength (dBm) |   |   |   |   |
|------------------|----------------------|---|---|---|---|
|                  | HH                   | HV| VV|
| Maximm            | Averag               | Minimm| Maximm            | Averag               | Minimm| Maximm            | Averag               | Minimm|
| 1               | -79                  | -89.8| -98| -77                  | -87.1| -95| -75                  | -86.4| -95|
| 0.6             | -78                  | -86.9| -93| -78                  | -85.9| -92| -78                  | -85.8| -92|
| 0.3             | -80                  | -86.5| -92| -79                  | -85.1| -92| -78                  | -84.4| -93|

Table 2. Signal-to-noise ratio test result.

| Cable spacing (m) | Signal-to-noise ratio (dB) |   |   |   |   |
|------------------|----------------------------|---|---|---|---|
|                  | HH                        | HV| VV|
| Maximm            | Averag               | Minimm| Maximm            | Averag               | Minimm| Maximm            | Averag               | Minimm|
| 1               | 32                      | 26.6| 17| 34                  | 19| 27| 28                  | 26.9| 19|
| 0.6             | 33                      | 27.44| 17| 32                  | 26.9| 17| 27                  | 26.9| 22|
| 0.3             | 33                      | 27| 16| 28                  | 26.8| 16| 34                  | 27.1| 19|

Table 3. Transmission rate test result.

| Cable spacing (m) | Upload/Download | HH | HV | VV |
|------------------|-----------------|---|---|---|
|                  | Maximm            | Averag               | Minimm| Maximm            | Averag               | Minimm| Maximm            | Averag               | Minimm|
| 1               | Upload 14.02     | 12.34| 6.78| 13.72| 11.86| 8.43| 14.18| 12.35| 8.17|
|                  | Download 44.56   | 20.58| 6.94| 49.78| 38.88| 9.74| 46.65| 30.2| 10.94|
| 0.6             | Upload 14.07     | 12.33| 6.32| 14.1| 12.1| 7.38| 14.61| 12.28| 5.78|
|                  | Download 44.07   | 23.04| 5.75| 44.62| 38.79| 10.34| 44.58| 36.35| 6.93|
| 0.3             | Upload 14.13     | 12.06| 9.58| 14.13| 12.34| 8.48| 14.22| 12.51| 7.85|
|                  | Download 41.92   | 22.3| 6.14| 45.64| 39.41| 9.57| 43.47| 27.07| 10.81|
In summary, when using a double leakage cable formed of a horizontally polarized leakage cable and a vertically polarized leakage cable and the spacing between the two leakage cables is 0.3 m, the optimal transmission rate can be achieved at the minimum cable spacing. Also, the transmission rate does not drop evidently when the cable spacing is 1 m. This scheme can be used as a deployment plan for leakage cables during subsequent operation line tests.

4. Conclusion
Based on quantitative simulation tests, it can be seen that LTE-M’s comprehensive networking solution using free waves and leakage waveguides can basically support the needs of urban rail transit integrated services. However, in order to improve the switching delay index in the leaky waveguide section, it is necessary to optimize the switching mechanism for the fading performance of the leaky waveguide. Through the research on the transmission characteristics and coupling characteristics of leakage coaxial cables, the testing and analysis of different double leakage cable coverage methods, this paper proposes a double leakage cable coverage scheme suitable for rail transit tunnel environments, so that the vehicle-ground wireless communication system based on LTE achieves a transmission rate increase of 20% to 30% compared to the single leakage coaxial cable coverage scheme, and the transmission rate drop rate is not greater than 10% compared to the existing double leakage coaxial cable coverage scheme. Under the conditions, the goal of reducing the cable spacing by 50%–60%, while enabling the system to meet the following indicators of the system network performance of rail transit-related services:

1) The probability that the single transmission delay of the train operation control service does not exceed 150 ms is not less than 98%; the probability that it does not exceed 2 s is not less than 99.92%; the packet loss rate is not more than 1%.

2) The probability that the transmission delay of the train emergency text delivery service does not exceed 300 ms is not less than 98%; the packet loss rate is not more than 1%.

3) The probability of video monitoring service transmission delay not exceeding 500 ms is not less than 98%; the packet loss rate is not more than 1%.

4) The probability of PIS service transmission delay not exceeding 300 ms is not less than 98%; the packet loss rate is not more than 1%.

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