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Analysis of Impact on BTM Antenna by Trackside Electromagnetic Environment in Integration of Multi-Network

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ABSTRACT: Large metropolitan areas have planned different types of rail transit integrating into transportation hubs. Owing to scenarios such as parallel or cross-line operation of a junction station, a complex electromagnetic environment may affect the normal operation of BTM equipment. Therefore, it is necessary to study the influence of the trackside electromagnetic environment on the BTM antenna. Taking the scenario in which the parallel section of a mainline railway and an urban rail transit enters the station, as well as the situation in which two trains are adjacent at the junction station, as an example, the model of the BTM antenna is established to analyze the electromagnetic interference of urban rail transit trains in operation. The induced voltage of the BTM antenna in urban rail transit trains is calculated based on electromagnetic environment data from the electromagnetic disturbance source collected on site to analyze the influence on its normal operation. The amplitude of the induced voltage at the BTM antenna port is lower than its normal operation scenario when the parallel section of a mainline railway and an urban rail transit enters the catenary hard across section. The amplitude satisfies the requirement of its starting electromagnetic environment when the urban rail train stops at the platform while the mainline train passes at speed. Under a multi-network integration background, research results show that the trackside electromagnetic environment along the mainline railway will not cause an electromagnetic interference problem for the BTM antenna of the urban rail train.

1. INTRODUCTION

As large metropolitan areas continue to expand, the demand for efficient rail-based commuting between central urban districts and surrounding towns is increasing. In this context, integrating multiple rail transit modes, such as mainline railways, intercity railways, metro lines, maglev systems, and urban rail transit, has become a key objective in the framework of “multi-network integration” [1, 2]. However, co-location and interconnection of these systems at shared stations and junction areas introduce considerable operational complexity. The railway department previously had no experience in handling such scenarios because mainline railways and suburban railways were managed by separate departments, lacking empirical data and technical support.

These diverse systems differ substantially in their traction power supplies and signalling architectures. Mainline and intercity railways typically employ a 25 kV AC power supply and the Chinese Train Control System (CTCS), whereas most metro lines adopt a 1.5 kV DC supply and Communication-Based Train Control System (CBTC). In scenarios where mainline and metro lines run in parallel, cross at junctions, or share station entry/exit tracks, the electromagnetic environment in the station’s vicinity becomes highly intricate. Both CTCS and CBTC on-board equipment rely on balise transmission module (BTM) antennas to receive trackside balise messages, and these antennas are known to be susceptible to ambient electromagnetic interference [3–7]. In particular, the AC 25 kV traction system of mainline and intercity railways generates significant pantograph arcing, return currents, and harmonic noise, which impose a more severe electromagnetic environment on the BTM equipment of adjacent metro trains [8–12].

At present, there are many simulation analysis methods for electromagnetic environments [13–16], but for the railway field, especially for electromagnetic compatibility analysis models of BTM equipment in typical scenarios, there are relatively few. No case study has reached a conclusion demonstrating that BTM equipment can operate normally and without interference in the interconnection-operation scenarios of mainline railways and urban rail transit

To address the problem, we developed a model of electromagnetic compatibility (EMC) analysis for BTM antenna based on the operating principles of BTM equipment. The paper investigates the impact of the on-site electromagnetic environment on BTM antennas. Considering the typical case of parallel co-location and connected station access between mainline railways and metro lines, we analyze the electromagnetic interference caused by the mainline rail-side environment on metro BTM antennas. The findings are intended to provide technical support for the future planning and safe operation of integrated multi-line co-location scenarios.

2. ANALYSIS AND MODELING OF ELECTROMAGNETIC INTERFERENCE FOR BTM EQUIPMENT

2.1. The Basic Working Principle of BTM Equipment

Train control systems rely on robust vehicle-to-ground communication to perform critical functions, including train position-

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ing, enforcement of line speed restrictions, and advance notification of track geometry and signalling conditions ahead. In both the Chinese Train Control System (CTCS) used on mainline railways and the Communication-Based Train Control System (CBTC) adopted for urban rail transit, the balise transmission module (BTM) is responsible for retrieving the line information stored in the trackside balises.

Figure 1 shows a schematic illustration of the main architecture of the BTM equipment. The system comprises a BTM host unit, also referred to as the transponder transmission unit, and a BTM antenna. The antenna is mounted on the underside of the train and connected to the host unit via a coaxial cable. The host unit itself is located inside the train-borne control equipment cabinet within the carriage.

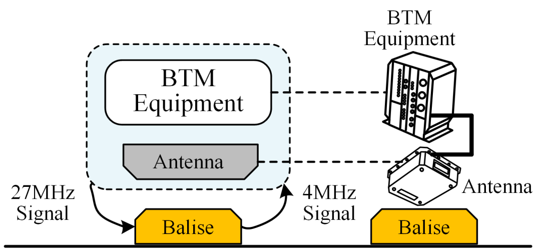

FIGURE 1. The functional block diagram of BTM equipment.

The BTM antenna employed a dual-antenna configuration comprising separate ring-shaped elements for transmission and reception. Upon receiving the uplink signal from the trackside balise, the received signal is filtered and decoded by the BTM host unit (i.e., the transponder transmission module) before being forwarded to the on-board train control equipment, where it is used for operational decision-making regarding train movement commands.

2.2. BTM Antenna Electromagnetic Interference Analysis

The BTM antenna in both mainline railway and urban rail transit systems is exposed to a complex electromagnetic environment in which power-intensive and weak-current subsystems coexist. High-order harmonics generated by high-power equipment and power conversion devices, including those within the traction power supply and train traction drive systems, constitute typical electromagnetic disturbance sources. These disturbances propagate through various coupling paths and ultimately appear as noise at BTM antenna ports. In addition, other on-board systems, such as the train control system, train information system, and communication equipment, emit electromagnetic disturbance signals, often in the form of current loops through the train body, grounding structures, and cables, contributing to the ambient electromagnetic field.

The BTM's working principle, structural design, and operational environment render it inherently susceptible to external electromagnetic interference. To ensure reliable performance, relevant technical specifications impose requirements on the uplink bit error rate and signal-to-noise ratio of message transmission [3]. Previous studies have reported electromagnetic interference incidents affecting BTM equipment on urban rail transit trains, where the antenna was identified as a critical coupling path [8, 10]. In co-location scenarios, such as parallel track sections and shared connection platforms between mainline railways and urban rail lines, the underside electromagnetic environment of urban rail trains becomes particularly severe. Owing to the influence of the 25 kV AC traction power supply system of the adjacent mainline, there is a risk that interference signals may be received at the BTM antenna port when the urban train is near such locations, potentially compromising the start-up or normal operation of the BTM equipment.

The specific simulation process is as follows: 1) Modeling: We model the BTM antenna using the finite element algorithm. 2) Antenna port processing: Set the antenna impedance to 50 Ω. 3) External interference source: Use a plane wave as the external interference source and assign the measured field strength to the amplitude of the plane wave. 4) Antenna port coupling voltage: Calculate the response voltage of the antenna port to the external electromagnetic environment.

2.3. Establish an Analytical Model

Analysis scenarios are shown in Fig. 2. Both mainline railway (high-speed rail) and urban rail lines are capable of bidirectional operations. After converging at a junction, the two lines share a common alignment and run parallel over a certain distance before entering the station. The mainline railway employs a 25 kV AC traction supply and the Chinese Train Control System (CTCS), whereas the urban rail line adopts a 1.5 kV DC supply and Communication-Based Train Control System (CBTC). In a planned cross-line operation, trains may switch tracks at the junction station and operate under the control of the other line. To evaluate the electromagnetic interference from the mainline railway on the BTM antenna port of the adjacent urban rail train, two representative scenarios were defined.

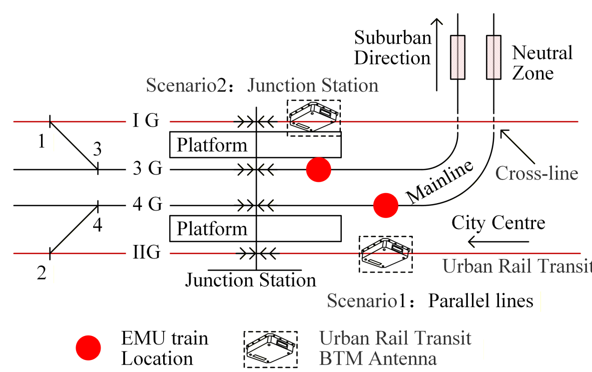

FIGURE 2. Diagram of the scenario to be analyzed.

1) Scenario 1: Parallel lines. The mainline and urban rail trains run in parallel for a short distance and enter the station through the hard crossbeam section of the overhead contact line. In this section, the varying pantograph-catenary interaction on the high-speed train tends to generate significant electromagnetic emissions. Using field-measured electromagnetic interference data from the trackside environment of the mainline railway, we analyzed the resulting disturbance at the BTM antenna port of the adjacent urban rail train.

2) Scenario 2: Junction station. In this configuration, as shown in Fig. 2, the mainline train proceeds along the outbound

TABLE 1. Measurement instrument.

Measurement equipment	Equipment model	Technical parameters
Measuring receiver	ESL	9 kHz–3 GHz
Real-time spectrum analyzer	RSA507B	9 kHz–7 GHz
Loop antenna	ZN30900B	9 kHz–30 MHz

TABLE 2. Manufacturers.

Equipment model	Manufacturer
ESL	Rohde & Schwarz (https://www.rohde-schwarz.com)
RSA507B	Tektronix (https://www.tek.com)
ZN30900B	DAZE (http://www.sstsa.cn)

track (3G), and the urban rail train is positioned on the platform's inbound side (1G), ready for departure toward the city center. The measured trackside electromagnetic interference data from the mainline railway are placed on the platform side, and the interference on the BTM antenna port of the urban rail train was assessed.

The BTM antenna model is depicted in Fig. 3, which includes an internal coil structure and antenna housing. Because the present study focuses on the receiving antenna, the transmitting section is not modelled. To account for the effect of the metallic mounting frame beneath the car body, the antenna was assumed to be directly attached to a simplified vehicle floor plate. For each of the two scenarios described above, interference signal sources were placed at appropriate locations to evaluate the induced response at the antenna port.

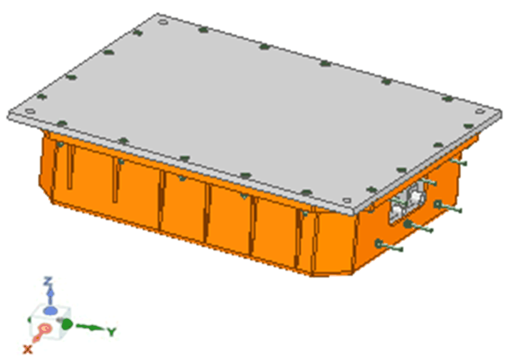

FIGURE 3. Diagram of the BTM antenna model.

3. TRACKSIDE ELECTROMAGNETIC ENVIRONMENT TESTING

3.1. Test Method

Sections in which the contact wire geometry varies are particularly susceptible to electromagnetic disturbances generated by pantograph-catenary interactions. Therefore, hard cross-beam and phase-break sections were selected as the primary locations for on-site electromagnetic environment data acquisition. Figs. 4 and 5 illustrate the test arrangement and actual measurement scene, respectively. The receiving antenna was

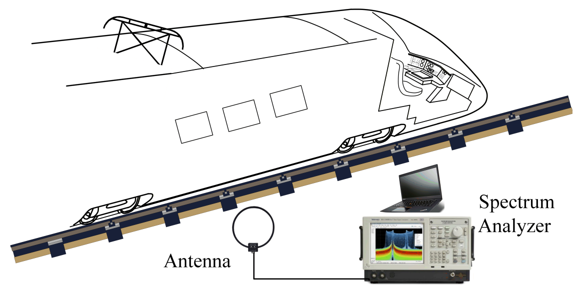

FIGURE 4. Diagram of trackside electromagnetic environment test.

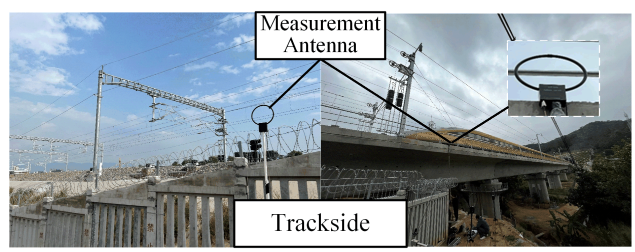

FIGURE 5. The trackside electromagnetic environment on-site test.

placed trackside, with its center aligned horizontally with the rail plane. The antenna was connected to the measurement system using a coaxial cable. To capture comprehensive spectral information while maintaining a manageable data volume, the system simultaneously employs both a measurement receiver and a real-time spectrum analyzer. Table 1 lists main specifications of the test equipment.

Table 2 shows the information of instrument manufacturers involved.

3.2. Test Results

Fig. 6 presents measured electromagnetic field strengths in the trackside space, with results shown in maximum-hold mode. The field-strength amplitude near the neutral section is generally significantly higher than that observed at other line locations. In the 3 MHz–5 MHz frequency band, the field-strength values at the trackside position ranged from 70 dBμV/m to 90 dBμV/m. The test point on the open line was located closer

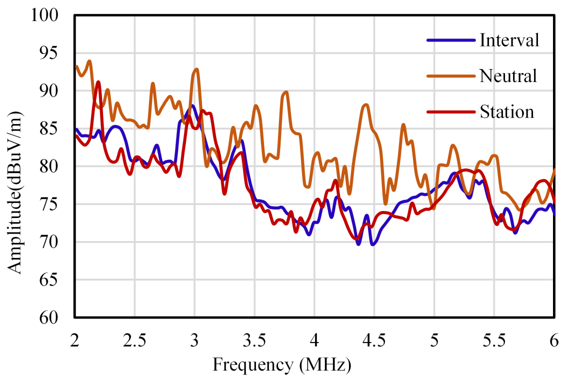

FIGURE 6. The on-site measurement curves of the trackside environment.

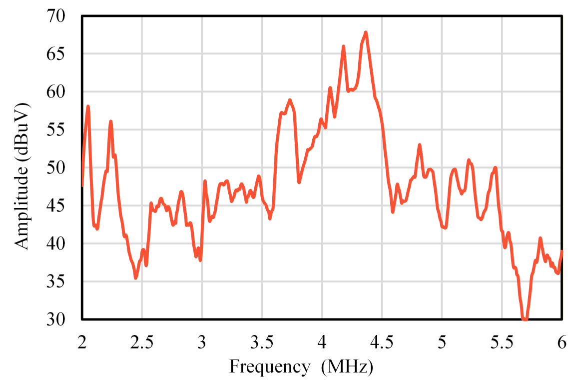

FIGURE 8. The received voltage curves of the BTM antenna in the junction station scenario.

to the rail, and the measured values were comparable to those obtained at the station yard hard-crossbeam section. To ensure consistency in all trackside measurement positions, the distance from the track center was normalized to a unified reference value.

4. RESULT ANALYSIS

Electromagnetic interference-induced malfunctions of BTM equipment are predominantly observed during train startup and en-route operations. Based on actual running test data, nominal operating frequencies for data bit “0” and data bit “1” of the BTM antenna port are 3.9 MHz and 4.5 MHz, respectively, with corresponding normal received signal strengths of approximately 56 dBμV and 58 dBμV. During passage over a trackside balise, the antenna receives a nominal signal of approximately 72 dBμV. A signal-to-noise ratio exceeding 13 dB is considered sufficient to guarantee proper BTM functionality [15], which implies that the interference level at the antenna port must remain below 59 dBμV.

4.1. Scenario 1

Figure 7 presents simulation results for the parallel-line scenario, where the mainline railway and urban rail line run side by side and enter the station. In this simulation, the electromagnetic interference source was placed 4 m above the center point of the BTM antenna, representing the passage of a mainline train on the adjacent track. Interference data were derived from station field measurements, with distance-normalized values applied. Simulation results indicate that received signal strengths at the BTM antenna port are 58.64 dBμV at 3.9 MHz and 53.91 dBμV at 4.5 MHz. Although Frequency-Shift Keying (FSK) uplink signals at both frequencies meet the required signal-to-noise ratio, the level at 3.9 MHz approaches the acceptable limit. Furthermore, within the adjacent frequency band of 3.5–4.5 MHz, the maximum value reaches 66.05 dBμV, suggesting a certain risk of electromagnetic interference.

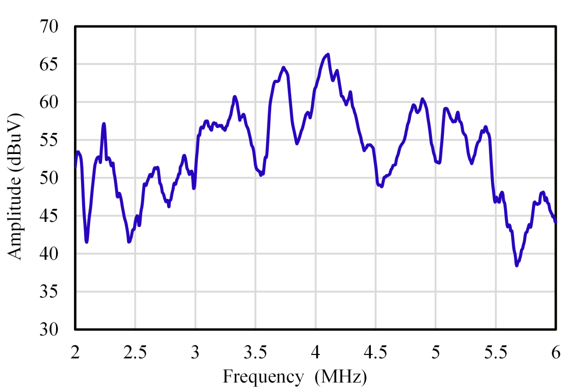

FIGURE 7. The received voltage curves of the BTM antenna in the parallel-lines scenario.

4.2. Scenario 2

Figure 8 presents simulation results for the adjacent-track scenario at the connection station where the mainline railway and urban rail line meet. In this case, the electromagnetic interference source was positioned 12 m above the center point of the BTM antenna, simulating the passage of a mainline railway EMU on the platform-side track. Interference data were obtained from field measurements on a normal interval section. Simulation results show that received signal strengths at the BTM antenna port are 52.43 dBμV at 3.9 MHz and 55.94 dBμV at 4.5 MHz, both of which satisfy signal-to-noise ratio requirements for FSK uplink signals. Although interference levels measured on the interval line were somewhat higher than those recorded at the station yard, the greater separation distance owing to the platform width, combined with shielding and reflection effects of the platform structure, led to lower simulated values than those obtained in the parallel-section scenario. Nevertheless, within the adjacent frequency band of 3.5 MHz–4.5 MHz, the maximum value reaches 67.59 dBμV, indicating a certain degree of electromagnetic interference risk.

If interference data sources in the two scenarios described above are replaced with on-board measurements taken at the phase-break section, the induced voltage at the BTM antenna port in the 2 MHz–6 MHz frequency range would increase by approximately 9 dB, potentially compromising normal BTM operation. To validate the proposed simulation approach, during actual train operation, the BTM antenna was connected to a spectrum analyzer via a matching connector, and measured port voltages were compared with simulation results for both scenarios. As shown in Fig. 9, the measured signal curve in

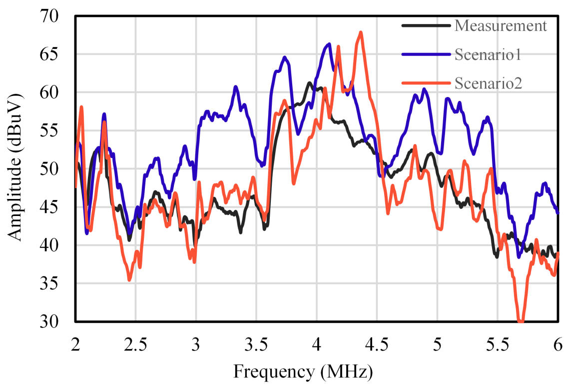

FIGURE 9. Comparison between simulation results and actual test data.

the 2 MHz–6 MHz band lies slightly above simulated curves, whereas overall amplitude-frequency characteristics exhibit a consistent trend. This agreement confirms that the analysis method established in this study has satisfactory accuracy and reliability.

5. CONCLUSION

This study has investigated the influence of the trackside electromagnetic environment of mainline railways on the BTM antenna of urban rail trains within the context of multi-network integration. To this end, an analytical model was established for two representative configurations: parallel sections where both lines enter the station and adjacent platform scenarios at connecting stations. The main conclusions are summarized as follows:

1) In parallel line and junction station scenarios, the BTM antenna of the urban rail train was not subject to electromagnetic interference from the mainline trackside environment at nominal BTM operating frequencies.

2) However, across the entire BTM operating frequency band, the induced voltage at the antenna port caused by the mainline trackside electromagnetic field may potentially compromise the normal operation and reduce the stability of the urban rail BTM equipment. To avoid such interference, crossing or parallel sections between the mainline and urban rail lines should be placed away from locations where catenary structure variations are likely to generate intense electromagnetic disturbances.

3) In sections with catenary structure changes, the trackside electromagnetic field amplitude of the mainline railway was greater than that in normal interval sections; additionally, the electric phase separation structure produced higher field strengths than the station-yard hard-crossbeam structure.

This analytical model indicates that in the multi-network integration scenario, the electromagnetic environment along railway mainlines will not cause electromagnetic interference issues for the BTM antenna of urban rail trains.

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