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Modular System-Level Modeling Method for the Susceptibility Prediction of Balise Information Transmission System

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Abstract: For high-speed train, balise transmission module (BTM) system is easily interfered with by other equipment of the train. This could cause the train to malfunction. Studying the electromagnetic susceptibility (EMS) of the BTM is very important for the performance and efficiency of the train. In this paper, a modular, system-level modeling method is proposed to predict the EMS of BTM systems. Based on object-oriented technology and a modular method, the BTM system is disassembled into several modules according to the electromagnetic characteristics of the whole system rather than the physical structure. All the modules are mutually independent, and the total EMS could be evaluated by the output of them. The modules of three key elements of electromagnetic compatibility (EMC), i.e., sources, coupling paths, and sensitive equipment, are established by the theoretical method, full-wave simulation method, and black-box test method, respectively, and put into different layers. According to the functions of the BTM system, the EMS of BTM is given by analyzing the interrelation of input and output of modules. Results of the proposed model were verified by measurement.

Keywords: BTM; electromagnetic susceptibility; modular system-level modeling

1. Introduction

The balise transmission module (BTM) system is a subsystem of the train operation control system for high-speed trains. It is responsible for detecting the presence of a balise and obtaining the location information of the train. As a positioning sensor, BTM system is comprised of BTM, on-board antenna, balise and wayside equipment, as shown in Figure 1. The on-board antenna at the bottom of the train receives the RF signal from balise to get the location information. Due to the complex and harsh train bottom electromagnetic environment, the RF signal from balise is interfered with easily and the BTM system will not work properly. This could lead to serious consequences, such as location information decoding error or stopping the train [1]. Thus, it is of great significance to study the EMS of BTM for ensuring the normal work of BTM system under interference condition and the efficient operation of the train.

There are several researches on the electromagnetic interference (EMI) of BTM systems. Most of them focus on analyzing the EMI coupling process in different balise allocated positions and different operating modes of the system [2–6]. The BTM system EMC issues are mentioned in European SUBSET 036 and European SUBSET 085, but not described in detail [7,8]. In European SUBSET 116, EMC test

methods are defined for analyzing the BTM system with disturbance [9], but it is still in draft. There are a few researches on the EMS of BTM system [10,11] presented the test method in the laboratory. It is recommended for EMS research of manufactured equipment, but not suitable in the design phase of BTM system. A more detailed and practical method for EMS prediction and system analysis should be investigated.

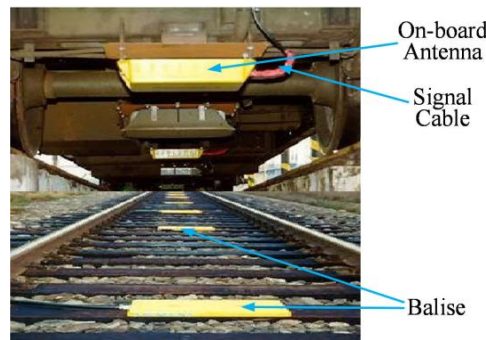


Figure 1. Balise-Based Train Positioning Structure.

From function perspective, a high-speed train consists of several subsystems: train operation control, traction power supply, brake control and network communication systems. BTM system is a subsystem in the train operation control system. From EMC perspective, the EMI of BTM system could be from different coupling paths and other subsystems in the train, i.e., it is a system-level problem which could not be solved only in device-level within the subsystem. A device-level issue means an issue related to certain devices. For example, the influence from traction converter of the traction power supply system to the balise is a device-level issue. When the disturbance to a BTM system occurs and it is not clear which devices or subsystems are the sources and which devices are the victims, the analysis on the interaction between all the devices of BTM system and all the subsystem of the train is a system-level issue. In practice, almost all the EMC problems are system-level issues. However, most of EMS prediction methods solve the device-level EMS issue [12–14]. Even if electromagnetic topology method is regarded as a typical approach for system-level EMC analysis [15–17] the complicated huge system cannot be settled due to the increasing complexity of the topology structure with a rapid increase of nodes and harassment transmission paths. The concept of hierarchical method is proposed to simplify the system-level EMC analysis problem [18]. It is a “flow down” method, which means it can solve the EMI problem from device-level to system-level, but ignores the interaction between device and system. It is not suitable for predicting the EMI problem of the BTM system in practical engineering applications which is in the unstable electromagnetic environment. The working environment of BTM system would be affected by the changes of other subsystems in the train, e.g., the pantograph off-line disturbance, the emission from rail return current and other disturbances from the traction power supply system. In addition, the EMS of the BTM system should also consider the function of the system itself.

Modular system-level modeling and prediction method is proposed in this paper based on the object-oriented analysis method (OOAM) [19]. For this approach, the system is rebuilt based on electromagnetic characteristics. The devices with the same electromagnetic characteristics are extracted as one object. Moreover, the objects with the same function are utilized to classify and integrate in a module model according to the concept of object-oriented technology and the modular method [20]. Based on the concept of a hierarchical structure, three layers are built according to EMC key elements, the EMI source, coupling path and sensitive device [21]. The module models are classified by these three layers and a complete system-level model is built. All these modules are interrelated with their input and output state. The interaction of devices in the whole system is realized through the interaction between modules. It is effective to simplify the system-level EMC analysis because modules are mutually independent and just affiliated with the attributes of objects. According to the needs of practical engineering problems, any

module could be selected or connected to simulate and analyze the device-level, subsystem-level, and system-level EMC problem. Moreover, for this model, the functions of device and system are defined as the attributes. The interrelation of functions and prediction could be got easily.

This paper is organized into five sections. In Section 2, the modular system-level prediction modeling procedure is presented. Module analysis for on-board device of BTM system is given in Section 3. In Section 4, the comparisons between the proposed modeling methodology and measurement are shown. Conclusions are given in Section 5.

2. Modular System-Level Modeling Approach

The BTM system has three normal functions. With some generality, it would cause the harmful consequences when the BTM system is interfered with [9], as listed in Table 1.

Table 1. The functions of BTM (Balise Transmission Module) system.

No.	Function	Consequence
F1	On-line Transmission Self-test	The interference effect could lead to temporary failures of the self-test with harmful consequences to operational reliability.
F2	Balise Detection Function	The interference effect would likely lead to a “false Balise detection” with harmful consequences to the operational reliability.
F3	Data Reception Function	The interference effect could lead to unrecognizable Balise telegrams with harmful consequences to operational reliability.

BTM system should take function F1 first before the system starts working. This function is enabled only when the BTM system starts to work. A test data package will transmit by radio-frequency energy transmitting antenna through route 1 and received by on-board antenna, as shown in Figure 2a. Secondly, after passing the self-test, the BTM system enforces function F2 to find the balise. This function is enabled all the time during travel. When the on-board antenna moved into the Main Lobe Zone of the balise shown in Figure 2b, function F3 is waking up [7]. This function will enable the on-board antenna to start receiving 2FSK message from balise through route 2, the air gap which is called interface A, as shown in Figure 2a, and help the BTM extract the location information from the message. During the above processes, a variety of disturbances could be coupled to on-board antenna and signal cable through different coupling path shown in Figure 2a at any time.

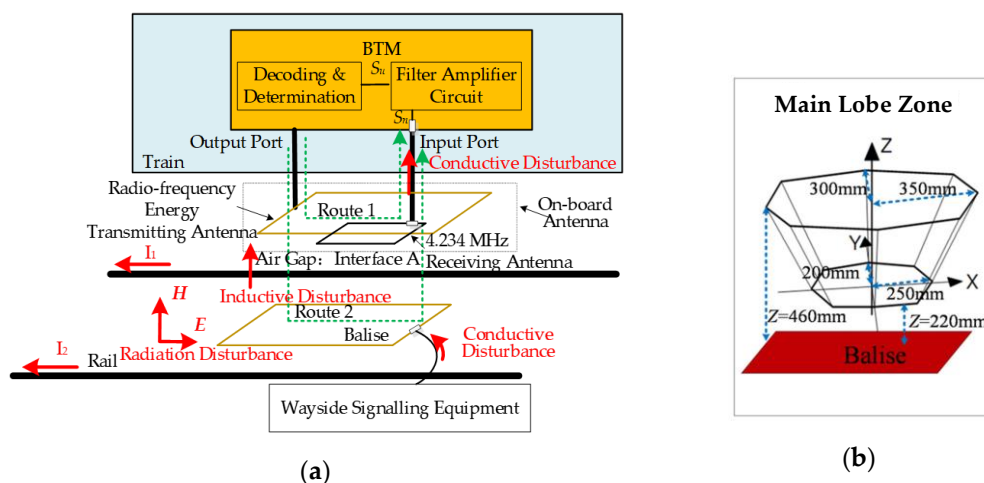


Figure 2. Operating Principle of Balise-Based Train Control System: (a) The route of signal and disturbance; (b) The contact zone.

2.1. Modular System-Level Model

The modular system-level model is made up of mutually independent modules. Thus, to build the modular system-level model, the electromagnetic characteristics of the whole system should be considered.

According to researches and on-site experience, the disturbance source could be classified into three forms: conducted, induced, and radiated form which are mutually independent. Therefore, three source modules are built for BTM system: radiation disturbance, conducted disturbance and induction disturbance modules. The devices in the BTM system, which are sensitive to interference, are encapsulated as sensitive equipment module. The disturbances need paths to “go” into BTM system like ground loops, radiation and the cable crosstalk coupling [22]. Thus, radiation, conduction, and induction coupling modules could be built according to the coupling path. All the modules are linked by the input and output port of them.

Each module is the encapsulation of objects, which are the devices or components with the same electromagnetic characteristics. For example, the radiation coupling modular model contains antenna, aperture, and wires object models. One object may have lots of properties. Table 2 lists a few object properties, which is utilized to build BTM EMS prediction model. The character of modules will be changed only by changing these electromagnetic properties of the object model.

Table 2. Objects and their properties.

Object	Properties
Cable	<ul style="list-style-type: none"> • Cable type and location • Wiring mode • Grounding method •
Antenna	<ul style="list-style-type: none"> • Antenna type • Antenna location • Distance from the EMI source •
Aperture	<ul style="list-style-type: none"> • location of Aperture • Aperture size • Aperture shape •

Then, all the modules are put into three layers and the whole modular system-level model is completed. The three layers are divided based on three elements of EMC, i.e., electromagnetic disturbance source, EMI coupling, and sensitive equipment layers, as shown in Figure 3.

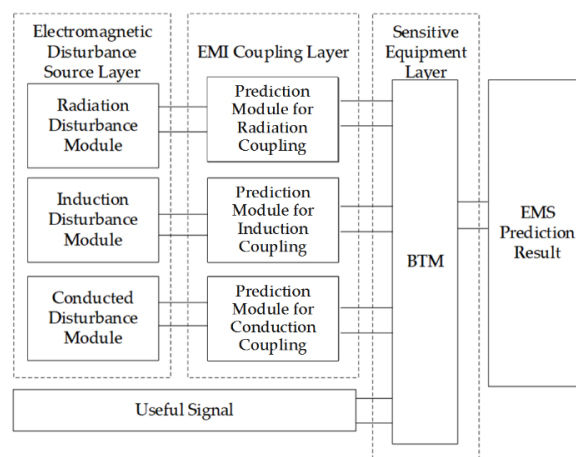


Figure 3. Modular System-level Model.

2.2. Prediction Procedure

To analyze EMS for BTM system, the only thing should be considered is the input and output of the modules in this prediction model. The prediction procedure for EMS prediction is shown in Figure 4.

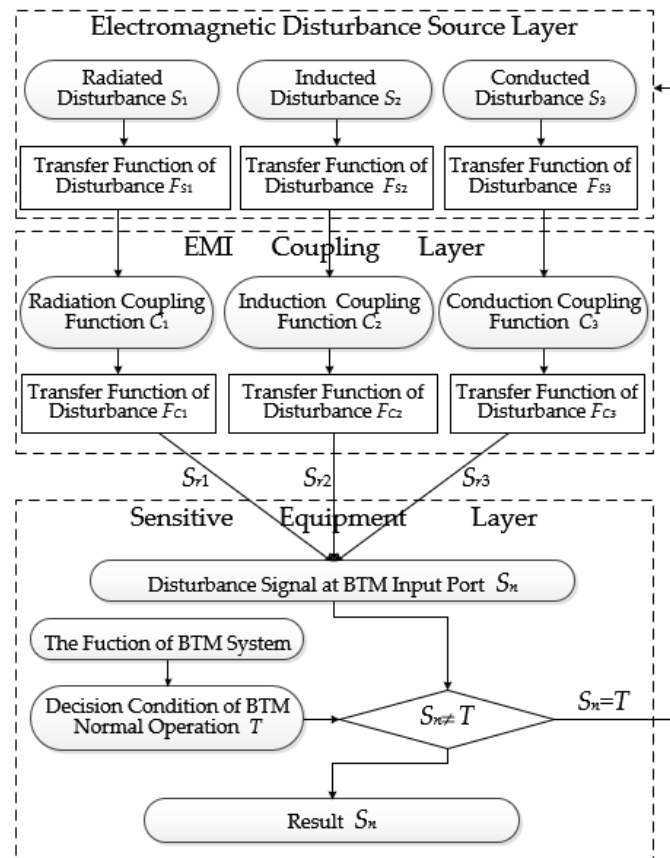


Figure 4. Prediction Process of Module System-level Model.

S_1, S_2, S_3 represent the radiated disturbance, induced disturbance, and conducted disturbance respectively. The value of disturbance S_1, S_2, S_3 depend on the train operation state or other subsystem working state. C_1, C_2, C_3 are the coupling function of radiation, induction, and conduction respectively. The gate function set is determined according to the relationship between the modules in different layers. Here, the gate function set consists of two types: F_s and F_c . F_s indicates the connection between the electromagnetic disturbance source layer and EMI coupling layer, while F_c is used to establish the connection between EMI coupling layer and sensitive equipment layer.

$$\begin{aligned}
 F_s &= \left\{ F_{s1}, F_{s2}, F_{s3} \right\} \\
 F_c &= \left\{ F_{c1}, F_{c2}, F_{c3} \right\}
 \end{aligned}
 \tag{1}$$

Due to the flexibility of object-oriented module modeling method, the module could be used as the requirement of system-level analysis. Every element of gate function set F consists of 0 or 1. “0” represents there is no connection between the two modules, and “1” is the opposite. For example, if induction disturbance module and inductive coupling module interact with each other, $F_{s2} = 1$, otherwise $F_{s2} = 0$.

S_{r1} is the disturbance signal produced from S_1 and went through the on-board antenna by radiation coupling. Meanwhile, S_{r2} is the disturbance signal produced from S_2 , effected by F_{s2} and goes through the antenna cable by inductive coupling like cables crosstalk or antenna by inductive coupling like

near field coupling. And disturbance signal S_{r3} is produced from S_3 and goes through the cables in the BTM system by conductive coupling. All these three disturbance signals S_{r1} , S_{r2} , and S_{r3} would act on the input port of BTM at the same time. S_n at the input port of BTM is composed of S_{r1} , S_{r2} and S_{r3} . EMS prediction of BTM system is to analyze what kind of disturbances will lead to inevitable performance degradation for the system. T is defined as the critical condition for sensitive equipment normal operation. That means T is the basic requirements of routine operation for sensitive equipment. The critical condition T relies on the three functions of the system mentioned at the beginning of Section 2. " $S_n = T$ " stands for the system could work well with the disturbance S_n . Increase the voltage of S_1 , S_2 or S_3 , until the disturbance S_n just make the system could not work properly. For easy manipulation on-site, voltage is chosen to assess the value of the disturbance S_n in EMS prediction. Thus, the disturbance voltage V_N is considered as the sensitivity level of BTM system. And V_N could be expressed as the summary of V_{r1} , V_{r2} and V_{r3} the voltages of S_{r1} , S_{r2} and S_{r3} .

$$V_N = V_{r1} + V_{r2} + V_{r3}, \tag{2}$$

where,

$$\begin{aligned} V_{r1} &= V_1 F_{s1} C_1 F_{c1} \\ V_{r2} &= V_2 F_{s2} C_2 F_{c2} , \\ V_{r3} &= V_3 F_{s3} C_3 F_{c3} \end{aligned} \tag{3}$$

where V_1 , V_2 , and V_3 are the voltages of disturbance signal S_1 , S_2 , and S_3 respectively. If the sensitivity level of BTM system is confirmed, the value of V_N is a determined value.

According to this prediction procedure, the sensitivity level of BTM system is a key factor and needed to be calculated for different BTM system functions.

2.3. Model for BTM Susceptibility Prediction

To find out the main disturbance coupling path for BTM system, the comparative experiment is taken during the train passes the neutral zone. The setup of the first experiment is shown in the Figure 5a: the disturbance received by the on-board antenna is measured directly by a spectrum analyzer. Another experiment configuration is shown in the Figure 5b: An impedance of 50Ω is used to take the place of BTM antenna, then the disturbance is measured by the spectrum analyzer in zero span mode.

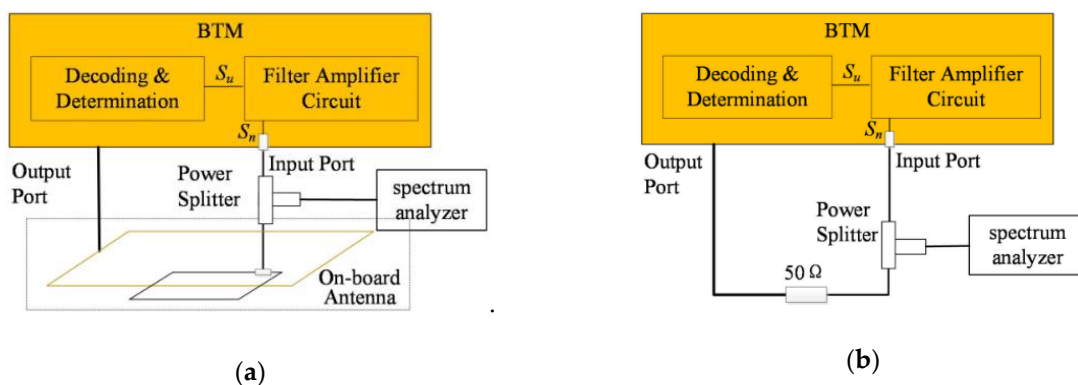


Figure 5. Setup to find out the main disturbance coupling path for BTM system: (a) The testing with the antenna connection; (b) The testing with 50Ω connection.

The comparison result is shown in Figure 6. The maximum disturbance voltage is $77 \text{ dB}\mu\text{V}$ when the antenna connection, shown in Figure 6a. The maximum disturbance voltage is $47 \text{ dB}\mu\text{V}$ when the antenna is disconnected and is replaced by 50Ω , shown in Figure 6b. Thus, the main disturbance coupling path for BTM system is antenna coupling.

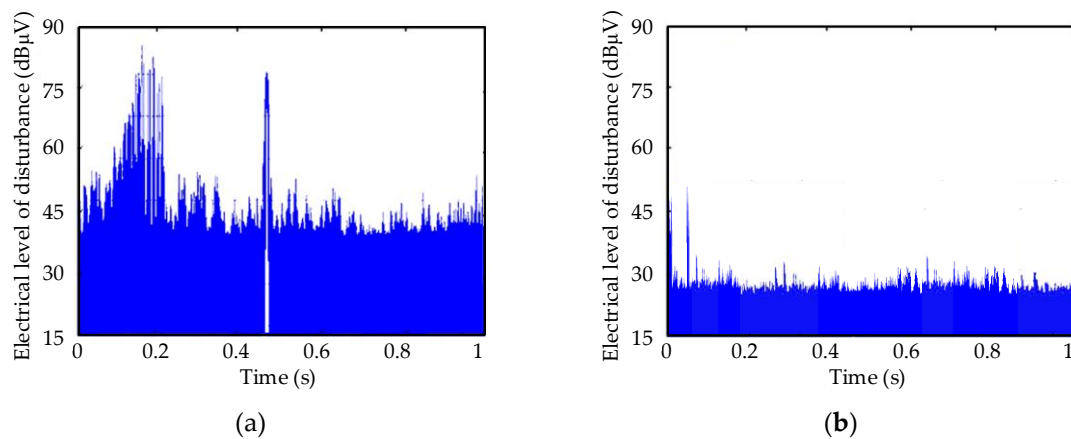


Figure 6. Disturbance in BTM system when the train passes through phase separation zones: (a) The disturbance received by the antenna. (b) The disturbance in BTM system when the antenna is disconnected.

For railway system, the two most serious disturbances are generated from traction power system. One is pantograph off-line disturbance when the train passes through phase separation zones, and the other one is traction return current. In order to confirm the main disturbance source, a further field tests have been done. An “antenna connection” setup is taken when the train is in a normal operational situation. In this situation, traction return current is considered to be the main disturbance source. And the disturbance received by the on-board antenna is shown in Figure 7. The disturbance levels are almost the same with the result in Figure 6a which is obtained with pantograph off-line disturbance. Thus, the main disturbance does not come from the pantograph off-line disturbance, but induces from traction return current flowing on the steel rails and some other disturbance from traction power system. Moreover, according to the loop physical structure and operation frequency of BTM antenna, the main disturbance is in the form of magnetic field [23].

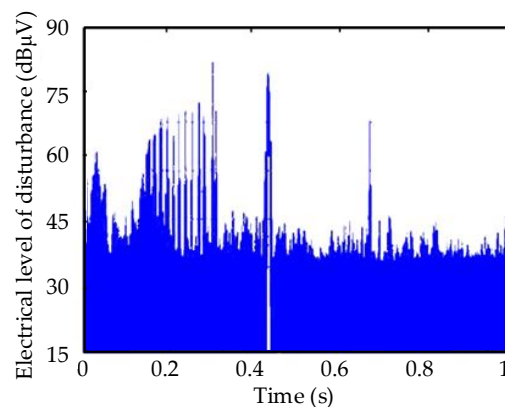


Figure 7. Disturbance received by the antenna when the train is in a normal operational situation.

Based on the analysis above, the influence of radiation disturbance and conductive disturbance could be ignored. Thus, it is assumed that the voltages of S_{r1} and S_{r3} in Figure 4 equal to zero. The modules for radiation and conducted disturbance could be ignored. For modular system-level modeling method in the paper, the module could be utilized alone according to requirements for practical problems. Thus, the BTM EMS prediction model could be simplified as induction disturbance, induction coupling, and sensitive equipment modules, as shown in Figure 8.

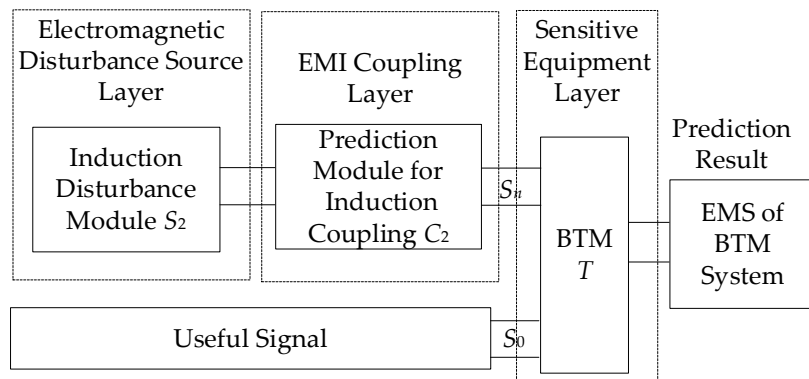


Figure 8. Model for Susceptibility Prediction of Balise-Based Train Control Systems.

Thus, according to the method the F_{s2}, F_{c2} equal to 1 and other elements of transfer function equal to 0., the disturbance voltage V_N could be obtained as Equation (4).

$$V_N = V_{r2} = V_2 C_2, \tag{4}$$

3. Modular Modeling for BTM System

The disturbance voltage V_N at the input port of BTM is defined as the sensitivity of BTM system. From Equation (4), disturbance voltage V_2 of induction disturbance module, coupling function C_2 of inductive coupling module and the critical condition T are important to get V_N . Thus, the key point of the system-level modeling approach is modular modeling, which could be dealt with by different methods. To establish the model in Figure 8, theory method, full-wave simulation method, and black-box test method are utilized for the induction disturbance source module, induction coupling module, and sensitive equipment module, respectively.

3.1. Modeling for Induction Disturbance Source Module

As a loop antenna, the on-board antenna gets the location information and other useful messages transmitted from balise by receiving the magnetic field signal. Meanwhile, the disturbance would be coupled to the on-board antenna too. To quantify the magnetic field disturbance, the induction disturbance source module is established by using a rectangular loop antenna with a current source I , as shown in Figure 9.

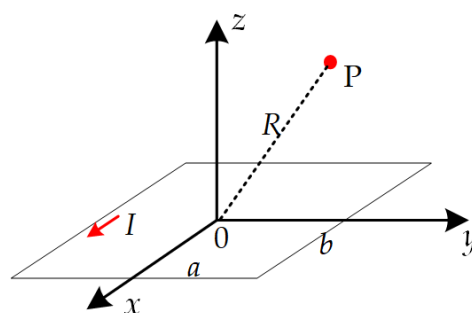


Figure 9. Rectangular Loop Antenna with Current I .

The side length of the rectangular loop antenna are a and b respectively. When the rectangular loop antenna is electrically small, the magnetic field intensity at the field point $P(x, y, z)$ could be calculated by Biot–Savart law [24],

$$B = -\frac{\mu_0 I}{4\pi} \oint_{loop} dl \times \nabla \frac{1}{R}. \tag{5}$$

According to Equation (5), the magnetic field disturbance is related to the size of the rectangular loop antenna, the distance R and the disturbance current I . Thus, when the position and the size of every device is fixed, the level of magnetic field disturbance is determined by current I . In the case of the electromagnetic environment on-site, these disturbances may be generated by the following sources which are laid close to the on-board antenna: current harmonics from the traction system, current from the rails and cables [23]. These disturbance currents could be pure sinusoidal continuous wave, transient, damped oscillation typology [9]. Using Fourier series, all of this disturbance could be described as a superposition of sinusoidal waves with different frequencies. Thus, to simplify the modeling process, pure sinusoidal continuous wave disturbance shall be applicable.

The voltage of induction disturbance S_2 could be obtained as [25]

$$V_2 = I \cdot R_s, \quad (6)$$

where R_s is the port impedance of the rectangular loop antenna.

3.2. Modeling for Inductive Coupling Module

Depending on the working principle of on-board antenna, the inductive disturbance coupling module is established in Ansys HFSS and the S-parameters are solved by using the finite element method (FEM), as shown in Figure 10.

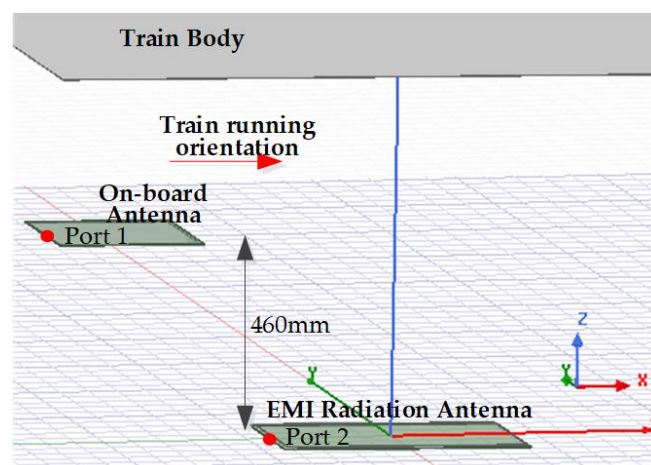


Figure 10. Numerical simulation model for radiation disturbance coupling.

The size of EMI radiation antenna and the voltage of the induction disturbance S_2 are considered as the output of induction disturbance source module. They perform as the input of the inductive coupling module. The size of the rectangular loop antenna is 240×430 mm. In addition, the size of the on-board antenna is 240×265 mm. Port 1 on the on-board antenna is the antenna receiving port, while the Port 2 on the EMI radiation antenna is disturbance transmitting port. The vertical distance of the two antennas is 460 mm based on the height from on-board antenna to the rail.

Set the center of the EMI radiation antenna to be at the ordinate origin. Train running orientation is the positive direction along Y-axis. The S-parameters of antennas shown in Figure 11a is the S_{12} as different horizontal distances between two antennas' centers. The value of S_{12} keeps stable within the scope of ± 0.2 m. Thus, S-parameter of the antenna system is used when on-board antenna is located right above the EMI radiation antenna.

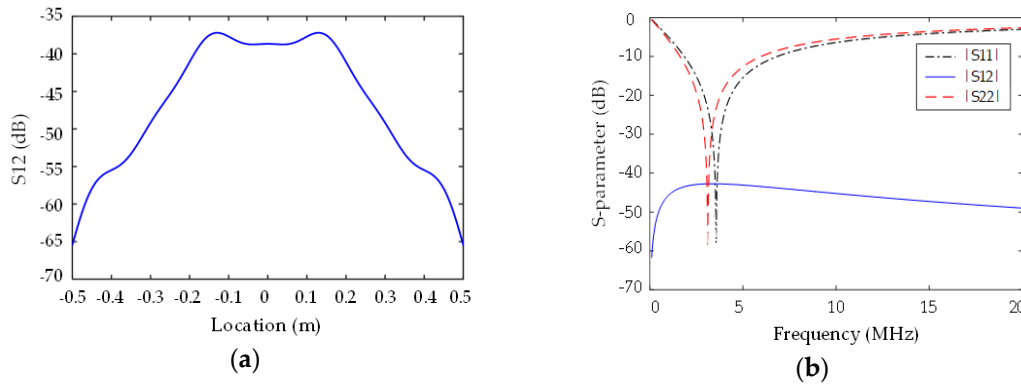


Figure 11. S-parameters of antenna system: (a) S12 with the location of on-board antenna. (b) S-parameters of antenna system when on-board antenna located right above the EMI radiation antenna.

The output power P_s from Port 2 and the input power P_r at Port 1 satisfy [26],

$$P_r = P_s \cdot |S_{12}|^2, \tag{7}$$

To ensure the signal transmission performance, R_s and R_{BTM} are set to 50Ω . V_{2_eff} and V_{r2_eff} are the effective values of V_2 and V_{r2} . Thus, P_s and P_r are expressed as

$$P_s = \frac{V_{2_eff}^2}{R_s}, \tag{8}$$

$$P_r = \frac{V_{r2_eff}^2}{R_{BTM}}, \tag{9}$$

Thus, the port voltage V_{r2} of on-board antenna is,

$$V_{r2} = V_2 S_{12} \sqrt{\frac{R_{BTM}}{R_s}}, \tag{10}$$

The R_{BTM} and R_s are the impedances of Port 1 and Port 2 respectively.

According to Equation (2), $V_N = V_{r2}$, the inductive coupling function C_2 is expressed as,

$$C_2 = S_{12} \sqrt{\frac{R_{BTM}}{R_s}}, \tag{11}$$

3.3. Modeling of Sensitive Equipment Module

For getting the critical condition T for sensitive equipment, the sensitive equipment module is modeled in two parts, as shown in Figure 2 with the filter amplifier circuit and the part for decoding and determination.

Ignoring cable loss, S_r is the input signal transmitting into the sensitive equipment module. It could be divided into two parts, useful signal S_0 and disturbance signal S_n . Since the modulation of BTM system signal is 2FSK, the signal S_r received by BTM could express as [27],

$$S_r(t) = S_0(t) + S_n(t), \tag{12}$$

where,

$$S_0(t) = U_{pp} \sum_{k=0}^N \left[\text{Rect} \left(\frac{t - kT_b}{T_b} \right) \bullet \cos \{ 2\pi [(f_c + \Delta f_c) + (2b_k - 1)(f_m + \Delta f_m)] t + \phi(kT_b) \} \right], \quad (13)$$

where f_c is the carrier frequency, f_m is frequency offset, while Δf_c and Δf_m are the instability of carrier frequency and frequency offset, respectively. k is the length of data. T_b is the cycle of the baseband data signal and b_k is the bit value. The useful signal $S_0(f)$ in the frequency domain is shown in Figure 12.

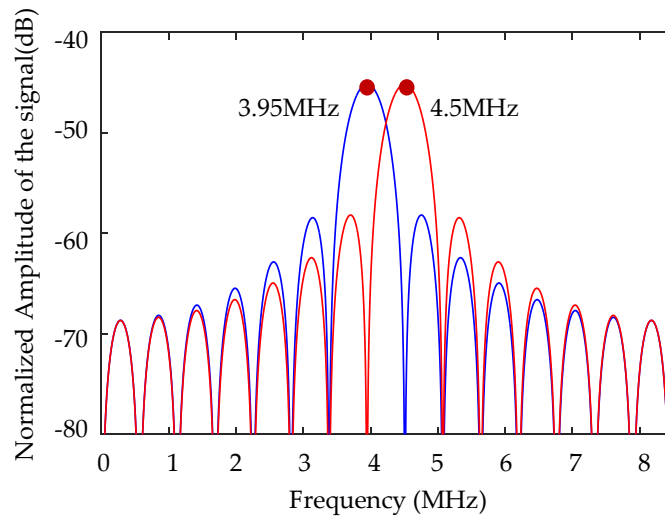


Figure 12. The signal of BTM ($U_{pp} = 1$ V).

S_u is the output signal from filter amplifier circuit [28],

$$S_u(f) = S_0(f)h + S_n(f)h, \quad (14)$$

where h is the transfer function of the filter amplifier circuit. It could be expressed as the magnitude-frequency characteristic of the filter amplifier circuit. The disturbance signal S_n going into the sensitive equipment could be quantified by measurement.

To get h , black-box testing method is used [29]. The setup of the test is shown in Figure 13.



Figure 13. The setup of the test for getting h .

As shown in Figure 14, the filter amplifier is a band pass filter working at the BTM band, and the amplifier factor is about 10 dB at 4.232 MHz. The BTM operating frequency range is defined as 3–6 MHz for this type of BTM system.

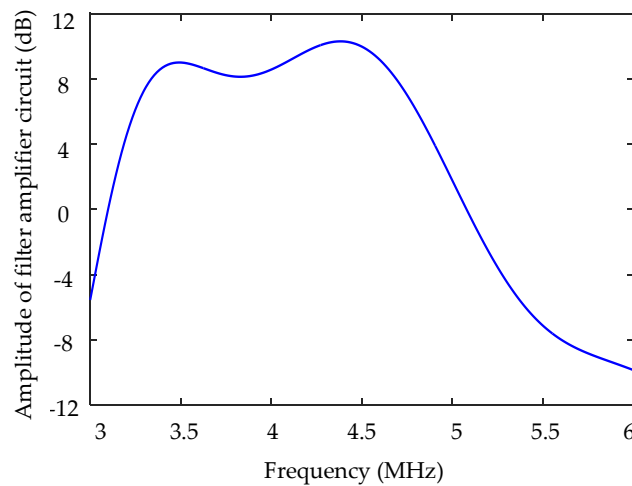


Figure 14. Magnitude-frequency characteristic of filter amplifier circuit.

The information will be transferred to the Automatic Train Protection (ATP) system after decoding. The bit error rate could be obtained from formulations (12), (13), and (14) when the instability of carrier frequency and frequency offset is equal to zero [27].

$$p_e = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{2E_N}} \right), \tag{15}$$

where the E_b is the energy of the useful signal S_0h . E_N is the energy of the disturbance signal S_nh [24].

$$\begin{aligned} E_b &= \int_T \frac{(S_0h)^2}{R_{BTM}} dt \\ E_N &= \int_T \frac{(S_nh)^2}{R_{BTM}} dt \end{aligned}, \tag{16}$$

where R_{BTM} is the input impedance of BTM.

For getting the critical condition T , the function of BTM system listed in Table 1 should be considered. Function F2 is simple comparing to the other two functions: F1 and F3, due to it does not involve signal analysis. Thus, the EMS for BTM system should be predicted in two ways for different functions.

3.3.1. T for BTM System with F2

In function F2, a balise shall be detected when the voltage of S_u at the output port of the filter amplifier circuit segment of BTM is higher than V_{th} during a minimum time. If the on-board antenna is not at the contact zone, and the voltage of S_u is larger than V_{th} , the BTM will erroneously report the existence of a balise. Thus, V_{th} is defined as the critical condition T in this function. Moreover, it is a known value for a certain BTM system.

3.3.2. T for BTM System with F1 or F3

The relationship between Signal Noise Ratio (SNR) and Bit Error Rate (BER) of BTM signal S_u could be calculated by Equation (15). According to European standard SUBSET 036, the BER of BTM system should be below 10^{-6} when BTM system carries out F1 [7] and F3 function. Thus, the SNR of output signal S_u should be larger than 13.5 dB according to BER of BTM system of Figure 15. That means, in function F1 and F3, the BTM should receive correct data when the SNR of S_u is larger than 13.5 dB. And if the SNR of S_u is lower than 13.5 dB, the BTM will fail to start or report erroneously localization of a balise even balise missing. Thus, the critical condition T could be set at SNR = 13.5 dB.

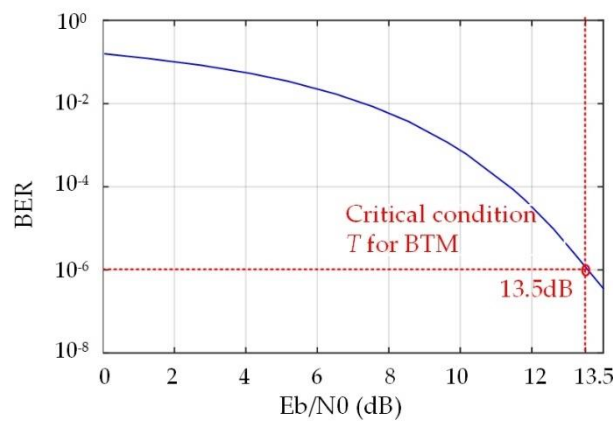


Figure 15. Relationship between SNR and BER of BTM signal.

Significantly, the useful signal levels are different in these two functions, as shown in Figure 16, thus the sensitive disturbance levels should be calculated separately.

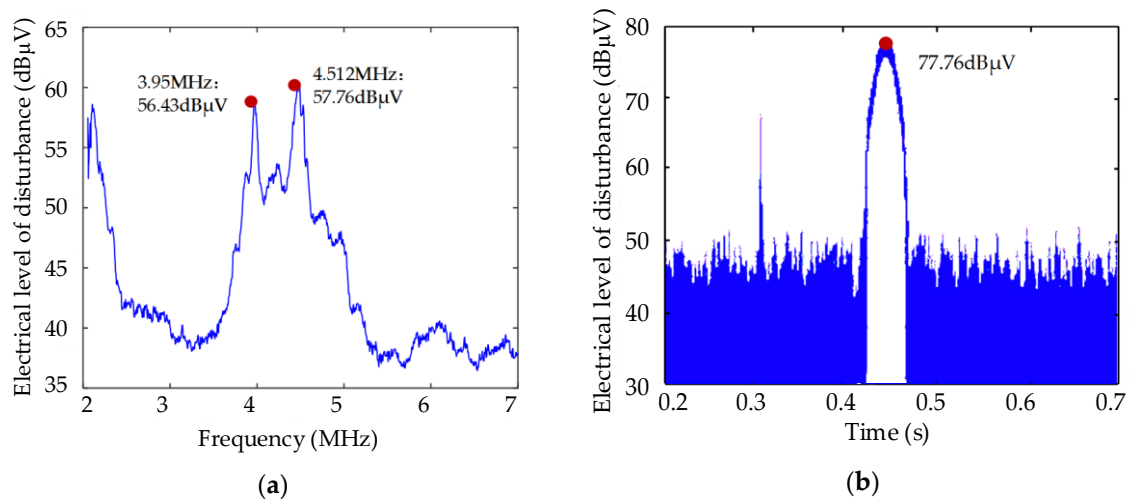


Figure 16. The signal received by on-board antenna: (a) The electrical level of self-test data; (b) The electrical level of balise message.

For a certain type of BTM system, the maximum electrical level of the test data received by BTM is 57.76 dB μ V at 4.512 MHz and 56.43 dB μ V at 3.95 MHz during “on-line transmission self-test” processing, shown in Figure 16a. It is the useful signal level in the self-test function. For “Data Reception Function”, the maximum signal level received by BTM is 77.76 dB μ V, shown in Figure 16b.

To validate sensitive equipment module, field tests are carried out, shown in Figure 17. The differential-mode disturbance at the input of BTM is tested by the spectrum analyzer when the train stops and runs. For this train, the exhaust system locates near the on-board antenna of BTM. It may produce disturbance. In the test, when the train is running normally, BTM system could normally operate. If the train is going to run and the exhaust system power on initially, BTM system cannot start and the train cannot run either. However, if shutting down the exhaust system and making the BTM system start first, the train could start to work successfully. The disturbance at the input of BTM is shown in Figure 18. When the exhaust system works, the disturbance level is 58.59 dB μ V at 3.95 MHz and 47.19 dB μ V at 4.512 MHz. If the exhaust system is powered off, the disturbance level is around 40 dB μ V at both 3.95 MHz and 4.512 MHz for this field test.

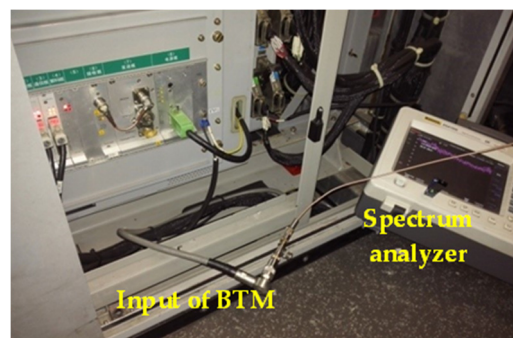


Figure 17. Field tests for the critical condition T of BTM system.

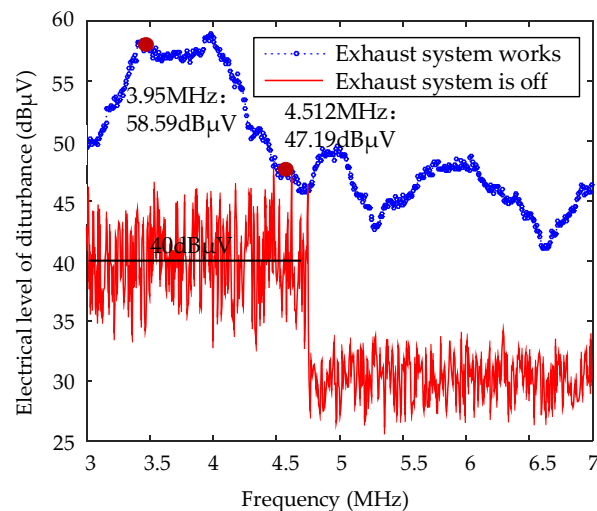


Figure 18. The disturbance level for exhaust system.

Based on the BTM signal level in Figure 16 and the disturbance level in Figure 18, the phenomenon could be explained by the modeling of sensitive equipment module.

When the exhaust system starts before the BTM system, the SNR is -2.16 dB at 3.95 MHz and 10.57 dB at 4.512 MHz. They are all smaller than the critical condition T (SNR = 13.5 dB). Thus, the on-line transmission self-test fails and BTM system will not start. As a result, the train cannot operate either.

When BTM system starts first without exhaust system, the noise is low, and the smallest SNR is 16.43 dB at 3.95 MHz (the disturbance source level is 40 dB μ V when exhaust system is powered off). Comparing to the critical condition T , the BTM system will pass on-line transmission self-test and start normally. During Data Reception function, the BTM useful signal is much higher than the noise. When the exhaust system started, the smallest SNR is 19.17 dB which is still larger than 13.5 dB. Therefore, the train could continue to operate normally.

Therefore, the model analysis could predict the EMS of BTM system well.

4. Analysis and Validation

Sensitivity of BTM system defined as the level of disturbance at the input port of BTM, which leads to the abnormal working status of BTM system.

To validate the modeling method, the sensitivity of BTM system is measured in a semi-anechoic chamber. Figure 19 shows the measurement set-up. The measurement was performed using two signal generators (RIGOL DG3121A signal generator and RIGOL DG1032Z signal generator) and a spectrum analyzer (ROHDE & SCHWARZ FSH8) to measure signals. The signal is fed from the signal generator to reference loop antenna, and the received terminal disturbance voltage at the BTM input port, which lead to BTM abnormal working status is measured by the spectrum analyzer. Depending on the site

installation requirements, the distance between the reference loop antenna and on-board antenna is 350 mm.

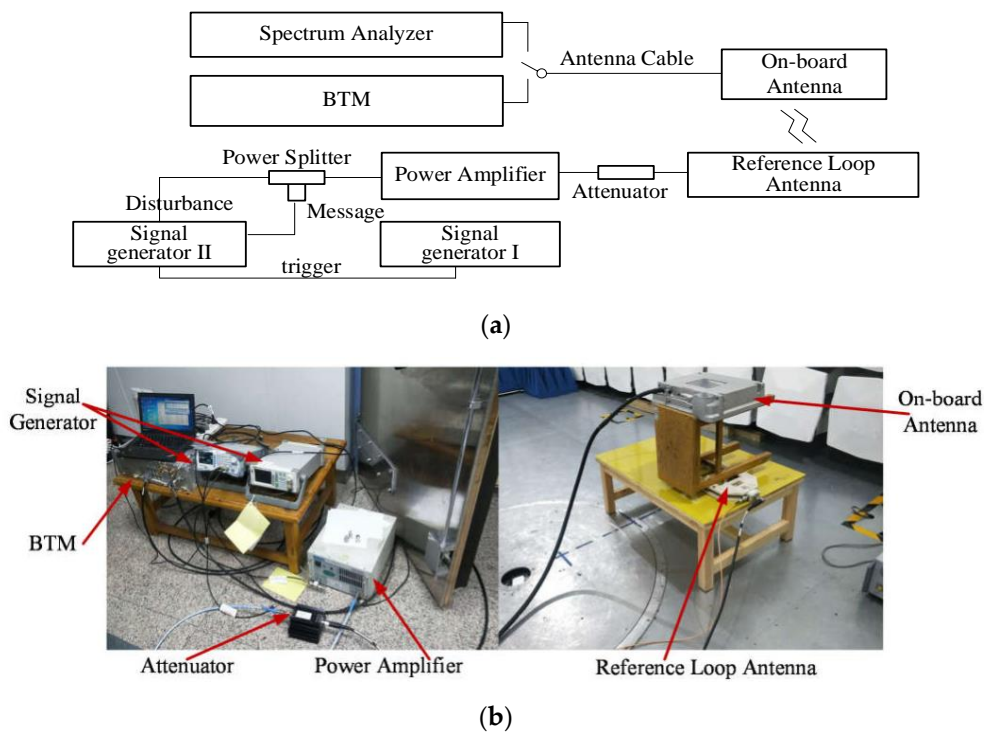


Figure 19. Measurement set-up: (a) Block diagram for device connection; (b) Experimental setup in semi-anechoic chamber.

Good agreement between measurements and simulation result of the model is shown in Figure 20.

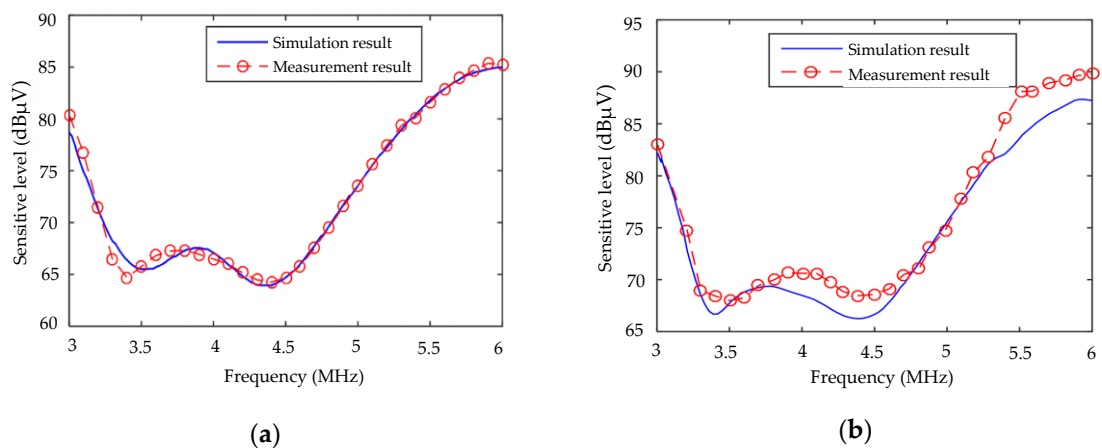


Figure 20. Sensitivity of BTM system: (a) Sensitivity of BTM system take the function F2: “Balise Detection Function”; (b) The sensitivity of BTM when the on-board antenna is at contact zone, carrying out the function F3: “Data Reception Function” and the useful signal current is $I_{U2} = 59 \text{ mA}$ [7].

The predicted result shows that no matter what function the BTM system carries out, the most sensitive frequency is in the BTM operating frequency range. According to Figure 20a, the maximum error between the results of measurement and our model is only 1.45 dB at 3.4 MHz when BTM system takes the function F2. Between 3.9 MHz and 4.6 MHz, the maximum absolute error is 0.4 dB. The BTM system will report an error when the voltage of disturbance S_n is larger than 64 dBµV. Figure 20b is the comparison result when the on-board antenna is in the contact zone and the BTM system carries out

the function F3. Between 3.4 MHz and 4.6 MHz, the maximum absolute error is 2.8 dB. In this band, the sensitivity level got from the simulation is lower than the result of the measurement. That difference may be caused by ignoring the self-error correcting ability of BTM system. Thus, this immunity of the testing on BTM system is better than the theory analysis result. The disturbance S_n should be smaller than 67 dB μ V to make sure the BTM system performs normal work.

5. Conclusions and Future Work

In this paper, a system-level modular modeling prediction method is proposed to predict the EMS of BTM systems more effectively. In this method, the modules are built by appropriate methods and they are mutually independent. This characteristic makes the model more flexible to be applied to practical problem on-site. Using this prediction model, the EMS of the BTM system could be forecasted under single frequency disturbance. Good agreement could be found between the measurements and the proposed methodology. It is an inverse problem approach. When the susceptibility of equipment and the coupling function of one disturbance are known, the upper limits of the disturbance could be obtained. However, this paper only considered the disturbance from the exhaust system, and the other actual disturbances in the railway system are not verified in the prediction. In the future, EMS for the BTM system under actual engineering conditions should be analyzed. The train operation state module and train operating environment module should be added to the model to obtain satisfactory results in the running train.

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