



Physics-Based Wireless Channel Modeling in Railway Environments: Theory and Applications

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Abstract

Radio channel characterization in railway environments is indispensable for the effective design and deployment of train communication systems. In this paper, our recent work on the development of a physics-based wireless channel model is summarized. The validity of our developed model is verified against experimental data in various practical scenarios including the London Underground subway network in UK. On the application side, the developed physics-based wireless channel is integrated with an optimization engine for the planning of wireless access points for train communication systems.

1 Introduction

With the continuing expansion of metropolitan areas, the demand for efficient mass transportation systems is increasing accordingly. Communication-based train control (CBTC) is an emerging wireless technology that can significantly improve the efficiency of light rail, subway, and high-speed train transit systems [1]. In CBTC systems, train control and navigation can be achieved through wireless communication between the train and a network of access points (APs) deployed along the track.

Wireless channel models, which can provide accurate path-loss predictions of corresponding communication links in railway environments, are of great importance for the deployment of CBTC systems. Such models can be either extracted based on measurements or derived based on physics-based methods. The former are known as parametric models for which the relevant parameters are extracted by fitting the models to measured data [2,3]. These models provide helpful insights into the propagation characteristics of the studied wireless channels; but they are not expected to provide an accurate received signal strength (RSS) estimate on a point-by-point basis. On the other hand, physics-based models, based on waveguide theory [4, 5], ray-tracing (RT) [6,7], and vector parabolic equation (VPE) methods [8,9], have been widely used.

Waveguide theory-based models can provide efficient and accurate results for canonical geometries by making the analogy between wave propagation in tunnels with overmoded waveguides. However, such models are too restrictive for complex tunnel environments. It was shown in [10]

that the mapping of a general arched tunnel to a waveguide model is not unique and depends on the position of the transmitter and receiver. Hence, the waveguide theory-based model can be used as a surrogate model of particular transmitter-receiver positions within the tunnel, rather than a global model. The RT method is based on geometrical optics and the uniform theory of diffraction, and it can be utilized to characterize tunnels with complex geometries. However, it can be quite computationally intensive depending on the underlying geometrical detail and it is generally not suitable for long guiding, Levy 00 structures. In addition, applying these methods to arched or curved tunnels leads to inaccuracies, specifically, a significant overprediction of power as the number of facets approximating the tunnel cross section increases [11]. On the other hand, the VPE method has found a prolific area of application in railway tunnels combining computational efficiency with numerical accuracy [12]. Since VPE is derived from the full-wave Helmholtz equation, the effects of reflection, diffraction, and radiation can be taken into account. More recently, improved VPE techniques have been introduced to enable propagation modeling in curved tunnels with various cross section geometries [13, 14].

In this paper, we present a high-fidelity, physics-based wireless channel model, based on the VPE method, to characterize radiowave propagation in realistic, complex railway environments. Its validity is verified against measurement campaigns in the London Underground subway network in UK. The usefulness of the developed model is demonstrated in the planning of CBTC systems, where the number and location of wireless APs in a CBTC system is optimized.

2 Physics-Based Wireless Channel Model

2.1 Vector Parabolic Equation Method

Assuming that the z -axis is the propagation direction, the standard VPE formulation, outlined by Popov *et al.* [15], can be expressed as

$$\frac{\partial \mathbf{W}}{\partial z} = \frac{1}{2jk_0} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \mathbf{W} \quad (1)$$

where k_0 is the free-space wave number and \mathbf{W} is the complex wave amplitude of the reduced plane wave propagating along the z -axis [15].

The VPE method can be numerically implemented through the Alternating-Direction-Implicit (ADI) finite-difference scheme [16]. The formulation for the ADI scheme is:

$$\begin{aligned} & \left(1 - \frac{r_x}{4jk_0} \delta_x\right) \left(1 - \frac{r_y}{4jk_0} \delta_y\right) \mathbf{W}_{i,j}^{k+1} \\ &= \left(1 + \frac{r_x}{4jk_0} \delta_x\right) \left(1 + \frac{r_y}{4jk_0} \delta_y\right) \mathbf{W}_{i,j}^k \\ &+ \mathcal{O}(\Delta z^3) + \mathcal{O}(\Delta z \Delta x^2) + \mathcal{O}(\Delta z \Delta y^2) \end{aligned} \quad (2)$$

where the following finite-difference approximations have been used for the second-order derivatives of (1):

$$\delta_x \mathbf{W}_{i,j}^k = \mathbf{W}_{i+1,j}^k - 2\mathbf{W}_{i,j}^k + \mathbf{W}_{i-1,j}^k \quad (3)$$

$$\delta_y \mathbf{W}_{i,j}^k = \mathbf{W}_{i,j+1}^k - 2\mathbf{W}_{i,j}^k + \mathbf{W}_{i,j-1}^k \quad (4)$$

and $r_x = \Delta z / \Delta x^2$, $r_y = \Delta z / \Delta y^2$.

Eqn. (2) can be split in two steps to obtain the fields for each direction separately:

$$\left(1 - \frac{r_x}{4jk_0} \delta_x\right) \tilde{\mathbf{W}}_{i,j}^{k+\frac{1}{2}} = \left(1 + \frac{r_y}{4jk_0} \delta_y\right) \mathbf{W}_{i,j}^k \quad (5a)$$

$$\left(1 - \frac{r_y}{4jk_0} \delta_y\right) \mathbf{W}_{i,j}^{k+1} = \left(1 + \frac{r_x}{4jk_0} \delta_x\right) \tilde{\mathbf{W}}_{i,j}^{k+\frac{1}{2}} \quad (5b)$$

where the index $k + 1/2$ corresponds to an intermediate plane introduced between the $z = k\Delta z$ and $z = (k + 1)\Delta z$ planes. The ADI scheme is unconditionally stable and very efficient because multi-dimensional fields are updated along one dimension at a time. A comprehensive error analysis and comparative study of different numerical schemes for radiowave propagation modeling is presented in [17].

2.2 Radiating Sources

The representation of radiating sources, such as transmitting antennas, requires the calculation, analytical if possible or numerical via another method such as ray-tracing, of the fields that the sources generate on the initial plane of VPE models. However, the solutions offered so far compromise either the accuracy or the efficiency of VPE.

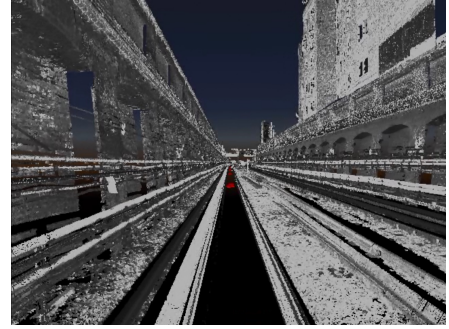
We have introduced a Gaussian beam approximation approach [8] that allows one to directly incorporate antennas into VPE models. As a result, radiating sources can be embedded into the propagation model without invoking other techniques and with no compromise on the efficiency.

2.3 Surface Roughness

The roughness of surface walls, a source of additional and often significant path loss, can play an important role in the accurate modeling of radiowave propagation in railway environments. We have introduced a systematic and robust approach to incorporate wall roughness into VPE models. The approach can be applied to environments with arbitrary cross-section geometries and large-scale surface roughness [18].

3 Validation against Measurement Data in Realistic Railway Environments: London Underground

The considered geometry is a section selected between the Finchley Road station to Baker Street station from the London Underground subway network in UK. The whole section consists of a couple of single-track and dual-track tunnel sections as well as open-air sections. The cross-section geometry of the tunnel section is close to an arch. The exact geometry of the environment is mapped using a laser scanner that produces volumetric data as a set of points to accurately represent an environment, as illustrated in Fig. 1.



(a)



(b)

Figure 1. Representation of the modeling environment using point cloud data. Source: Thales Canada.

The process is referred to as *laser survey* and the produced data is referred to as *point cloud data*. The point cloud data not only captures the cross-sectional but also the elevation and curvature information along the tunnel. With the point cloud data, a three-dimensional, detailed input model can be generated. A diagram showing the modeling environment that is reconstructed through point cloud data is illustrated in Fig. 2.

The measurement data, provided by Thales Canada and UK, is obtained by fixing the receiving equipment on a trolley which moves along the railway track and records the fields. The transmitter, a 14 dBi vertically polarized Yagi antenna, is placed at a height of 3.07 m and 0.25 m away from the side wall. The operating frequency is

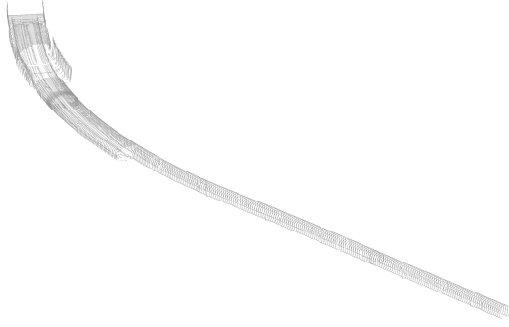


Figure 2. Diagram of the modeling environments.

2.44 GHz and the effective isotropic radiated power (EIRP) is 20 dBm. The receiving antennas, emulating the antennas on the train and operating in a continuous wave (CW) mode, are mounted on a trolley that is driven down the tracks of the London Underground line from Baker Street station to Finchley Road station. There are two receivers, which are at a height of 3.6 m and 1.28 m apart. The maximum power received by either of these two receivers is selected as the received power at each location. The tunnels walls are concrete and modeled using a relative permittivity, $\epsilon_r = 5.5$, and conductivity, $\sigma = 0.01$ S/m.

In Fig. 3, the simulated RSS obtained from our developed propagation model is compared to measured data. It can be observed that the simulated results have good agreement with the measured data.

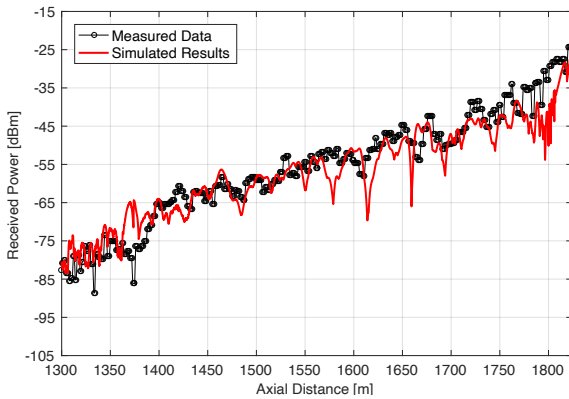


Figure 3. Comparison between simulated and measured received power.

4 Application: Optimization of Access Points Placement for CBTC Systems

As for any wireless communication system, quality of CBTC service depends on the strength of the signal received by the train. The scope of CBTC system planning is to ensure that the number and the position of access points will maintain wireless connectivity for the trains. In practice, the placement of APs is mainly determined by mea-

surements. One possible way to distribute APs is to place one at the beginning, then determine a distance where the RSS associated with the initial AP is below a threshold value and place a new AP at that location. This procedure is carried out until the entire length of railway track is covered by APs. However, such a process is time-consuming and resource-intensive.

Our developed physics-based wireless channel model can be combined with an optimization engine to optimize the placement of APs, by minimizing average path loss experienced by the train. As an example, this simulation-based optimization framework is applied to one section selected from the London Underground subway network, as illustrated in Fig. 5. Details on the optimization framework can be found in [19].

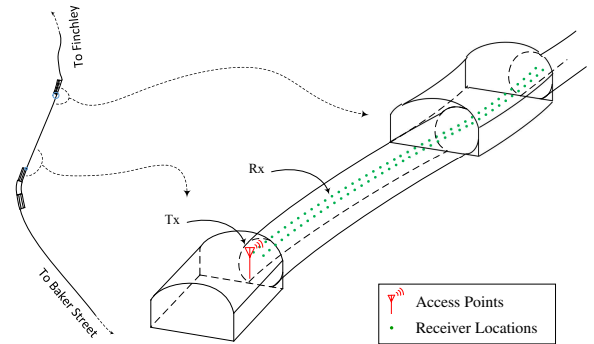


Figure 4. The geometry profile of the section selected from the London Underground subway network.

The results obtained from the optimization framework are compared against the measurement-based placement of

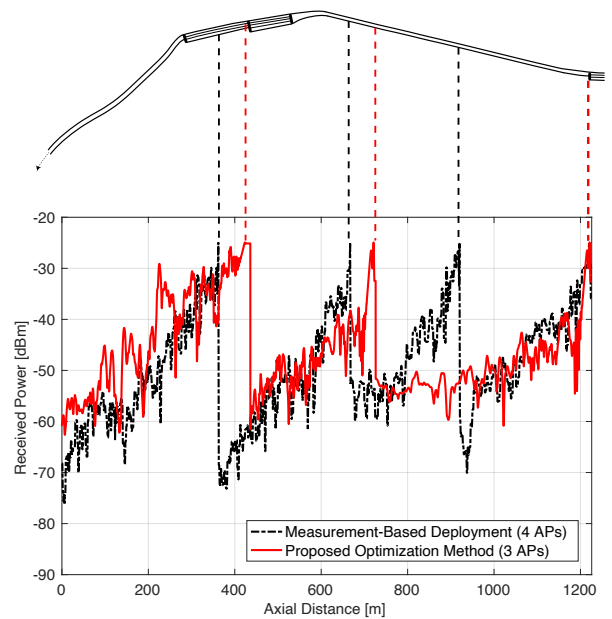


Figure 5. Comparison of received power in the London Underground subway network.

APs, as shown in Fig. 5. It can be observed that the optimization framework results in fewer APs and the average path loss is still better than the average path loss achieved by the measurement-based procedure.

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