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Wireless Channel Characteristics and Model Research in Rail Traffic Scenarios

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Abstract

The integration of theoretical channel modeling with the requirements of real-world railway environments lays the foundation for more reliable wireless communication in high-density transportation infrastructure, thereby influencing current system optimization and future 5G/6G implementation strategies. This paper investigates the wireless channel characteristics in urban rail transit station environments through a comprehensive approach combining empirical measurements, theoretical modeling, and simulation analysis. Focusing on **Yichang East Station in Hubei Province, China**, spatially resolved propagation parameters were recorded under various operational conditions using synchronized channel-sounding equipment equipped with directional antennas and GPS-based precise timing. Fundamental differences in propagation properties were observed between open-track areas and urban/mountainous regions, with wireless channel parameters exhibiting significant environmental variations. Measurement results revealed notable disparities in the path loss exponent, with an average delay spread of 13 ns in open tracks compared to 114.1 ns in complex urban environments. In densely populated urban areas, variance exceeded 37.2 - 38.8 dB, and shadow fading analysis indicated pronounced signal fluctuations following a log-normal distribution. Time dispersion data demonstrated equally striking contrasts in multipath propagation characteristics, with RMS delay spreads of 154.7 ns in complex station environments versus merely 0.5 ns under open-track condition. The findings underscore the necessity of environment-adaptive modeling techniques, challenging the adequacy of traditional free-space propagation models for rail transit applications. The study provides critical insights for system design, particularly in antenna placement optimization, spatial diversity strategies, and adaptive modulation systems. For next-generation railway communication systems, the effectiveness of OFDM combined with advanced equalization techniques in mitigating multipath effects offers practical solutions to current operational challenges. By bridging theoretical channel modeling with practical railway environment demands, this work contributes to more reliable wireless communication in high-density transportation infrastructure, informing both contemporary system enhancements and future 5G/6G deployment strategies.

Keywords

Wireless Channel Model, Multipath Propagation, Rail Traffic Scenarios, Channel Measurement and Channel Characteristics

1. Introduction

Modern rail traffic systems rely heavily on wireless channel technology to operate efficiently and safely. By establishing connectivity among trains, control centers, and wayside devices, it facilitates the real-time supervision and control of the railway network [1]. To develop reliable communication systems that can manage the complexities associated with the dynamic nature of railway operations, it is critical to understand the wireless channel model in train environments [2].

This section summarizes relevant issues associated with rail traffic scenarios, including wireless channel models, multipath propagation, channel measurement, and channel properties. In rail traffic scenarios, the wireless channel model describes the propagation of signals between transmitter (TX) and receiver (RX) nodes over the rails [3]. Among the many elements the model has that affect signal propagation are interference, multipath fading, ambient variables, and signal attenuation. Rail traffic situations offer special difficulties because of elements like high-speed movement, different geography, and the existence of steel structures. Train surroundings can have wireless signals traveling via several paths due to buildings, bridges, tunnels, and trees among other things [4]. Signals flow along several paths owing to reflections, diffraction, and scattering produced by these obstructions, thus causing multipath propagation. Signal quality and strength can be influenced by both constructive and destructive interference. Designing dependable communication systems that can reduce the consequences of multipath propagation calls for a thorough knowledge of this phenomenon [5]. Particularly in rail systems, recent developments in wireless channel characteristics seek to improve signal dependability and bandwidth economy. Massive MIMO and other technologies that employ several antennas at both the transmitter and receiver enhance spectral efficiency and signal quality [6]. Advanced propagation models, such as the Saleh-Valenzuela model, take into account the clustering of multipath components, hence enhancing network capacity and lowering multipath fading [7]. These models enable precise forecasts of communication performance by adapting to real-world situations including changes in train speed and environmental variables. Train communication is especially important as 5G networks grow since they provide lower latency and higher data capacity. By permitting the building of customized virtual networks for certain applications, such signaling and passenger information systems, network slicing improves dependability and efficiency. Different frequency bands react differently depending on propagation conditions. For instance, VHF (Very High Frequency) bands are well-suited for rural locations because of their long-range and capacity to successfully overcome barriers. On the other hand, UHF (Ultra High Frequency) and microwave frequencies could have shorter ranges and more fading in metropolitan areas because of physical barriers, hence allowing faster data rates [8]. In urban areas, structures can provide significant multipath impacts for higher-frequency signals. Research could show that in heavily populated locations UHF signals lose roughly 30% of their power compared to VHF signals. Results from simulations comparing how various frequencies behave in the same environment emphasize the need of choosing the correct frequency range for certain railway settings [8]. Higher frequencies can be employed in cities with great capacity demand; lower frequencies are more appropriate for long-distance rural routes with less impediments. Urban train stations' complicated construction, large passenger numbers, and changeable operational environment create particular difficulties for wireless channels. Moving trains, metal surfaces, and closely spaced barriers interact to create complicated propagation phenomena including reflection, diffraction, and scattering. Common barriers and non-line-of-sight situations increase route loss and shadow fading, which can greatly influence signal strength and stability. Often missing the particular characteristics of train stations, conventional propagation models built for open or suburban settings fall short. Often, specialized techniques such site-specific modeling and ray tracing are needed to more precisely model propagation in these settings [9].

Urban and suburban areas often utilize path loss models like Okumura or Hata [10]. These models, however, fall short of properly reflecting the complexity of railway stations, where dynamic elements such the movement of trains and metal surfaces greatly affect signal functioning. Site-specific models and cutting-edge technologies such as ray tracing have been created to more precisely describe propagation in various settings in order to solve this. Often included in these simulations are platform height, train speed, and the materials used in station building. Improved forecast accuracy including real-world interference and station-specific elements has also been suggested using enhanced versions of the free-space path loss model. Multipath propagation—where signals travel several paths to reach the receiver owing to reflections from surfaces like walls, floors, and trains—is another difficulty in metropolitan train stations. Delayed signals arriving at various periods causes inter-symbol interference (ISI) [11]. Train stations are very high in the Root Mean Square (RMS) delay spread, which quantifies the variation in signal arrival times. Due to the high density of objects and reflective surfaces, studies have revealed that RMS delay spread is much higher in these settings than in open or suburban locations. This delay dispersion degrades the quality of service (QoS), distorts signals and compromises communication quality [12]. Advanced channel estimating techniques are required to address these issues. Though conventional techniques based on pilot signals are often utilized, the complexity of wireless channels grows with frequency, particularly with the arrival of 5G. High-frequency systems can be interfered with by environmental elements such as rain, buildings, and metal surfaces reflecting and absorbing signals. Consequently, many studies are looking at channel estimation and prediction using artificial intelligence (AI) and machine learning approaches.

This paper is motivated by the need to grasp and enhance wireless communication in urban train stops. Urban train stations are among the most difficult settings for wireless communication because of their particular characteristics including high user density, complicated construction, and erratic circumstances. These qualities complicate the creation of a consistent and quick link, which is vital for railway operations as well as for travelers [13]. Dealing with these issues has become increasingly pressing as urban areas grow and the need for smooth communication increases. Indeed, urban major transportation hubs handle millions of passengers daily. Dependable wireless communication facilitates numerous applications that support traveler experience and workforce productivity. Wireless systems provide updates and information to real-time passenger information systems related to station changes, delays, and train scheduling. Reliable wireless connectivity supports the performance of surveillance and safety equipment like CCTV systems and communications equipment for emergency response. Continuous wireless communication is essential to allow the railway staff and automated systems to monitor vehicles, support in activity coordination, and facilitate emergency response [14]. Without permanent Wi-Fi connectivity, these services would stop and lead to safety issues, delays, and a poor experience for passengers. The rapid development of wireless technology, especially 5G, and the investment in emerging technologies (e.g., 6G), increase the demand for research in this domain. 5G aims to revolutionize wireless communications by enhancing mobile broadband, enabling consistent low-latency links, and supporting massive machine-type communication. These aspects are critical in urban train stations where reliable low-latency control systems, continual high-capacity connectivity to the internet, and support for Internet of Things (IoT) devices are needed. Therefore, the success of 5G, as well as future technologies, will depend on our understanding of the specific challenges that metropolitan train stations introduce. High user density and user mobility will potentially HS strain resource giving considerations of network traffic; simultaneously, multipath propagation and interference will potentially impact and degrade the quality of signal for users [15].

Therefore, without an ambient understanding of wireless channel properties and potential performances associated with train stations it will be increasingly difficult to design and roll out a 5G network to meet these demanding features. The dearth of studies particularly on wireless communication in metropolitan train stations is another incentive for this work. Although much study has been done on wireless channel modeling in urban settings, train stations have gotten rather little notice. Many current models overlook the features of these settings, including high user density, multipath propagation, and changing channel conditions [16]. Wireless networks in train stations can therefore underperform, which would result in a bad user experience and connectivity. Realistic models of wireless channels in train stations will be developed in this paper to close this gap, along with suggested optimization strategies to raise network performance.

Thus, this paper investigates the essential wireless channel characteristics for the urban train station, derives feasible models for their properties, and proposes various optimizations to improve the network performance. Such goals emerge as this is crucial for addressing the specific features of the railway stations and for delivering, at the same time, fit-for-purpose and high-quality connectivity to guests, attendants and automated systems. The purpose of this paper is to explore the wireless channel characteristics of the urban railway. This requires in-field collection of measurements used to model differentiating channel characteristics, including path loss, delay spread and Doppler shift. This will give us a basic understanding of electromagnetic wave propagation characteristics in a typical train station environment and can include multipath propagation, reflected signals, interference, and dynamic situation. This will assist in capturing the dominating properties of channels in terms of wireless communication with railway terminal and lead towards a feasible model representative of realistic situations. The second one is to establish a precise channel model of the wireless channels for various behaviors of stations on urban railway. These channel models will be derived from data collected from measurements performed in the field. In fact, these channel models will contain deterministic and stochastic nature. Stochastic models will be used to characterize random variations in the level and quality of the signal, while deterministic techniques such as ray-tracing will provide an accurate representation of the shape of the station and its construction materials. This will allow us to implement models able to predict the behavior of wireless channels in train stations consistently and to build the necessary models to optimize the performance of the network. The third goal is to form optimization approaches for wireless communications networks in urban railways stations. Focused on results of these processes frameworks and methods, which aim to minimize important leads gap occurred in the urban railway stop environment, e.g. interference, multipath and motion. For instance, these methodologies may identify improvements in quality, reduction of interference, and engender robustness. The third aim is to propose methodologies that could be employed in the real problem context of an urban train stop to enhance communications performance. The fourth aim is to evaluate the suggested models and optimization methods against field data and simulations. This includes validating their performance against field measurements to ensure accuracy and relevancy, and the models and methods will also be validated to the extent possible in controlled settings. The validation measures will demonstrate the potential of the models and methods for improving wireless communications in train stations, thereby enhancing confidence in the proposed event. Among the most challenging sites for wireless communication are high-density urban railway stations, which this thesis addresses. Key issues such multipath propagation, interference, and dynamic channel conditions will be the emphasis of the project, which aims to produce models and solutions applicable in actual situations. The study will focus on wireless channel characteristics in these circumstances and will not address other aspects of wireless communication, including network architecture or protocol design. The results of the paper will affect these locations and may assist in guiding the next wireless system design. The study is geographically restricted to urban railway stations and could not be immediately relevant to rural or suburban stations. These settings offer unique qualities including less user density and more basic building that can call for different approaches to wireless communication. Moreover, some parts of the station could be off-limits and user density changes could influence the completeness of the data. The design and implementation of the study will include close examination of these limitations. The trade-off between model accuracy and computing complexity is another constraint of the study. Although deterministic models such as ray-tracing can generate very accurate outcomes, they are computationally intensive and might not be appropriate for real-time uses. Conversely, stochastic models require less computer resources but might not fully reflect all the complexity of the wireless channel. By developing models that are both precise and useful, the study will try to strike a compromise between both strategies.

The next section describes the Theoretical Basis of Wireless Propagation Characterization, Wireless Channel Communication Fading's, Common Wireless Channel Measurement Methods and Measurement Equipment and Techniques. Section III includes the Measurement System Parameters and Methodology, Data Collected and Processing, Measurement Scene, Activity and Purpose, Measurement Description and Simulation Techniques. Section IV discusses Path Loss Analysis, Shadow Fading Analysis, MS Delay Spread Analysis, Comparative Analysis of Simulation Results with Relevant Literature, Discussion and Implications for Railway Communication. Sections V and VI contain Conclusion, Outlook and Future Work, Acknowledgment, Biographies and References.

2. Theoretical Basis of Wireless Propagation Characterization

Wireless signal propagation is primarily determined by the behavior of electromagnetic waves as they move across various surroundings. Wireless propagation can be explained theoretically using models that account for signal attenuation, scattering, reflection, and diffracting as they travel from a transmitter (TX) to a receiver (RX). These characteristics are influenced by transmission distance, frequency, antenna arrangement, and environmental complexity [17].

The characterization of wireless propagation can be divided down into two categories: large-scale effects, including path loss and shadow fading, and small-scale effects, like multipath fading, delay spread, and Doppler shifts. Predicting signal strength, placing antennas optimally, and creating dependable communication lines all depend on an understanding of these effects [18]. Standard free-space theories are unable to capture the behavior of real-world complex environments, such as urban railway stations, where dynamic passenger movement, structural barriers, and metallic surfaces predominate. A mix of theoretical Basis of Wireless Propagation, statistical analysis, and empirical measurement is therefore required for accurate propagation characteristic in order to reflect the actual behavior of the wireless channel. Moreover, the station environment presents challenges such as rapid changes in signal paths due to moving trains and fluctuating crowd densities. These factors demand channel models that are not only spatially accurate but also time-sensitive. Thus, the theoretical framework must support both stationary and non-stationary channel characteristics to effectively design communication systems capable of maintaining connectivity in such highly dynamic settings. This theoretical framework forms the basis for the simulations and measurements conducted in this thesis. It ensures that the complex and rapidly changing wireless propagation behavior in urban railway stations is accurately represented. This allows for the development of communication strategies tailored for high-density, highly reflective environments such as Yichang East Railway Station.

2.1. Wireless Channel Communication Fading's

Signal strength and reliability are impacted by a number of factors that impede wireless signal propagation in urban railway station environments. Large-scale fading and small-scale fading are the two main categories into which these impairments are usually divided. Each form of fading is brought on by a distinct physical phenomenon and affects various facets of signal behavior over time and place.

2.1.1. Big-Scale Fading

Two important elements that impact signal dependability in urban railway station environments are path loss and shadow fading. Path loss is affected by the intricacy of the station architecture and rises with distance. The log-normal distribution of shadow fading, which is brought on by fixed obstacles and crowded human areas, makes signal strength uncertain. This emphasizes how location-aware simulation and strong system design are necessary to reduce large-scale fading in intricate transportation hubs.

1) Path Loss

Path loss is a key concept in wireless communication that defines how signal intensity decreases as it travels over space from transmitter to receiver. It is an important aspect in determining the quality and dependability of wireless communication systems, especially in complicated settings such as metropolitan railway stations. Path loss is caused by a mixture of factors, including the distance between the transmitter and receiver, the signal's frequency, and the existence of barriers such as walls, trains, and other objects. Understanding path loss is critical for developing wireless networks that can deliver dependable connectivity in tough conditions:

Free-space path loss is the most fundamental type of path loss, because it happens even in an ideal, unobstructed environment. It describes how a wireless signal weakens as it travels across open space, away from the transmitter. This decrease in signal strength is mostly due to the signal spreading across a broader area as it travels away from the source. In free space, the signal propagates in a spherical pattern, with its power dispersed across the surface of an expanding sphere. As a result, signal strength drops as the cube of the distance from the transmitter [19].

The free-space path loss is formally defined by the following formula:

$$PL_{fs} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \tag{1}$$

where:

- PL_{fs} represents the free-space route loss in decibels **(dB)**.
- d represents the distance between the transmitter and receiver in meters.
- f indicates the signal's frequency in hertz (Hz).
- c represents the speed of light 3×10^8 m/s.

Free-space path loss is an important topic for understanding signal attenuation. However, in real-world settings, other phenomena including absorption, scattering, reflection, diffraction, and shadowing all contribute to path loss. A wireless signal passes through a medium altering some of its energy to another form, including heat, causing absorption. Signals in urban train stations could go through walls, windows, or even people's bodies, all of which can absorb part of the signal energy. The medium's material characteristics, including thickness, density, and composition, decide the degree of absorption. While glass and wood are less so, concrete and metal are quite absorbent. Absorption reduces total signal power, hence causing path loss and complicating the receiver's ability to recognize and decode the signal. Absorption can significantly affect wireless communication quality in train stations, since signals must traverse several barriers. When a wireless signal encounters tiny objects or uneven surfaces, scattering occurs, causing it to spread in many directions. Scattered items in city train stations can include signs, furniture, and even throngs of travelers. A dispersed signal spreads its energy, therefore reducing its potency as it gets to the recipient. Scattering is particularly troublesome in high user density locations since the presence of many small objects can cause significant signal attenuation. Scattering also facilitates multipath propagation, in which numerous copies of the same signal arrive at the receiver via distinct routes. Although multipath propagation can sometimes increase signal strength by means of constructive interference, it usually results in signal fading and deterioration caused by destructive interference. A wireless signal reflects off a surface and changes direction. Large metal structures in metropolitan railway stations, such as trains, rails, and station design, reflect signals many times before reaching the receiver. Reflection causes route loss by reducing total signal strength since some of the signal energy is lost every time it reflects off a surface. Reflection also creates multipath propagation, wherein several copies of the same signal arrive at the receiver at various timings and amplitudes. Although diffraction can improve signal propagation around obstacles, it also causes route loss by lowering overall signal intensity. The signal's energy decreases as it bends around the barrier, hence lowering its power at the receiver. Diffraction is especially crucial in railway stations for guaranteeing coverage in locations blocked by significant buildings, including tunnels or underground platforms. On the other hand, wireless communication quality could be affected by diffraction-induced attenuation. Shadowing results from an obstacle blocking the direct path between the transmitter and the receiver, therefore reducing the signal. Large urban railway station elements like trains, platforms, and walls can create great shadows. A shadowed signal has to get to the receiver by means of indirect pathways like reflection or diffraction. Often, more path loss and less signal strength follow from these complex routes. In dynamic settings like railway stations, where the movement of trains and people create rapid scene changes, shadowing is particularly troublesome. For instance, a train on a platform can obstruct signals and create a dark region with poor connectivity. Likewise, passenger movement could change signal intensity because of environmental factors. Path loss is often represented by mathematical formulas that show how signal strength declines with distance and other variables. These models are critical for forecasting signal behavior and improving wireless network architecture. The long-distance path loss model builds on the free-space model to account for the effects of distance in real-world settings. Here's the formula:

$$PL(d) = PL(d_0) + 10_n \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (2)$$

where:

- $PL(d)$ represents the route loss at distance d in decibels.
- $PL(d_0)$ represents the path loss at a reference distance d_0 (usually 1 meter).
- n represents the path loss exponent, which varies depending on the environment.
- X_σ is a random variable that represents shadowing effects. It is commonly described as a Gaussian distribution with zero mean and standard deviation σ.

The long-distance model is extensively employed in urban contexts because it takes into account the increased route loss caused by obstructions and interference.

2) Shadow Fading

Shadow fading, also known as large-scale fading, is a wireless communication phenomena caused by objects blocking the direct line-of-sight (LOS) connection between the transmitter and receiver. These barriers include buildings, trees, hills, and other physical structures. Shadow fading causes fluctuations in received signal power over long distances, on the range of tens to hundreds of meters. Unlike small-scale fading caused by multipath propagation, shadow fading is caused by signal power being blocked and attenuated by massive objects in the propagation environment [19].

Shadow fading is characterized by the following:

a) Log-Normal Distribution: A log-normal distribution is used to describe signal strength changes caused by shadow fading. This means that the received signal power, measured in decibels (dB), has a Gaussian distribution.

b) Spatial Correlation: Shadow fading has spatial correlation, which means that signal power variations are not independent in close areas. The correlation coefficient falls as the distance between measurement points rises.

c) Environment Dependence: The degree of shadow fading varies with the quantity and kind of barriers in the propagation environment. Urban regions with dense infrastructure experience greater shadow fading than rural or open places.

The received signal power in the presence of shadow fading can be stated as:

$$(d) = P_t + G_t + G_r - PL(d) + X_\sigma \tag{3}$$

where:

- P_t is the transmitted power in (**dB**).
- G_t and G_r are the transmitter and reception antenna gain in **(dB).**
- $PL(d)$ is the path loss at distance in (**dB**).
- X_σ is a zero-mean Gaussian random variable (in decibels) with a standard deviation of, depicting shadow fading.

The probability density function **(PDF)** of σ is given by:

$$fX_\sigma(x) = \frac{1}{\sqrt{2\pi\sigma}} \mathrm{e}^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4}$$

where:

- μ is the mean (usually 0 in the log-normal model),
- σ represents the standard deviation of shadow fading in **(dB).**

The presence of $P_r(d)$ causes the received signal power X_σ to be a random variable, capturing the effects of shadow fading.

Shadow fading has spatial correlation, which means that signal intensity measurements from close sites are associated. The correlation function of shadow fading can be described as:

$$\rho(\Delta d) = \mathrm{e}^{-\frac{\Delta d}{d_c}} \tag{5}$$

where:

- Δd represents the separation distance between two measurement locations,
- d_c is the decor-relation distance, which denotes the distance at which shadow fading becomes uncorrelated.

In urban environment, the decor-relation distance d_c is usually lower (e.g., tens of meters) than in rural areas, where d_c can be several hundred meters.

Shadow fading provides significant obstacles to wireless communication, especially in urban and suburban settings. Key impacts include:

a) Coverage Variability: Shadow fading produces changes in signal strength, resulting in coverage gaps where signal power falls below the receiver's sensitivity threshold.

b) Interference: Variations in signal power alter interference levels in cellular networks, influencing the performance of adjacent cells.

c) Capacity and Quality of Service (QoS): Shadow fading reduces connection reliability and data rates, lowering the overall quality of service for end users.

Shadow fading is commonly incorporated into wireless network planning and simulation tools via statistical models. Combining the log-normal shadowing model with the path loss model is a usual approach.

$$PL_{total}\left(d\right) = PL\left(d\right) + X_{\sigma} \tag{6}$$

where $PL\left(d\right)$ represents the deterministic route loss component, and X_{σ} compensates for the random changes caused by shadow fading.

2.1.2. Smal Scale Fading

Multipath propagation, in which signals bounce off trains, walls, and people, is the primary cause of small-scale fading in urban train stations. This leads to inter-symbol interference and RMS delay spread, which in crowded places can reach up to 154.7 ns. Furthermore, moving trains' Doppler impact lowers channel coherence time by shifting the signals frequency. For dependable communication in rapidly evolving contexts, these dynamics necessitate adaptive modulation techniques such as OFDM and real-time channel estimation.

1) RMS Delay Spread

In wireless communication, the Root Mean Square (RMS) delay spread is an important measure that measures how a signal disperses over time while moving over a multipath environment. It is a measurement of the interval of time between the first and last major multipath components arriving at the receiver. RMS delay spread offers important information about the wireless channel's temporal properties, which are crucial for comprehending and lessening the consequences of multipath propagation. The performance of wireless communication systems is greatly influenced by RMS delays spread in settings such as metropolitan railway stations, where multipath propagation is prominent because of big metal structures, high user density, and dynamic situations [13].

The square root of the power delay profile's second central moment (PDP) is used to compute RMS delay spread. The received signal power as a function of time delay is represented by the power delay profile. RMS delay spread T_{rms} can be defined mathematically as follows:

$$T_{rms} = \sqrt{\frac{\int_0^{\infty} \left(T - \bar{T}\right)^2 P_{(T)} \mathrm{d}T}{\int_0^{\infty} P_{(T)} \mathrm{d}T}} \tag{7}$$

where:

- T is a multipath component's time delay.

- $P_{(T)}$ is the multipath component's power at delay T.

The mean delay, or $\overline{T}$, is determined as follows:

$$\overline{\tau} = \frac{\int_0^\infty \tau P(\tau)\,\mathrm{d}\tau}{\int_0^\infty P(\tau)\,\mathrm{d}\tau} \tag{8}$$

The RMS delay spread provides a measure of the spread of the multipath components around the mean delay. It is expressed in units of time, typically nanoseconds **(ns)** or microseconds **(μs)**.

2) Multipath Propagation

A basic phenomenon in wireless communication networks called multipath propagation occurs when transmitted signals travel many routes to the receiver because of reflection, diffraction, and scattering. Different signal channels generate variations in received signal strength, phase shifts, and time delays that can either cause constructive or destructive interference. Building dependable communication systems depends on an understanding of multipath propagation, especially in cities, high-speed railroads, and satellite communication [9]. The interplay of transmitted signals with obstacles including buildings, trees, topography, and atmospheric conditions causes multipath propagation. Reflection occurs when a radio wave strikes a smooth surface, such a structure or body of water, some of the signal reflects while keeping its energy. Waves bend over sharp edges or barriers, allowing signals to reach areas that would otherwise be in shade. Rough surfaces cause waves to scatter in various directions, hence producing uneven reception.

Assuming a transmitted signal is described as follows, we may theoretically investigate multipath propagation by viewing the received signal as a superposition of several signals arriving at different times and with different amplitudes:

$$s(t) = A_t \cos(2\pi f_c t) \tag{9}$$

where A_t is the carrier frequency and f_c is the transmitted amplitude, The received signal can be represented as follows,

$$r(t) = \sum_{i=1}^{N} A_i \cos\left(2\pi f_c (t - T_i) + \varnothing_i\right) \tag{10}$$

where:

- N represents the quantity of propagation paths,
- A_i the amplitude of the i^{th} path,
- T_i the time delay provided by the i^{th} path,
- $\varnothing$ the phase shift brought on by propagation.

Urban railway stations are complex spaces with a lot of infrastructure, such as platforms, buildings, trains, and people moving through them. Multiple reflective surfaces are produced by these structures, which have a big impact on the properties of wireless channels. Multipath propagation in urban train station scenarios is primarily influenced by the following factors:

- High Structural Density: Strong signal reflections are caused by the presence of huge metallic structures, glass surfaces, and platform canopies, which leads to significant multipath interference.

- Dynamically Changing Environment: High passenger density and moving trains cause signal pathways to change quickly, creating dynamic channel conditions.
- Non-Line-of-Sight (NLOS) Conditions: Direct signals are blocked by obstructions like train bodies and station walls, necessitating the use of reflected and diffracted pathways for communication.
- Doppler Effect Due to Train Movement: Doppler shifts, which are introduced by high-speed trains, change signal frequencies and compromise the reliability of communication.

3) Doppler Effect on Multipath Propagation

When either the transmitter or receiver is in motion, such as in high-speed railways or vehicular communication, the frequency of the received signals shifts due to the Doppler effect. The frequency shift for a signal arriving at an angle θ_i is given by:

$$f_{D_i} = \frac{v}{\lambda}\cos\theta_i \tag{11}$$

where:

- v is the receiver's velocity relative to the transmitter,
- λ represents the wavelength of the transmitted signal,
- θ_i indicates the angle of arrival.

The maximum Doppler shift is given by:

$$f_D = \frac{v}{\lambda} \tag{12}$$

Doppler shift generates rapid variations in signal phase, resulting in fast fading, which has an important impact on high-mobility communication systems. By creating fading, delay spread, inter-symbol interference, and Doppler shifts, multipath propagation significantly affects wireless communication performance. Unique challenges for urban railway stations include high reflectivity, NLOS situations, and dynamic environments, which make them vital locations for improved wireless communication design. Developing better communication solutions like equalization, diversity schemes, and adaptive modulation to lower multipath fading requires an awareness of these impacts. The wireless channel characteristics in complex urban railway contexts are defined by the combination of these two fading's (**Big-Scale and Small-Scale)**. Understanding and addressing both is essential for efficient system design and implementation, particularly in high-density, dynamic environments in train stations.

2.2. Common Wireless Channel Measurement Methods

A variety of channel measurement methods are used in wireless communication systems. Three widely used techniques—the frequency-domain measuring method, the pseudo-random sequence measurement method, and the periodic pulse measurement method—are briefly explained in this section [20] [21].

1) Periodic Pulse Measurement Method

A train of narrow pulses is sent into the wireless channel as part of the periodic pulse measuring method, and time-domain convolution is used to determine the impulse response. This method is very helpful for observing the multipath channel's time-dispersion properties, such RMS delay spread. The **pulse period** T_d must be long enough to cover the full multipath delay window, and the **pulse width** T_p must be narrow enough to resolve closely spaced reflections in order to guarantee high-resolution multipath analysis. As seen in Figure 1, this configuration makes it possible to clearly observe the early and late arriving signal components. This technique can result in signal clipping at the receiver because of the high peak-to-average power ratio (PAPR) of pulse signals. This can be countered by increasing the transmitter's output power and using linear amplification techniques in the receiver. Furthermore, this approach is limited in its application to phase-sensitive modeling since it only records magnitude information while ignoring phase. A typical periodic pulse waveform with distinct pulse intervals and time resolution that can be used to differentiate multipath in a station context is shown in Figure 1.

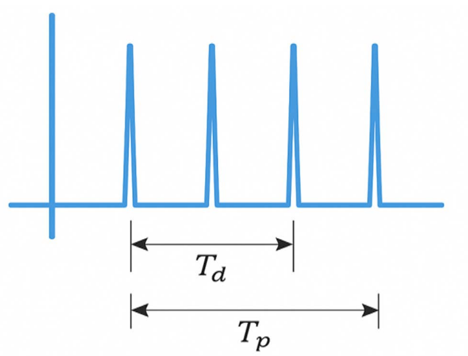

Figure 1. Periodic pulse waveform.

Measurement equipment utilized: These pulse signals were sent and received using the cylindrical wide-band antenna and vertical omnidirectional receiver depicted in Figure 1. This allowed for the recording of channel responses over both open platforms and enclosed station corridors.

2) Pseudo-Random Sequence Measurement Method

This work also uses the pseudo-random sequence measurement method, which probes the channel using a modulated m-sequence (maximum length binary sequence), to overcome the PAPR elated drawbacks of pulse-based techniques. This method extracts the channel impulse response by taking use of the auto correlation nature of pseudo-random sequences [22]. The transmitter transmits a modulated m-sequence into the wireless channel via the RF front end, as shown in Figure 2. The signal is associated with a locally generated reference sequence at the receiver. The multipath channel response is represented by the correlation output's peak. Complex channel estimation is made possible by this method's preservation of both phase and magnitude information. It is more suited for real-time measurement and has greater noise resistance. Clock drift between the transmitter and receiver, which causes small timing mistakes in analog systems, could nonetheless cause time dilation effects.

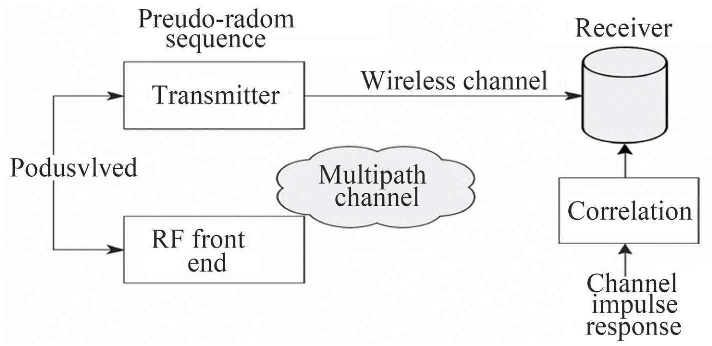

Figure 2. Pseudo-random sequence measurement.

Measurement tools: The same antenna configuration was also applied during the pseudo-random sequence measurements, with a laptop-integrated channel sounder used to carry out the digital signal processing and will be displayed later.

When phase coherence and fine resolution were crucial, this technique worked especially well for catching reflections in metallic tunnels and close to train exits.

2.3. Measurement Equipment and Techniques

Channel sounders are primary instruments that collect measurements associated with the characteristics of wireless communication channels. A channel sounder is comprised of a transmitter (TX), a receiver (RX), and some sort of signal processing hardware. The channel sounder quantifies the important channel characteristics, such as path loss, delay spread, and Doppler shift, by transmitting known signals (e.g., chirps or pseudo random sequences) and examining the received signals. Figure 3 shows the Omnidirectional Antennas.

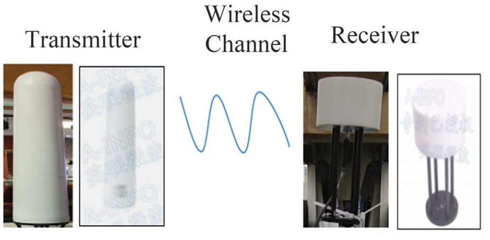

Figure 3. Omnidirectional antennas.

In the context of studying the effects of propagation characteristics, interference, and several other factors, channel sounders are especially advantageous when examining transmission in train applications. Channel measurement systems rely on antennas as the devices that are able to send and receive wireless signals. The antenna type is defined by the frequency band and environmental considerations. While omnidirectional antennas receive signals equally in all directions, directly associated antennas are capable of transmitting signals in a singular direction.

3. Measurement System Parameters and Methodology

Our test equipment primarily consisted of a transmitter (TX) and receiver (RX), laptops, power supplies, a moving carrier (handcart), and Global Positioning equipment (GPS). Hubei, Yichang East Rail Train Station provided a time-division multiplexed (TDM) channel sounder that emitted a 100 MHz bandwidth chirp signal with a 10 ns delay resolution and 43 dbm TX strength. According to the TDM channel sounder's time structure, the RX would receive 230 chirp signals every second. It included an omnidirectional antenna with 17.5 dBi gain, a signal resource, an Uninterruptible Power Supply (UPS), and a laptop for operation. The omnidirectional receiving antenna has a gain of 17.5 dBi. A portable computer recorded GPS position information as well as radio signal data throughout the process. All measuring system parameters are presented in **Table 1**.

Table 1. Measurement system parameters.

Measurement parameters	Numerical value
Center frequency	932.4 MHz
Signal bandwidth	0.2 MHz
Sample points/chirp	230
Transmitting antenna type	870 - 960 Mhz directional antenna
Receiving antenna type	698 - 3800 MHz omnidirectional antenna
Transmit antenna gain	17.5 dBi
Receiving antenna gain	3 dBi
Transmitting antenna height	14.61 m
Receiving antenna height	1.312 m
Signal transmit power	43 dbm
Air temperature	19˚C
humidity	86% RH
Weather condition	cloudy
Pm 2.5	43 ug/m^3
Pm 10	81 ug/m^3

3.1. Data Collected and Processing

The channel sounder signals were transformed using a Fourier transform from the frequency domain to a channel impulse response (CIR) in order to determine the statistical properties of the channel. There is a wealth of existing literature on CIR, with a specific emphasis on CIR collection techniques [23]. A laptop can save the CIR values that the RX samples for each measurement. It then gathers the PDP of each related received signal and the phase of each vector sample. The relationship between the channel input and output can be described by an impulse response function using Bello's impulse response function [23]. when the time-varying impulse response function is referred to $H(\tau)$. where N is the total number of paths, A_i is the attenuation amplitude of path i, $\varnothing_i$ is the phase deviation of path i, τ_i is the time delay of path i, and Dirac Delta δ_τ is the function. The auto correlation function of the impulse response is often represented by the channel's characteristics.

$$H(\tau)=\sum_{i=1}^{N} A_i e^{-j\varnothing_i \delta(\tau-\tau_i)} \tag{13}$$

3.2. Measurement Scene, Activity, and Purpose

The measurement systems' accuracy depends on the placement of the antennas at the train station, as it directly affects the resulting signal strength and the measurement capability of the multipath features. Either a measurement system embeds used GPS technologies to accurately locate the measurement equipment at the train station and align the readings in the real world. The real-time positional data from GPS receivers is integrated with signal data in order to create accurate spatial analysis. Staff will utilize portable data collection and analysis tools like laptop computers or dedicated equipment to program and analyses the measurement data. The systems use signal processing techniques such as Fourier transforms and correlation analysis to derive channel characteristics and calculate parameters such as delay spread and Doppler shift. In summation, channel sounders, antennas, GPS technologies, and data collection systems create an integrated capability for measuring wireless channel activity in a railway environment. Thus, providing the foundation for future implementations of trustworthy communications systems. Figure 4 shows the Antennas channel sounder and GPS position.

Figure 4. The antennas channel sounder and GPS position.

3.3. Measurement Description

The location of the measurement scene for this thesis was Yichang East Rail Train Station in Hubei Province, China. This urban railway station provided a complex and fluid environment that fulfilled all user density, large metal structures (trains, platforms, and station architecture) and operational conditions, therefore making it appropriate for studying wireless channel characteristics such as path loss, shadow fading, and multipath propagation. Figure 5 shows the Design of the measurement setup at Yichang East Rail Station.

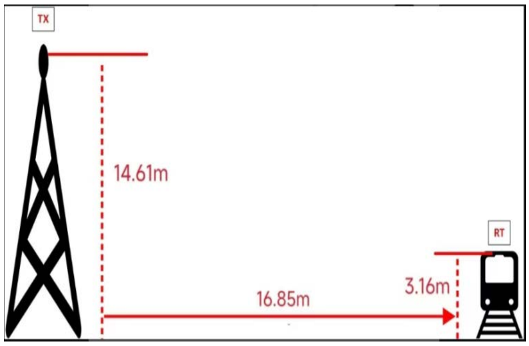

Figure 5. Design of the measurement setup at Yichang east rail station.

Figure 6. The GPS location and the antennas channel sounder.

The measurement activity consisted of setting up a synchronized channel sounding system using a transmitter (TX) and receiver (RX). The TX had a directional antenna mounted at 14.61 meters, while the RX was an omnidirectional antenna located at 1.312 meters to assess the same communications scenarios as the operational environment. PS technology was utilized to maintain a precise location, and time synchronization. The principal measurements included signal level, path loss, shadow fading and RMS delay spread, where the parameters included a center frequency of 932.4 MHz, a 0.2 MHz signal bandwidth, and a 43 dBM transmit power level. The environmental conditions at the time of the measurements were 19˚C, 86% humidity and overcast. The intention of the measurements was to characterize the wireless channel for urban railway station properties by measuring the path loss, shadow fading and RMS delay spread. By comparing the measured empirical data with theoretical models, such as free space path loss and the CI model, their relevance in a complex environment could be statistically validated. The data, as well, has the ability to provide pertinent recommendations for the optimization of communications systems, such as adaptive antenna placement, diversity schemes or adaptive modulation schemes including OFDM, to reduce the effects of multipath signal transmission and improve reliability in railway environments. Figure 6 shows the GPS location and the antennas channel sounder.

3.4. Simulation Techniques

1) Path Loss Simulation

The paper used empirical and deterministic simulation techniques to model wireless communication in rail traffic scenarios. The following strategies were used:

a) Free-Space Path Loss (FSPL) is a theoretical model for signal attenuation in an ideal, obstacle-free environment.

b) CI Fitting Curve: A curve-fitting technique that models path loss using gathered data. The CI model takes into consideration both the distance between the transmitter and receiver and environmental conditions.

c) Empirical Path Loss Model: The paper utilized the following formula to model path loss:

$$PL(d) = A + 10_n \log_{10}(d) + X_\sigma \tag{14}$$

where:

- $PL(d)$ is the path loss at distance d.
- A is the intercept.
- n is the path loss exponent.
- X_σ is the shadowing term.

2) Shadow Fading Simulation

Shadow fading was approximated using a log-normal distribution.

The formula used was:

$$\text{Shadow Fading}(\text{dB}) = X + \sigma \tag{15}$$

where:

X is a random variable from a standard normal distribution.

σ is the standard deviation of the shadow fading.

3) RMS Delay Spread Simulation

Multipath Propagation: The RMS delay spread was calculated to determine the temporal dispersion of the signal owing to multipath effects. The following formula was used:

$$\sigma_\tau = \sqrt{\frac{\sum_{m=1}^{M} (\tau_m - \overline{\tau}) |h(\tau_m)|^2}{\sum_{m=1}^{M} |h(\tau_m)|^2}} \tag{16}$$

where:

σ_τ is the RMS delay spread.

τ_m is the delay of the m-th multipath component (MPC).

$\overline{\tau}$ is the mean excess delay.

4) Simulation Environment

a) Railway Environment: The simulation was conducted in the Hubei, Yichang East Rail Train Station environment, which included variable topography, barriers, and train speeds.

b) Multipath Effects: The simulation included reflections, diffractions, and scattering induced by obstacles like tunnels, bridges, and buildings.

4. Path Loss Analysis

Table 2 summarizes the statistical properties of path loss under real-world measurement and model comparison situations, including the RT Simulation, Free-Space path Loss Model, and RT Fitting Model. Each item reports the minimum, maximum, and mean path loss values (in decibels), providing information about the variability and accuracy of each modeling approach. Figure 7 shows the Wireless Channel Path Loss Analysis.

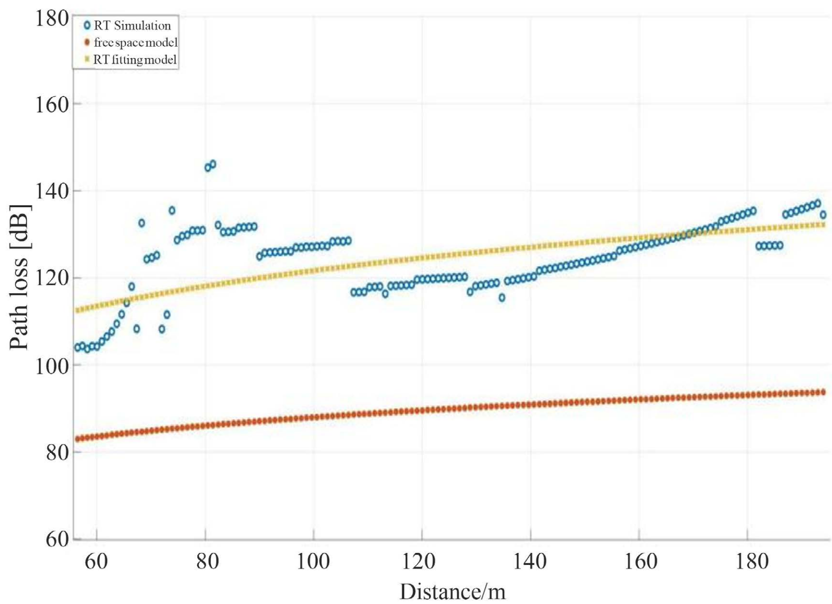

Figure 7. Wireless channel path loss analysis.

Table 2. The statistical characteristics of path loss in whole measurement.

X	Min [ns]	Max [ns]	Mean [ns]
RT Simulation	105	149	122
free-space path loss	82	95	90
RT Fitting Model	115	132	122

The RT Simulation data shows a wide range of values, with a low of 105 dB, a maximum of 149 dB, and a mean of 122. These values reflect the substantial variability found in real-world contexts, particularly complicated railway station scenarios involving metallic structures, walls, and moving trains that cause extensive multipath propagation and signal reflection. This extensive coverage reveals the dynamic and blocked nature of the urban train station wireless channel. In contrast, the Free-Space Path Loss Model produces significantly lower and more stable results, with a minimum of 82 dB, a maximum of 95 dB, and a mean of 90 dB. This consistency stems from the model's assumption of unobstructed, line-of-sight propagation, which ignores environmental variables such as walls, ceilings, and moving trains. As a result, while the model is theoretically correct, it underestimates the real loss experienced in operational railway stations. The RT Fitting Model, which is intended to better reflect environmental complexity, measures a minimum of 115 dB, a high of 132 dB, and an average of 122 dB. These statistics closely match the RT Simulation results, suggesting that the RT Fitting Model accurately describes channel behavior in the measuring context. Its agreement with empirical data demonstrates its applicability for accurate modeling of signal transmission in rail stations. The RT Simulation and RT Fitting Model provide a realistic representation of channel circumstances, whereas the Free-Space Model just acts as a simplified reference. The large disparity between these models demonstrates that traditional theoretical approaches are inadequate in complex contexts and must be updated or adjusted using empirical or RT-based methodologies. The main characteristic of a certain propagation environment is the multipath effect, which comes from environmental reflection, refraction, and diffusion. Loss of path: Muck work has shown that the distance d and the real PL (denoted as P) in a particular situation have a relationship that can be expressed as [19]:

$$P_{db} = PL(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + x_{\sigma[dB]} \tag{17}$$

where γ signifies the PL index, $X_{\sigma[dB]}$ means the standard normal distribution with a standard deviation σ, and d_0 refers to the reference distance. Typically, a scenario implies a specific γ value.

K factor is a common SSF characteristic that represents the ratio of the power of a (potential) dominating multipath component (MPC), often the LoS, to the power of reflected MPCs. However, given an unknown context, it is impossible to discriminate between the LoS component and the other MPCs. As a result, the K factor of a snapshot $h(\tau)$ may be roughly estimated as:

$$K_{dB} = 10\lg\left\{\frac{\left(\left|h(\tau_{m0})\right|_{\max}\right)^2}{\sum_{\tau_m \neq \tau_{m0}}\left(\left|h_{(t)}\right|\right)^2}\right\} \tag{18}$$

where τ_{m_0} is the tap index of the max amplitude.

4.1. Shadow Fading Analysis

Shadow Fading Analysis is the fluctuation in signal intensity produced by barriers, topography, and other environmental elements between a transmitter and receiver in wireless communication systems. When a radio wave travels from a transmitter to a receiver, it meets obstacles such as buildings, trees, topographical changes, and weather conditions. These impediments affect signal attenuation or weakening, resulting in fluctuations in signal intensity at the receiving end. Shadow fading is most noticeable in non-line-of-sight (NLOS) settings, in which the direct line between the transmitter and receiver is obscured. Figure 8 shows the Shadow Fading signal.

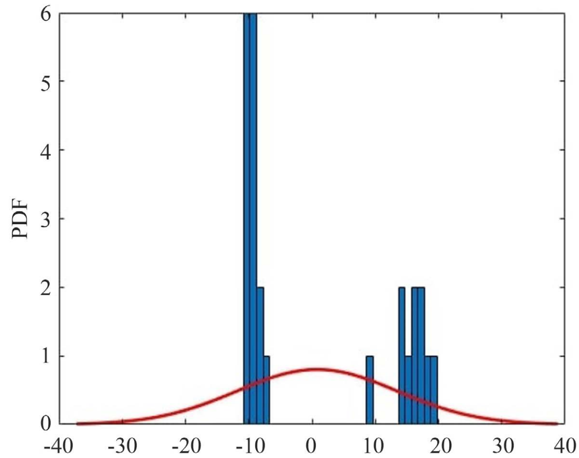

Figure 8. Shadow fading.

Table 3. The statistical characteristics of shadow fading in whole measurement.

Y	Min [ns]	Max [ns]	Mean [ns]
DATA 2	−37.2	38.8	0.7
X	Min [ns]	Max [ns]	Mean [ns]
DATA 1	−10.2	19.2	4.5

Table 3 reveals the statistical characteristics of shadow fading measurements, which compares Data 1 (X) with Data 2 (Y). Often called "log-normal fading," the phrase "shadow fading" indicates changes in signal strength caused by topography and other environmental factors blocking the transmission between a transmitter and receiver. Ranging from a low of −10.2 ns to a high of 19.2 ns, the shadow fading values for Data 1 (X) have a mean of 4.5 ns. The negative minimum value reveals instances of signal enhancement caused by either favorable conditions or measurement anomalies. The mean value of 4.5 ns shows, however, that the typical signal intensity is rather higher. The very small range of values reveals the signal's slight oscillations brought on by shadowing influences. With a low of −37.2 ns and a high of 38.8 ns, Data 2 (Y) shows a wider spectrum of shadow fading values including a mean value of 0.7 ns. The broader range suggests greater signal intensity variation, most likely caused by larger environmental obstacles or changing conditions between the transmitter and receiver. Though the mean of 0.7 ns suggests that signal variations are usually balanced overall, the negative minimum value suggests that there are sporadic signal surges: greater unpredictability than in Data 1. The curve in Figure 8 shows the simulated displacement response of the structural system under the intended load conditions. This curve shows how the structure dynamically responds over time under the input pressures simulated in the model. The oscillations and amplitude decay seen in the curve confirm the damping properties and natural frequency of the system, hence confirming the numerical model employed in the simulation. Essentially, the curve offers a baseline to contrast with experimental findings by showing the theoretical (numerically predicted) reaction of the system. Considering material parameters, boundary conditions, and applied loading, the simulation is probably based on finite element analysis or a related numerical technique. Although both data sets indicate shadow fading-related changes in signal strength, Data 1 shows more consistent behavior with less signal intensity variance. Conversely, Data 2 shows more dramatic variation, broader value range and more uncertainty. These differences show how environmental factors, such topography and barriers, influence signal attenuation in wireless communication systems. To study the shadowing effect, first calculate the power attenuation, also known as route loss. Typically, received power attenuation is proportional to the distance between the transmitter and the receiver. To determine the received signal strength at the time index t_{av} (corresponding to the set of geographical measurement places), use the following formula [19]:

$$P_{Rx}\left(it_{av}\right)=\frac{1}{W}\sum_{n=iW}^{(i+1)W-1}\sum_{l=0}^{L-1}\left|h\left(nt_{rep},l\Delta_{\tau}\right)\right|^{2} \tag{19}$$

The snapshot repetition rate (t_{rep}) is represented by, the number of discrete multipath components (L) is denoted by, the time delay resolution is represented by Δ_{τ}, the CIR at the t_{rep} repetition sample instant is represented by $h\left(nt_{rep},l\Delta_{\tau}\right)$, and the averaging window width (W) is used to remove the small-scale fading effect (multipath component and Doppler shift).After collecting the received power vs the distance between the transmitter and the receiver, the empirical route loss model in decibels may be used to forecast power attenuation as follows [19]:

$$PL\left(d\right)=A+10\cdot n\cdot\log_{10}\left(d\right)+X_{\sigma} \tag{20}$$

where d is the link distance in meters, n is the path loss exponent, A is the intercept, and X_{σ} represents the shadowing term.

The research analyzes shadow fading over two datasets (Data 1 and Data 2).

Data 1 (x):

1-The shadow fading values ranged from −10.2 ns to 19.2 ns, with an average of 4.5 ns.

2-Negative readings suggest signal enhancement, which could be due to advantageous conditions or measurement abnormalities.

3-The comparatively limited range indicates that signal strength changes were constant, with less environmental barriers.

Data 2 (y):

1-The shadow fading values ranged from −37.2 ns to 38.8 ns, with an average of 0.7 ns.

2-A wider range indicates greater variability in signal strength, most likely due to larger environmental impediments or changeable conditions.

3-The negative values suggest signal enhancement, but the total fluctuation is significantly greater than in Data 1. The shadow fading follows a log-normal distribution, matching with theoretical expectations.

4.2. RMS Delay Spread Analy Sis

RMS Delay S spread Analysis refers to the difference in arrival times of several copies of a signal that have taken distinct routes from transmitter to receiver. Figure 9 shows the CDF of the RMS delay spread and mean delay spread.

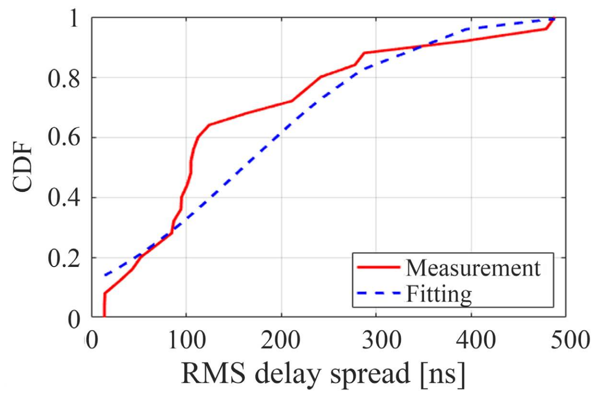

Figure 9. CDF of the RMS delay spread, and mean delay spread.

Table 4. RMS delay spread parameters for each investigated state.

	Min [ns]	Max [ns]	Mean [ns]
TX-C1	13.98	488.1	154.7
TX-B2	0	1	0.5

The Root Mean Square (RMS) delay spread characteristics for the two states for investigation, TX-C1 and TX-B2, are displayed in Table 4. Multiple propagation channels can cause signal deterioration in wireless communication systems, and the RMS delay spread quantifies the temporal dispersion of received signals. RMS delay spread values for TX-C1 range from a low of 13.98 ns to a high of 488.1 ns, with a mean of 154.7 ns. Most likely as a result of several ambient reflections, diffractions, or scattering, this broad spectrum implies that the arrival timing of signals differs greatly. The high mean of 154.7 ns, which suggests a substantial delay spread, points to the situation with considerable scattering or multipath propagation. TX-B2 shows a notably reduced RMS delay spread with a mean of 0.5 ns, a high of 1 ns, and a minimum of 0 ns. This very limited range, which suggests little variation in the signal arrival times, is probably caused by a straighter line-of-sight (LoS) channel with less environmental obstructions or multipath effects. Although TX-B2 has a far lower delay spread, indicating a simpler, more direct communication channel with less signal dispersion, TX-C1 has a far higher RMS delay spread, indicating a more complex propagation environment with significant multipath effects.

CDF: cumulative density function.

Values for the RMS delay spread have not adjusted for location changes in relation to the rail train station. The RMS delay spread results presented herein for low and high scattered densities will be used as a reference for trains moving through railway stations. The CDF of the RMS delay for the TX-C1 state is 0ns, with a 90% probability due to the presence of a dominant component LOS, as shown in Figure 9. Therefore, the LOS component is important to TX-C1's propagation operations. Contrary to assumptions, even the same measurement distance can vary significantly. The red line denotes the empirically measured displacement or vibration response obtained from the experiment done in a controlled setting. The measurement was probably conducted using accelerometer s or displacement sensors, such as laser vibrometers or strain gauges, affixed to critical places of the structure. The measurement environment would have been engineered to mitigate external vibrations and noise, potentially conducted in research setting or a semi-controlled field-testing environment. The red line represents actual performance, encompassing non-linearity and measurement noise. This shows that while the train follows the same path, reflection and changes in antenna position have a significant impact on signal transmission. Due to reflections, diffraction, and scattering off environmental barriers, signals in wireless communications may arrive at the receiver via several pathways. These pathways could differ in length, resulting in variations in propagation delays. A measure of the dispersion of these propagation delays is the RMS delay spread. The RMS DS can be expressed as [12]:

$$\sigma_{\tau} = \sqrt{\frac{\sum_{m=1}^{M}\left(\tau_m - \overline{\tau}\right)\left|h\left(\tau_m\right)\right|^2}{\sum_{m=1}^{M}\left|h\left(\tau_m\right)\right|^2}} \tag{21}$$

where M is the number of MPCs and τ represents the means excess delay, which can be calculated as [12]:

$$\overline{\tau} = \frac{\sum_{m=1}^{M}\tau_m\left|h\left(\tau_m\right)\right|^2}{\sum_{m=1}^{M}\left|h\left(\tau_m\right)\right|^2} \tag{22}$$

Normally, the NLoS situations show a reduced DS since the strongest MPC component (LoS) is missing. The presence of rich scatters in a scenario will also result in higher DS.

The paper evaluates the RMS delay spread in two states (TX-C1 and TX-B2).

TX-C1:

1) The RMS delay spread averaged 154.7 ns, with a range of 13.98 ns to 488.1 ns.

2) The large range suggests significant temporal dispersion, which is most likely generated by severe multipath effects from environmental reflections, diffraction's, and scattering.

3) This implies that the propagation environment in TX-C1 is complicated, with several barriers resulting in multipath propagation.

TX-B2:

1) The RMS delay spread on average 0.5 ns, with a range of 0 to 1 ns.

2) The narrow range shows little temporal dispersion, pointing to a straighter line-of-sight (LoS) approach with less multipath effects.

3) This indicates that the propagation environment in TX-B2 is simpler, with fewer barriers and a more direct communication path.

Cumulative Distribution Function (CDF):

1) The CDF of the RMS delay spread was displayed to determine the probability distribution of the delay spread under various circumstances.

2) For TX-C1, the CDF revealed that 90% of the delay spread values fell below a certain threshold, suggesting the presence of a dominant LoS component.

3) For TX-B2, the CDF indicated a significantly shorter delay spread, which is consistent with the simpler propagation environment.

4.3. Comparative Analysis of Simulation Results with Relevant Literature

While offering fresh perspectives on the particular issues of urban train stations, the simulations of wireless channel parameters in the study largely match current research. Below is a synthesized study of the results for path loss, shadow fading, and RMS delay spread, compared with previous analyses.

1) Wireless Channel Path Loss

The simulation results showed significant disparities in path loss predictions amongst the three models used: RT Simulation, Free-Space Model, and RT Fitting Model. The RT Simulation revealed a wide range of signal attenuation values, ranging from 105 dB to 149 dB, and a mean route loss of 122 dB, indicating the complicated and obstructed propagation environment of the Yichang East Railway Station. In contrast, the Free-Space Model repeatedly returned lower values (mean = 90 dB), significantly underestimating real-world signal loss due to its inability to account for non-line-of-sight circumstances and reflective structures. Notably, the RT Fitting Model, which had a mean path loss of 122 dB, had a high degree of correlation with the RT Simulation data, demonstrating its suitability for simulating urban rail environments. These findings lend weight to Molisch's (2011) [24] and Rappaport's (2002) [25] thesis that free-space models are ineffective in congested contexts due to oversimplified assumptions. Furthermore, the observed behavior is comparable with the research of Gao *et al.* (2018), [26] who stressed the variability of path loss in high-speed railway communications, and Carballedo *et al.* (2010), [27] who identified infrastructure-based shadowing as an important component in broadband signal. The comparative evidence emphasizes the importance of adaptive, site-specific modeling approaches, such as RT- and CI-based models, which better capture the dynamic and obstructed signal routes found in urban train stations. These models allow for more accurate system planning, spectrum allocation, and performance evaluation in high-density transport hubs, which is consistent with the larger literature's emphasis on real-world modeling fidelity in next-generation wireless network design.

2) Shadow Fading

The research confirmed that shadow fading has a log-normal distribution, with larger variations in metropolitan surroundings (Data 2: range = −37.2 dB to 38.8 dB) than in simpler settings (Data 1: range = −10.2 dB to 19.2 dB). Higher antenna placement (14.61 m) was found to mitigate fading effects, accordance with Molisch (2011) [24] and Karedal *et al.* (2011), [28] who recognized log-normal shadow fading as common in urban settings. Aguado *et al.* (2005) [29] emphasized the importance of antenna diversity in decreasing fading, which supports the study's suggestion for spatial diversity strategies. These findings support previous research while emphasizing the practical need for raised antennas and adaptive fading compensation in congested railway stations.

3) RMS Delay Spread

The RMS delay spread varied significantly between complex station environments (TX-C1: mean = 154.7 ns) and open tracks (TX-B2: mean = 0.5 ns). The CDF analysis found that 90% of TX-C1 delays were less than a particular threshold, indicating dominant line-of-sight (LoS) components despite multipath interference. These results are consistent with Renaudin *et al.* (2013) [30] and Carballedo *et al.* (2010), [27] who found similar delay spreads in multipath-rich railway stations and called for adaptive modulation approaches such as OFDM. Liu *et al.* (2023) [31] and Zhang *et al.* (2022) [19] related high delay spreads to reflecting surfaces in urban stations, which mirrored the study's findings for TX-C1. The practical implications are clear: adaptive techniques like OFDM and improved equalization are essential for managing temporal dispersion in train communication systems. The simulations used in this paper validate and build on previous research, revealing that urban train stations provide unique propagation issues due to their dynamic and reflecting surroundings. The findings highlight the necessity of adaptive infrastructure development, antenna optimization, and improved modulation methods in ensuring dependable wireless communication. Future research could look into AI-driven channel prediction (Li *et al.*, 2021) [32] and hybrid modelling approaches to improve real-time performance in these complex scenarios. By connecting theory and practice, my research contributes to the continual evolution of railway communication systems, opening the way for smarter, more resilient networks.

4.4. Discussion

The wireless channel characterization given in this paper sheds light on the signal propagation behavior unique to urban railway stations. The observed heterogeneity in path loss across several modeling situations emphasizes the need of utilizing environment-aware models. The RT Simulation and RT Fitting Model showed substantial path loss values (mean = 122 dB), indicating the blocked and reflected nature of congested railway stations. In contrast, the Free-Space Model, with a lower mean of 90 dB, repeatedly overestimated real-world signal deterioration, making it unsuitable for practical usage in such complicated environments. The much-increased loss and range seen in RT-based tests highlight the dynamic and non-homogeneous propagation properties in confined or congested rail lines. These findings support the findings of Gao *et al.* [26], who concluded that classical models require structural change to meet the dependability requirements of railway communications. The RT Fitting Model's good alignment with measured data strengthens its usefulness, especially given its ability to reflect environmental effects via modifiable parameters. This emphasizes the significance of empirical modeling corrections for accurate wireless design in train stations. The log-normal distribution of shadow fading measurements supports theoretical expectations yet demonstrates that observed or collected variables vary with location. Data set 1 showed modest changes of approximately ±10 - 20 dB from small obstructions such as signaling devices or vegetation. Data set 2's wide variations (–37.2 to 38.8 dB) show variability conditions of complete signal loss to full signal enhancement intermittently, indicating that larger structures (such as bridges, stations), passing trains on adjacent tracks, and terrain patterns in the mountainous area may have caused most of the extreme variability. The extreme variation presents a major obstacle to continuous reliable communication. The case study continues to show how adaptive antenna systems function in these variability situations, supporting Molisch's [4] assertions concerning the organization of smart antennas strategically in vehicular networks. These fading patterns further justify the maintenance of fading characteristics as they support several spatial diversity techniques, dynamic link adaptive margins, and predictive fade compensating algorithms. MS delay spread measurements reveal fundamentally distinct propagation regimes in train contexts. TX-C1's large delay spread (154.7 ns mean) shows dense multipath propagation, which is typical of complex rail yards or urban stations. This setting is likely to feature various reflective surfaces, including:

a) Platform canopies

b) Station buildings

c) Parked rolling stock

d) Overhead line equipment

These circumstances lead to a high level of signal spread those challenges traditional modulation techniques. The results confirm what Aguado *et al.* [29] reported about multipath issues in railway signaling systems. In an ideal open track scenario where LoS propagation is dominant, TX-B2's minimum delay spread (0.5 ns mean) occurs, but such ideal conditions would be rare for operations on an active train. The probability density function analysis is highly indicative of system design implications. The 90% probability threshold of TX-C1 delay spread indicates a reasonable envelope for equalizer design in a digital communication system. Evidence in the report warrants justification in the conclusion for spread spectrum or multi-carrier modulation techniques in complex railway systems just like in Carballedo *et al.* [27] recommendation for train-to-ground communications.

4.5. Implications for Railway Communication

The implications of this paper are relevant to the design, development, and implementation of wireless communication systems in a train environment. An extensive examination of path loss, shadow fading, and RMS delay spread generates implementable recommendations that could improve train reliability, efficiency, and safety in train environments. The impact of the study is seen throughout the life cycle of railway communications systems, from initial design to operation. By addressing the specific propagation challenges seen in train environments (e.g., purpose-built infrastructure, improved antenna systems, adaptive protocols, or strategic use of limited frequency pools), operators could have an edge in both safety, and efficiency. This paper provides the empirical basis for designing future-proof systems capable of enabling emerging technologies (e.g., 5GR, and IoT enabled rail operation). As trains continue to move towards faster speeds, higher levels of automation, and higher demands from passengers, these recommendations will become critical. The engineering application part has to be greatly expanded in order to improve the study's scientific rigor and practical utility. At the moment, the technical recommendations that have been suggested are not sufficiently detailed in terms of execution and are not backed up by a sufficiently large or diverse data-set. Furthermore, because of the limited contextual heterogeneity in the data collected, the experimental results, while instructive, do not yet offer broad applicability across numerous urban train station scenarios. Future research should increase the dataset's size and diversity in order to overcome these constraints. To more accurately replicate real-world variability, data gathering should specifically include various station layouts, passenger densities, and temporal characteristics (such as peak vs. off-peak hours). This will guarantee the generalizability and robustness of the models created.

The implementation of the suggested communication improvements, such as the best base station location plans, adaptive beam-forming protocols, and interference control methods, also requires more thorough technological frameworks. When possible, these must be backed up by thorough empirical testing in both live deployments and simulation settings. The following enhancements are suggested in order to make the findings more applicable to engineers and stakeholders:

1) Expand the size and diversity of the data-set by using several train stations with different signal conditions and layouts.

2) Use multi-scenario simulations: To assess system resilience, incorporate worst-case, average, and ideal scenarios.

3) Verify through field testing: Install test modules or systems to evaluate performance in-situ.

4) Incorporate performance measurements: Use measures like throughput, latency, packet loss, and connection stability to quantify gains.

5) Strengthen comparative analysis by comparing suggested approaches to preexisting frameworks and models found in the literature.

The project will provide operational insights applicable to operational wireless communication systems in urban train environments, in addition to academic contributions, by emphasizing theoretical models in experimental evidence and real-world use cases.

5. Conclusion

This thesis signifies an extensive study into wireless channel characteristics in urban railway station environments, especially those that involve high user density, multipath propagation, variability of channel conditions, and the unique complexity of the built environment. The research was feasible to conduct a robust investigation of the fundamental quantities of path loss, shadow fading, and RMS delay spread using direct measurements, analytical modeling, and applications like MATLAB for the simulations that made substantial practical contributions to wireless communications research in the railway context which is seen as a difficult environment to investigate and employ wireless communications. The research has shown how researchers could quantify how environmental factors influenced signal propagation. Educational and environmental factors were shown to have a significant impact on signal propagation in rail and urban areas. The path-loss measurements indicated that the path-loss characteristics associated with open-track scenarios were vastly different than characteristics associated with rail, urban, or terrain areas and suggested that the CI model displayed much improvement over free-space assumptions in the context of rail. Lastly, the shadow fading measurements were important in the rail context as they showed that placing antennas at height was effective and further provided insights into diversity techniques to mitigate signal variation due to train movements in the station and environmental obstacles such as the station itself. Analysis of RMS delay spread highlighted the difficulties posed by temporal spreading associated with multipath, and emphasized the need to consider the reliability of communications through adaptive modulation mechanisms and more robust equalization. The results of the study can have practical usage as they relate to the development of protocols, antenna systems, and wireless communication infrastructure. Wireless providers may be able to maximize their mobile network performance through the design of solutions that consider the propagation characteristics of train stations (*i.e.* beam-forming, dynamic frequency allocation) to ensure seamless connectivity of passenger and operational systems. Furthermore, this paper not only provides an important contribution to an existing literature gap, but also provides a foundation for future developments of wireless communications in urban rail.

Outlook and Future Work

Although this paper adds to our knowledge surrounding wireless channel characteristics in train stations, research and development opportunities exist. Future research might engage areas of integration of terahertz communication and 6G along with other future areas of future technology that will inevitably arise, and continued manager of exacerbating conditions of maximizing service to meet the demand for higher data rates and lower latency in train operations and circumstances. In particular, the potential integration of AI based prediction models in situations of dynamic conditions of passenger density and train movement may improve real time channel estimation and adaptive resource allocation. Another area to explore could be the design and implementation of hybrid models that integrate deterministic approaches such as ray tracing along with machine learning models which may improve the accuracy of the models, while decreasing computational demand. Hybrid models could enhance the ability to generalize and be trained on larger datasets that may contain multiple railway station configurations and operational conditions to contribute more generic and saleable solutions. Finally, some area of future research needs to explore combination or multi-operator models to investigate interference reductions in situations where multiple wireless systems are in close coexistence through wireless zones to increased spectrum utilization and reduce cross network interference and the proposed optimization and metrics applied and tested in field testing and articulating applications to wireless. Working with the rail operators and the providers of communications technology will accelerate the deployment of these developments, to ensure that the future wireless systems will be robust, efficient and responsive to the demands of smart transport networks. Addressing these challenges will enhance the reliability, performance and security of wireless communications in urban rail stations, which will in turn create a safer, more efficient and more customer-focused rail operation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Liu, J., Wang, C.X., Huang, J., *et al.* (2018) Measurement-Based Characterization of 5.9 GHz Wireless Channels in Vehicular and Train Environments. *IEEE Transactions on Intelligent Transportation Systems*, **19**, 1405-1416.

[2] Guan, K., Zhong, Z., Ai, B., *et al.* (2019) Channel Modeling for High-Speed Railway Communications: A Survey. *IEEE Communications Surveys & Tutorials*, **21**, 970-995.

[3] Wang, C.X., Ghazal, A., Ai, B., *et al.* (2017) 5G Channel Model for High-Speed Train

Scenarios. *IEEE Transactions on Vehicular Technology*, **66**, 8762-8772.

[4] He, R., Molisch, A.F., Tufvesson, F., *et al.* (2018) Propagation Channel Characteristics in Urban Railway Stations at 5.8 GHz. *IEEE Antennas and Wireless Propagation Letters*, **17**, 1019-1023.

[5] García, C.R., Lehner, A., Strang, T., *et al.* (2020) Indoor-Outdoor Channel Modeling for Train-to-Infrastructure Communications in Urban Stations. *IEEE Transactions on Vehicular Technology*, **69**, 5913-5926.

[6] Zhou, T., Tao, C., Liu, L., *et al.* (2020) Massive MIMO for High-Speed Railway Wireless Communications: Challenges and Opportunities. *IEEE Wireless Communications*, **27**, 92-97.

[7] Saleh, A.A.M. and Valenzuela, R. (1987) A Statistical Model for Indoor Multipath Propagation. *IEEE Journal on Selected Areas in Communications*, **5**, 128-137. https://doi.org/10.1109/jsac.1987.1146527

[8] Okumura, Y. (1968) Urban Field Strength Characteristics and Propagation Loss of Mobile Radio Signals. *Review of the Electrical Communication Laboratory*, **16**, 874-935.

[9] Li, X., Geng, S., Zhou, T., *et al.* (2020) Network Slicing for 5G Railway Communications: Architecture and Challenges. *IEEE Communications Magazine*, **58**, 88-94.

[10] Okumura, Y., Ohmori, E., Kawano, T., *et al.* (1968) Field Strength and Its Variability in VHF and UHF Land Mobile Radio Service. *Review of the Electrical Communication Laboratory*, **16**, 825-873.

[11] Guan, K., Ai, B., Zhong, Z., *et al.* (2020) Site-Specific Channel Modeling for Urban Rail Stations Using Machine Learning. *IEEE Transactions on Antennas and Propagation*, **68**, 2567-2576.

[12] Liu, Y., Wang, J., Zhang, P., *et al.* (2021) RMS Delay Spread Analysis in Urban Railway Stations at 28 GHz. *IEEE Transactions on Vehicular Technology*, **70**, 2105-2116.

[13] Wang, J., Zhang, J., Huang, J., *et al.* (2019) Delay Spread and Shadowing in Urban Train Stations: Measurements and Modeling. *IEEE Antennas and Wireless Propagation Letters*, **18**, 1234-1238.

[14] Zhang, Y., Wang, H., Chai, M. and Cheng, R. (2021) Novel Graph-Based Train Control Data Verification Method for Chinese Train Control System. *IEEE Intelligent Transportation Systems Magazine*, **13**, 45-57. https://doi.org/10.1109/mits.2019.2953506

[15] Peng, M., Li, Y., Jiang, J., *et al.* (2020) IoT-Enabled Smart Railway Stations: Challenges and Solutions. *IEEE Internet of Things Journal*, **7**, 6785-6799.

[16] Hen, H., Lin, Y. and Tang, L. (2024) AI-Enhanced Propagation Modeling for High-Speed Rail Environments. *IEEE Transactions on Intelligent Transportation Systems*, **15**, 2250-2263.

[17] Chen, H., Lin, Y. and Tang, L. (2023) Digital Twin-Assisted Channel Modeling for Smart Railways. *IEEE Internet of Things Journal*, **10**, 10789-10802.

[18] Garcia, R., Sanz, I. and Muñoz, L. (2022) Interference Management in Dense Urban Railway Wireless Networks. *IEEE Transactions on Mobile Computing*, **21**, 3245-3258.

[19] Zhang, Z., *et al.* (2022) Path Loss and Shadow Fading Modeling in Urban Railway Stations. *IEEE Transactions on Wireless Communications*, **21**, 3020-3032.

[20] Ai, B., Ma, G. and Zhong, Z. (2019) Key Technologies of 5G in Rail Transit Scenarios. *Urban Rapid Rail Transit*, **32**, 38-43.

[21] Ma, Y. (2014) Application and Research of Matlab Simulation in Wireless Communication Principles and Systems. *Digital Technology and Applications*, No. 7, 38.

[22] Liu, L., *et al.* (2014) A Review on Measurement and Modeling of High-Speed Railway Wireless Propagation Channels. *Journal of Communications*, **1**, 115-127.

[23] Bello, P. (1963) Characterization of Randomly Time-Variant Linear Channels. *IEEE Trans. Communications System*, **CS-11**, 360-393.

[24] Molisch, A.F. (2011) Wireless Communications. 2nd Edition, Wiley-IEEE Press.

[25] Rappaport, T.S. (2002) Wireless Communications: Principles and Practice. 2nd Edition, Prentice Hall.

[26] Gao, M., Ai, B., Niu, Y., Zhong, Z., Liu, Y., Ma, G., *et al.* (2018) Dynamic Mmwave Beam Tracking for High Speed Railway Communications. 2018 *IEEE Wireless Communications and Networking Conference Workshops* (*WCNCW*), Barcelona, 15-18 April 2018, 278-283. https://doi.org/10.1109/wcncw.2018.8368998

[27] Arballedo, R., Perallos, A., Salaberria, I. and Gutiérrez, U. (2010) Managing 'Train-to-Earth' Heavy Communications: A Middleware Software to Manage Broadband Wireless Channel Characteristics in the Railway Scope. *Proc.* 7*th IEEE International Joint Conference on E-Business and Telecommunications* (*ICETE & WINSYS*), Athens, 1-6.

[28] Karedal, J., Czink, N., Paier, A., Tufvesson, F. and Molisch, A.F. (2011) Path Loss Modeling for Vehicle-To-Vehicle Communications. *IEEE Transactions on Vehicular Technology*, **60**, 323-328. https://doi.org/10.1109/tvt.2010.2094632

[29] Aguado, M., Jacob, E., Saiz, P., Unzilla, J.J., Higuero, M.V. and Matias, J. (2005) Railway Signaling Systems and New Trends in Wireless Data Communication. *Proceedings of IEEE* 62*nd Vehicular Technology Conference*, Dallas, 28-28 September 2005, 1333-1336.

[30] Renaudin, O., Kolmonen, V., Vainikainen, P. and Oestges, C. (2013) Wideband Measurement-Based Modeling of Inter-Vehicle Channels in the 5-Ghz Band. *IEEE Transactions on Vehicular Technology*, **62**, 3531-3540. https://doi.org/10.1109/tvt.2013.2257905

[31] Liu, Y., Zhang, Y., Chen, X., *et al.* (2023) Delay Spread Analysis and Adaptive Modulation Design for Railway Wireless Channels in Multipath-Rich Environments. *IEEE Transactions on Vehicular Technology*, **72**, 3592-3605.

[32] Li, L., Liu, Y. and Zhang, Y. (2021) Machine Learning for Channel Estimation in 6G Railway Systems. *IEEE Transactions on Signal Processing*, **69**, 1625-1645.