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Analyzing the Impact of Radio Signal Fading on Train Positioning Accuracy in Tunnel Environments

Ziran Ge

Xihua University, Chengdu 610039, Sichuan, China

Abstract: Accurate and reliable train positioning is a fundamental requirement for modern rail transit signal systems. This requirement faces particular challenges in tunnel environments, as wireless signals are severely affected by multipath fading, shadowing effects, and attenuation. This study systematically analyzed the impact of specific fading phenomena in tunnel environments on positioning accuracy through ray-tracing simulations and random channel modeling. We simulated typical urban subway tunnel environments and evaluated the performance of positioning technologies such as received signal strength indication, arrival time, and carrier phase in damaged channels. The results showed that signal fading could cause positioning errors ranging from several meters to several tens of meters, and the error distribution was closely related to the type of fading, tunnel cross-section, and algorithm robustness. Deep fading would lead to local failure of positioning capabilities, while shadow fading would cause systematic deviations. To address these challenges, the study proposed comprehensive strategies, such as using inertial navigation units for multi-sensor fusion, deploying distributed antenna systems, and applying advanced channel estimation and filtering algorithms. Only through the organic combination of physical layer redundancy, intelligent infrastructure, and advanced data processing can high-integrity positioning required for safety-critical applications in tunnel environments be achieved, ensuring the safety and efficiency of underground rail transit operations.

Keywords: Tunnel positioning; Signal fading; Multipath effect; Sensor fusion; Railway communications

1. Introduction

The relentless pursuit of greater capacity, efficiency, and safety in rail transport has propelled the industry towards increasingly sophisticated train control paradigms. From moving-block signaling in Communications-Based Train Control to the envisioned future of fully autonomous train operations, the common thread is an insatiable demand for continuous, high-precision, and ultra-reliable train positioning [1]. Knowledge of a train's location is no longer a simple discrete datum for track circuit occupation but a continuous, dynamic state variable that directly governs braking curves, movement authorities, and energy management strategies [2]. This paradigm shift places unprecedented demands on the performance of positioning systems [3]. While Global Navigation Satellite Systems have revolutionized positioning in open-sky environments, their inherent weakness is starkly exposed in the very terrains where high-capacity rail transport is often most needed: tunnels, underground metros, and urban canyons [4].

Within the confined, complex, and electromagnetically challenging environment of a railway tunnel, radio-frequency-based positioning systems must operate [5]. These systems, which may rely on dedicated wireless communications networks, leaky feeder cables, or other radio-frequency identification technologies, face a propagation scenario far removed from free space [6]. The tunnel acts as a lossy, irregular waveguide, giving rise to a multitude of signal degradation phenomena collectively termed fading. Signal fading in tunnels is not a singular impairment but a confluence of distinct physical processes [7]. Large-scale or slow fading, primarily caused by shadowing from tunnel portals, ventilation ducts, passing trains, and other infrastructure, results in a gradual variation of the local mean signal power over distance. Small-scale or fast fading, on the other hand, arises from the constructive and destructive interference of multiple signal paths, direct, reflected, and diffracted, that reach the receiver with minute differences in time and phase. This interference creates rapid fluctuations in signal amplitude and phase over very short distances or time intervals, often following a Rayleigh or Rician distribution [8].

The impact of these fading mechanisms on positioning accuracy is profound and multifaceted. Positioning algorithms, such as those based on trilateration using Received Signal Strength Indication or time-of-flight measurements like Time Difference of Arrival, inherently assume a stable and predictable relationship between the measured radio signal parameter and the geometric distance [9–12]. Fading systematically violates these assumptions. Fast fading can cause the instantaneous received signal strength to deviate wildly from its distance-dependent mean, introducing large, unpredictable errors in RSSI-based range estimates [13]. Similarly, the distortion of the signal waveform due to multipath propagation can severely bias the estimation of signal arrival time, corrupting Time of Arrival and related techniques. Phase-based methods, while offering higher potential precision, are exceptionally vulnerable to phase discontinuities and noise introduced by the dynamic channel [14]. Consequently, the positioning solution can exhibit errors that are not merely additive Gaussian noise but are correlated, biased, and potentially divergent [15].

Despite the critical importance of this issue, a holistic analysis quantifying the specific impact of different fading types on various positioning technologies within a realistic railway tunnel context remains a salient research gap. Many studies focus on general channel characterization or the performance of communication links, while positioning accuracy is often evaluated under simplified or idealistic channel models. This paper aims to bridge this gap by providing a detailed, simulation-driven analysis. We construct a high-fidelity electromagnetic model of a representative tunnel segment and employ advanced propagation modeling techniques to generate realistic fading profiles. These channel realizations are then used to degrade the signals input to models of standard positioning algorithms. By systematically varying the tunnel geometry, the density of infrastructure scatterers, and the positioning technique, we isolate and quantify the contribution of specific fading phenomena to the overall positioning error budget. The ultimate goal is not only to diagnose the problem but to inform the design of next-generation tunnel positioning systems that are inherently resilient to the challenging radio environment, thereby underpinning the safety and capacity gains promised by advanced train control systems.

2. Experimental method

To investigate the intricate relationship between radio signal fading and positioning accuracy, a multi-stage, simulation-based experimental framework was established. The core of this framework was a meticulously constructed virtual model of a standard urban railway tunnel, designed to capture the essential electromagnetic characteristics that influence radio wave propagation. The baseline tunnel model featured a circular cross-section with an internal diameter of 5.5 meters, constructed from concrete with a relative permittivity of 7 and a conductivity of 0.01 S/m. A straight section of 500 meters was modeled to observe longitudinal fading effects, with a standard track bed, rails, and periodic installations such as cable trays, lighting fixtures, and emergency exits acting as potential scatterers. A distributed antenna system was modeled, comprising linear antenna arrays spaced at 150-meter intervals along the tunnel wall, operating at a carrier frequency of 2.4 GHz, representative of common industrial, scientific, and medical band systems.

The propagation of radio signals within this environment was simulated using a hybrid approach that combined deterministic and stochastic elements. A ray-tracing engine, capable of accounting for specular reflections, diffraction, and penetration losses, was employed to generate a site-specific path loss map and to identify dominant propagation paths between transmitters and a receiver moving along the track. This provided the large-scale path loss and shadow fading component. Superimposed upon this deterministic baseline was a small-scale fading model. To simulate fast fading, the multiple reflected rays identified by the ray-tracer were synthesized at the receiver, with each ray assigned a complex amplitude, delay, and a time-varying phase shift to model the Doppler effect caused by the moving train. The receiver's trajectory was sampled at one-centimeter intervals, simulating a train speed of 80 km/h, to capture the rapid spatial variation of the fast fading envelope. The composite received signal at each point was characterized by its amplitude, phase, and time delay spread [16].

Three distinct positioning techniques were then subjected to this impaired channel. The first was a basic RSSI-based trilateration algorithm, which converted the received power from at least three antennas into a distance estimate using a log-distance path loss model calibrated for free-space conditions [17]. The inherent mismatch between this simple model and the complex tunnel channel was a key source of error under investigation. The second technique was a Time of Arrival system, where the time of reception of a known signal from each antenna was estimated. In our simulation, the first detectable signal path crossing a power-based threshold was designated as the arrival time. Multipath propagation, however, could cause a non-line-of-sight reflected path to be stronger than the direct path, leading to a positive bias in the time estimate, a phenomenon known as the multipath error. The third method evaluated was a carrier-phase differential positioning approach, which tracked the phase of the received carrier wave. While theoretically capable of centimeter-level accuracy, this method's performance was critically dependent on maintaining continuous phase lock, a condition threatened by deep fast fades and rapid phase changes [18].

The experiment was structured around a series of controlled scenarios to isolate the impact of different variables. A baseline scenario with minimal scatterers and a single dominant path established a performance lower bound. Subsequent scenarios introduced increasing clutter density to exacerbate multipath conditions, modeled a passing train in an adjacent track as a major moving shadowing object, and varied the tunnel cross-section to a rectangular shape to alter reflection patterns. For each scenario and each positioning algorithm, the receiver's true position was compared to the estimated position over the entire 500-meter run. The error statistics, including mean error, root mean square error, maximum error, and the cumulative distribution function of the error, were computed and analyzed. Furthermore, the instantaneous channel parameters, such as the Ricean K-factor (ratio of direct to scattered signal power) and the delay spread, were logged alongside the positioning error to establish direct correlations (**Table 1**, **Table 2** and **Table 3**).

Table 1. Tunnel simulation environment parameters

Parameter	Specification	Rationale
Tunnel model	500m length, 5.5m dia. circular / 6m x 5m rectangular	Represents typical metro tunnel geometries
Construction material	Concrete (ε_r = 7, σ = 0.01 S/m)	Standard building material with known RF properties
Carrier frequency	2.4 GHz	Common ISM band for wireless positioning/communication
Antenna deployment	Linear arrays, 150m spacing along wall	Model of a typical distributed antenna system
Scatterer model	Cable trays, lights, signs, periodic recesses	Incorporates common tunnel infrastructure
Train speed	80 km/h	Representative urban metro operating speed

Table 2. Channel impairment scenarios

Scenario ID	Primary characteristic	Key fading mechanism induced
S1 (Baseline)	Clean tunnel, minimal scatterers	Primarily distance-dependent path loss
S2 (Dense Clutter)	High density of internal infrastructure scatterers	Severe multipath, rich scattering, low K-factor
S3 (Moving Shadow)	Presence of a second train in adjacent track	Large-scale shadow fading, dynamic blockage
S4 (Geometry Change)	Rectangular tunnel cross-section	Altered reflection pattern, waveguide modes

Table 3. Positioning algorithms under evaluation

Algorithm	Principle	Measured quantity	Primary vulnerability
RSSI trilateration	Signal strength to distance mapping	Received Power (dBm)	Fast fading, shadowing, model mismatch
Time of arrival	Signal propagation time	Time of first detectable path	Multipath (NLOS bias), noise
Carrier-phase differential	Phase of carrier wave	Phase (cycles)	Cycle slips, phase noise, deep fades

3. Results

The simulation results provided a vivid and quantitative depiction of how tunnel-induced signal fading corrupts positioning estimates. The error statistics revealed stark differences not only between the various positioning algorithms but also in how each algorithm responded to different types of fading impairment.

In the baseline Scenario S1, all three methods performed reasonably well, though with inherent limitations. The RSSI-based trilateration exhibited a root mean square error of approximately 3.5 meters, with errors primarily stemming from the imperfection of the log-distance path loss model when applied to the tunnel waveguide. The Time of Arrival method achieved a superior RMSE of 1.2 meters, as the direct path was consistently the strongest. The carrier-phase method, after resolving integer ambiguities in a fixed initialization zone, demonstrated its potential with sub-decimeter RMSE. However, this scenario served merely as a reference, as it represents an unrealistic, idealized tunnel.

The introduction of dense clutter in Scenario S2 precipitated a severe degradation in performance, particularly for the RSSI and ToA methods. The fast-fading envelope for a single link showed deep nulls exceeding 30 dB of attenuation over distances as short as half a wavelength. For RSSI trilateration, this translated into catastrophic, spike-like errors. The RMS error soared to over 15 meters, and the maximum error observed exceeded 50 meters when the receiver traversed a deep fade relative to two of the three positioning anchors simultaneously. The error distribution was highly non-Gaussian, with a heavy tail. The ToA method was similarly impacted by multipath. The delay spread increased significantly, and in numerous locations, a reflected path arrived with greater power than the attenuated direct path. This resulted in consistent positive biases in the range estimates, manifesting as an RMSE of 8.7 meters with a mean error of +6.5 meters, indicating a systemic over-estimation of distance. The carrier-phase method struggled to maintain lock through the deep fades, experiencing cycle slips that introduced integer-wavelength jumps in the estimated range. While sophisticated algorithms could potentially detect and correct some slips, in our basic model, this led to intermittent large errors, raising the RMSE to 2.1 meters.

Scenario S3, featuring a moving shadow, illustrated the impact of large-scale fading. As the passing train occluded the line-of-sight to one or more antennas, the received signal underwent a slow, deep attenuation of 20–25 dB over several tens of meters. For the RSSI method, this was misinterpreted as the train being much farther from the occluded antenna than it truly was, creating a large, smooth bias in the position solution that persisted for the duration of the blockage. The ToA method was less affected by the pure attenuation unless the signal dropped below the detection threshold, causing a complete loss of measurement. The carrier-phase method, if it could maintain lock at the lower SNR, was relatively robust to this slow variation, though the increased noise degraded precision (**Table 4** and **Table 5**).

Table 4. Positioning performance summary (root mean square error in meters)

Algorithm/ Scenario	S1 (Baseline)	S2 (Dense Clutter)	S3 (Moving Shadow)	S4 (Rectangular)
RSSI trilateration	3.5 m	15.2 m	9.8 m	6.7 m
Time of arrival	1.2 m	8.7 m	2.5 m*	4.3 m
Carrier-phase differential	0.08 m	2.1 m**	0.15 m	0.9 m

Table 5. Error distribution characteristics (Scenario S2: Dense Clutter)

Algorithm	Mean error	Max error	95th percentile error	Error distribution type
RSSI trilateration	-0.5 m	54 m	32 m	Heavy-tailed, non-stationary
Time of arrival	+ 6.5 m	22 m	17 m	Biased, moderately spread
Carrier-phase differential	0.01 m	5.8 m (slip)	0.25 m	Gaussian with outlier spikes

The change to a rectangular cross-section in Scenario S4 altered the fading structure. The parallel walls created a more regular, waveguide-like propagation environment with distinct modes. This actually reduced the severity of the deepest fast fades compared to the circular tunnel with random clutter, leading to an improvement in RSSI and ToA performance relative to S2. However, it introduced a different kind of systematic error pattern correlated with the modal structure. The carrier-phase method showed increased susceptibility to phase distortion due to the excitation of multiple modes.

A critical finding was the spatial correlation of errors. High error regions for RSSI and ToA were not randomly distributed but were clustered in specific zones of the tunnel corresponding to complex scattering environments or specific geometric relationships with the antennas. This spatial correlation has important implications for safety analyses, as it means positioning failures are not independent, identically distributed events but can affect extended sections of track.

4. Discussion

The empirical findings of this study reveal a complex and multifaceted challenge at the intersection of railway engineering, wireless communications, and safety-critical systems design. The observed positioning errors, ranging from systematic biases in Time of Arrival methods to catastrophic spikes in RSSI-based solutions, are not merely statistical anomalies but direct manifestations of fundamental electromagnetic phenomena inherent to the tunnel environment. This necessitates a deeper examination beyond the quantitative results, focusing on the operational implications, the limitations of current system design paradigms, and the conceptual shift required for resilient positioning.

A paramount concern arising from the data is the challenge these error profiles pose to established safety assurance frameworks. Railway safety standards, such as those outlined in EN 50129, rely on probabilistic risk assessments that often assume failure modes are independent and follow predictable distributions. The spatially correlated nature of positioning errors induced by fading, particularly the clustering of large errors in specific tunnel sections, directly contradicts this assumption. For instance, when a train passes a zone of dense infrastructure clutter, multiple positioning anchors may experience simultaneous deep fades, leading to a correlated failure across redundant measurement channels. This “common-cause” failure scenario, triggered by the physical environment, is notoriously difficult to guard against and necessitates a fundamental re-evaluation of how redundancy and diversity are implemented. Redundancy must be designed not just in hardware duplication but in electromagnetic and geometric diversity, ensuring that backup sensors or communication links are not susceptible to the same environmental disturbance at the same time.

The performance differential between the evaluated algorithms underscores a critical trade-off between complexity, cost, and robustness. While carrier-phase differential positioning demonstrates the potential for centimeter-level accuracy, its fragility in the face of cycle slips presents a significant operational risk. In a safety-critical context, an undetected cycle slip is functionally equivalent to a latent fault, the system continues to operate, but with a dangerously incorrect position estimate. This creates a paradox where the most precise technology may, under specific fading conditions, become the least reliable. Consequently, the selection of a positioning technology for tunnel applications cannot be based on peak performance in ideal conditions but must be driven by a worst-case analysis of its failure modes under impaired channel conditions. This may lead to the counterintuitive conclusion that a less precise but more predictable and monitorable technology could be preferable as a primary safety layer, with high-precision methods used in a supervised, non-vital capacity to enhance efficiency.

The simulation’s focus on generic tunnel models, while illustrative, points to a significant practical limitation: the high degree of site-specificity in fading characteristics. The error magnitude and patterns in a straight, concrete, circular tunnel will differ markedly from those in a curved, steel-reinforced, rectangular tunnel or one with frequent cross-passages and station cavities. This variability implies that a one-size-fits-all positioning solution or a generic channel model is insufficient. The deployment of a high-integrity positioning system in any given tunnel may require extensive pre-operational channel sounding and the development of a site-specific “fading map.” This map could inform the placement of infrastructure, the tuning of algorithms, and the definition of “black zones” where positioning integrity is known to be degraded, requiring alternative operational procedures such as reduced speed or reliance on inertial coasting (**Table 6**).

Table 6. Implications of fading-induced errors for system design

Fading phenomenon	Primary impact on positioning	Implication for safety & operation	Potential mitigation strategy
Fast (Multipath) fading	Rapid, large-magnitude RSSI fluctuations; NLOS bias in ToA; cycle slips in phase tracking	Unpredictable, spike-like position jumps; persistent distance overestimation; undetected integer-wavelength errors	Use of wideband signals; multi-antenna spatial diversity; robust filtering (e.g., particle filters) to reject outliers
Slow (Shadow) fading	Gradual, large-scale attenuation of signal strength over distance	Smooth but large positioning bias during blockage events; potential complete loss of signal	Dense deployment of antennas or leaky feeder cables; multi-link trilateration; tight coupling with IMU
Spatial error correlation	Errors clustered in specific geographic zones related to geometry/scatterers	Violates assumption of independent failures; risk of common-cause failures in redundant systems	Geographically diverse anchor placement; fusion with non-RF sensors (odometer, IMU); operational procedures for known weak zones
Non-Gaussian error distributions	Heavy-tailed error statistics (e.g., RSSI), biased distributions (e.g., ToA)	Classical Kalman filtering (assuming Gaussian noise) becomes suboptimal and can diverge	Employment of Robust Kalman Filters or non-parametric Bayesian filters designed for non-Gaussian noise

Finally, the discussion must extend to the evolving landscape of railway communications. The industry's migration towards future systems like the Future Railway Mobile Communication System (FRMCS) and the exploration of higher frequency bands (e.g., in the millimeter-wave range for high-capacity train-to-wayside links) will introduce new propagation dynamics. Higher frequencies are typically more susceptible to blockage and attenuation, potentially exacerbating shadow fading effects, though they may offer wider bandwidths to combat multipath. This evolution means that the fading challenge is not static. The positioning system must be co-designed with the communication system, leveraging shared infrastructure (antennas, fiber backhaul) and potentially using the communication signals themselves for positioning in an integrated approach. Research into joint communication and sensing techniques, where the same waveform is used for both data transmission and radar-like ranging, presents a promising avenue to optimize resource use and build inherent resilience against the very channel impairments it must characterize.

In conclusion, the problem of fading is not merely a technical impairment to be overcome with higher gain or more power; it is a fundamental shaping constraint on the architecture of train control systems for underground operations. Addressing it requires a holistic view that spans electromagnetic theory, signal processing, safety engineering, and infrastructure planning. The goal must be to develop systems that do not just function in a fading environment but are designed for and informed by it, transforming a major source of uncertainty into a managed and bounded parameter within the overall safety case.

5. Conclusion

This analysis has systematically deconstructed the detrimental impact of tunnel-induced radio signal fading on the accuracy of train positioning systems. By employing high-fidelity simulation across a range of realistic scenarios, we have quantified how multipath fast fading and shadow slow fading introduce substantial, structured errors into common positioning algorithms, with root mean square errors escalating from meters to tens of meters under adverse conditions. The vulnerability is not uniform; it starkly exposes the limitations of simplistic signal-strength-based methods while revealing the more subtle yet hazardous biases and fragilities in time-based and phase-based techniques. The findings underscore a critical reality: achieving the high-integrity positioning required for advanced train control in tunnels cannot rely on a single, pure radio-frequency technology operating with algorithms designed for benign channels. The path forward necessitates a system-level solution characterized by resilience through diversity. This encompasses diversity in physical infrastructure, such as optimized antenna deployment; diversity in sensing modalities, through the tight coupling of RF systems with inertial and potentially other sensors like odometers; and diversity in data processing, via intelligent filtering and channel-aware algorithms. The tunnel environment, with its unique and severe fading characteristics, must be a first-order design constraint, not an afterthought. Future research and development must focus on creating and validating these integrated, robust positioning systems. Their successful implementation is a fundamental enabler for unlocking the full potential of high-capacity, safe, and efficient underground rail transport, ensuring that the constricted geometry of a tunnel does not become a constriction on operational performance or safety.

Disclosure statement

The author declares no conflict of interest.

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