Postprint: IMT-A-Based Time-Varying Channel Modeling for High-Speed Railway Mobile Communications

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Abstract

Channel modeling and its simulation methods are challenging aspects in the design of high-speed railway mobile communication systems, while existing research on IMT-A time-varying channel modeling for high-mobility scenarios remains insufficient. To address these challenges, a modeling approach based on IMT-A channels with time-varying parameters under high-speed railway mobility is proposed. First, for the urban macrocell scenario of IMT-A, a Markov process is designed to simulate the temporal variation in the number of clusters, followed by the derivation of expressions for channel parameters that vary with time, including cluster delay, power, angle of departure, and angle of arrival, and the channel impulse response is obtained; second, the time-varying space-time cross-correlation function, time-varying autocorrelation function, and stationarity interval of the channel are analyzed; finally, the statistical properties of the proposed channel model are simulated, verifying that the model exhibits time-varying characteristics and that high-speed railway channels possess non-stationarity, and demonstrating the feasibility of using the proposed channel model to simulate high-speed railway channels.

Full Text

Preamble

Time-varying IMT-A channel modeling for high-speed train mobile communication scenario

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Abstract: Channel modeling and its simulation method represent a critical challenge in the design of high-speed railway mobile communication systems. Meanwhile, existing research on IMT-A time-varying channel modeling for high-speed mobility scenarios remains inadequate. To address these challenges, this paper proposes a modeling approach based on the IMT-A channel with time-varying parameters for high-speed train environments. First, for the urban macro-cell (UMA) scenario of IMT-A, we design a Markov process to simulate the temporal evolution of cluster numbers, then derive expressions for time-varying channel parameters including cluster delays, powers, angles of departure (AoD), and angles of arrival (AoA), and obtain the channel impulse response (CIR). Second, we analyze the time-varying space-time cross-correlation function (CCF), time-varying auto-correlation function (ACF), and stationary interval of the channel. Finally, simulations of the statistical properties of the proposed channel model verify its time-varying nature and the non-stationarity characteristic of high-speed railway channels, demonstrating the feasibility of using the proposed model to simulate high-speed railway channels.

Keywords: high-speed mobile communication; channel modeling; time-varying parameters; Markov process; non-stationarity

0 Introduction

In recent years, with the development of high-speed railways, passengers have increasingly demanded high-quality, high-rate data and multimedia communication services. However, existing wireless communication technologies still cannot meet the quality requirements for multimedia communication on trains operating at speeds above 300 km/h. As is well known, the channel forms the foundation of any communication system, and its model and simulation method play a crucial role in designing communication systems for specific scenarios. Currently, standardized channel models for high-speed railway scenarios mainly include IMT-Advanced (IMT-A) [1] and WINNER II channel models, both of which assume wide-sense stationary (WSS) channels and ignore their non-stationary characteristics. Channel measurement results in [2] show that standard channel models exhibit significantly longer stationary intervals (defined as the maximum duration during which the channel satisfies WSS conditions) compared to actual measured high-speed railway channels, while the WSS assumption is only valid for short time intervals in real wireless channels. In summary, conventional stationary channel modeling approaches for high-speed railway channels face increasingly severe challenges.

Extensive research has been conducted domestically and internationally on channel modeling for high-speed railway mobile communication scenarios, particularly regarding non-geometrical stochastic models (NGSM). Reference [3] proposed an NGSM for high-speed railway wireless communication based on finite-state Markov chains, using Markov chains to characterize the birth-death properties of moving clusters (MC). The proposed model can track channel state variations across different received SNR intervals using Markov chains, thereby capturing the time-varying characteristics of high-speed railway wireless channels. However, the non-stationary statistical properties of this model are difficult to derive analytically. Additionally, reference [4] proposed a non-stationary vehicle-to-vehicle channel model based on NGSM. Based on high-speed railway channel measurement data from viaduct and narrow corridor scenarios, reference [5] proposed a finite-state Markov channel model. The results demonstrate that the Rice distribution effectively characterizes the small-scale fading amplitude in both high-speed railway scenarios, and NGSM can effectively capture the dynamic nature of fast fading in high-speed railway channels. However, among existing NGSM research methods, there is currently no modeling approach for IMT-A time-varying channels. Therefore, to improve and complete the theoretical framework of high-speed railway wireless channel modeling, research on channel modeling methods suitable for high-speed railway mobile communication scenarios holds significant practical value.

Consequently, this paper proposes an IMT-A-based channel modeling method with time-varying parameters—including cluster numbers, powers, delays, angles of departure (AoD), and angles of arrival (AoA)—for NGSM scenarios in high-speed railway mobile communication. First, we theoretically analyze important statistical properties of the proposed model, including local space cross-correlation function (CCF), local time auto-correlation function (ACF), and stationary interval. Second, MATLAB simulations verify the non-stationary nature of the channel model, thereby confirming the correctness of the theoretical analysis and derivations.

1 IMT-A Based Channel Modeling

In high-mobility environments, the rapid movement of observable moving clusters (MC) or mobile stations (MS) may violate the aforementioned WSS assumption. Under these conditions, we propose an IMT-A-based channel modeling approach with time-varying parameters. The geometric schematic diagram is shown in [Figure 1: see original paper], and the channel impulse response (CIR) can be expressed as

$$h(t,\tau) = \sum_{p=1}^{P(t)} h_p(t)\delta(\tau - \tau_p(t))$$

where

$$h_p(t) = \sqrt{\frac{P_p(t)}{Q}} \sum_{q=1}^{Q} \exp\left(j\Phi_{pq}\right) \times \exp\left(j\frac{2\pi}{\lambda}\left(k_T(\alpha_{pq}^T(t)) \cdot v_{MS} + k_R(\alpha_{pq}^R(t)) \cdot v_{MC}\right) t\right)$$

Here, $P(t)$ represents the number of clusters at time t, $\tau_p(t)$ denotes the delay of the p-th cluster, $P_p(t)$ is the power of the p-th cluster, Q is the number of sub-paths within each cluster, Φ_{pq} is the random initial phase uniformly distributed in $[0, 2\pi)$, λ is the wavelength, $k_T(\alpha_{pq}^T(t))$ and $k_R(\alpha_{pq}^R(t))$ are the wave vectors for the q-th sub-path within the p-th cluster at the transmitter and receiver respectively, and v_{MS} and v_{MC} represent the velocity vectors of the MS and MC respectively.

Due to the movement of MS and/or MC, the channel model parameters need to be expressed using appropriate time-varying functions. The time-varying AoD $\alpha_{pq}^T(t)$ and AoA $\alpha_{pq}^R(t)$ can be expressed as

$$\alpha_{pq}^T(t) = \alpha_{pq}^{T0}(t) + \Delta\alpha_{pq}^T(t)$$

$$\alpha_{pq}^R(t) = \alpha_{pq}^{R0}(t) + \Delta\alpha_{pq}^R(t)$$

where $\alpha_{pq}^{T0}(t)$ and $\alpha_{pq}^{R0}(t)$ represent the initial AoD and initial AoA respectively, while $\Delta\alpha_{pq}^T(t)$ and $\Delta\alpha_{pq}^R(t)$ denote the AoD offset and AoA offset. The subscripts p and q indicate the AoD and AoA associated with the q-th sub-path within the p-th path in the wideband channel.

The schematic diagram in [Figure 1: see original paper] illustrates the time-varying parameters for IMT-A channel modeling. Based on the movement directions of MC_1, MC_2, and the MS, the distances between the BS, MC, and MS will vary with time t. By considering the concept of relative velocities, we can assume that the MS moves only relative to MC_1. After obtaining the distances from channel measurements, the time-varying distances at time t can be expressed by equations (3), (4), and (5). The channel parameter definitions in [Figure 1: see original paper] are provided in .

To derive the required time-varying angular parameters, we define four auxiliary angles to further simplify the expressions. It should be noted that in the diagram, only the LoS path and the p-th scattering propagation path are shown. As an example, cluster MC_1 and cluster MC_2 correspond to the first and last bounce clusters of the p-th scattering path respectively. If MC_1 and/or MC_2 are stationary, their velocities can be set to zero, which does not affect the generation process of time-varying channel parameters in this IMT-A based channel modeling.

Based on the above description, the implementation of channel parameters for the IMT-A based channel modeling can be obtained through the following steps, as illustrated in [Figure 2: see original paper].

2.1 Generation of Time-Varying Clusters

In high-speed railway mobile communication scenarios, the propagation environment between the MS and BS changes as the MS moves. Additionally, the movement of mobile scatterers within the environment also impacts the propagation environment. Consequently, during travel, some paths disappear while new paths emerge. Reference [6] proposed a birth-death process modeling approach for moving clusters. In time-varying scenarios, clusters are considered to exist only within specific time intervals. Over time, new clusters appear (birth), persist for a certain duration (survival), and eventually disappear (death). It should be noted that the time-varying clusters assume a multipath channel, but unlike traditional channels, the number of paths P in this multipath channel varies with time, and its state transitions are continuous, which aligns with the continuous state transition behavior of Markov processes.

Therefore, based on the cluster generation and recombination process, the channel fluctuations caused by the movement of MC_1 and the movement of MC_2 within the time interval between t_{k-1} and t_k can be represented. By observing the time series of this CIR, each cluster maintains a survival probability R_{MC} from one CIR at time t_{k-1} to the subsequent CIR at time t_k. Thus, the expected number of new clusters generated through the Markov process is

$$E\{P_{new}\} = 1 - e^{-(\rho_1+\rho_2)\varepsilon}$$

where ρ_1 and ρ_2 are the cluster generation rate and recombination rate respectively, and ε is the time interval. The correlation between two clusters after evolution is quantified by R_{MC}. Higher values of R_{MC} lead to lower correlation between the attributes of ancestor clusters at time t_{k-1} and their descendant clusters at time t_k.

In the NLoS urban macro-cell (UMA) scenario, we assume that the number of clusters changes according to a Markov process, and each change only considers transitions between adjacent state values. Based on the above considerations, we conduct MATLAB simulations of the Markov birth-death process with the following parameters: $P(t_0) = 18$, $\rho_1 = 0.6/m$, $\rho_2 = 0.03/m$, $v_{MS} = 60m/s$, $v_1 = 15m/s$, $v_P = 5m/s$, and $R_{MC} = 0.3$. The resulting distribution of time-varying cluster numbers is shown in [Figure 3: see original paper].

As observed in [Figure 3: see original paper], the initial number of clusters is 18, and this number changes over time, with five possible cases: 16, 17, 18, 19, and 20 clusters.

2.2 Time-Varying Delay

As MC_1, MC_2, and the MS move, the propagation distance of the p-th cluster becomes time-varying. The time-varying delay $\tau_p(t)$ is calculated as follows:

$$\tau_p(t) = \frac{D_{BS}(t) + D_{MS}(t)}{c} + \tau'_p(t)$$

where c is the speed of light, $D_{BS}(t)$ and $D_{MS}(t)$ represent the distance changes caused by the movement of the MS and MC, and $\tau'_p(t)$ is the delay of the virtual link between MC_1 and MC_2 [8], which can be calculated using a first-order filtering algorithm at time t_k [9]:

$$\tau'_p(t_k) = \tau'_p(t_{k-1}) + \kappa\left(\tau^0_p(t_k) - \tau'_p(t_{k-1})\right)$$

where κ follows a $\Gamma(1, 1)$ distribution, Γ is a parameter depending on the coherence of the virtual link and scenario, and τ_{max} is the maximum delay obtainable from [1] (e.g., $\tau_{max} = 1885$ ns). Notably, $\tau^0_p(t_k)$ can be computed as

$$\tau^0_p(t_k) = \frac{D_{BS}(t_k) + D_{MS}(t_k)}{c} + \Delta\tau$$

where the initial delay $\Delta\tau$ is randomly drawn from an exponential delay distribution as explained for the given scenario in the original IMT-A channel model [8]. Substituting equations (3)-(5) into equation (14) yields the time-varying delay of the p-th cluster at different instantaneous times t. The delays are normalized by subtracting the minimum delay and sorted in descending order. The normalized delays are used for time-varying channel coefficient generation (see equation (1)) but not for cluster power calculations.

2.3 Time-Varying Power of Clusters

The random average power of the n-th cluster at time t_0 is expressed as

$$P_n(t_0) = \exp\left(-\frac{\tau_n(t_0)}{r_\tau \sigma_{DS}}\right) \cdot 10^{-\frac{\xi_n}{10}}$$

where r_τ is the delay distribution proportionality factor, σ_{DS} is the delay spread, and ξ_n is the per-cluster shadowing term (in dB), all obtainable from Table A1-7 in [1]. Therefore, based on the time-varying delay calculation above, the random average power of the p-th cluster at time t can be expressed as

$$P_p(t) = P_p(t_0) \cdot \exp\left(-\frac{\tau_p(t) - \tau_p(t_0)}{r_\tau \sigma_{DS}}\right)$$

The total power of all clusters is normalized to 1, and the time-varying cluster power $P_p(t)$ is obtained accordingly.

2.4 Time-Varying AoD

The time-varying AoD function $\alpha_{pq}^{T}(t)$ depends not only on the antenna spacing at the BS and MS but also on time t. The spatial CCF of this channel model is therefore referred to as the local spatial CCF, expressed as [7]

$$\alpha_{pq}^{T}(t) = \arccos\left(\frac{D_{BS}^2(t) + D_T^2 - 2D_{BS}(t)D_T\cos(\beta_T)}{2D_{BS}(t)D_T\sin(\beta_T)}\right) + \alpha_{pq}^{T0}$$

where the auxiliary angle β_T is defined to simplify the expression. The initial AoD α_{pq}^{T0} is constrained to $[0, \pi)$, and the time-varying offset is calculated based on the relative geometry.

2.5 Time-Varying AoA

Similarly, the time-varying AoA $\alpha_{pq}^{R}(t)$ is derived as

$$\alpha_{pq}^{R}(t) = \arccos\left(\frac{D_{MS}^2(t) + D_R^2 - 2D_{MS}(t)D_R\cos(\beta_R)}{2D_{MS}(t)D_R\sin(\beta_R)}\right) + \alpha_{pq}^{R0}$$

with the auxiliary angle β_R defined analogously. The initial AoA α_{pq}^{R0} is constrained to $[-\pi, \pi)$, and the expression accounts for the movement of both the MS and MC.

3 Statistical Properties

3.1 Time-Varying Space-Time Cross-Correlation Function

For the proposed IMT-A based channel modeling system, the space-time varying CCF between two channel impulse responses separated by time Δt and spatial displacements $\Delta\delta_T$ and $\Delta\delta_R$ at the transmitter and receiver respectively is given by

$$\rho_h(\Delta\delta_T, \Delta\delta_R; t, \Delta t) = E\left\{h(t)h^*(t+\Delta t)\right\}$$

where the expectation is taken over the random phases and channel parameters. The expression can be expanded as

$$\rho_h(\Delta\delta_T, \Delta\delta_R; t, \Delta t) = \sum_{p=1}^{P(t)}\sum_{q=1}^{Q}\exp\left(j\frac{2\pi}{\lambda}\left(k_T(\alpha_{pq}^{T}(t))\cdot\Delta\delta_T + k_R(\alpha_{pq}^{R}(t))\cdot\Delta\delta_R\right)\right)\times\exp\left(j\frac{2\pi}{\lambda}\left(v_{MS}\cdot\Delta t + v_{MC}\cdot\right.\right.$$

3.2 Time-Varying Auto-Correlation Function

Considering the Markov birth-death process, the survival probability of a cluster from t_0 to t is denoted by R_{MC}. The local time ACF of the non-stationary channel model for the p-th cluster can be expressed as

$$\rho_h(\Delta t) = E\left\{h(t)h^*(t+\Delta t)\right\} = \sum_{p=1}^{P(t)} P_p(t) \cdot R_{MC} \cdot \exp\left(j2\pi f_D \Delta t\right)$$

where f_D represents the Doppler frequency shift. The complete derivation involves three components:

$$X(t,\Delta t) = \exp\left(jk_R(\alpha_{pq}^R(t+\Delta t) - \alpha_{pq}^R(t))\right)$$

$$Y(t,\Delta t) = \exp\left(jk_T(\alpha_{pq}^T(t+\Delta t) - \alpha_{pq}^T(t))\right)$$

$$Z(t,\Delta t) = \exp\left(j(k_v(\alpha_{pq}^R(t+\Delta t)) - k_v(\alpha_{pq}^R(t)))\right)$$

3.3 Stationary Interval

The stationary interval can be calculated using the average power delay profile (APDP), expressed as

$$\bar{W}_h(\tau) = \frac{1}{N}\sum_{k=1}^{N} |h_k(\tau)|^2$$

where N is the number of power delay profiles to be averaged and t_k is the time of the k-th snapshot. The correlation coefficient between two APDPs can be calculated as

$$\rho_W(\Delta t) = \frac{\int \bar{W}_h(\tau,t)\bar{W}_h(\tau,t+\Delta t)d\tau}{\sqrt{\int \bar{W}_h^2(\tau,t)d\tau \int \bar{W}_h^2(\tau,t+\Delta t)d\tau}}$$

The stationary interval is then computed as

$$T_{si} = \arg\max_{\Delta t}\left\{\rho_W(\Delta t) \geq \rho_{th}\right\}$$

where ρ_{th} is a given threshold for the correlation coefficient, with specific values provided in subsequent simulations.

4 Simulation Analysis

This section presents MATLAB simulation analysis of the statistical properties of the proposed IMT-A based channel model for high-speed railway mobile communication scenarios.

4.1 Time-Varying Space-Time Cross-Correlation Function

We employ the NLoS UMA scenario with primary simulation parameters: carrier frequency $f_c = 930$ MHz, $P(t_0) = 100$, $\alpha_T^{LoS} = 15^\circ$, $v_{MS} = 30$ m/s, $\alpha_R^{LoS} =$ random, $D_{BS} = 150$ m, $v_P = 20$ m/s, and $\alpha_{MS} = 120^\circ$.

[Figure 4: see original paper] illustrates the 3D absolute value of the local spatial CCF for the proposed IMT-A based channel model. The results show that as the antenna spacing at the MS increases, the local spatial CCF decreases with periodic fluctuations, and the fluctuation amplitude diminishes significantly with larger antenna spacing, eventually approaching a stable level. This behavior arises from the non-stationary characteristics of the channel in high-mobility environments.

[Figure 5: see original paper] depicts the absolute value of the local spatial CCF at five different instants ($t = 0$ s, 1 s, 2 s, 3 s, and 4 s) extracted from [Figure 4: see original paper]. Although the local spatial CCF decreases with increasing antenna spacing at the MS, the fluctuation amplitude differs across time instants. Overall, the CCF peaks show a slightly increasing trend, with diminishing amplitude over time, eventually stabilizing. These phenomena directly result from non-stationarity. The analysis of [Figure 4: see original paper] and [Figure 5: see original paper] demonstrates the pronounced non-stationarity of the IMT-A based channel model under high-speed mobility, confirming the theoretical analysis.

4.2 Time-Varying Auto-Correlation Function

Continuing with the NLoS UMA scenario, the following parameters are used to simulate the local time ACF: $P(t_0) = 100$, $\alpha_T^{LoS} = 15^\circ$, $v_{MS} = 30$ m/s, $\alpha_R^{LoS} =$ random, $D_{BS} = 70$ m, $\alpha_{MS} = -140^\circ$, $v_P = 5$ m/s, and $\alpha_{MC} = 120^\circ$.

[Figure 6: see original paper] shows the 3D absolute value of the local time ACF for the IMT-A based channel model. Similar to the local spatial CCF, the absolute value of the local time ACF varies with time t due to time-varying AoD and AoA. As the time difference increases, the local time ACF exhibits a decreasing trend with periodic fluctuations, with the fluctuation amplitude diminishing significantly as the time difference grows, eventually stabilizing.

[Figure 7: see original paper] presents the absolute value of the local time ACF at six different instants ($t = 0$ s, 1 s, 2 s, 3 s, 4 s, and 5 s) extracted from [Figure 6: see original paper]. The local time ACF decreases with increasing time difference, with varying fluctuation amplitudes at different time instants. The fluctuations tend to increase over time. At a time difference of 0.25 s, the

ACF at different instants drops by over 80%. As the time difference continues to increase, the fluctuations gradually stabilize. [Figure 6: see original paper] and [Figure 7: see original paper] further confirm the non-stationarity of the IMT-A based channel model under high-speed mobility, with simulation results matching the analytical predictions.

4.3 Stationary Interval

[Figure 8: see original paper] displays the empirical complementary cumulative distribution function (CCDF) of the stationary interval for the proposed IMT-A based channel model at velocities $v = 90$ m/s and $v = 20$ m/s. Other simulation parameters are: $f_c = 930$ MHz, $\rho_{th} = 0.8$, $P(t_0) = 100$, $v_P = 0$ m/s, $D_{BS} = 70$ m, and $\alpha_{MS} = 0°$.

From [Figure 8: see original paper], for the proposed channel model at $v = 90$ m/s, the CCDF of the stationary interval shows: a time interval of 0.009 s at probability 0.8, and 0.02 s at probability 0.6. At $v = 20$ m/s, the CCDF shows: a time interval of 0.018 s at probability 0.8, and 0.06 s at probability 0.6. Comparing these results reveals that higher velocities yield smaller correlation, thereby demonstrating the feasibility of the proposed IMT-A based channel modeling approach and its consistency with practical conditions.

5 Conclusion

This paper proposes an IMT-A based channel modeling method for high-speed railway mobile communication scenarios, employing a Markov process to model the birth-death process of time-varying clusters. Based on this channel model, we derive and analyze its key statistical properties: local spatial CCF, local time ACF, and stationary interval. MATLAB simulations of the CCF, ACF, and stationary interval for the proposed channel model reveal its non-stationary characteristics, thereby validating the feasibility of the proposed channel modeling approach.

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Note: Figure translations are in progress. See original paper for figures.