

A Ray Tracing-Based Approach for Generation of Non-Stationary V2V Channels

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Abstract—Investigating vehicle-to-vehicle (V2V) networks requires models that reflect physical road traffic behaviors. Standard models assume vehicles travel at constant speeds, omitting the effects of acceleration and braking. This paper presents a method connecting discrete ray-tracing (RT) environment data with continuous vehicular movement. By applying a polynomial phase rotation over short time intervals, the model captures the time-varying mobility of both accelerating vehicles and moving scatterers. Simulation results illustrate the physical effects of this approach: vehicular acceleration induces continuous frequency smearing in the Doppler power spectral density (DPSD) and generates power variations in the power delay profile (PDP).

Keywords—Doppler Shift, Fifth Generation, Non-Stationary Channel, Ray-Tracing, Vehicle-to-Vehicle.

I. INTRODUCTION

Integrated sensing and communication (ISAC) is considered a key technology for future 6th generation (6G) wireless networks, as it enhances how vehicles interact with their environment [1], [2]. By allowing radar and communication systems to share the same hardware and spectrum, ISAC enables sophisticated vehicle-to-everything (V2X) applications. However, testing these systems requires deterministic channel models that accurately represent the electromagnetic phase and multipath geometry in dynamic scenarios.

In such dynamic environments, the relative movement among transmitters, receivers, and environmental scatterers induces continuous phase variations over time. To model these effects, channel models utilize the Doppler frequency shift to dictate the temporal evolution of each multipath component (MPC). For ISAC operations, this temporal evolution is a fundamental requirement not only for data decoding, but also for environmental sensing [3], [4]. Modern vehicular networks utilize the communication waveform to perform radar-like functions, which require extracting velocity and acceleration profiles from the channel backscatter [1], [2]. Therefore, the accuracy of both the communication link and the sensing parameter estimation depends directly on how the vehicular mobility and the resulting Doppler effects are mathematically formulated. Despite the phase accuracy required by ISAC systems, standard channel models usually rely on the wide-sense stationary uncorrelated scattering (WSSUS) assumption [5]. By assuming a constant velocity, these models do not account for the continuously arbitrary trajectories of vehicular traffic [6], nor the pervasive channel properties required over various 6G scenarios [7]. The physical inertia and acceleration of the nodes cause the quasi-stationary interval of the channel

to shrink [5], making static Doppler models insufficient for high-mobility evaluations.

To address these limitations, recent work has illustrated the efficacy of coupling high-resolution ray-tracing (RT) with phase-coherent Doppler evolution for ISAC and digital twin environments [3]. Furthermore, applying non-stationary evolution directly at the ray level is critical to correctly capture spatial consistency in highly dynamic channels [8]. Based on this concept, we propose a deterministic channel modeling architecture that combines discrete geometric data with continuous non-stationary mobility. Our baseline framework relies on the Raymobtime methodology, which integrates traffic simulators with RT engines to generate spatially consistent datasets [9]. The main contribution of this work is the expansion of this methodology via an intra-scene polynomial-phase evolution algorithm. By extracting three-dimensional (3D) acceleration and velocity vectors from the traffic simulator and projecting them onto the multipath geometry, the proposed architecture rotates the electromagnetic phase over the micro-time. This work provides a non-stationary vehicle-to-vehicle (V2V) channel model that supports the high-mobility requirements of 6G evaluations.

This paper is organized as follows. Section II details the proposed non-stationary system model, encompassing the mobility data extraction, the vectorial Doppler formulation, and the intra-scene baseband channel assembly. Section III presents the simulation setup and results, evaluating the impacts of vehicular mobility on the Doppler power spectral density (DPSD) and the power delay profile (PDP). Finally, Section IV draws the conclusions and outlines future work.

II. SYSTEM MODEL

This section details the proposed deterministic, non-stationary channel model. First, the spatial data extraction and mobility processing are described. Then, the vectorial formulations for the Doppler shift and rate are derived. Finally, the local phase-rotation algorithm and the baseband matrix assembly are presented.

A. Raymobtime overview and mobility processing

geometry-based stochastic models (GBSM) are utilized in vehicular channel modeling [6], generating scatterer locations based on statistical distributions. As reported in [10], standard vehicular models often assume constant velocities and uniform rectilinear motion for the nodes. Extending these models to incorporate arbitrary trajectories and multi-mobility environments involves continuous re-clustering, which adds structural complexity to the formulation [6]. As an alternative

method, the deterministic RT approach extracts discrete spatial coordinates and mobility vectors directly from a traffic simulator, without requiring statistical clustering. To present this deterministic method, this section describes the data extraction and mobility reconstruction for the proposed channel model. The baseline framework relies on the Raymobtime methodology [9], which integrates the simulation of urban Mobility (SUMO) traffic simulator and a RT engine. In this work, the Wireless InSite (WI) engine is utilized to generate spatially consistent datasets. The simulation is organized into independent observation windows called *episodes*. Each episode is subdivided into discrete snapshots, referred to as *scenes*, which are separated by a *macroscopic* sampling period T_s .

Within this pipeline, the WI engine processes each scene to compute the discrete electromagnetic parameters for each MPC. Specifically, the outputs include the static geometric phase ϕ_{0_i} , the time of flight (ToF), the angle of arrival (AoA) and angle of departure (AoD) for elevation and azimuth, and the received power (internally computed via material-dependent Fresnel reflection and diffraction coefficients). Concurrently, SUMO provides the 3D coordinates, scalar velocity (v_{mag}), acceleration (a_{mag}), and heading angle (θ_{sumo}) for each vehicular node.

To reconstruct the 3D Cartesian vectors of velocity and acceleration from the scalar data, a spherical projection onto a horizontal plane is performed. Thus, the directional unit vector of movement is defined as:

$$\hat{\mathbf{u}}_{mov} = [\sin \theta_{sumo}, \cos \theta_{sumo}, 0]^T \quad (1)$$

Consequently, the 3D velocity and acceleration vectors are formulated as $\mathbf{v} = v_{mag} \cdot \hat{\mathbf{u}}_{mov}$ and $\mathbf{a} = a_{mag} \cdot \hat{\mathbf{u}}_{mov}$, respectively.

To process these outputs and implement the non-wide-sense stationary uncorrelated scattering (Non-WSSUS) channel evolution [5], the algorithm filters the scenario data to categorize the elements of the environment. For objects that act as static scatterers (e.g., buildings and fixed infrastructure), the mobility feature vectors are set to zero ($\mathbf{v} = \mathbf{0}, \mathbf{a} = \mathbf{0}$). This step ensures that the mobility dynamics are isolated exclusively to the vehicular objects, providing the required basis for the time-varying Doppler evaluation.

B. Vectorial Doppler shift and Doppler rate formulation

To capture the non-stationary frequency evolution of the channel, the Doppler shift (f_{d_i}) and Doppler rate ($\dot{f}_{d_i}$) are formulated for each MPC.

For the line-of-sight (LOS) MPC, the mobility depends strictly on the relative movement between the transmitter (Tx) and the receiver (Rx). This direct propagation path is evaluated using a single unit direction vector pointing from the Tx to the Rx, denoted as $\hat{\mathbf{r}}_{LOS}$. Therefore, the Doppler shift and Doppler rate for the LOS component are defined as:

$$f_{d_{LOS}} = \frac{1}{\lambda} ((\mathbf{v}_{Rx} - \mathbf{v}_{Tx}) \cdot \hat{\mathbf{r}}_{LOS}) \quad (2)$$

$$\dot{f}_{d_{LOS}} = \frac{1}{\lambda} ((\mathbf{a}_{Rx} - \mathbf{a}_{Tx}) \cdot \hat{\mathbf{r}}_{LOS}). \quad (3)$$

where λ is the carrier wavelength.

For the non-line-of-sight (NLOS) MPCs, intermediate interactions with mobile scatterers occur. As illustrated in Fig. 1, the unit direction vectors must account for the relative movement at each interaction node to accurately compute the phase evolution. Geometrically, an MPC with P intermediate interactions is defined by a sequence of 3D spatial coordinates $[\mathbf{p}_0, \mathbf{p}_1, \dots, \mathbf{p}_P, \mathbf{p}_{P+1}]$, where the initial node $\mathbf{p}_0$ is the Tx and the final node $\mathbf{p}_{P+1}$ is the Rx. Consequently, the directional unit vector ($\hat{\mathbf{r}}_p$) departing from the $(p-1)$ -th node to the p -th node is computed through the normalized difference of their coordinates:

$$\hat{\mathbf{r}}_p = \frac{\mathbf{p}_p - \mathbf{p}_{p-1}}{\|\mathbf{p}_p - \mathbf{p}_{p-1}\|} \quad (4)$$

where $\|\cdot\|$ denotes the Euclidean norm.

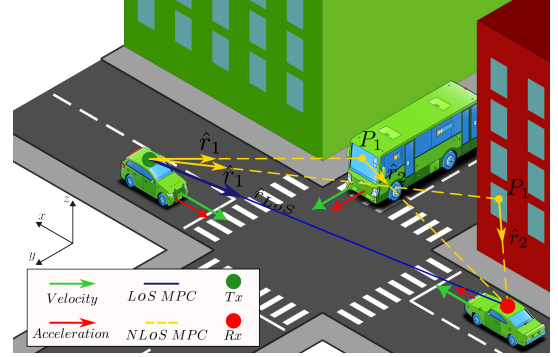


Fig. 1: Schematic representation of the geometric mobility.

Following the ray-launched Doppler tracking formalized in the Sionna RT¹ framework, the Doppler shift and rate of an NLOS MPC can be computed by superposing the mobility contributions along the propagation path. In realistic V2V scenarios, modeling this multi-mobility is useful to represent dynamic propagation conditions where moving scatterers (such as other vehicles) possess individual velocity and acceleration vectors [10], yielding:

$$f_{d_{NLOS}} = \frac{1}{\lambda} \left[\mathbf{v}_{Rx} \cdot \hat{\mathbf{r}}_{P+1} - \mathbf{v}_{Tx} \cdot \hat{\mathbf{r}}_1 + \sum_{p=1}^P [\mathbf{v}_{S_p} \cdot (\hat{\mathbf{r}}_p - \hat{\mathbf{r}}_{p+1})] \right] \quad (5)$$

$$\dot{f}_{d_{NLOS}} = \frac{1}{\lambda} \left[\mathbf{a}_{Rx} \cdot \hat{\mathbf{r}}_{P+1} - \mathbf{a}_{Tx} \cdot \hat{\mathbf{r}}_1 + \sum_{p=1}^P [\mathbf{a}_{S_p} \cdot (\hat{\mathbf{r}}_p - \hat{\mathbf{r}}_{p+1})] \right]. \quad (6)$$

where $\hat{\mathbf{r}}_1$ is the unit vector departing from the Tx, $\hat{\mathbf{r}}_{P+1}$ is the unit vector arriving at the Rx, while $\mathbf{v}_{S_p}$ and $\mathbf{a}_{S_p}$ represent the velocity and acceleration vectors of the p -th mobile scatterer, respectively.

C. Intra-scene non-stationary channel synthesis

As discussed, the Raymobtime methodology generates a dataset consisting of discrete geometric scenes separated by a macroscopic sampling period T_s [9]. To incorporate the intra-scene mobility into the channel synthesis, a local micro-time

¹Available at: <https://nvlabs.github.io/sionna/>

variable, τ , is introduced. This variable is constrained within the interval of a single scene, such that $\tau \in (0, T_s]$.

As τ evolves from zero, the mobility features extracted from SUMO perturb the electromagnetic phase. Within this local update, the instantaneous Doppler shift for each MPC l is approximated using a first-order Taylor expansion. Consequently, the Doppler shift evolves linearly over the micro-time as a function of the Doppler rate [5], [10]:

$$f_{d_l}(\tau) \approx f_{d_l} + \dot{f}_{d_l}\tau. \quad (7)$$

However, due to the high-mobility characteristics of the environment, this linear approximation is valid only for short observation intervals [5], [10]. To ensure that the phase evolution does not violate the WSSUS assumption of the underlying geometric scene, it is necessary to monitor the time-variant Doppler spread, $B_D(\tau)$, within each scene. This metric represents the dispersion of the MPCs instantaneous frequencies, the random variables, weighted by their normalized power P_l [5]:

$$B_D(\tau) = \sqrt{\sum_{l=1}^L P_l [f_{d_l}(\tau)]^2 - \left(\sum_{l=1}^L P_l f_{d_l}(\tau)\right)^2} \quad (8)$$

The degradation of the channel's stationarity over time is quantified by the relative stochastic error $\varepsilon(\tau)$ [5]:

$$\varepsilon(\tau) = \frac{|B_D(\tau) - B_D(0)|}{B_D(0)}. \quad (9)$$

Based on this metric, the quasi-stationary interval T_c is defined as the maximum duration of τ for which this error remains below a tolerance threshold of 10% ($\varepsilon = 0.1$). Therefore, to guarantee that the synthesized channel preserves the temporal and spatial consistency of the initial Raymobtime snapshot, the micro-time evolution is truncated at a maximum bound:

$$\tau_{max} = \min(T_s, T_c). \quad (10)$$

D. Baseband channel assembly

Based on the established mobility boundaries, the final baseband channel is synthesized. The phase for each MPC is actively rotated over the micro-time τ using a second-order Taylor polynomial [5]:

$$\phi_l(\tau) = \phi_{0_l} + 2\pi \left(f_{d_l}\tau + \frac{1}{2}\dot{f}_{d_l}\tau^2 \right) \quad (11)$$

The quadratic term in (11) incorporates the acceleration into the channel, capturing the Doppler smearing effect caused by vehicular mobility. By restricting the intra-scene phase rotation up to τ_{max} , the algorithm ensures that the continuous mobility effects are applied without violating the quasi-stationary boundaries of the original geometric scene.

For a MIMO system equipped with uniform planar arrays at both the Tx and Rx, the complex baseband channel transfer matrix $\mathbf{H}(\tau, f) \in \mathbb{C}^{N_{rx} \times N_{tx}}$ at a given micro-time τ and subcarrier frequency f is constructed by the superposition of L discrete MPCs:

$$\mathbf{H}(\tau, f) = \sum_{l=1}^L \sqrt{P_l} e^{j(\phi_l(\tau) - 2\pi f \tau_{0_l})} \times \mathbf{a}_{rx}(\theta_l^{AoA}, \phi_l^{AoA}) \mathbf{a}_{tx}^H(\theta_l^{AoD}, \phi_l^{AoD}) \quad (12)$$

where P_l and τ_{0_l} denote the discrete received power and the initial Time of Flight (ToF) of the l -th MPC extracted from the RT snapshot, respectively. The terms $\mathbf{a}_{rx}(\cdot)$ and $\mathbf{a}_{tx}(\cdot)$ represent the spatial steering vectors of the receiving and transmitting antenna arrays, evaluated at the respective elevation and azimuth angles. This formulation combines the static geometric spatial outputs of traditional RT simulators with the non-stationary fading processes necessary for high mobility V2V evaluations.

III. SIMULATION RESULTS

This section evaluates the proposed framework in a deterministic urban intersection, analyzing the vehicular mobility effects via the DPSD and PDP.

A. Simulation setup

The proposed non-stationary channel synthesis is evaluated using a deterministic dataset representing an urban intersection in São Paulo, Brazil. The system operates at a carrier frequency of 5.9 GHz, and 100 MHz bandwidth, with a macroscopic sampling period $T_s = 100$ ms with 230 scenes in one episode, totalizing 23 seconds of simulation. Measurements at this specific frequency indicate that the stationary time in V2V scenarios is short and dependent on relative mobility [11]. Therefore, the proposed intra-scene phase rotation is applied to model the channel's operation over T_s . The 3D propagation environment consists of an urban intersection, simulating a dynamic V2V scenario, as depicted in Fig. 2. The transmitting antenna operates at 0 dBm with omnidirectional vertical polarization, considering ideal hardware conditions without impairments.

To evaluate the effects of vehicular mobility, specific scenes were selected from the 230-scene episode based on their mobility profiles. As illustrated in the relative distance profile in Fig. 3, the distance between Tx and Rx decreases from Scene 0 to Scene 115, indicating an approach phase. After crossing at Scene 115, the distance increases, denoting a departure phase.

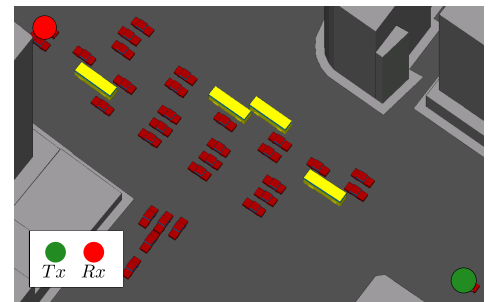


Fig. 2: Orthogonal view of the scene 61.

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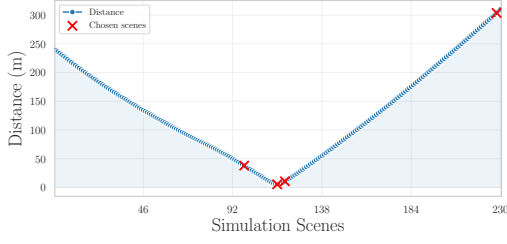


Fig. 3: Evolution of the relative distance between Tx and Rx along the scenes.

Based on the velocity and acceleration profiles in Fig. 4, Scene 120 serves as a reference for stable movement, presenting an acceleration near zero. In contrast, Scene 98 represents a dynamic state during the approach phase, exhibiting negative acceleration. Scene 228 represents a dynamic state during the departure phase, exhibiting positive acceleration. Furthermore, Scene 115 marks the exact point of crossing between the vehicles, where the relative distance is at its minimum.

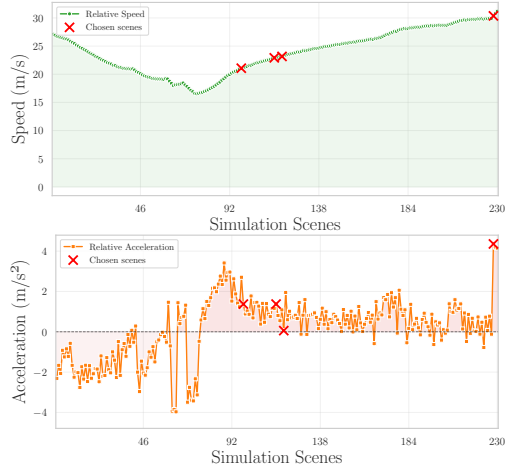


Fig. 4: Mobility extracted from SUMO, illustrating the evolution of the relative speed (top) and acceleration (bottom) between Tx and Rx along the scenes.

B. Doppler power spectral density

The effect of vehicular mobility on the frequency domain is evaluated through the DPSD. In Scene 120, where acceleration is low, the DPSD in Fig. 6a exhibits discrete spectral peaks. This behavior is consistent with models based on constant velocity.

During dynamic states, the relative acceleration activates the quadratic term of the phase polynomial. For Scene 98 in Fig. 6c, the vehicles are approaching, producing a positive

Doppler shift [5]. Due to the deceleration present in this scene, the base of the spectral peak broadens. For Scene 228 in Fig. 7c, the vehicles are moving apart, producing a negative Doppler shift. The positive acceleration in this scene similarly enlarges the spectral peak base. This phenomenon, known as Doppler smearing [4], illustrates that vehicular mobility alters the frequency orthogonality within the micro-time τ .

Moreover, Fig. 7a captures the transition between the approach and departure phases in Scene 115. The crossing geometry causes the relative radial velocity to momentarily approach zero. Consequently, the main spectral peak is concentrated near 0 Hz, marking the boundary between the positive and negative Doppler shifts.

C. Power delay profile

The channel dispersion is analyzed using the PDP. The evaluation is divided into macro and microscopic time scales to independently observe the geometric drift and the phase rotation. As illustrated in Fig. 5, the continuous PDP change is evaluated across the 23 s simulation. The V-shape of the main clusters corresponds to the relative distance profile. At $t = 11.5$ s (Scene 115), the minimum relative distance is reached, and the absolute ToF decreases to its lowest value.

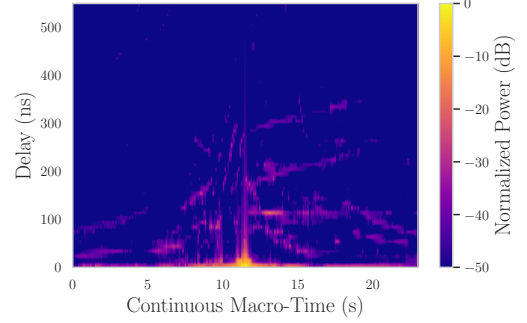


Fig. 5: Macroscopic PDP evolution across the continuous macro-time.

On a microscopic scale, the intra-scene PDPs over the micro-time τ reveal that propagation delays remain constant. This indicates that delay deviations are negligible for sub-6 GHz systems at this scale [5]. For the dynamic states (Scenes 98, 115, and 228), the power intensity changes across the τ axis, producing the intra-scene fading seen in Figs. 6d, 7b, and 7d. This fading is a consequence of the non-linear phase rotation induced by the second-order Taylor polynomial, demonstrating that mobility affects the channel phase before altering the geometric delays in the baseband. Furthermore, delay values in Scene 115 reach their lower bounds in Fig. 7b

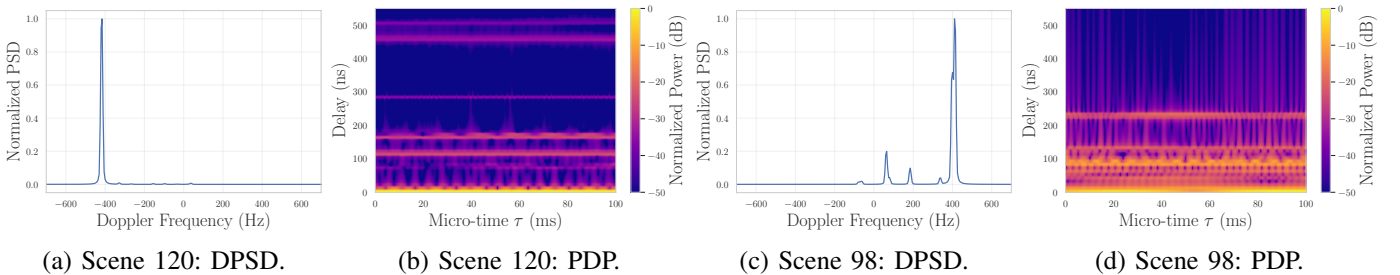


Fig. 6: DPSD and PDP for scenes 120 and 98.

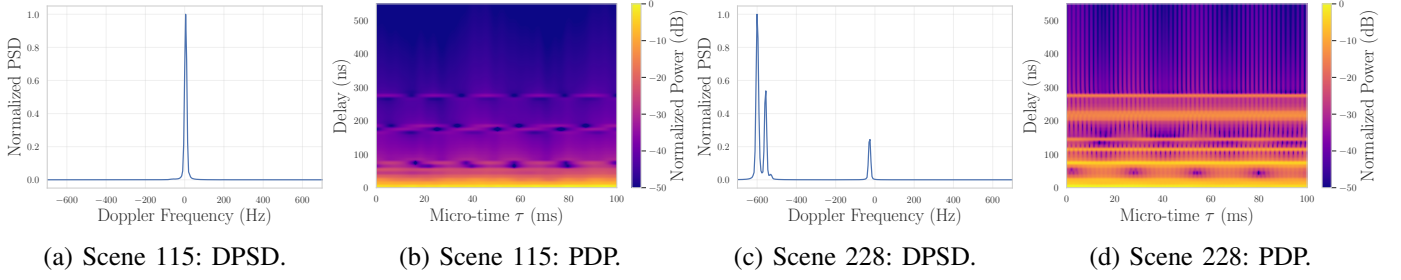


Fig. 7: DPSD and PDP for scenes 115 and 228.

due to the crossing geometry, while Scene 120 illustrates the baseline stable mobility conduct in Fig. 6b.

To evaluate this intra-scene phase rotation, the relative stochastic error $\epsilon(\tau)$ is analyzed with respect to the chosen macroscopic sampling period T_s . During the dynamic states (Scenes 98 and 228), the non-zero acceleration increases the magnitude of the Doppler rate ($\dot{f}_d$), which accelerates the phase decorrelation. For the simulated urban intersection parameters, numerical computations of the time-variant Doppler spread indicate that $\epsilon(\tau)$ remains below the 10% threshold over the 100 ms duration. This represents that the local quasi-stationary interval T_c exceeds T_s , indicating that the proposed framework operates within the physical correlation limits of the original RT snapshots. By bounding the micro-time evolution by $\tau_{\max} = \min(T_s, T_c)$, the architecture preserves the channel's spatial consistency, while adapting if other mobility profiles cause T_c to shrink below T_s .

The observed Doppler smearing and intra-scene power variations have implications for physical layer designs in 6G networks. In standard orthogonal frequency-division multiplexing (OFDM) systems, the assumption of a static Doppler shift allows receivers to compensate for carrier frequency offsets. However, the continuous frequency broadening induced by the Doppler rate ($\dot{f}_d$) breaches this orthogonality over the micro-time, resulting in inter-carrier interference (ICI) [4]. Consequently, the non-stationary channel synthesis proposed in this work provides a baseline for evaluating equalization techniques and multi-carrier waveforms under high-mobility vehicular conditions.

IV. CONCLUSIONS

This paper presented a deterministic channel modeling architecture to synthesize non-stationary V2V channels. By extending the Raymobtime framework, the proposed algorithm connects discrete geometric RT outputs with continuous phase rotation. A second-order Taylor polynomial, constrained by the quasi-stationary interval, integrates the vehicular mobility into the baseband channel matrix.

Evaluations across macro and microscopic time scales illustrated that time-varying mobility alters fundamental channel properties. In the frequency domain, DPSD analyses revealed that acceleration and deceleration induce Doppler smearing, broadening the spectral peak bases during both approach and departure phases. In the time domain, the PDP showed that while propagation delays remain constant within the quasi-stationary interval for sub-6 GHz systems, non-linear phase rotations produce intra-scene fading. Consequently, models

based solely on constant-velocity assumptions omit these non-stationary spectral and temporal variations.

Future work will expand the proposed architecture to incorporate continuous-time-variant drifts in propagation delays. While analytically negligible for sub-6 GHz systems over short observation windows, modeling non-stationary delay deviations is critical for ultra-wideband 6G ISAC systems and millimeter wave sensing, which require sub-nanosecond resolution. Furthermore, the simulation findings will be validated against real-world vehicular channel measurements.

V. ACKNOWLEDGMENTS

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