Comparing mmWave Channel Simulators in Vehicular Environments

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***Abstract*—With the emerging 5G solutions for vehicular networking, the spectrum of radio communication technologies also extends into the mmWave band. This is further supported by the recent move towards RADar based COMmunication (RADCOM), i.e., the deeply integrated use of the 77 GHz band for communication and sensing. mmWave communication has widely been explored both analytically as well as in experiments, particularly for indoor usage and semi-stationary outdoor scenarios. In this paper, we explore the capabilities of existing simulators for the vehicular use case. We selected WinProp using deterministic ray-tracing techniques and NYUSIM relying on stochastic simulation of the channel. We compare both with a strong focus on simulation accuracy, usability, and computational performance.**

***Index Terms*—Channel simulator, NYUSIM, WinProp.**

I. INTRODUCTION

Modern Intelligent Transportation Systems (ITS) rely heavily on communication to realize more efficient, reliable, and enjoyable transportation. To support this communication, such applications are currently based on Dedicated Short Range Communication (DSRC) in the sub-6 GHz band, as well as cellular technologies, such as Long-Term Evolution (LTE)-Vehicle-to-everything (V2X) [1].

With the upcoming 5G standardization, it is anticipated that these communication methods will converge, to support Cellular V2X (C-V2X) with both Device to Device (D2D) and 5G New Radio (5G-NR). In addition, with the move to 5G, the use Millimeter Wave (mmWave) frequencies in the 28 GHz band has become available to cellular networks, sparking large research interest. mmWave communication is currently already becoming widely available in the 60 GHz ISM band, e.g., in the context of IEEE 802.11ad [2]. At these frequencies, virtually vast amounts of spectrum are available to users, supporting channel bandwidths in excess of 1 GHz.

Automotive applications, however, may benefit of the 77 GHz band that is reserved for vehicular radar applications [3], [4]. Radar sensors operating in these frequencies can be used to gather critical application such as distances for stable platooning, or awareness for intersection assistant systems. Since these sensors are already deployed in modern vehicles, dual-purposing them for sensing and communication by the use of RADar based COMmunication (RADCOM) is a promising technology [5]. With RADCOM, simultaneous sensing and communication is enabled, that may complement other communication technologies.

However, even though first field tests show promising insights, the channel characteristics for these frequencies are not yet fully explored [6], [7]. At the same time, simulation frameworks have been developed, again, mainly focusing on rather stationary environments but at least also covering outdoor effects such as rain and snow on mmWave communication [8].

These simulation frameworks feature different approaches, including stochastic approaches (e.g., NYUSIM [7], MilliCar [9]) and deterministic models (e.g., WinProp[1]). This leads to differences, but also similarities, in key aspects of the simulators, such as the usability, or accuracy of the results. Still, none of these simulators has yet been integrated in state-of-the-art simulation frameworks for vehicular networks such as Veins [10] or Artery [11], which cover models for sub-6 GHz communication based on Wireless LAN (WLAN), DSRC, and C-V2X.

In this paper, we explore the possibilities focusing on widely used and community-validated mmWave simulators NYUSIM and WinProp and how these could be used for supporting mmWave communication in RADCOM-based vehicular environments. These simulators use different approaches, while both allow for fine-tuning (by specifying the environment in WinProp, and configuring parameters in NYUSIM) to allow for the use in different scenarios. We focus on typical vehicular communication scenarios and compare the simulators in terms of accuracy, required computational resources, and complexity of the toolkit.

Our key contributions are:

- We analyze the use of NYUSIM and WinProp in RADCOM-enabled vehicular communication contexts;
- we outline key differences, detailing the advantages of each simulator; and
- we design representative vehicular scenarios and conduct a comparative simulation study using both frameworks.

II. RELATED WORK

mmWave communication is a potential solution to the increasing demands for higher communication speed and capacity in wireless networks. The propagation characteristics in these frequencies are different from the propagation at lower frequencies. Thus, it is important to obtain a better

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[1] https://www.altair.com/feko-applications

understanding of the channel characteristics. One possibility to derive a channel model is to rely on extensive measurements performed on different scenarios and at different frequencies. Even though such measurement campaigns are very expensive in terms of time and cost, several measurements have been performed over the last years for indoor and outdoor scenarios at frequencies of 28, 38, 60 and 73 GHz [7], [12], [13]. Yet, these measurements of course did not cover all possible scenarios and configurations.

An alternative solution is to use deterministic channel models and particularly ray tracing techniques for investigating the propagation characteristics for specific scenarios [14]. Well-known examples are the simulation tools WinProp and Wireless InSite.[2] WinProp provides the user with the possibility to simulate electromagnetic wave propagation and handles a wide range of communication scenarios such as indoor, urban, rural, and vehicular. The simulator covers frequencies of up to 100 GHz and offers different models, i.e., empirical, semi-empirical, and ray-optical models. InSite has similar features but does not explicitly support vehicular use cases.

Even more flexibility can be achieved using stochastic models, which are simple models in terms of time and computation complexity. Several non-deterministic mmWave channel models and a few channel model simulators have been developed to explore the propagation characteristics in the mmWave frequency band, e.g., QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa) [15] and NYUSIM [7]. QuaDRiGa is an open-source channel model that supports a wide range of frequencies ranging from 0.45–100 GHz. It is based on the 3rd Generation Partnership Project (3GPP) channel model and offers additional specifications for generating realistic channel simulations. NYUSIM is another open-source channel model simulator supporting a wide range of frequencies from 0.5–100 GHz. The channel model is build upon extensive measurements conducted at frequencies from 28–73 GHz. Similarly to QuaDRiGa, NYUSIM has been extended by the spatial consistency model. Recently, a new ns-3 module has been developed, called MilliCar, which enables full stack end to end simulations for Vehicle-to-Vehicle (V2V) mmWave network [9]. The channel model used in MilliCar is implemented according to the 3GPP specifications for V2V communications. The model is similar to the one used in NYUSIM but simplified for performance reasons.

III. MMWAVE CHANNEL SIMULATORS

We selected the de-facto standards in each category, i.e., WinProp for deterministic models and NYUSIM for stochastic models to study their applicability for vehicular scenarios. Both are conceptually very different, thus, we expect them to perform differently, as well. In the following, we introduce the tools and describe the differences between the simulators in the most relevant aspects with the aim to have an optimal description of the propagation channel for future RADCOM-applications.

A. WinProp

The channel simulator software WinProp is a commercial product by Altair. It is comprised of different tools that can be used to investigate different aspects of wireless propagation, e.g., for the purpose of radio network planning. WinProp's propagation tool supports the use of multiple models: empirical, semi-empirical and ray-optical, which compute different output parameters (such as delay, path loss, angular spread, and Doppler frequency shift) of the arriving waves. The models differ in their method of computation. The empirical model is based on five empirical material parameters, namely the loss of diffracted rays, reflection loss, transmission loss, minimum loss of incident ray, and maximum loss of incident ray. The deterministic model combines the Fresnel equations with the geometrical theory of diffraction (GTD) and uniform theory of diffraction (UTD) to observe the reflection and transmission loss and diffraction loss, respectively. This model takes into account the three fundamental material parameters (permittivity, permeability, and conductivity), which, however, leads so higher demands on computational resources.[3] A wide range of frequencies (up to 100 GHz) is supported by WinProp and it can be used for a variety of applications in different scenarios, ranging from large-scale suburban scenes to dynamic indoor environments. WinProp also found widespread application in research, in particular for the study of the channel propagation [16]–[19].

B. NYUSIM

NYUSIM [7] is an open-source mmWave channel model simulator developed at NYU WIRELESS. The simulator is based on MATLAB and it supports a wide range of frequencies from 0.5–100 GHz and bandwidth up to 800 MHz. NYUSIM uses a statistical spatial channel model (SSCM), which is built upon the measurements conducted at frequencies of 28–73 GHz in various outdoor scenarios. The channel model employs the concept of time clusters (TC) and spatial lobes (SL) for generating Channel Impulse Responses (CIR), dividing the temporal and spatial statistics. According to [7], TCs are comprised of Multi Path Component (MPC) traveling close in time, which can come from different angular directions during a short propagation delay time window. SLs represent the main direction of arrival (departure) on which energy arrives over a time window in the range of nanoseconds.

The close-in (CI) free space reference distance path-loss model is incorporated in the NYUSIM, with an additional variable capturing the attenuation due to the atmospheric effects. Furthermore, the simulator has been extended by the spatial consistency feature [20], which is an essential part of the 5G applications such as V2X communications, for characterizing the channel variation due to receiver mobility.

C. Simulators Validation

Several measurement campaigns have been conducted over the last years for the validation of NYUSIM [12], [13] and

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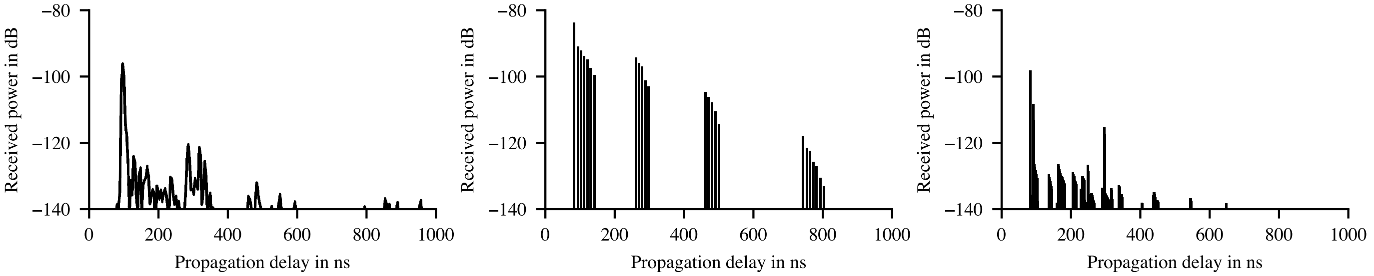
[2] https://www.remcom.com/wireless-insite-em-propagation-software

[3] https://www.altair.com/resource/altair-winprop-datasheet



(a) Measurements [21]

(b) NYUSIM

(c) WinProp

Figure 1. Validation results

WinProp [14] channel models. Besides this work, we have further validated the accuracy of these tools at 60 GHz, by reconstructing the outdoor measurement scenario at Leipziger Platz, Berlin, described in [21], and compared the measurement results with the results obtained in simulations [22]. The open square of octagonal shape is sourrounded by buildings and consists of a wide street with six lanes, some green spaces covered with grass and trees, and side walks. The transmitter is placed at a height of 3.5 m and about 25 m away from the static receiver at a height of 1.5 m. The metric selected for the validation is the average power-delay-profile (PDP). The exact measurement results are given in Figure 1a. For simulating the aforementioned scenario, the relevant parameter values are obtained from the considered work and listed in Table I.

In the case of NYUSIM, due to the stochastic nature of the simulator, the results are averaged over 200 runs and the resultant average PDP values are presented in Figure 1b. In the case of WinProp, the most crucial step was to reconstruct the scenario in detail as presented in [21]. The obtained results are presented in Figure 1c.

The plots illustrate the received power for each multipath component as a function of the propagation delay. In the simulations and the measurements, the first MPC, corresponding to the Line of Sight (LOS) path, reaches the destination with a delay of approximately 83 ns, due to the communication distance of 25 m. The other components from the reflections reach the destination with a higher propagation delay and a decreased power. While the measurements MPCs observe delays of up to 950 ns, for WinProp the maximum delay is in the range of 650 ns due to the predefined number of paths fixed to 500. The NYUSIM results, on the other hand, are slightly more optimistic, with components reaching the destination with delays up to 1160 ns. In terms of the received power, the results of WinProp are very close to the real measurements and differ from the NYUSIM results, which are overoptimistic by predicting higher receiver power with roughly 10 dB mean difference. However, the plot demonstrates a similar behavior as obtained in the outdoor measurements, and the difference is certainly due to the stochastic approach of NYUSIM. Other validation scenarios have demonstrated similar comparable results with NYUSIM and a detailed discussion is provided in [8]. The antennas are chosen isotropic for comparison, but will be replaced by directional ones in the future to overcome the severe path loss experienced at high frequency. Altogether, these results indicate that NYUSIM and WinProp can provide close-to-real-world channel characterization at frequencies above 60 GHz and can be further used for comparison.

Table I
SUMMARY OF THE SIMULATION PARAMETERS VALUE FOR THE VALIDATION.

	WinProp	NYUSIM
Frequency / Bandwidth	60 GHz / undefined	60 GHz / 250 MHz
Antenna / Transmit Power	isotropic / 15 dBm	isotropic / 15 dBm
Distance	25 m	25 m

D. Conceptual Approach

The WinProp simulator uses a ray tracing approach to simulating the channel between a transmitter and receiver. Individual rays, which are emitted from the transmitter, are traced through a model of the surroundings, and those hitting the receiver are accounted for. This makes the simulation deterministic and very accurate, giving a detailed description of the surroundings.

NYUSIM, on the other hand, uses a stochastic approach. Based on empiric measurements, the authors derived patterns in the received signal that are typical for the environment, e.g., a suburban neighborhood. These measurements show, that signals arrive clustered at both similar arrival times as well as in angles of arrival at the receiver, which correspond to similar paths that part of the signal was reflected along. The simulator generates a channel impulse response that matches the observed real world behavior based on its parameterization such as, e.g., number of clusters and subpaths within a cluster.

E. Usability

Both simulators come with graphical front-ends that allow users to configure simulations. The actual use of the simulators differs greatly, owing to the complementary approaches taken.

With WinProp, the user creates a complete scenario of the scene that is to be simulated. The general workflow in WinProp is processed internally with different tools. This includes detailed 3D modeling of the objects of the scene, specifying the individual materials first. The materials have a defined thickness, μ_r, ε_r, σ, and scattering matrices or loss parameters for transmission, reflection, scattering, and diffraction. These properties can also be defined such that they depend on the used frequency. Additionally, the propagation effects to be evaluated for the material can be defined. This process is aided by a database of models of materials that the user can chose from, and is free to extend, if the necessary model cannot be found. Afterwards, the atmospheric properties and communication parameters, such as the antennas or carrier frequency, besides the transmitter and receiver positions can be defined. Overall, while the effort depends on the level-of-detail, this process is very work intensive. With NYUSIM, the scenes are not directly modeled; rather the user selects fitting values for the simulation parameters. Based on knowledge about the scene, this can include setting the number of TCs or SLs that are expected, or using randomized values.

F. Accuracy

The approach taken by NYUSIM generates results, that, in general, fit the observed real-world behavior well [8]. However, the accuracy of the results depends on the similarity between the simulated scenario, and the environment of the original measurements. While it is possible to modify the simulator's source code to adapt it for sufficiently different scenarios, extended validation is necessary.

WinProp's ray tracing approach avoids this issue, since it simulates the exact scene the user defined. Its results have been shown to match real-world measurements [14]. Nonetheless, the scene will never match reality perfectly, and as such the accuracy depends highly on the level of detail of the scene. The data gained from one simulation is very specific to its scene and does not generalize well to other scenarios.

IV. Evaluation and Discussion

For the evaluation of the simulators' feasibility for studying RADCOM communication, we devised scenarios that are simulated in both simulators. Given the results, we can then determine, how well they model each given situation. Additionally, we observe the complexity and work required for modeling each scenario with the respective simulators.

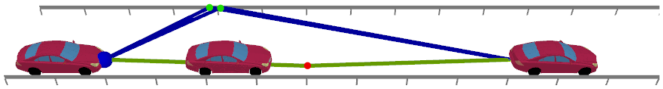
A. Scenarios

We selected a typical cooperative driving application in which vehicular communication is used for real-time communication of safety critical information, namely platooning [1]. This is a prime application domain for RADCOM. In platooning, the vehicles' positions relative to each other are relatively static. We devised two scenarios that model a typical LOS and non Line-of-Sight (NLOS) situation to capture and single out individual effects, such as shadowing, ground reflection and scattering, reflections and scattering at the road's guardrail.

We modeled the scenarios in both WinProp and NYUSIM, comparing a single static time step. However, both NYUSIM and WinProp can consider dynamic and static scenarios. The scenarios were created as 3D models that accurately depict the scene (cf. Figure 2), which can be used in WinProp.

WinProp allows to model a very detailed car. Each is built out of 4439 objects/walls, most of these made of car body material (3131 objects). It is highly conductive (28 kS/m) and permeable. Other materials are the radiator, the lights, windows, the wheels or the underbody of the vehicle. The computation of the signal level along the propagation path will be on the basis of the Fresnel coefficients for the transmission and reflection and the GTD/UTD for diffraction based on the material parameters like permittivity, permeability, conductivity, and thickness. No frequency dependent attenuation is defined. The superposition of the contributions of different rays is chosen to be coherent. Thus, the phases of the paths are considered. The propagation was fixed to one transmission and one reflection. The evaluated paths additionally use a maximum path loss of 200 dB, the maximum number of paths per single receiver, to 500 and dynamic range of the considered paths are again to 200 dB. The path loss exponent for the ray-optical models was set to 2.

(a) LOS scenario: Two vehicles communicate with each other without any obstacles between them.



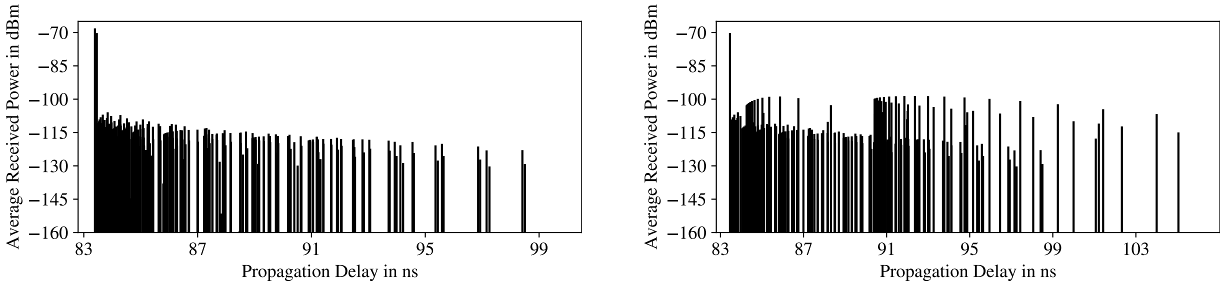
(b) NLOS scenario: An intermediate vehicle blocks LOS and a guardrail further reflects and scatters the signal. Reflections (red dot), scattering (green dots), and the ground reflection path in green.

Figure 2. Simulated LOS and NLOS scenarios

For NYUSIM, we take a different approach to model the scenarios. We modify the parameters such as the number of different path clusters to correspond to the amount that is expected by the geometry. Even though no direct measurements are available for vehicular scenarios, the results of the ray tracing simulation are likely more representative of the real world, which is why we used them as a baseline, adapting the parameters for the NYUSIM simulator.

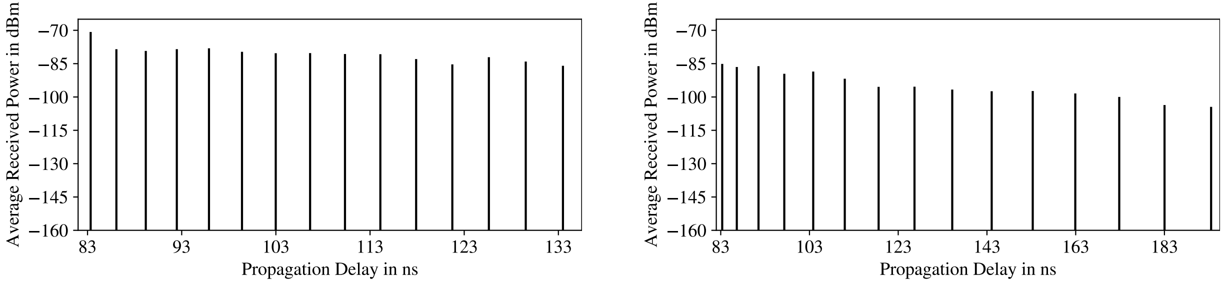
The number of the time clusters and the subpath components in the NYUSIM is fixed to 1 and 15 correspondingly, for both scenarios. With these updated parameters, the NYUSIM's results match those of WinProp much closer. The path loss exponent for the LOS scenario is set to 2 and for the NLOS scenario is set to 3.2, as recommended by the simulator. Since NYUSIM is built upon a stochastic channel model, 100 simulation runs are conducted for each of the scenarios to obtain meaningful results.

LOS Scenario (direct communication to successor): This scenario models a highway with two vehicles that follow each other on a single lane. In the scene depicted in Figure 2a, two cars have direct LOS communication capabilities. Both the transmitter and receiver are mounted at the front- and rear bumper of the respective vehicle. We used different distances between the vehicles in the range of 5–50 m) with a step size of 5 m. The results which we present are exemplary results for the inter-vehicle-distance of 25 m. No other objects are present, in particular there is no guard rail or additional vehicles. The material parameters were given by the Altair: $\varepsilon_\mathrm{r} = 8$, $\mu_\mathrm{r} = 1$,



(a) WinProp: LOS scenario

(b) WinProp: NLOS scenario



(c) NYUSIM: LOS scenario

(d) NYUSIM: NLOS scenario

Figure 3. Simulation results

$\sigma = 0.1\, S/m$ and a scattering matrix $S_{vv} = 0.6, S_{vh} = S_{hv} = 0.2, S_{hh} = 0.6$. Reflections and scattering were computed, but diffraction was excluded.

NLOS Scenario (indirect communication): This scenario extends the first scenario to increase the complexity. First, the LOS path between the sender and receiver is blocked by a third vehicle in between (cf. Figure 2b). Additionally, guard rails are added to the road at a distance of 1 m and 6.5 m, respectively, which corresponds to the width of two lanes. This way, we can observe a signal without a LOS component, that is only comprised of the reflections and scatterings of the surrounding. The material parameters of the guard rail are defined to $\varepsilon_\mathrm{r} = 1$, $\mu_\mathrm{r} = 20$, $\sigma = 28\, kS/m$ and the scattering matrix to $S_{vv} = 0.99, S_{vh} = S_{hv} = 0.1, S_{hh} = 0.99$.

Isotropic antennas were placed at the bumper at 0.5 m height. The output power was chosen to 30 dBm at 77 GHz without considering polarization. The most relevant simulation parameters are summarized in Table II.

B. Comparison of the Simulators

The simulation results computed by WinProp allow to clearly identify the individual components of the simulated scenario. Figure 3a shows the LOS component of the signal that arrives at the receiver with a delay of 83.4 ns and a signal strength of –68 dBm, as well as the ground reflection of similar strength (–70 dBm) shortly thereafter. In addition to these primary components, additional components are received, which were scattered from the ground, with a delay of up to 99 ns, but only negligible power of up to −106 dBm.

Table II
KEY PARAMETERS OF THE SIMULATION SETUP.

	WinProp	NYUSIM
Frequency	77 GHz	77 GHz
Antenna height above ground	0.5 m	undefined
Antenna / Transmit Power	isotropic / 30 dBm	isotropic/ 30 dBm
Inter-vehicle-distance	25 m	25 m

In the second scenario (see Figure 3b), the LOS component is not present anymore and the overall signal strength is reduced due to the higher path loss. The scattered ground reflection can be observed as well, since it is not blocked by the intermediate vehicle due to its ground clearance. In addition, we observe two additional groups of received signals, which comprise the reflections and the scattering at the guardrails. Due to the different positions of the guardrails, this yields two different delays of up to 105 ns. Even though the delay is greater, these reflections are received with a larger power (up to –98 dBm) compared to the ground scattering, since the guardrail material is a much better reflector than the ground.

Using our initial configuration of NYUSIM, the obtained results appeared very different at a first glance, however, the delay and signal strength of the most important component are very similar at 83.3 ns and –71 dBm, respectively. Beyond this, the signal for the LOS scenario was spread out over a larger time of up to 1000 ns. The large mismatch to the results computed by WinProp lead us to revisit this parameterization. As previously mentioned, the number of the clusters and the subpath components in the NYUSIM is fixed to 1 and 15 correspondingly. With the updated parameters not only do the first signal components agree relatively well, but the additional paths are more comparable as well (see Figure 3c for the LOS scenario). The total number of components is lower and their individual signal strength is stronger (up to –71 dBm), as well as more delayed (up to 133 ns). Increasing the number of the components (e.g., max 30) would better approximate the results in terms of power, but the signal would spread out over a larger time. However, these differences only have a minor effect on communication. In the NLOS scenario, the overall signal strength is reduced to about −85 dBm (see Figure 3d), which is a result of the NLOS condition, that increases the overall path loss. From the NLOS results, is observed that the absolute time delay of the first subpath component is roughly the same as the delay of the LOS component in the first scenario. Even though in reality this is not true, an approximation is made in the simulator, computing the propagation delay of the first subpath component in the same way for both the LOS and NLOS scenarios. Furthermore, since the surrounding environment can not be specified in the NYUSIM, the reflections coming from the guardrail are not visible. To capture this behavior would require further parameter modifications.

C. Computational Costs

Compared to the setup, the simulation time of both simulators is negligible. For the scenarios described in this paper, WinProp's simulations took 5 s and 8 s for the LOS and NLOS scenario, respectively, while NYUSIM's simulation runs were conducted in 16.2 s. The simulation time of NYUSIM could be reduced further by removing parts of the simulation not relevant to our results, such that they could be conducted in 2.3 s. The time consuming part, however, is the simulation setup. For the simulation scenarios that have been conducted, it took several days of work for WinProp. However, this effort can not be generalized and is therefore difficult to quantify. While the simulation parameters for NYUSIM need to be carefully selected, since they need to be justified for the scenario, the simulation setup in NYUSIM can be completed within hours and in consequence being significantly faster.

V. CONCLUSION

We compared two popular mmWave simulators, NYUSIM and WinProp, which use different simulation approaches, to evaluate their feasibility for typical RADCOM scenarios. The lack of real-world measurements for these scenarios complicates in the research in this domain, so determining which readily available tools can be used is a crucial step towards a deeper understanding of this topic.

We observed, that both simulation frameworks have their individual advantages and disadvantages. WinProp's results map well to the individual scenario, however, at a high effort to model each scene. NYUSIM is very flexible, and can be quickly adapted, even though the justification of the concrete parameterization of the channel model can get difficult. Going forward, we aim to integrate the simulation frameworks into large-scale vehicular networking simulators, to enable in depth analysis of RADCOM communication approaches.

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