mmWave on the Road: Investigating the Weather Impact on 60 GHz V2X Communication Channels

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***Abstract*—We study the impact of a diverse set of weather conditions on 60 GHz communication channels. In this context, we are primarily interested in next-generation Vehicle-to-everything (V2X) communication using mmWave frequencies. Given the application constraints of this scenario, we focus on rain and snow – and different rain and snow intensities. We extended the MilliCar ns-3 model to incorporate standardized rain and snow based attenuation models as suggested, for example, by the ITU. We cross-validated our simulator using as a reference the results obtained from the validated–well-known NYUSIM channel model simulator. In the core of this paper, we present an extensive simulation study on the impact of rain and snow in a realistic vehicular network at 60 GHz channels. Our results show that weather conditions can reduce the communication distance significantly (by up to 60 m).**

I. Introduction

In recent years, a substantial amount of research has been conducted to improve modern Intelligent Transportation Systems (ITS). The main aim behind such ITS is to enhance traffic efficiency, road safety, and driving comfort using Vehicle-to-everything (V2X) communication [1]. In this regard, the ITS applications proposed so far utilize sub-6 GHz communication. Recently, Millimeter Wave (mmWave) communication has emerged as a promising alternative [2]–[4] to address the increasing demands for higher communication speed and capacity in V2X communication by offering wider bandwidths in the 60 GHz and 77 GHz spectrums.

However, despite the large bandwidths, the communication range in the mmWave band is limited to very short distances due to the high path-loss. This increased path-loss is not only an attribute of the high transmission frequency. Other factors, such as atmosphere and weather variation, further attenuate the propagating signal [5]. The main contributors to the atmospheric attenuation in mmWaves are the water vapor and oxygen molecules. The attenuation from oxygen molecules can reach a maximum value of 15 dB/km at 60 GHz [6]. Additionally, because of very short wavelengths in the order of raindrops size, weather variations are also a crucial attenuation contributor in the mmWaves [5].

Several fading prediction methods have been developed to estimate the attenuation due to pure rain in the mmWave, and the most widely adopted is the one developed by the International Telecommunication Union (ITU) [7], [8]. Recent results have shown that this model does not perform well in short communication distances [9], however, minor modifications can improve the estimated attenuation. In the case of wet snow, the fading can be even higher than the attenuation from pure rain [7]. Additionally, due to the difficulty in collecting experimental data, the only fading prediction method available has been developed by ITU that estimates the attenuation for combined rain and wet snow [10].

For the transmission of time-critical information, especially in V2X, high availability and reliability are the foremost requirements from the communication channel. For this reason, characterization of these communication links is required, which is typically done through empirical and statistical channel models in order to understand the signal propagation characteristics. In the last years, several mmWave channel models (e.g., Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) [11]), and a few channel model simulators (e.g., QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa) [12] and NYUSIM [13]) have been developed with the sole purpose of investigating the communications in mmWave band. These channel models mostly target the cellular networks and do not cover Vehicle-to-Vehicle (V2V) scenarios, where, due to the dynamic topology, the channel undergoes rapid variations.

Recently an open-source ns-3 module has been developed, called MilliCar, which enables simulations in mmWave frequency band for V2V networks. The channel model used in MilliCar is implemented according to the 3rd Generation Partnership Project (3GPP) channel specifications [14] for V2V communications in mmWave frequencies. This work builds upon the MilliCar module, particularly its channel model, and incorporates the ITU weather models of pure rain and wet snow, for the characterization of outdoor 60 GHz channel for V2V communication applications. We first validated the accuracy of the MilliCar's path loss model by using the empirically validated–well-known NYUSIM simulator as reference (in previous work, we compared it to deterministic simulation [15]), and then extended the module with ITU recommendation for the prediction of attenuation in different weather conditions. We conducted an extensive simulation study to reveal new insights on mmWave-based V2V communication in a realistic vehicular scenario. In particular, we used the traffic scenario for Paderborn city (Germany) to obtain a realistic road traffic pattern.

Our contributions can be summarized as follows:

- We extended the MilliCar module by incorporating the ITU standardized fading prediction method and the proposed modifications in [9] and investigate the impact of weather variations on the 60 GHz radio link.

- We investigated the impact of weather (rain and snow) on the mmWave communication and compared the channel characterized by the basic MilliCar model with the ITU prediction method.
- In order to assess the impact of adverse weather effects in realistic scenarios, we studied mmWave communication on the road for traffic in a typical city environment (Paderborn city).

II. Related Work

Weather is an essential element influencing the mmWave communications due to the sizes of raindrops or snowflakes in the order of the wavelength [5]. It has been shown that the two forms of precipitations having a high influence on signal attenuation are rain [16] and wet snow [10]. Even-though it is stated that the influence of rain is not severe for small communication distances up to 200 m [5], other measurements such as in [16], has shown that the attenuation from rain can not be ignored especially in the tropical and equatorial locations, even for short distance ranges.

In terms of rain, the two commonly used fading prediction methods are the ones developed by Crane [17] and the ITU [7]. The attenuation due to rain is calculated as a function of volume density of raindrops, rain intensity, and drop sizes and shapes. However, since only the rain intensity can be measured, most of the prediction methods, including the aforementioned methods, compute the attenuation based on the rain intensity. Both methods make use of regression coefficients, which are frequency and polarization-dependent. Nevertheless, recent results [9] have shown that the rain fading prediction method proposed by the ITU does not work properly for short communication distances. The authors recommend slight modifications in the method for estimating the attenuation from rain, such that the estimated values can approach the measurement results. According to [9], rain further contributes to the total attenuation through the effect of the wet antenna. This becomes crucial, particularly when rain intensities are strong, but can be reduced with additional protection via antenna Radome.

In the case of snow, the attenuation from non-melting ice particles like dry snow, ice crystals, and hail is negligible as compared to attenuation from the rain at frequencies above 10 GHz [18]. However, the attenuation from wet snow can be stronger than the attenuation from pure rain [7]. The progress for developing accurate prediction methods for wet snow is rather slow, due to the difficulty in collecting experimental data. The only prediction method so far has been developed by ITU that estimates the attenuation from combined rain and wet snow [7].

The huge available bandwidths in mmWaves potentially solve many issues (e.g., channel congestion) with existing wireless technologies. In this regard, the IEEE 802.11bd standard and the 3GPP in Release 16 support communications in the mmWave frequencies for vehicular scenarios. However, as discussed above, due to the very small wavelengths, mmWaves experience increased sensitivity towards effects like rain and shadowing by vegetation or the human body in addition to higher path-loss. These challenges become stronger, especially in the V2V scenarios where the network topology variations are more frequent [19]. Currently, using experimental testbeds to study the signal propagation characteristics and to evaluate the performance of design solutions for mmWave communications is very expensive, which makes simulation studies, the most reasonable investigation approach.

Existing simulators, such as Veins, offer realistic vehicular network simulations, however, the communication is not extended for the mmWave frequencies. Moreover, the simulators covering the mmWave frequency band, such as NYUSIM, QuaDRiGa, or the ns-3 mmWave module developed by the NYU in collaboration with the University of Padova, are focused on the cellular network infrastructures. Recently, a new ns-3 module called MillCar has been developed, which according to [19], enables full-stack end-to-end simulations in mmWave frequency band for V2V networks. The channel model included in MilliCar, is implemented based on the 3GPP channel specifications for the V2V communications in mmWave frequencies [14]. The module also differentiates between different communication conditions and propagation environments (urban, highway).

Our work here extends this MilliCar module by implementing and integrating the fading prediction methods developed by the ITU along with the proposed modifications [9] in order to further investigate the impact of rain and combined rain and wet snow on the radio links at 60 GHz for V2V communications.

III. mmWave Channel Simulator

A. Simulation Framework

MilliCar is an open-source ns-3 module, which enables simulations at mmWave frequencies in V2V networks [19], [20]. According to [19], the channel model used in MilliCar is implemented based on the 3GPP channel specification for V2V networks, including propagation, shadow fading standard deviation (SF), beamforming operation, physical and MAC layer using the frame structure as defined in 3GPP NR V2X.

The path loss model described in the 3GPP standard differentiates between two scenarios (urban and highway) and the following communication conditions [20]:

- Line of Sight (LOS): the communication path between the transmitter and the receiver is not blocked by any static (i.e., environmental objects) or dynamic blockages (i.e., other vehicles).
- Non Line of Sight (NLOS): the communication path is blocked by static blockages.
- Vehicle Non Line of Sight (NLOSv): the communication path is blocked by dynamic blockages. The blocker height, relative to the antenna height of the transmitter and the receiver is an important factor that influences attenuation in the communication.

The path loss analytics for each scenario, along with the corresponding parameters are given in the 3GPP standard [14].

Additionally, the physical layer uses the frame structure for NR V2X, with Orthogonal Frequency Division Multiplexing (OFDM) numerologies 2 and 3. The MAC layer is designed to adopt the Time Division Multiple Access (TDMA) access scheme, with each vehicle being assigned with a slot for transmission, according to a pre-defined scheduling algorithm. The physical and the MAC layer are further integrated with higher layers of the protocol stack to provide end-to-end simulations.

B. Simulator Validation

The measurement campaigns conducted over the last years in the V2V context at mmWave frequency band have been very limited, essentially due to the very expensive experimental testbeds. Not long ago, the 3GPP has specified a channel model dedicated to the V2V communications in mmWave frequencies, which, however, has not yet been fully evaluated in realistic vehicular scenarios. Some first validation results of the proposed path loss model are presented in [20]. Besides this initial validation, in this works, we further validate the accuracy of 3GPP path loss model within MilliCar, by reconstructing a similar simulation scenario in the NYUSIM simulator and then compare the results.

NYUSIM is an open-source channel model simulator focused on the cellular networks. The simulator has been developed at the NYU WIRELESS, and it is based on the measurements conducted between 28–73 GHz frequencies in various outdoor environments such as urban microcell (UMi) [13]. In addition to the validation performed by the NYU WIRELES, we have also validated the accuracy of NYUSIM at 60 GHz by reconstructing the outdoor measurement scenarios presented in other papers and compared the simulation results with measured data [21]. Altogether, these papers and our validation indicated that NYUSIM can provide a close-to-real-world channel characterization. For this reason, we used NYUSIM as a reference to compare the path loss results obtained with MilliCar.

For the validation, we have selected an outdoor scenario that consists of a fixed transmitter and a mobile receiver moving in the distance ranging from 1 to 200 m. The communication environment is fixed to UMi in the case of NYUSIM, for both LOS and NLOS conditions, whereas, in the case of MilliCar, the path loss model differentiates between two communication environments (urban, highway) for the LOS case and uses the same equation for the NLOS condition. The relevant parameter values for running these simulations are listed in Table I. Considering the stochastic nature of the simulators, the path loss results are averaged over 100 simulations, and the resultant path loss values are presented as a function of the communication distance in Figure 1.

Table I
SIMULATION PARAMETER VALUES USED FOR THE VALIDATION.

Parameter	Values
Frequency / Bandwidth	60 GHz / 250 MHz
Receiver speed	20 m/s
SF MilliCar LOS / NLOS MilliCar	3 / 4
SF NYUSIM LOS / NLOS	4 / 7

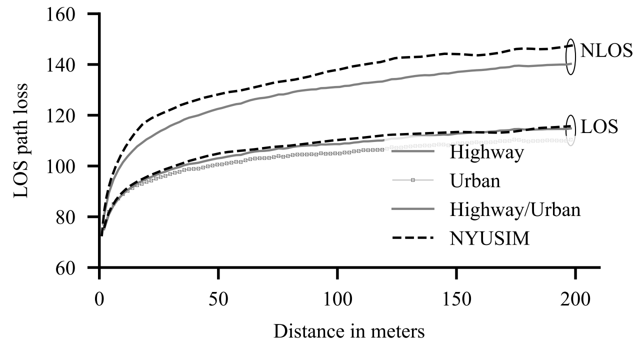


Figure 1. Path loss with increasing Tx-Rx distance at 60 GHz.

The MilliCar results show that in the LOS case, propagation in the urban scenario experiences fewer losses compared to the propagation in the highway scenario. As it is also mentioned in [20], this behavior might be a result of a larger number of reflections from static blockage present in the street canyons compared to the highway case. The difference between the obtained path loss is small for very short communication distance and can reach approx. 5 dB at distances beyond 200 m.

Compared to the NYUSIM, the results for the LOS case are very similar to the highway scenario, whereas, in the case of the NLOS communication, a difference of roughly 8 dB is observed at the distance of 200 m. This difference comes as a result of the parameters used in each path loss model, such as shadow fading standard deviation (SF). However, the behavior of the results collected from both the simulators is similar, with the path loss values increasing rapidly with the communication distance. We are therefore considering the MilliCar module to further use in analyzing the impact of the weather conditions on the radio link at 60 GHz.

IV. ITU Rain & Snow Models for mmWave

Rain is a liquid form of precipitation, which, according to the meteorologists [22], is characterized by drop diameter equal or larger than 0.5 mm. The size of the raindrop is an important component that defines the drop shape. The raindrops reaching the surface of the earth rarely have a diameter larger than 6 mm due to collisions between the raindrops and the increasing instability as the drops grow larger. A raindrop with a diameter smaller than 2 mm resembles a sphere shape, and as this diameter increases, the air pressure gets larger at the bottom and smaller on the sides, leading to a shape which is flattened on the bottom and wider on the sides. Due to the raindrop shape, the attenuation from rain is expected to be higher for horizontal polarization as compared to vertical polarization, especially with larger diameter raindrops.

Another form of precipitation formed by solid water is snow, which based on the amount of water, can be classified as *dry* and *wet snow*. The attenuation from the wet snow, or differently called the melting layer, has shown to reach high values, sometimes larger than the attenuation from rain [10]. The wet snow is formed by the snowflakes falling through air above the freezing temperature and characterized by high level of moist. Due to these conditions the particles melt, getting covered by a layer of water, acting as a glue when it is in contact with other particles, producing a larger snowflake, that attenuates as the particle was entirely water. As the particles keep melting, the level of water increases, and due to the instability, the drop gets divided into smaller raindrops.

A. ITU-R Rain Model

The International Telecommunication Union, Radiocommunication Sector (ITU-R) model for estimating the attenuation from rain is an empirical step by step approach described in ITU-R P.530-15 [7] using the regression coefficients specified in ITU-R P.838-3 [8]. The main input parameter required by this model is the rain intensity R in mm/h, exceeded for the 0.01 % of an average year, with an integration time of 1 min. This can be obtained from local long term measurements. In case of lack of data, the rain intensity can be derived from the digital maps published in ITU-R P.837-7 (incl. Annex 1).

In this paper, our aim is to investigate the attenuation from rain in different scenarios and for discrete values of rain rate, without being restricted to a particular location. For this reason, during the computations, we assume that the rain intensities have an integration time of 1 min with a percentage probability of exceedance 0.01 %. The following steps are used for computing the attenuation from rain:

Step 1: Select the rain intensity exceeded for the 0.01 % of an average year, with an integration time of 1 min.

Step 2: Compute the specific rain attenuation, γ_R(dB/km), using the following power-law relationship

$$\gamma_R = kR^{\alpha}, \tag{1}$$

where the regression coefficients k and α are a function of the frequency (1–1000 GHz) and polarization and can be derived using the formulas given in ITU-R P.838-3 [8]. For the aforementioned coefficients the standard provides a list of numerical values at different frequencies including 60 GHz. Furthermore, for a given rain intensity, the value of the specific rain attenuation depends on the selected rain Drop Size Distribution (DSD). The rain DSD gives the distribution density of the raindrop diameters, and as mentioned in [23], is a function of the climate zone. For modeling the distribution density of the raindrop diameters, the ITU model uses the Laws and Parson distribution [24], which at the same time is the most widely used DSD for the temperate climate.

Step 3: Compute the effective distance given as a multiplication of the actual path length with a distance factor r as

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073\alpha}f^{0.123} - 10.579(1-\exp(-0.024d))}, \tag{2}$$

where d is the communication distance, f represents the communication frequency, and α is the exponent in the specific attenuation defined in Step 2. According to ITU-R P.530-15 [7], the maximum recommended value for the distance factor is $r = 2.5$, even though the value of the denominator can get smaller than 0.4. The reason of the multiplication between the communication distance and the distance factor is to capture the in-homogeneity, or the variation of the rain rate in the propagation path [25].

Step 4: Compute the rain attenuation as

$$A = \gamma_R d_{eff} = \gamma_R dr. \tag{3}$$

B. ITU-R Combined Method for Rain and Wet Snow

Besides the rain attenuation, the propagation signal at high latitudes or high link altitudes might be effected by higher values of attenuation, due to the wet snow. The attenuation from the wet snow can be estimated using the combined method for rain and wet snow, described in ITU-R P.530-15 [7]. According to this model, the level of attenuation is a function of the communication link height in relation to the rain height, and can be computed using the following steps:

Step 1: Determine the median rain height, h_{rainm}, meters above the mean sea level, using the formula given in ITU-R P.839 [26]. In order to compute the h_{rainm}, the 0° isotherm height above the mean sea level needs to be specified for a specific location. The 0° isotherm height varies with the geographical position and can be obtained using the digital map provided in ITU-R P.839 [26].

Step 2: Compute the rain height at the center of the communication link, using as input, the height in meters above the mean sea level of the transmitter and receiver as

$$h_{link} = 0.5(h_1 + h_2) - (D^2/17), \tag{4}$$

where $h_{1,2}$ are the heights of link terminals above mean sea level and D is the length of the communication link in km.

Step 3: Test whether the communication link is affected by the melting layer using

$$h_{link} \leq h_{rainm} - 3600. \tag{5}$$

If the test is passed, the communication link is not affected by the melting layer and the only attenuation is due to pure rain. Otherwise, the following steps are used to determine the corresponding attenuation.

Step 4: Initialize the multiplying factor *F* with zero.

Step 5: In order to model the rain height variability, the method uses 49 intervals of 100 m relative to h_{rainm}, each with probability associated according to ITU-R P.530-15 [7, Table I]. For each interval represented by an index i, an addition to the multiplying factor is computed using the following steps:

i) Compute the rain height h_{rain} as

$$h_{rain} = h_{rainm} - 2400 + 100i. \tag{6}$$

ii) Determine the communication link height relative to the rain height as

$$\Delta h = h_{\text{link}} - h_{\text{rain}}. \tag{7}$$

iii) For the corresponding interval, compute the addition to the multiplying factor as

$$\Delta F = \Gamma(\Delta h)P_i, \tag{8}$$

where $\Gamma(\Delta h)$ is a multiplying factor computed from Equation (9); it considers the specific attenuation for the corresponding link height relative to the rain height and P represents the probability that the calculated rain height will be in the corresponding interval. The values of this parameter are listed in ITU-R P.530-15 [7, Table 1].

$$\Gamma(\Delta h) = \begin{cases} 0 & 0 < \Delta h \\ \frac{4\left(1-\mathrm{e}^{\Delta h/70}\right)^2}{\left(1+\left(1-\mathrm{e}^{-(\Delta h/600)^2}\right)^2\left(4\left(1-\mathrm{e}^{\Delta h/70}\right)^2-1\right)\right)} & -1200 \leq \Delta h \leq 0 \\ 1 & \Delta h < -1200 \end{cases} \tag{9}$$

iv) ΔF for the corresponding interval is added to the total multiplying factor as

$$F = F + \Delta F. \tag{10}$$

Step 6: Finally, the attenuation from combined rain and wet snow is estimated as

$$A_{rs} = A_p F, \tag{11}$$

where A_p represents the attenuation from rain estimated using the ITU fading prediction model. According to [7], the combined rain and wet snow attenuation, A_{rs}, can be larger or smaller than the attenuation from pure rain A_p.

In order to investigate the impact of pure rain and wet snow in the radio link at 60 GHz, we integrated the ITU fading prediction methods discussed above with the MilliCar channel model. Since MilliCar is a ns-3 module implemented in C++, these fading prediction methods are also incorporated into the ns-3 module. The validation of these models is done in MATLAB and the results are presented in [21].

V. Performance Evaluation

To investigate the impact of weather variation, in particular with pure rain and wet snow, on radio propagation at 60 GHz, we have conducted an extensive set of simulations. In a first step, we studied the impact of rain and snow in a simple, artificial setup to precisely see the impact on the transmissions. In a second step, we assessed the practical impact by applying mmWave communication in a realistic vehicular scenario.

A. Simulation Setup

The simulations are conducted using rain rates selected according to the classification provided by the German Meteorological Service for rain and melting snow, using the threshold given in Table II.

The regression coefficients for estimating the attenuation from the rain at 60 GHz are obtained from the ITU-R P.838-3 [8]. The values of the regression coefficients are $k_H = 0.8606, \alpha_H = 0.7656$ and $k_V = 0.8515, \alpha_V = 0.7486$ for horizontal and vertical polarization, respectively. As previously mentioned, the results published in [9] have shown that the ITU rain fading prediction method is not accurate for short communication distances. In this work, we have also considered the modification recommended by the authors in [9] to compare the rain attenuation results. The rain fading prediction method used by the authors in [9] is presented in the standard version ITU-R P.530-17 [27] and is the same as the one in ITU-R P.530-15 [7].

The fading prediction method for estimating the attenuation from combined rain and wet snow additionally requires a specific location to determine the mean annual 0 °C isotherm height, which varies with the geographical position. In this work, for evaluation purposes, the location selected is Paderborn, Germany, with an altitude of approximately 122 m, and mean annual 0 °C isotherm height $h_0 = 2000\,\mathrm{m}$.

B. Attenuation Due to Rain

The attenuation values due to rain are estimated using the fading prediction method described in ITU-R P.530-15 (for both horizontal and vertical polarization). The latest results [9] have shown that the ITU method does not predict accurate attenuation values for short communication distances. As also explained in [9], the ITU method limits the value of distance factor *r* to a maximum of 2.5, even though this value can largely exceed for short distances. For instance, at 60 GHz frequency and the rain intensity 50 mm/h, the distance factor exceeds the value 2.5 for the distances around 300 m. In order to improve the estimation to approach the real attenuation measurements for short communication distances, it is suggested in [9] to use the distance factor without limiting it.

Figure 2 presents the rain attenuation as a function of communication distance ranging from 1–200 m and for three different rain intensities 10, 50 and 250 mm/h. The plot also compares the generic ITU model with the modified version, i.e., without distance factor limitations.

For each rain intensity case, the figure shows that the attenuation from rain increases with the communication distance. Since the volume of rain increases with increasing distance, this causes more absorption and scattering and, thus, leads to a higher attenuation. At very short communication distances, e.g., 25 m, the attenuation from rain is very small in the range of 4 dB. However, for very strong rain intensities, e.g., 250 mm/h, the modified prediction method, estimates high attenuation even at very short distances such as 25 m. The overall estimated attenuation by the modified model is higher compared to the ITU fading prediction method. The difference becomes more significant with higher rain rates and for very short communication distances.

Additionally, the impact of polarization is rather noticeable for strong rain intensities, where the raindrop size is large

Table II
Rain and melting snow classifications based on intensity, according to the German Meteorological Service.

	Light	Moderate	Strong	Very Strong
Rain	< 2.5 mm/h	2.5–10 mm/h	10–50 mm/h	$\geq$ 50 mm/h
Snow	< 1 mm/h	1–5 mm/h	$\geq$ 5 mm/h	–

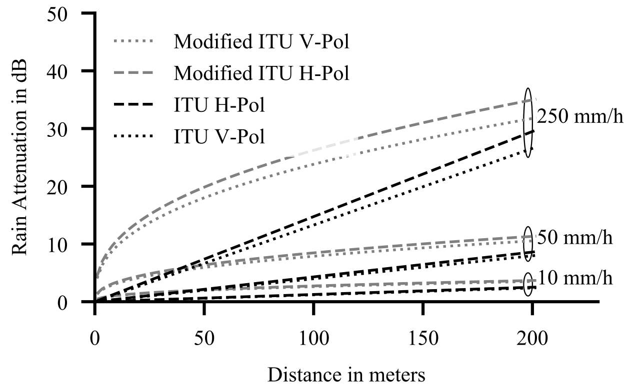


Figure 2. Comparison of estimated rain attenuation results using the ITU method and the modified ITU method based on the recommendation in [9].

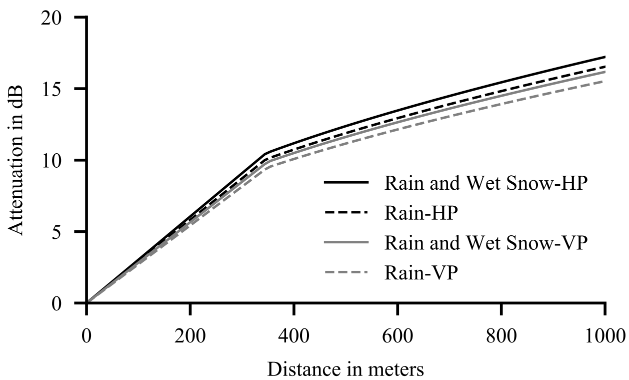


Figure 3. Comparison of attenuation due to pure rain and combined rain and wet snow using the ITU prediction model.

and more flatten and, therefore, causing more attenuation with horizontal polarization. For instance, with a rain intensity of 250 mm/h, the difference due to polarization can reach up to 3 dB at a communications distance of 200 m. These results certainly demonstrate that the polarization type has a clear impact on the attenuation levels, and thus, should not be ignored. Additionally, the attenuation prediction difference between the standardized ITU model and the modified model is clearly noticeable and rather significant at higher rain intensities.

C. Attenuation Due to Wet Snow

The attenuation due to wet snow represents the total combined attenuation from rain and wet snow for a given communication distance, as explained in Section IV. Figure 3 depicts the impact of pure rain and combined rain and wet snow as a function of communication distance ranging from 1–1000 m for horizontal and vertical antenna polarization. Since the intensities of wet snow are rather low as compared to pure rain, therefore, an average intensity level of 30 mm/h is used for computing the attenuation levels in both cases.

It can be seen in the plot that the attenuation from combined rain and wet snow is relatively high as compared to the

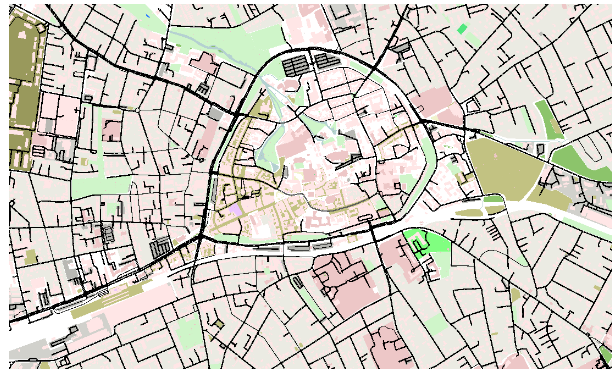


Figure 4. Paderborn scenario considered for the simulations.

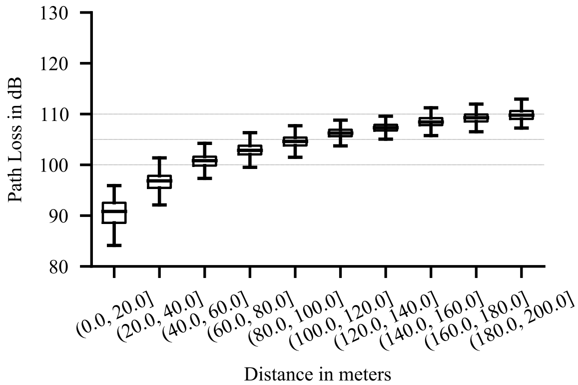
attenuation due to pure rain for each antenna polarization. This is a consequence of the particles in the melting layer, which behave like water but with a larger size and, thus, cause more attenuation. The difference between the estimated attenuations in both cases is quite small for short distances such as 100 m, but for large communication distances such as 1000 m, the deviation goes as high as approx. 1 dB. Additionally, the difference in the estimated attenuation from combined rain and wet snow between the two antenna polarization types is negligible for short communication distances such as 100 m, and it increases to approx. 1 dB for the communication distance of 1000 m. Furthermore, the attenuation due to wet snow is rather small for path lengths ranging from 1–200 m, reaching values approx. 5 dB for the chosen location and rain intensity. Nevertheless, it is still larger than the attenuation observed for pure rain. However, as previously mentioned, the measurements conducted for exploring the attenuation from combined rain and wet snow have been very limited. As a result, the developed fading prediction model requires further validation, particularly for short communication distances.

D. mmWave on the Road in a Typical City Environment

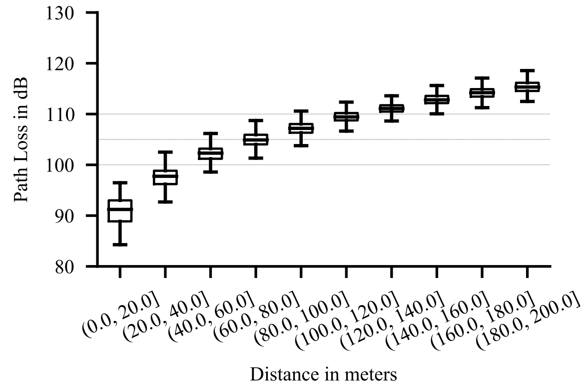
In order to study the weather impact in a realistic vehicular network, we used the coupling implementation[1] of ns-3[2] with Simulation of Urban MObility (SUMO) [28] and the scenario for the city of Paderborn, Germany [29] – shown in Figure 4. In the scenario vehicles follow each other in the city of Paderborn, always considering the presence of a LOS component.

From the previous results, it can be seen that the weather variations certainly have a significant impact on the radio links. With the integration of the generic ITU prediction models in MilliCar, we first analyze the resulting path loss in the case of pure rain and then with combined rain and wet snow. The communication condition is assumed LOS and the scenario in MilliCar is fixed to urban. The path loss results are collected every 1 ms from various pairs of vehicles communicating in a distance lower than 200 m and are averaged over 10 simulation

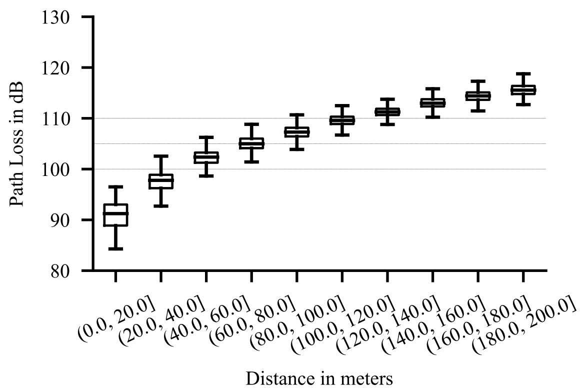
[1]https://github.com/vodafone-chair/ns3-sumo-coupling
[2]https://www.nsnam.org/



(a) Path Loss on a sunny day



(b) Path Loss with rain



(c) Path Loss with combined rain and wet snow

Figure 5. Total path loss results for a rain intensity of 30 mm/h. The horizontal lines indicate a path loss of 100, 105 and 110 dB, respectively

runs. The antenna polarization for the following simulations is fixed to horizontal. Figure 5a depicts the results obtained from the basic MilliCar model, whereas Figures 5b and 5c show the path loss collected with both the ITU models for rain and combined rain and wet snow respectively. The intensity of rain considered to explore the weather impact is 30 mm/h. To understand the distribution of the collected data over distance intervals of 20 m, we have used box-plots. Here, the bar shows the median, the box extends to the 1st and 3rd quartile and the whiskers indicate the 1st and 99th percentile of the data.

Similar to the conclusions derived for the rain attenuation, the path loss plots for each weather condition show that the influence of strong rain and combined rain and wet snow on the radio links is rather small and almost negligible for very short communication distances. As the distance between the vehicles increases, the weather impact becomes more noticeable. For instance, at a distance range of 180–200 m, the attenuation difference due to combined rain and wet snow goes as high as 5 dB for the median value. However, the attenuation difference between path loss with pure rain and combine rain and wet snow is very small for the same distance range and almost negligible.

As previously mentioned, measurements in the V2V networks at mmWave frequencies are very limited. As a result, information on possible communication distance for inter-vehicle communication, under different conditions is limited as well. In these circumstances, from our simulation results, we study the limitation on the communication distance due to the weather conditions for a fixed path loss value. The path loss values considered as threshold are 100, 105 and 110 dB; a horizontal line is drawn for each point on the plot Figure 5. The distance along with the percentage of the communications taking place is extracted, for each of the aforementioned path losses and the results are listed in Table III.

Table III
PARAMETERS EXTRACTED FROM THE SIMULATION RESULTS.

Max. loss	Environment	Distance	Comm. success
100 dB	Sunny day	71 m	60 %
	Rain	50.7 m	54.5 %
	Rain and wet snow	49.7 m	54.5 %
105 dB	Sunny day	138 m	74.5 %
	Rain	92.72 m	69 %
	Rain and wet snow	92.69 m	69 %
110 dB	Sunny day	200 m	96 %
	Rain	141 m	85.5 %
	Rain and wet snow	140.7 m	85.5 %

The maximum communication distance that can be reached for the path loss of 100 dB under no weather effect is 71 m, and it drops by roughly 20 m under weather conditions such as rain and snow. The limitation on the distance due to the weather effects increases for higher losses. The same pattern can be seen in the percentage of communications taking place. These results show that rain and snow can strongly limit the communication length.

VI. Conclusion

We investigated the impact of different weather conditions on the wireless channel at mmWave frequencies. We concentrated on the 60 GHz band, which is currently used for WLAN communication, and it is also considered together with the 77 GHz band for next generation V2X communication. Most relevant weather situations that increase the signal attenuation include rain and snow. These also represent very typical weather conditions in the vehicular application domain, so that their impact needs to be understood to develop reliable communication platforms. In order to assess the impact on the signal propagation, we extended the ns-3 MilliCar model, to incorporate the most recent ITU-R recommendations. The coupling of ns-3 with SUMO is used to get realistic vehicular traces in the scenarios such as the city of Paderborn. Our simulation results substantiate the impact of rain and combined rain and wet snow on the communication quality and distance. For a fixed value of the path loss, the presence of weather effects can reduce the communication distance by up to 60 m (depending on the sensitivity of the receiver).

Our toolkit, which we have released as Open Source,[3] is now ready for more and detailed simulations.

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