Chapter 15 – Vehicular Environments

Vitaly Petrov, Johannes M. Eckhardt, Dmitri Moltchanov, and
Yevgeni Koucheryavy

Abstract High-rate data exchange between the prospective (semi-)autonomous vehicles is one of the promising usage scenarios for THz band communication systems. However, the vehicular scenarios have certain specifics to be taken into account when developing THz vehicular communication technologies. Particularly, the propagation of the THz signal in vehicular scenarios differs from the one in conventional indoor or outdoor cellular setups. This chapter summarizes the preliminary findings in the area of THz communications in vehicular environments.

Key words: Vehicular Communications; Reflection Losses; Penetration Losses; Directional Communications; THz Band communications

1 Motivation and Specifics of THz Vehicular Communications

The prospective dynamic networks formed by smart connected vehicles are expected to generate and exchange massive amounts of data coming from heterogeneous sensors: up to 1 TB/h by a single vehicle, according to [1]. Such high volumes cannot be delivered with state-of-the-art communications technologies. Therefore, the research community is actively exploring the adaptation of extremely-high-rate THz communication systems to vehicle-centric scenarios [2]. At the same time, the successful adoption of THz communications in vehicular deployments requires a better understanding of the major vehicle-specific propagation effects, as outlined further in this chapter.

Vitaly Petrov, Dmitri Moltchanov, and Yevgeni Koucheryavy
Unit of Electrical Engineering, Tampere University, Korkeakoulunkatu 1, FI-33720, Tampere, Finland. e-mail: firstname.lastname@tuni.fi

Johannes M. Eckhardt
Institute for Communication Technology, Technische Universität Braunschweig, Schleinitzstrasse 22, 38106 Braunschweig, Germany. e-mail: eckhardt@ifn.ing.tu-bs.de

Following prior chapters, the characteristics of the THz channel highly depend on the scenario geometry and the materials in the environment. Even minor changes, such as the road signs, may notably affect the performance [3]. There are not many measurement campaigns reported to date for THz or sub-THz frequencies [4–6]. When extrapolating the results available for the millimeter wave bands [7–11], we expect the non-negligible impact of the reflections and scattering from the vehicle bodies, the road infrastructure, the roadbed itself, and even the plants surrounding the road. Admitting the importance of all the listed effects, in this chapter, we focus on the two phenomena that are crucial for the design and evaluation of the prospective THz vehicular communication systems, namely, *vehicular blockage*, detailed in Section 2, and *vehicle-specific interference*, discussed in Section 3.

2 Vehicle-body Blockage

2.1 Measuring the Impact of Blockage

To characterize the impact of vehicular blockage in THz communications, the measurement campaign has been conducted in [4]. The authors explored the setup, where the signal propagates through the vehicle body (see Fig. 1). For this study, the low-THz (sub-THz) channel sounder manufactured by Ilmsens was used. The measurements were conducted in a sub-THz frequency range: from 300.2 GHz to 308.2 GHz. Both the transmitter (Tx) and receiver (Rx) sides were equipped with horn antennas, each featured by approximately ≈8° beamwidth and ≈26 dBi gain.

Fig. 1: Measuring vehicle-body penetration loss at sub-THz frequencies.

Measured path	Loss
Bumper level, $h \in [0.9\,\text{m} ... 1.1\,\text{m}]$	45 dB
Engine level, $h \in [1.1\,\text{m} ... 1.2\,\text{m}]$	50 dB
Front & rear windows, $h \in [1.4\,\text{m} ... 1.6\,\text{m}]$	40 dB
Near the rooftop, $h = 1.6\,\text{m}$	20 dB
Front side windows, $h \in [1.25\,\text{m} ... 1.4\,\text{m}]$	33 dB
Rear side windows, $h \in [1.25\,\text{m} ... 1.4\,\text{m}]$	28 dB

Table 1: Penetration losses in vehicular communications at 300 GHz.

The selected results of this campaign are reported in Table 1. As can be observed from this table, the vehicle-body blockage has a notable effect. Additional attention from 28 dB to 50 dB is introduced on top of already high propagation losses, discussed in prior chapters. The exact penetration losses depend primarily on the height of the THz V2V link. Particularly, the propagation at the engine-level, $h \in [1.1\text{ m} ... 1.2\text{ m}]$, is affected the most, as the signal has to penetrate through or diffract around many metal constructions. In contrast, the weakest attenuation is observed at the window level, $h \in [1.4\,\mathrm{m} \ldots 1.6\,\mathrm{m}]$, as the signal penetrates only two narrow pieces of glass. Similar observations are made for side propagation.

Summarizing, the following conclusions are made:

1. **Vehicle-body penetration loss is highly *height-selective*.** Therefore, in contrast to human-body blockage, where the obstacle can be modeled as a homogeneous cylinder (e.g., as in [12, 13]), the vehicle-body blockage calls for the development of more fine-graded models. Particularly, the height of the THz signal and its direction, when propagating through the vehicle body, must be accounted for.
2. **Vehicle-body is a *non-negligible* blocker for THz communication systems.** The introduction of ≥28 dB loss in Table 1 may change the signal-to-noise (SNR) level at the RX from, e.g., 10 dB (reliable data exchange) to −18 dB (outage with most of the modulation and coding schemes). Therefore, additional techniques should be applied for blockage mitigation in THz vehicular communication systems.

2.2 Blockage Mitigation

The vehicle-body blockage has a major impact on THz vehicular communications. In this subsection, we introduce two possible approaches for blockage mitigation.

Under-vehicle Propagation. As detailed in [4], THz signals reflect from the road with moderate losses and thus can propagate under the vehicle body. This approach is particularly beneficial for direct V2V THz communications in case Tx and Rx antennas are located at the bumper level (close to the road surface). Hence, a notable part of the THz beam is not blocked. In addition, the angle of incidence when reflecting from the road is close to 90°, thus leading to moderate reflection losses.

Multi-Connectivity. Another possible solution to mitigate the unexpected blockage in THz vehicular communications is by utilizing the *multi-connetivity* technique. The approach suggests the target Tx and Rx devices stay connected via other vehicles in proximity. When the primary path (e.g., a direct link) is blocked, the nodes can utilize one of the alternative options. The ubiquitous use of this approach leads to the appearance of directional vehicular mesh networks [14]. However, the constant maintenance of many connectivity paths increases system complexity. Therefore, the number of used paths, termed as *degree of multi-connectivity*, must be properly selected, balancing the target reliability level and the associated overheads [15].

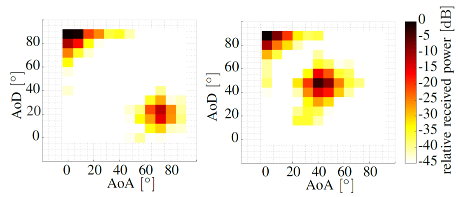
3 Directional Interference in Vehicular Setups

3.1 Measuring the Impact of Interference

To study the multipath interference in THz vehicular communication systems, the impact of side reflections from the neighboring vehicles has been measured in [4].

In this measurement setup, the separation distance between the Tx and Rx vehicles varied from 2 m to 12 m, while the car on the side lane was always distant equally from both sides. In addition, custom rotation units were used, allowing to obtain the power angular profile (PAP) in all the considered configurations (see Fig. 2).

Fig. 2: Measuring the vehicle side reflection for the multipath interference modeling at THz frequencies.



(a) $d = 2$ m (b) $d = 6$ m

Fig. 3: Power angular profile for the side reflection at 300 GHz.

The selected results of this study are presented in Fig. 3, illustrating the power angular profile (PAP) for the Tx-Rx distances of 2 m and 6 m. The presented results are normalized to the corresponding values for the LoS path (top left corners of the plots). We observe that the side reflection effect is visible for both distances. However, the difference in terms of the power and the angles is greater for the shorter distances: 3.5 dB and ≈24° for $d = 6$ m vs. 12 dB and ≈40° for $d = 2$ m. Hence, the reflections from the neighboring vehicles contribute to the multipath interference.

The THz vehicular communications may be affected not only by the multipath interference but also by the direct interference coming from the neighboring vehicles. To analyze this effect, a detailed study has been conducted in [5]. For this purpose, mathematical and simulation-based frameworks were developed for two typical deployments: (i) *highway*, characterized by large separation distances between the vehicles (tens of meters), and (ii) *urban*, characterized by short and random inter-vehicle distance (a few meters). It has been observed that the impact of interference is non-negligible in both deployment options. In addition, the average interference power grows fast with the beamwidth of the employed radiation patterns and slowly decreases with the distance between the vehicles on the neighboring lanes.

Summarizing, the following conclusions are made:

1. **The impact of the multipath interference is *distance-dependent*.** As illustrated in both [4] and [5], the interference caused by the multipath reflections from the vehicles on the neighbouring lanes is non-negligible. Particularly, the power of the reflected signal may be just 3 dB–6 dB lower than the one of the direct line-of-sight (LoS) path. At the same time, the actual impact of the interference greatly depends on the separation distance between the Tx and Rx vehicles. When the distance is short, beams cannot reach the vehicles on other lanes and thus do not contribute to the interference level. In contrast, for longer distances, the length of the reflected path becomes comparable to the one of the LoS path, while the reflection losses also decrease as the reflection angle of incident approaches 90°.

2. **The impact of the inter-vehicle interference is *density-dependent*.** A high density of vehicular traffic (e.g., in urban cities) leads to low separation distances between the Tx and Rx vehicles. Hence, most of the interference coming from the neighboring lanes is blocked by the vehicle bodies. In contrast, a low density of vehicular traffic (e.g., in empty highways) leads to a low quantity of vehicles interfering with the target link. Finally, as discussed in [6], the most profound impact of inter-vehicle interference is observed for moderate densities of traffic ($\approx$10–20 m between the vehicles). For such a setup, the density is high enough to cause collided transmissions, while the scenario geometry still allows most of the interference to reach the target Rx (low probability of blockage by the vehicles).

3.2 Interference Mitigation

Both the multipath interference and direct interference from the neighboring vehicles play an important role in THz vehicular communications. In this subsection, we present two possible approaches for interference mitigation in vehicular setups.

Narrow THz beams. A straightforward approach to mitigate directional interference is to reduce the beamwidth of the employed radiation patterns. Following [5], the average interference power (both the multipath self-interference and the interference from other vehicles) decreases notably when narrowing the beam. Particularly, the utilization of the antenna radiation patterns of less than 5° beamwidth leads to favorable conditions for THz band vehicular communications in a highway scenario. However, the utilization of extremely-directional radiation patterns challenges the beam steering and beam tracking in the presence of mobile nodes [16].

Directional CSMA. Another possible approach to mitigate the interference in THz vehicular communications is by applying the *directional carrier sense multiple access (CSMA) approach*, as detailed in [6] and [17]. The measurements reported in [4] and [6] illustrate that the THz signal reflects from the front and rear of the vehicle with moderate losses. Therefore, almost any vehicle that may potentially interfere with the target THz link may sense the channel before sending any data and postpone its transmission in the case an active data exchange is detected. Particularly, the use of robust physical-layer preambles is suggested in [6] to facilitate the reliable detection of active communication. With the presented approach, both the range and the capacity of THz vehicular communications are improved by over 30% each.

4 Conclusions

Vehicle-centric setups have multiple specific features that must be considered when developing the THz vehicular communication systems. In this chapter, we discussed the two major relevant features: (i) vehicle-body blockage; and (ii) vehicle-centric interference. The research on THz vehicular systems is still at an early stage, and many questions remain open. Nevertheless, the presented first-order performance estimations, together with the listed approaches to mitigate these effects, will facilitate the development of reliable and efficient THz vehicular communication systems.

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