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ABSTRACT

Connected and automated vehicles are becoming a reality, and the necessity of assessing the performance of their technical enablers plays a pivotal role in the automotive field. Several technologies have been proposed by different standardization bodies, with the aim of enabling the connectivity between vehicles, and between vehicles and the infrastructure. Before the deployment of any technology, it is fundamental to perform a testing and validation phase, which is often performed in simulation environments. However, in order to assess the actual performance of a V2X (Vehicle-to-Everything) communication technology, field tests are of utmost importance. In this paper, we present the results of an extensive field test campaign of non-mmWave and mmWave IEEE 802.11 technologies for V2I (Vehicle-to-Infrastructure) communications, namely, IEEE 802.11p, IEEE 802.11ac, and IEEE 802.11ad. We assess the performance of each of them, in terms of connection stability, received signal level, Round Trip Time and UDP throughput, in both Line-Of-Sight and Non-Line-Of-Sight conditions. Our results show that, although not specifically designed for vehicular communications, IEEE 802.11ac and IEEE 802.11ad emerge as very promising technologies.

CCS CONCEPTS

• **Networks** → **Network performance evaluation**; **Network experimentation**; **Network performance analysis**; • **Hardware** → *Wireless devices.*

KEYWORDS

V2X communications, connected vehicles, mmWave, field test measurements, IEEE 802.11 standards

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1 INTRODUCTION

The latest advances in wireless communication technologies are playing a fundamental role in shaping the future of the automotive industry. Intelligent Transportation Systems (ITSs) are now a concrete reality and the vast majority of the involved OEMs are focusing their efforts on the Connected and Autonomous Vehicles (CAVs) paradigm. One of the key technologies to unleash all the potential of CAVs is represented by vehicle-to-everything (V2X) communications, providing direct connectivity among vehicles (vehicle-to-vehicle, V2V), as well as with road-side units and cellular base stations (vehicle-to-infrastructure and vehicle-to-network, V2I and V2N).

Because of the logistical, economic, and safety-related limitations which occur whenever working with real vehicles, the assessment and performance evaluation of V2X technologies is frequently carried out in a simulation environment. Hence, in recent years several simulation frameworks have been developed for V2X simulation [14, 20, 24, 26], modeling the entire communication stack, from the applications down to the physical layer. However, the closer the simulated phenomenon gets to the physical medium, the more difficult it is for the model to accurately reflect reality, due to hard-to-predict effects such as Doppler shift, shadowing and multi-path fading. Moreover, simulation models take into account only the most important aspects of reality, as it would be impossible to exactly shape all the involved variables. It follows that, beside simulation study, it is critical for the assessment of V2X communications to perform field tests, as they reflect the actual capabilities of the devices under test.

In this paper we present the results of a campaign of dynamic field tests involving a number of devices implementing different amendments of the IEEE 802.11 family of standards. In particular, we have tested the capability of IEEE 802.11p, 802.11ac and 802.11ad to provide vehicles with V2I connectivity, and the quality thereof. Notice that, among the three technologies, only IEEE 802.11p has been developed specifically to support vehicular communications, but we also included IEEE 802.11ac and 802.11ad in our study, as their application to the automotive field appears to be promising.

The tested technologies differ in some fundamental aspects, such as the operating frequency, the maximum transmission power and the antenna directivity. The aim of this paper is to analyze the impact of these different configurations, and the advantages or disadvantages in choosing one technology over the others. The performance metrics we analyze include: service availability, communication latency, RSSI (Received Signal Strength Indicator), and UDP throughput. All the results have been collected through properly equipped vehicles and increasing the distance between the communicating devices, so as to assess the real-world performances of the various access technologies. The measurements have been performed in scenarios both with Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) conditions.

To the best of our knowledge, this is the first work comparing non-mmWave (802.11p and 802.11ac) and mmWave technologies (802.11ad) on the field for V2X communications, leveraging open, and low-cost commercially available solutions for V2I scenarios.

The reminder of the paper is organized as follows. Section 2 offers a wide overview of the existing field test studies for V2X communications. Section 3 describes our testbed, along with the software used to perform the measurements. The most important results of our measurement campaigns are presented in Section 4, while Section 5 draws our conclusions and presents an outline of future work.

2 RELATED WORK

The importance of field tests for validating V2X technologies is highlighted by several works in the literature, including [5, 15, 23]. Different technologies are usually evaluated with respect to some metrics of choice, such as in [15] in which 802.11p UDP throughput is tested in a V2I urban scenario, by relying on an open custom implementation, based on PC Engines ALIX.2 boards. ALIX.2 boards represent the previous generation of the system boards we use in this work. Most of the previous studies, however, focus on a single technology.

Concerning the assessment of IEEE 802.11p, a number of examples can be found in literature, such as [2], in which the results of extensive field trials in Europe, USA and Australia are presented, or [4], in which open and low-cost solutions are used. In [12], the authors present field test results and investigate the effects of interference due to hidden terminals, presenting also an exhaustive list of other related works. Our study differs from [12], as we evaluate the maximum range in LOS and NLOS conditions, which was deemed as future work in [12], and we assess the performance of mmWave solutions for V2X communications. In fact, while other works compare IEEE 802.11p with other technologies, none of them considers IEEE 802.11ad.

In [23], Shi et al. present an experimental evaluation of IEEE 802.11p and LTE C-V2X, focusing not only on communication parameters but also on application-oriented metrics and considering different scenarios and driving patterns. Some of our findings confirm the results obtained by Shi et al., for instance concerning the latency that always remains low as long as the connection is stable, or concerning the NLOS conditions noticeably reducing the reachable range. In [5], Chen et al. perform a comparative analysis of IEEE 802.11p and 802.11n, considering four scenarios. For what 802.11p is concerned, 20 dBm devices with 5 dBi antenna are used, yielding a similar Equivalent Isotropic Radiated Power (EIRP) as the one tested in our work. However, a 2.4 GHz device is used for IEEE 802.11n, which is an older amendment than IEEE 802.11ac. A heterogeneous V2X communication system is studied in [13], which compares the performance of IEEE 802.11p against that of LTE and general-purpose Wi-Fi (leveraging an IEEE 802.11a/b/g/n wireless card). On the contrary, the assessment of IEEE 802.11ac in vehicular networks has been scarcely addressed. One of the few works that have studied this aspect is [22], where the use of IEEE 802.11ac in automotive scenarios is investigated by simulation only.

Considering IEEE 802.11ad, an interesting work describing the standard and its design assumptions, besides the study of the transition from omnidirectional to highly directional communication, is [16]. Specifically-targeted works focusing on field tests in the automotive domain are scarce, since most studies are simulation-based. In [7], the authors compare the performance of IEEE 802.11p and the mmWave technology by simulation, when supporting V2V communications. LTE and mmWave for V2I communications are instead evaluated in [8]. Both works found that IEEE 802.11p and LTE outperform mmWave in terms of connection robustness and reliability. However, only a mmWave technology can address the demand for extreme high throughput by several emerging automotive applications, such as “See Through” and “Birds Eye View” [6], which are pivotal to enable such relevant use cases as adaptive platooning. Another study of the mmWave technology applied to vehicular scenarios can be found in [25], which proposes a beam switching solution based on the vehicle position prediction in a V2I network. MmWave-based V2V communication is also addressed in [17], which introduces a framework to efficiently pair vehicles and optimize both transmission and reception beamwidths by jointly using matching theory and swarm intelligence. In particular, it considers both Channel State Information (CSI) and Queue State Information (QSI) when establishing the link between vehicles; the results, however, are obtained via simulations only.

Novelty. The novel contribution of this work is thus the comparison of different 802.11-based technologies on the field, while considering both mmWave and non-mmWave devices. We also perform a thorough investigation, varying different parameters for the same technologies. For instance, IEEE 802.11p is evaluated by fixing different physical data rates (as opposed to [23]) and 802.11ac is evaluated considering different transmission power values.

3 EXPERIMENTAL TESTBED

We conducted our measurement campaign in a rural area close to Turin, Italy, where few long straight roads allowed us to test the devices in both LOS and NLOS conditions.

The measurements focused on V2I scenarios, using two cars equipped with the radio interfaces to be tested and considering a direct communication between the two. Each test has been carried

Figure 1: Test setup for measurements under NLOS conditions.

out by fixing the position of one vehicle and letting the other move progressively away from the former, at an average speed of 15 km/h. Notice that, as we consider a V2I scenario, the stationary vehicle acts as a Road Side Unit (RSU) and the moving vehicle as an On Board Unit (OBU).

We assessed the performance as the distance between the two communicating devices varied. To this end, we equipped the moving vehicle with a GNSS receiver (Navilock NL-8012U, update rate: 5 Hz), so as to track its position and thus the distance from the fixed device. Furthermore, in the LOS tests, the antennas have been placed on the roof of both cars. Instead, to create NLOS conditions, the fixed device was placed in the trunk of the stationary vehicle, as shown in Figure 1, thus making such vehicle act as an obstacle between the two communicating devices.

The setup and configurations tested for the various communication scenarios are detailed in the next section, along with the software and hardware we used to carry out our measurements.

3.1 IEEE 802.11p setup

The platform chosen to test IEEE 802.11p is the open-source framework presented in [18]. The platform is composed of two PC Engines APU1D embedded boards, running a patched version of OpenWrt 18.06 (named OpenWrt - V2X), enabling IEEE 802.11p communications when proper wireless cards are installed [9]. OpenWrt is an open source Linux distribution specifically targeting embedded and network devices. The patches introduced in this system enable *i)* the usage of OCB mode (Outside Context of a BSS) through the `iw` tool, *ii)* the selection of different Traffic Classes ("Best Effort" was always used as a baseline in this work), and *iii)* the use of frequency bands at 5.9 GHz. As 5.9 GHz-compatible wireless cards, we installed two UNEX DHXA-222. These cards have already been validated in static scenarios in a prior research work [18], and proved to reliably enable IEEE 802.11p communication at different physical data rates, when coupled with OpenWrt-V2X. The platform also enables the manual selection of three physical data rates (3, 6, and 12 Mb/s), corresponding to the mandatory modulations foreseen by the standard [1].

During the measurement sessions, the devices could directly communicate thanks to the IEEE 802.11p OCB mode. Thus, the obtained results, even though directly comparable with the other technologies in the V2I scenarios, can be considered valid also when a V2V communication is in place.

3.2 IEEE 802.11ac setup

Similarly to the 802.11p case, the platform chosen for IEEE 802.11ac is composed of two PC Engines APU1D embedded boards. The two devices run a clean version of OpenWrt 19.07.1 and the wireless cards used to enable the communication are two COMPEX WLE900V5, allowing the communication via IEEE 802.11ac in the 5 GHz band with a maximum transmit power of 30 dBm, also thanks to their 3X3 MIMO (Multiple-Input and Multiple-Output) configuration and to an auxiliary 5 V power supply.

In the measurements involving IEEE 802.11ac, the static device is equipped with three outdoor, high gain, omnidirectional antennas mounted on an industrial tripod. Moreover, the static device is configured to act as an Access Point (AP), while the moving device acts as a wireless station. So doing, these settings represent a V2I scenario, with the static node in RSU-like configuration, and the moving node acting as a vehicular OBU connected to the the network infrastructure.

As mentioned, although IEEE 802.11ac was not originally designed to enable connectivity in a vehicular environment, it is interesting to explore this opportunity, given the maturity of the protocol and the great availability of devices that implement this technology, including standard smartphones.

3.3 IEEE 802.11ad and mmWave setup

The mmWave scenario is composed of two 802.11ad-compliant MikroTik wAP 60G routers. These devices are equipped with a Qualcomm Atheros QCA6335 60 GHz chipset, with a planar phased antenna array of 6x6 elements able to cover an angular range of 60 degrees. Five different non-overlapping channels with a 2.16 GHz bandwidth are supported, from 58.32 GHz to 66.00 GHz (the maximum link distance declared by the manufacturer is up to 200 m).

The installed OS is a proprietary Linux-based distribution called *RouterOS* (version 6.48 has been used in this experimental evaluation). This operating system provides a reduced set of available tools with respect to OpenWrt; however, it proved to be very effective in managing the devices and obtaining the desired metrics, thanks to its full integration with the MikroTik firmware.

The high frequencies at which mmWave technology operates are subject to severe path loss and harsh propagation over the air. Despite the high potential mobility of nodes, mmWave has

Table 1: Experimental testbed settings

Technology	txpower	Rate adaptation	RSU antennas	OBU antennas	Channel
IEEE 802.11p	18 dBm	off (3, 6, 12 Mb/s)	2x 6 dBi MobileMark ECOM6-5500 - omnidirectional	2x 6 dBi MobileMark ECOM6-5500 - omnidirectional	178 (5.890 GHz @ 10 MHz)
IEEE 802.11ac	18, 30 dBm	on	3x 12 dBi Interline Horizon Maxi - omnidirectional	3x 6 dBi MobileMark ECOM6-5500 - omnidirectional	149 (5.745 GHz @ 20 MHz)
IEEE 802.11ad	auto	on	6x6 embedded antenna array	6x6 embedded antenna array	1 (58.320 GHz @ 2160 MHz)

been studied for vehicular applications since it is the only 802.11-based technology achieving data rates of the order of Gb/s and a RTT smaller than 2 ms. As noted via simulation in several works and highlighted by our measurements, mmWave could be initially coupled with more reliable technologies (e.g., IEEE 802.11p) to achieve at the same time robustness and reliability, as well as low latency and high throughput.

Similarly to the IEEE 802.11ac case, the static device acts as an AP and the moving one as a station. To assess the performance of IEEE 802.11ad in controlled conditions, the moving vehicle always follows a straight line path, keeping the angle between the two devices close to 0 degrees. Further details on the setup of the three access technologies can be found in Table 1.

3.4 Software tools and testbed setup

To evaluate the performance of the considered technologies, we focus on three main metrics, namely, RSSI, RTT and UDP throughput, all gathered with respect to the distance between the two communicating devices. As part of our testbed setup, we relied upon different open-source software tools to successfully collect the metrics of interest, none of them however enables synchronization between the device transmissions and the GNSS receiver. To overcome this issue, we developed three utility programs, one for each metric, able to output synchronized network KPIs and distance information. These tools rely on the Haversine formula [21] to compute a good estimate of the distance between the devices, considering the mean Earth radius.

As far as the RSSI measurements are concerned, each device, acting either as OBU or RSU, is connected to a laptop via Gigabit Ethernet. Both laptops are equipped with Intel I219-V cards. As the devices can update the value of the measured RSSI only when data is actively received, a ping session is started from the fixed device to the device on the moving vehicle, with an inter-packet frequency of 100 ms. Then, the laptop on the moving vehicle is used to gather the RSSI metrics every 200 ms (i.e., at the same frequency as our GNSS receiver updates), by relying upon: *(i)* the Linux `iw` tool for the APU boards, or *(ii)* the `/monitor` command for the wAP 60G devices. Both commands are launched from the laptop to which the GNSS receiver is connected, via the `ssh` protocol.

We use instead iperf 2.0.13, as a reliable and state-of-the-art tool for throughput measurements [11]. The physical devices (either the APU boards or the MikroTik routers) are set in bridge mode, in order to act as bridges between the laptops running the measurement tool. The fixed laptop is set to push as much UDP traffic as possible toward the moving vehicle hosting an iperf client (trying to reach a 1 Gb/s traffic load with packets of 1470 bytes), while the moving vehicle's laptop is running an iperf server that measures the maximum achievable throughput. To produce the final logs, the aforementioned utility programs have been used.

The last set of tests involved the measurement of the RTT between the two devices. As in the previous case, the physical devices are set in bridge mode and a GNSS data synchronization utility is used. As software tool, we rely on LaTe v0.1.6-beta, an open-source and flexible latency measurement software leveraging a custom application layer protocol, called LaMP and encapsulated inside UDP [10, 19].

As LaTe follows a client-server approach, a LaTe client is launched on the laptop inside the moving vehicle, while a LaTe server is launched on the stationary device, i.e., the one acting as RSU. The packet periodicity is set to 50 ms and the UDP packet size to 24 bytes (the smallest packets that can be sent with LaTe). LaTe can reliably measure RTT, and react to a network disconnection longer than 4 s (i.e., when no packets are received at either side for more than 4 s) by terminating the current test and automatically relaunching the server.

4 RESULTS AND DISCUSSION

To assess the performance of the different 802.11-based solutions, we have performed several field tests, in both LOS and NLOS conditions. Although we collected and analyzed the data for all the mandatory data rates of IEEE 802.11p, for the sake of brevity, only the one yielding the best results for each metric are shown here. The same applies to the levels of tested *txpower* (i.e., the transmission power level set in OpenWrt) for IEEE 802.11ac: only the 18 dBm case is reported, as it can be compared to the maximum *txpower* value that can be set for IEEE 802.11p.

With the aim of extracting a meaningful trend and taking into account the error of the GNSS device (in the order of maximum 3 m in open air, with a an accuracy of 2.5 m Circular Error Probable, according to the data sheet), the collected data points have been grouped into bins of 5 meters each, over which the metrics of interest have been averaged. Each bin is then represented by its central point, e.g., if a bin goes from 0 to 5 meters, a new point at 2.5 m is inserted in the plot. The size of the bins has been, however, increased from 5 to 15 meters when showing the RSSI results, in order to improve the readability of the figures and better show the overall evolution with respect to the distance. This holds for all the plots but the one in Figure 2, which reports exact distance values.

The first field test campaign was aimed at determining the maximum achievable distance by the three technologies under study,

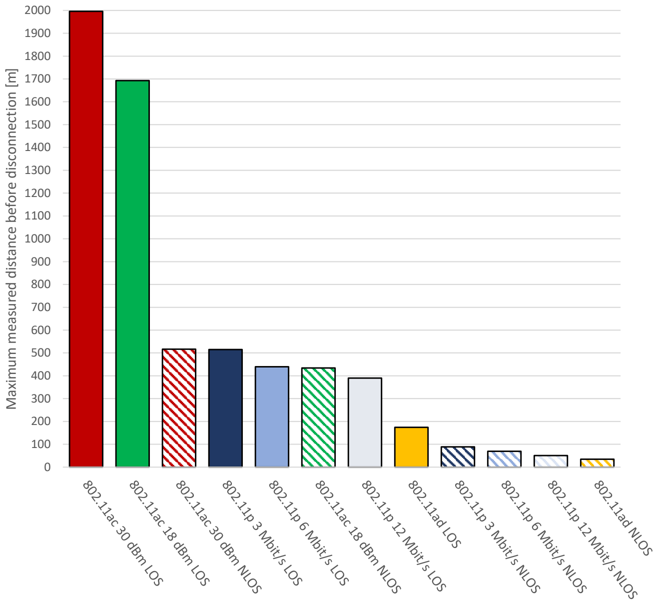

Figure 2: Comparison among IEEE 802.11p, 802.11ac, and 802.11ad: maximum achievable distance before a disconnection between two communicating devices is detected, under LOS and NLOS conditions.

before a disconnection is observed between the communicating devices. As software tool, we relied on LaTe, by which we recall that a disconnection occurs when no packets are received for more than 4 s. The results, shown in Figure 2, highlight that IEEE 802.11ac reaches the greatest distance, while providing an acceptable stability of the connection. This can also be explained thanks to *(i)* the usage of the lowest frequency among all the technology considered, and *(ii)* the high-gain antennas and maximum configurable transmission power of the IEEE 802.11ac platform, enabling higher values of EIRP than the ones of the other communication systems. On the other hand, IEEE 802.11ad, which operates at 60 GHz, can reach substantially lower distances, although, as detailed later, it provides the highest throughput and the lowest RTT. Nevertheless, it is worth mentioning how even this technology can achieve few tens of meters in NLOS conditions (we measured an achievable distance of around 34 m), which could be enough to support high throughput data exchange in dense inner-city scenarios. Another important observation is about the impact of NLOS conditions: for the considered technologies, NLOS implies a reduction in the radio coverage of more than 50% with respect to LOS. This confirms the importance of accounting for NLOS conditions when designing V2X communication systems.

Next, Figure 3 presents the evolution of the RSSI as a function of the distance between two communicating devices, in LOS (top plot) and NLOS (bottom plot) conditions. Comparing the two plots (note the different scale of the x-axis in the two plots), one can see that, for IEEE 802.11p and 802.11ac, the highest values of RSSI in NLOS are 20-25 dBm lower than the respective values in LOS conditions. The behavior of IEEE 802.11ad is instead different, due

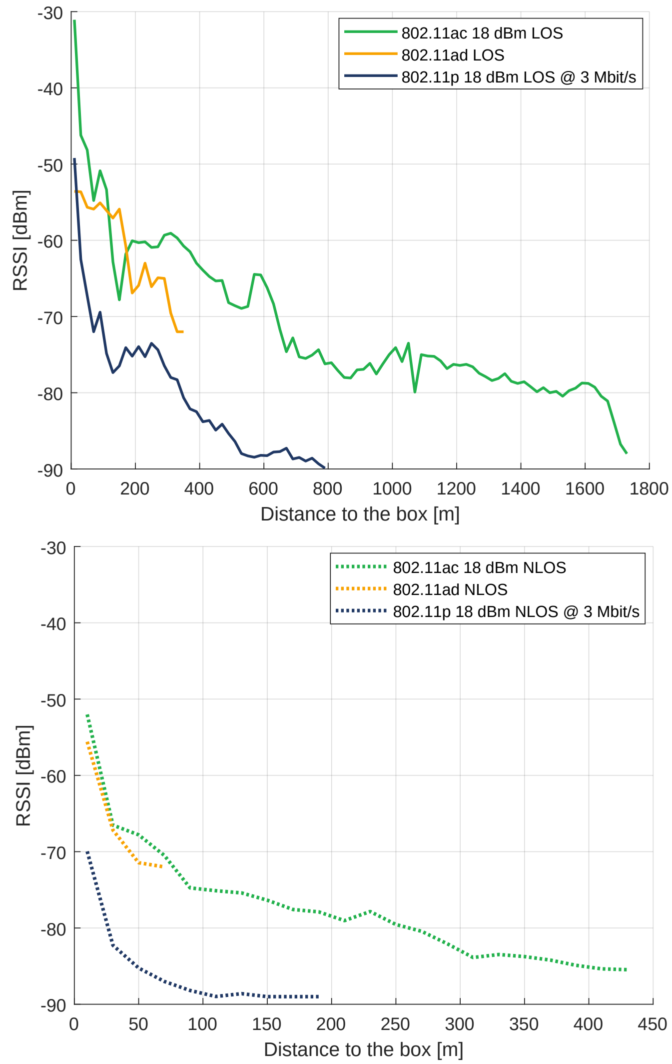

Figure 3: RSSI measurements with IEEE 802.11p (18 dBm and 3 Mb/s), 802.11ac (18 dBm), and 802.11ad. LOS (top) and NLOS (bottom) conditions.

to beamforming and the significantly different frequencies at which the technologies operate. In this case, the RSSI is just slightly higher in LOS condition for sufficiently short distances, while it drops very rapidly in NLOS conditions, relatively to the LOS scenario. In general, looking also at the KPIs presented in the following, it is clear that 802.11ad cannot support a stable communication when the RSSI is below -71 dBm, which is consistent with the receiver sensitivity values reported in the standard [1]. On the contrary, with 802.11ac, one starts experiencing communication disruptions only when the RSSI is lower than -82 dBm, while with 802.11p a quite stable connection can be maintained, on average, till -87 dBm is reached. Thus, 802.11p (with its mandatory modulation schemes) appears to be the best technology in terms of connection stability, which is consistent with the fact that it is indeed a technology specifically designed for vehicular communications.

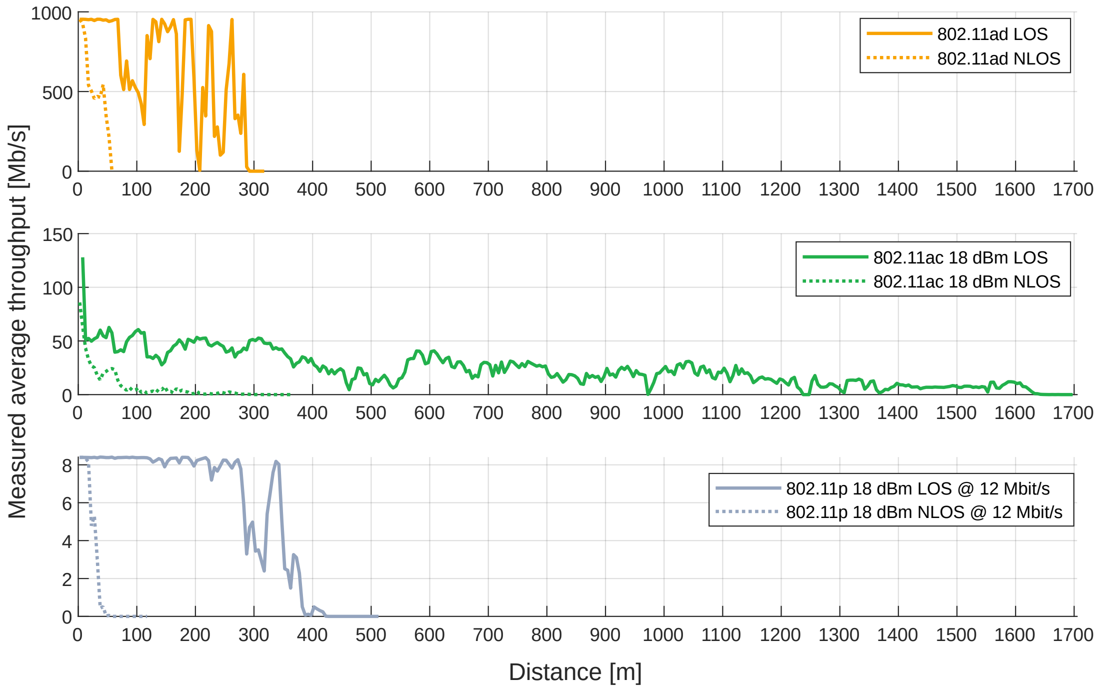

Figure 4: UDP Throughput as a function of the distance (LOS and NLOS conditions).

The UDP throughput results are depicted in Figure 4. Looking at all the technologies, when the distance is very short, the same values of throughput can be achieved in LOS and NLOS conditions, even though the drop is much faster than in the case of LOS when the distance increases. As mentioned earlier, IEEE 802.11ad can provide very high values of throughput, exceeding 1 Gb/s (here capped at around 953 Mb/s due to the Gigabit Ethernet connection to the laptops), even though the maximum reachable distance is quite low, especially in NLOS conditions. IEEE 802.11ac can instead provide up to 127 Mb/s in LOS conditions and below few meters, which is then quite smoothly reduced as the distance increases, thanks to the rate adaptation mechanism. On the contrary, the absence of an active rate adaptation in the IEEE 802.11p system causes the throughput to oscillate much more when the connection becomes less stable. It is important to take into account that IEEE 802.11p, even though providing a lower throughput (around 8.3 Mb/s when the physical data rate is set to 12 Mb/s), works on a dedicated spectrum and 10 MHz-wide channels, providing a higher degree of resiliency with respect to interference from non-V2X communications and high speeds. As these tests focus on a baseline characterization involving two vehicles only, these advantages are not clearly visible here, but they have nevertheless to be taken into account. It is also worth mentioning that no association procedure is foreseen in IEEE 802.11p, thus enabling direct communication between the devices, as opposed to IEEE 802.11ad and IEEE 802.11ac.

Figure 5 presents the experimental data on the RTT. It is evident from the plot that the latency remains quite stable for all the technologies over all the measured distances, until the RSSI can no longer guarantee a stable connection. When this happens, the latency rapidly increases until a disconnection occurs. The exception is the 802.11ac NLOS case. This technology can reach a longer range than 802.11p, as highlighted before, but it provides a less stable RTT when non-ideal conditions are in place (i.e., in NLOS conditions). By comparing the different values when a stable connection is established, IEEE 802.11ad provides the lowest RTT values (around 1.5 ms), then 802.11ac provides on average around 3 ms in LOS and NLOS condition, which is very similar to what can be achieved with 802.11p (i.e., around 3.4 ms). These values can also be explained by looking at the maximum reachable throughput: the higher the throughput, the lower the overall transmission time. All these values are, in any case, low enough to fully support safety applications that exploit V2X communications, when taking as reference the latency-critical use cases reported in [3].

Finally, Figure 6 presents a comparison between the IEEE 802.11ac RSSI measured when transmitting at 18 dBm and 30 dBm, both in LOS and NLOS conditions. As can be seen, NLOS causes a drop in the measured RSSI in the order of 20 to 26 dBm, depending on the selected value of *txpower*[1]. Increasing the transmission power can lead to visible advantages until relatively high distances are reached (1.5 km). Then, both the 30 dBm and the 18 dBm case lead to an unstable connection (causing, for instance, the throughput to drop to 0) between 1.6 and 1.7 km, with a gain of less than 100 m when transmitting at 30 dBm (also due to RSSI values reaching around

[1]It is important to remember that this value is not always equivalent to the overall EIRP, which also includes the contribution of the specific antennas.

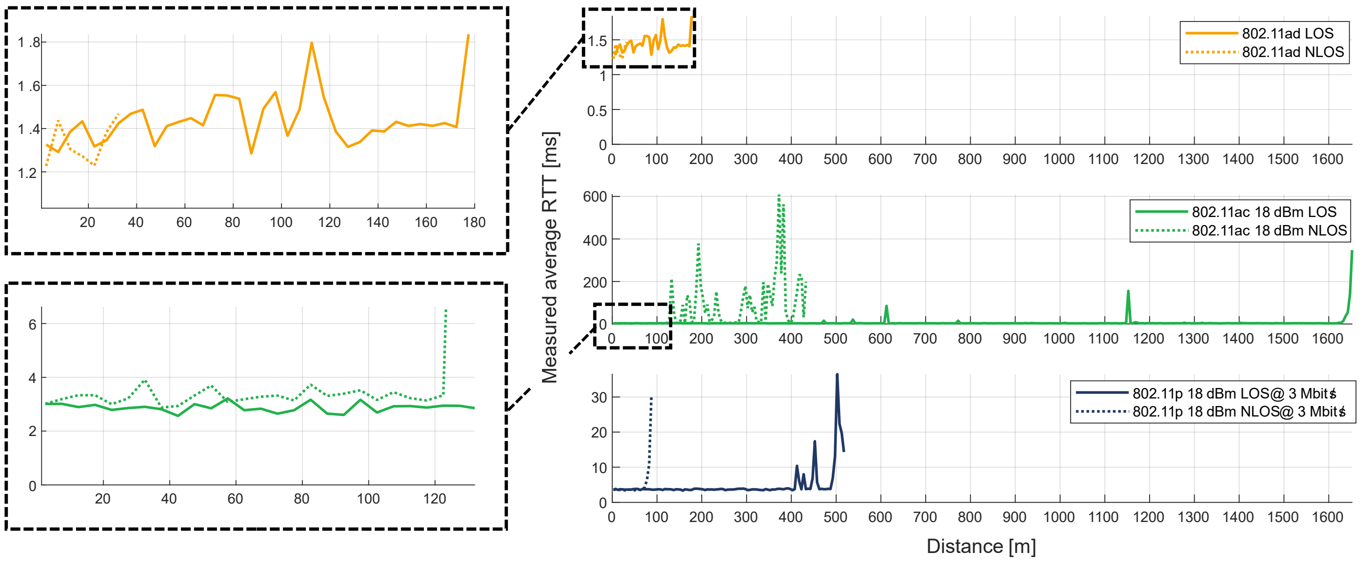

Figure 5: Round Trip Time as a function of the distance (LOS and NLOS conditions). The zoomed portions of the plots are intended to facilitate the interpretation of the results.

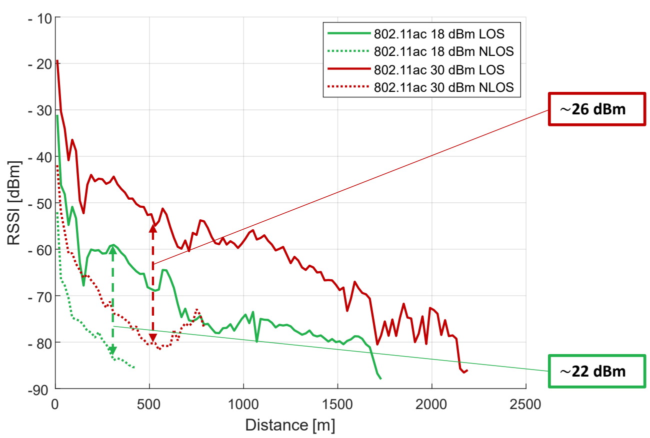

Figure 6: RSSI measurements with IEEE 802.11ac, for two values of *txpower* and in LOS and NLOS conditions.

-82 dBm). Thus, for very large distances, the reported results show that there is no evident advantage in increasing the 802.11ac transmission power to its maximum, as the gain in the reachable range and RSSI is negligible.

5 CONCLUSIONS AND FUTURE WORK

Wireless communication technologies have attracted a great deal of interest, as they play a pivotal role in the delivery of ground-braking V2X applications. This paper has assessed the ability of IEEE 802.11-based technologies to support V2I communications, through an extensive experimental field test campaign. Both non-mmWave (IEEE 802.11p and 802.11ac) and mmWave (IEEE 802.11ad) technologies have been considered and compared, showing advantages and disadvantages.

The technologies herein presented have been evaluated under multiple aspects and in various configurations, considering both LOS and NLOS scenarios. Comparing the different technologies, IEEE 802.11ac proved to be the one maximizing the radio range, both in LOS and NLOS, providing acceptable throughput up to 1.5 km-distance. However, in non-ideal NLOS conditions the RTT becomes less stable after around 120 m, as opposed to IEEE 802.11p, which provides an almost constant latency until the RSSI drops below -87 dBm (considering a physical data rate of 3 Mb/s), which is the lowest value among all the tested technologies. On the other hand, IEEE 802.11ad can provide the highest throughput, even exceeding 1 Gb/s, and the lowest latency, also thanks to a very small transmission time, at the price of a noticeably reduced radio range and of the need for an association procedure, which is absent in IEEE 802.11p. Therefore, IEEE 802.11ad appears to be a promising technology for the short-range transmission of large quantities of data, like in the case of upload and download of sensor data at intersections. Even though the radio range is relatively short, it is worth highlighting that it is possible to reach few tens of meters even when there are obstacles between the communicating devices. This could be sufficient to enable automotive use cases which require very high throughput and low latency in dense urban scenarios, despite the usage of the 60 GHz frequency spectrum which is commonly thought to suffer from complete communication disruption under NLOS conditions. IEEE 802.11ad could also be used in combination with longer-range access technologies, to provide very high throughput in proximity of mmWave dedicated RSUs, while providing at the same time an extended range thanks to the coverage capability of the other technologies.

Future work will investigate the effect of medium to high longitudinal speeds on the studied access technologies, as well as the impact of the antenna height. For what IEEE 802.11ad is concerned, further field tests will be performed to evaluate the effect of the angle between communicating devices as a function of their relative distance, as the antenna array is highly directional and the angular range is limited to 60 degrees. Finally, future work will also address V2V scenarios.

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