Vehicular Communications 1 (2014) 91–96

Contents lists available at ScienceDirect

Vehicular Communications

www.elsevier.com/locate/vehcom

Vehicular networks using the IEEE 802.11p standard: An experimental analysis

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ARTICLE INFO

Article history:
Received 13 January 2014
Accepted 16 April 2014
Available online 24 April 2014

Keywords:
Vehicular networks
IEEE 802.11p
Mobile networks
Experimental analysis

ABSTRACT

The IEEE 802.11 working group proposed a standard for the physical and medium access control layers of vehicular networks called 802.11p. In this paper we report experimental results obtained from communication between vehicles using 802.11p in a real scenario. The main motivation is the lack of studies in the literature with performance data obtained from off-the-shelf 801.11p devices. Our study characterizes the typical conditions of an 802.11p point-to-point communication. Such a study serves as a reference for more refined simulation models or to motivate enhancements in the PHY/MAC layers. Field tests were carried out varying the vehicle's speed between 20 and 60 km/h and the packet length between 150 and 1460 bytes, in order to characterize the range, throughput, latency, jitter and packet delivery rates of 802.11p links. It was observed that communication with vehicles in motion is unstable sometimes. However, it was possible to transfer data at distances over 300 m, with data rates sometimes exceeding 8 Mbit/s.

1. Introduction

Vehicular networks, also known as *VANETs* (*Vehicular Ad hoc NETworks*) or VAN (*Vehicle Area Networks*), are composed by vehicles as well as access points located at the edges of the roads [1,2]. Such networks allow several applications, such as traffic safety, driver assistance and entertainment for passengers [3]. The constant movement of vehicles at varying speeds causes constant changes in the network topology. Further, vehicles have a limited time to exchange data among other vehicles or the access points. Therefore, it is necessary to employ protocols developed to take full advantage of the contacts between vehicles and the infrastructure [2].

IEEE proposed a family of standards for vehicular networks called WAVE (*Wireless Access in the Vehicular Environment*). WAVE is composed by two categories of standards: (i) 802.11p for PHY and MAC layers and (ii) IEEE 1609 for security, network management as well as other aspects of VANETs. Since those standards are fairly recent, most experimental research on VANETs has employed traditional 802.11 radios [4–7]. These radios, however, are not appropriate for vehicular networks, because they have a long association time [8], and communication is unstable due to the high rate of data losses [9]. Recently, some works performed field experiments with 802.11p [10–12], however those studies did not measure important link metrics such as jitter and the association time.

Existing related works focus primarily on the analysis of the throughput or loss rate, which are important to entertainment applications, however driver assistance and safety applications depend on another set of link metrics. In driver safety applications, for example in the case of collision warning, the communication must present low delivery delay and high delivery rate, while throughput is secondary. For driver assistance, for example for the formation of convoys [13], data must arrive with predictable jitter and delays, in order to ensure timely control decisions.

This paper presents field experiments using IEEE 802.11p, which focus on the link metrics important for driver assistance and safety. We measure performance metrics such as throughput, delay, jitter, loss rate and association time. To the best of our knowledge, this is the first study that evaluates the association time and jitter in field experiments with moving vehicles. The data results of this paper will help improve future studies on VANETs. With this information, more reliable simulations can be carried out, contributing to the evaluation of the feasibility of applications, services and

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http://dx.doi.org/10.1016/j.vehcom.2014.04.001
2214-2096/

protocols proposed for vehicular networks. Further, those results can be used to motivate refinements in the 802.11p and WAVE standards.

The remainder of this paper is organized as follows. Section 2 discusses the types of applications proposed for VANETs, highlighting the importance of vehicle safety applications and how the metrics evaluated in this work will contribute to the development of these applications. Section 3 presents the IEEE 802.11p protocol. The related works are presented in Section 4. The methodology of the experiments and results are described in Sections 5 and 6, respectively. Section 7 concludes the paper.

2. Vehicular networks

Vehicular networks have two distinct classes of applications, which are driver assistance and vehicle safety, and onboard entertainment applications. These classes require different QoS characteristics, due to their different communication patters, which are described below.

Applications for vehicle safety and driver assistance are intended for vehicles that exchange messages among themselves, in order to identify dangerous situations or events that may occur in the vicinity. When a safety alert is received, the vehicle warns the driver through sound or light indications, giving him/her enough time to react and avoid an accident. Examples of alerts are sudden braking, skidding vehicles and vehicles in collision course [2]. Other situations may arise as well, for example the creation of convoys, where the leader vehicle defines the route taken by several cars behind him [13]. Vehicle-to-vehicle communication is employed, in this case, to provide inputs for intelligent driving algorithms, in order to maintain the distance, speed and trajectory according to those defined by the leader. Those applications are characterized by small messages, intended for vehicles which are close to the sender, and must be received as soon as possible to avoid an accident. Thus, those communications will occur among vehicles, through a transport protocol based on datagrams, such as UDP. Such applications do not require large bandwidth, instead depending on low latency, jitter and loss rates.

The second class of application involves on-board entertainment, providing weather forecast, Internet access, television and radio streaming, among other features. These applications require a connection with a metropolitan area network, through 3G/4G or by relaying messages using the access points installed at the edge of the tracks, which are called *RoadSide Units* (RSUs). Since such communications are more time consuming and typically involve larger amounts of data than driver safety and driver assistance applications, they tend to employ connection-based protocols, such as TCP. In these applications, the throughput and jitter are key QoS metrics.

Entertainment applications can be implemented at low cost with widespread telecommunication technologies, such as 3G and 4G networks, or by using existing personal devices such as cell phones and tablets. Meanwhile, the innovative applications on VANETs are the applications related to driver assistance and safety. Those applications should not rely on 3G/4G networks, since they should operate even in situations where there is little to no network coverage due to the lack of pre-existent communication infrastructure. Further, in order to reduce the end-to-end delay, those messages should be exchanged from vehicle to vehicle, without requiring to pass through fixed infrastructure. Thus, new communication standards intended for VANETs were developed.

3. The IEEE 802.11p standard

Several initiatives have been developed in order to standardize and optimize the communication between vehicles. In 1999, the FCC allocated 75 MHz in the 5.9 GHz band for DSRC (*Dedicated Short Range Communications*) in VANETs [8]. In 2010, the 802.11 group finished the 802.11p standard which describes the communication in VANETs. The 802.11p standardizes the physical layer as well as the medium access control protocols [14]. Meanwhile, the WAVE standards define the message formats, the allocation of channels for each kind of application, as well as management and security aspects.

The main modifications in 802.11p, when compared with the traditional 802.11 are described as follows [8]. In the MAC layer, the overhead to establish a communication was reduced, due to the reduced time of contact between vehicles. In traditional 802.11, devices connected through an access point define a group called IBSS (*Independent Basic Service Set*), which must be identified when a connection is established. On the other hand, 802.11p defines a new type of BSS called WBSS (WAVE BSS), which has a fixed identifier and transmits beacons on demand. A beacon contains the essential information to establish a communication, as well as the list of services offered by the group, eliminating the authentication process. Finally, in order to eliminate the need of scanning the channels in order to find the desired network, the functions of each channel are fixed.

The spectrum band reserved for 802.11p is divided into seven 10 MHz channels, numbered between 172 and 184. Channel 178 is intended for control information, and is restricted to security applications [15]. The other channels are allocated for data transmission from different services. There are also two channels dedicated to critical applications such as life safety and public safety. The physical layer is based on the 802.11a standard and uses OFDM (*Orthogonal Frequency-Division Multiplexing*) modulation. The bandwidth was changed from 20 MHz to 10 MHz [9] in order to reduce the spreading delay (*Root Mean Square delay spread*) in VANETs. Optionally, the bandwidth can be set at 5 MHz. Also, performance improvements reduce the amount of losses caused by the interference between adjacent channels. The standard provides communication at theoretical distances of up to 1000 m, both in V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) modes, with absolute and relative speeds up to 30 m/s (108 km/h) in several environments (rural, highway, urban). With 10 MHz bandwidth channels, the expected bitrate is between 3 and 27 Mbps, whereas with 5 MHz or 20 MHz bandwidth channels the maximum bitrate is 13.5 Mbps and 54 Mbps, respectively.

4. Related work

Since IEEE 802.11p is a recent standard, most existing works in vehicular network employ traditional 802.11 (802.11a/b/g/n) transceivers. In [16], a set of cars equipped with IEEE 802.11b cards with external antennas communicated with an access point. The car speeds ranged between 80 and 180 km/h. The authors showed that the bitrate is low for distances above 250 m, with 1250 byte frames. On the other hand, the bitrate reaches about 4 Mbps regardless of the vehicle's speed. Bychkovsky et al. [6] performed tests with nine vehicles, which were observed for almost one year. The cars were connected to different open access points and transferred data to a specific destination. The maximum bitrate measured in TCP connections was approximately 700 kbps. In [7], performance data was collected using 802.11a/g devices.

Balasubramanian et al. investigated the effects of WiFi handoffs on VANETs, and proposed a set of enhancements [4]. The authors conducted tests in two different cities of the United States. In the first city, a network *VanLAN* was created, composed of eleven access points and two vehicles at 40 km/h. On the other hand, in the second city, a network named *DieselNet* was created, and was composed of 24 access points. The authors showed that such networks can handle handoffs, with close to ideal performance in

(a) (b)

Fig. 1. General view of the experiment, with the external antenna in detail (a), and aerial view of the experimentation area (b). (Source: Google Maps.)

WiFi. In [5], the limits of 802.11b were experimentally evaluated through the communication between a moving vehicle and an access point. The authors suggest that, in order to improve communication, it is essential to reduce the number of authentication and authorization stages present in 802.11b.

In [17] the authors analyzed the performance of a preliminary version of 802.11p protocols through simulations and analytical methods. In this work, the probability of collision, bitrate and delay were considered. The authors showed that 802.11p can prioritize messages. However, in networks with a large number of devices or with many data flows, the bitrate decreases while the delay grows considerably. Bilstrup et al. [18] also analyze 802.11p using simulations. The authors studied the network capacity and the delay. Results showed that the standard's prioritization schemes work well, and even in the presence of operations based in multiple channels, as dictated in IEEE 1609.4, the delay of high priority control messages is in the order of tens of milliseconds. Our work complements this evaluation, with results obtained through field experiments. Our results may be used to calibrate future simulations, bringing them closer to real scenarios.

In [10–12], field experiments were conducted with the IEEE 802.11p standard. The authors in [10] investigated the V2I communication, through and analysis of the contact time, the signal strength and the throughput. Martelli et al. [11] evaluated the process of beaconing in V2V communication according to two metrics: PDR (*Packet Delivery Rate*) and PIR (*Packet Interval Rate*). Finally, in [12] the authors investigated the communication between two vehicles with and without line of sight, moving at 30 and 50 km/h. The RSSI and packet delivery rates were measured, however the authors did not measure delay, jitter and the association time. Further, the authors found that the simulation models of vehicular networks developed in the NS3 simulator were not consistent with the results obtained in the experiments, thus showing the importance of conducting field experiments. This work differs from the previous ones by evaluating new metrics, which are essential for the development of driver safety and driver assistance applications.

5. Experiment description

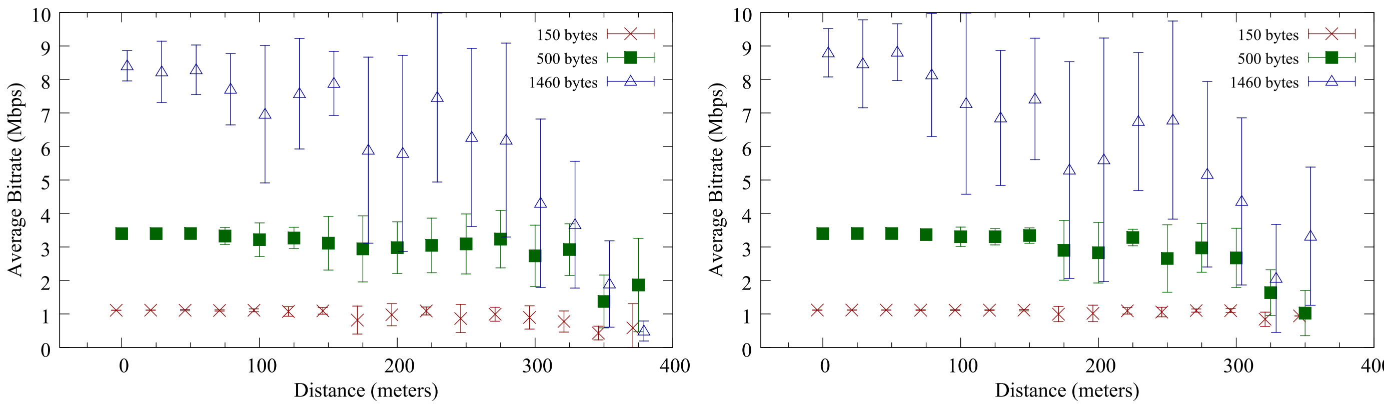
The experiments were divided into two stages. In both, we used two laptops running a Linux distribution. Each laptop was equipped with DCMA86-P2 cards [19], which implement the IEEE 802.11p standard. The DCMA86-P2 is based on Atheros chipset AR5414A-B2B, and operates in the frequency range of 5.85–5.925 GHz. Each board was connected to a 5 dBi external antenna, attached outside the cars.

The main goal of the first step was to calculate the association time in the best case, i.e. with the laptops side by side on a laboratory. The association time is an important metric in vehicle networks, because of the very short amount of time available to send data between vehicles (e.g. 10 s for two cars moving in opposite directions at 60 km/h [7]). Thus, a shorter link establishment time allows vehicles to send more data. We performed fifteen repetitions of the same experiment.

In the second step, the laptops were installed in separate vehicles and the antennas were attached to their ceiling. We employed a 5.870 GHz channel with bandwidth of 10 MHz for data transmission. This step was conducted in an avenue located near the university premises, on a stretch of approximately 650 meters in length, represented by the points marked in Fig. 1. In this stretch, the vehicles had line of sight for about 600 meters, while in the remaining 50 meters there was a small curve obstructing the sight. A vehicle was maintained still at the point highlighted in Fig. 1, while the other vehicle was moving on the avenue. In order to measure the displacement of the vehicle, a GPS was also installed in the laptop of the car in motion, whose coordinates were collected through the experiments. The GPS antenna was also attached to the ceiling of the vehicle, in order to reduce location and speed errors.

Since we consider that road safety applications are the main topic of VANETs when compared to traditional metropolitan networks (e.g. 3G and 4G), we chose to measure the link performance using UDP datagrams. Such datagrams represent short messages needed for sending requests and alerts, which are typically transmitted from vehicle to vehicle (V2V). We measured the performance of the wireless link by varying the size of datagrams from 150, 500 up to 1460 bytes. These tests were performed with the moving vehicle at speeds of 20 km/h, 40 km/h and 60 km/h.

We developed our own data collection program, in which a client sends numbered UDP datagrams of fixed length at regular intervals. Upon receiving a datagram, the server responds immediately by sending a short UDP datagram which indicates the number of the received datagram. The client records the datagram loss rate, throughput, delay and jitter, each of them averaged over a fixed time interval (1 s in the experiments). For this step, four independent experiments were performed for each scenario. The



(a) Average bitrate at 20 km/h (b) Average bitrate at 40 km/h

Fig. 2. Average bitrate.

figures plot the average of the four experiments, as well as the 90% confidence intervals.

6. Results

This section describes the obtained results. In the first stage, we measured the association time of two 802.11p devices, whereas in the second stage we measured the transmission performance of UDP datagrams on a moving vehicle.

6.1. Association time

In this experiment, we measured the association time of two laptops with 802.11p cards. Both the frequency and the ESSID were fixed it a priori, thus avoiding the time to scan the environment, as done in a VANET following the WAVE standard. In order to eliminate the IP address request time, we defined static addresses for both computers. In one of the laptops, we ran a client program that sends data every microsecond to the second laptop. The second laptop was configured as server, and was already associated in the VANET. When the client's network card is activated through the command *ifconfig* from Linux, the running program starts a timer, and stops only when the client receives an acknowledgment from the server. Thus, the measured time takes into account the network card activation and its association in the VANET, the sending of ARP packets in order to find the server's MAC address, the sending of a UDP datagram to the server and the acknowledgment reception. We made fifteen repetitions of this experiment, and obtained an association time of 1.035 ± 0.0024 s.

6.2. Performance with a moving vehicle

In this stage we measured the performance of the 802.11p devices in an outdoor environment, where two cars exchange data among themselves, as described in the previous section. We performed four repetitions of each experiment, with a confidence interval of 90%.

Figs. 2a and 2b show the average bitrate, in Megabits per second, versus the distance of the stopped vehicle relative to the moving vehicle for the speeds of 20 km/h and 40 km/h, respectively. The bitrate affects the performance in entertainment applications (e.g. audio and video streaming). At all measured speeds it was observed that when the two vehicles were close to each other (less than 100 m), the average bitrate was around 1 Mbps for 150 byte frames, 3 Mbps for 500 byte frames and 8 Mbps for 1460 byte frames.

A noticeable decrease in the bitrate occurred for the transmissions using 1460 byte frames for distances above 300 m. As the signal-to-noise ratio becomes smaller, the bit error probability increases, and this penalizes larger frames, reducing the chances of a successful delivery. This effect was more significant when the vehicle was located in the stretch without line of sight. On the other hand, the bitrate decrease was smoother for 150 and 500 byte frames, since the delivery time became smaller, thus the risk of packet loss due to interference became smaller.

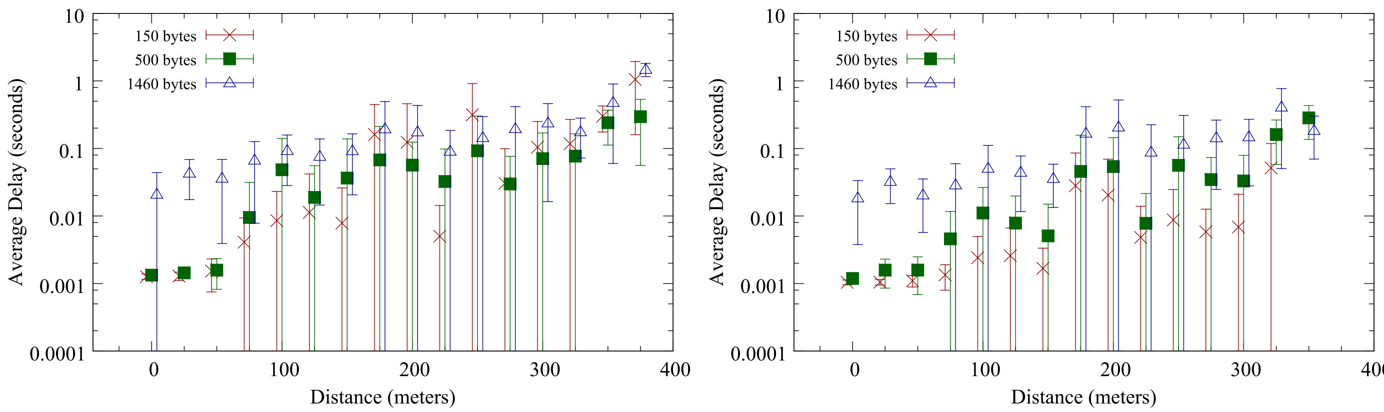
We also observed large variations in the bitrate when increasing the speed, which could be observed by the larger confidence interval, especially for 1460 byte frames. This indicates, besides the effect of distance as expected, the effect of speed on the achieved performance. This occurs due to the higher amount of changes in the environment (fading, reflections) generated by a higher speed, as well as stronger Doppler effect variations.

Figs. 3a and 3b show the average delay versus distance at speeds of 20 km/h and 60 km/h, respectively, placed on a logarithmic scale in the Y axis. In applications such as warning of sudden braking, long delays in message delivery can increase the driver's reaction time. Here, we observed a gradual increase in delay depending on the distance for all frame sizes, which was also expected. This increase is caused by a higher number of retransmissions, due to frame losses from reception errors. We observed an average delay close to 10 ms for 150 byte frames, while the delay ranged between 20 ms and 500 ms for 1460 byte frames.

Figs. 4a and 4b show the average jitter obtained from tests at speeds of 20 and 40 km/h, respectively, placed on a logarithmic scale on the Y axis. Jitter impacts streaming applications, e.g., emergency voice communications. The results obtained for 60 km/h were similar to those shown in the figures and therefore will not be shown in this article due to space constraints. For 500 byte frames, the jitter grew gradually when as distance increased. For other frame sizes the rate of increase was smaller. This effect is higher for distances above 150 meters. The jitter for 1460 byte frames was the largest, as expected due to the longer time required to transmit a larger frame.

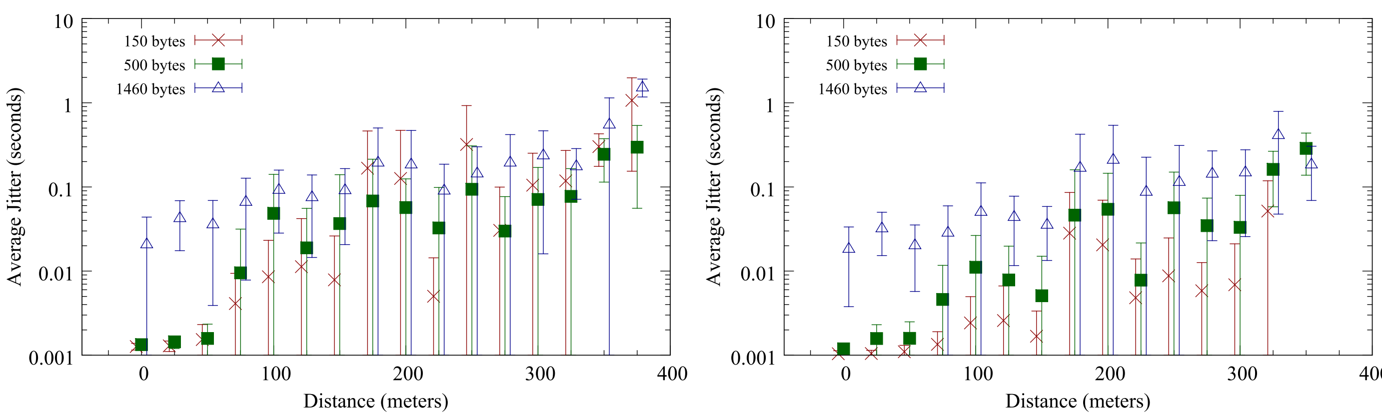
The loss rate for tests at speeds of 20 km/h and 60 km/h is shown in Figs. 5a and 5b, respectively, with logarithmic scale on the Y axis. The loss rate should be minimized in VANETs, because messages carrying emergency alerts that are not received may reduce the chances of a driver reacting on time when adverse events occur. For most of the distances and speeds, the loss rate was close to 1%, exceeding 10% only at distances greater than 300 meters.

For all measured metrics, 500 byte frames obtained the best performance, followed by the 150 byte frames, which presented an average bitrate about 60% lower. Although the bitrate for 1460 byte frames was higher, the behavior for 500 bytes was less variable. Therefore, we conclude that messages having around 500 bytes



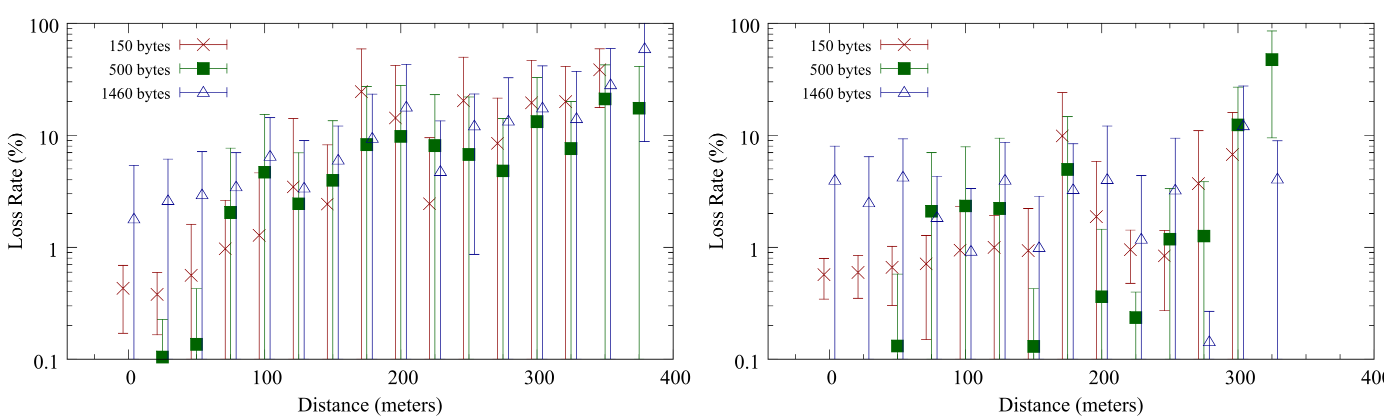
(a) Average delay at 20 km/h (b) Average delay at 60 km/h

Fig. 3. Average delay.



(a) Average jitter at 20 km/h (b) Average jitter at 40 km/h

Fig. 4. Average jitter.



(a) Average loss rate at 20 km/h (b) Average loss rate at 60 km/h

Fig. 5. Average loss rate.

are more efficient for road safety applications, which do not require high bitrate. However, for entertainment applications, longer frames should be employed in order to increase the bitrate. Moreover, we see that the vehicle's speed affects the delivery delay and the frame loss.

7. Conclusion

In this work we presented performance measurements obtained through off-the-shelf IEEE 802.11p devices, aiming to characterize the standard's performance in a real scenario. Although the standard was completed in 2010, only now the first commercial cards were produced. We conducted field experiments using the UDP protocol, since it the most suitable transport protocol for driver assistance and road safety applications. We measured the bitrate, delay, jitter, loss rate and the average time of association between two 802.11p devices. The results showed that IEEE 802.11p with 500 byte frames obtained the best performance, followed by the 150 byte frames, which presented an average bitrate about 60% lower. Although the bitrate for 1460 byte frames was higher, the behavior for 500 bytes was less variable. We showed too that the association time has been 1.035 ± 0.0024 s.

As a future work we intend to perform the same experiments with two or more moving vehicles in environments with constant traffic and multi-hop communications, as well as a substantial number of obstacles along the way, in order to analyze the impact of these factors on communication performance between 802.11p devices. We will also evaluate the throughput using TCP, focusing on entertainment applications.

Acknowledgements

The authors would like to thank RNP, CAPES, Fapemig and CNPq for their financial support.

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