This is the author's version of a work that was submitted/accepted for publication in the following source:


This file was downloaded from: http://eprints.qut.edu.au/51539/

© Copyright 2012 IEEE

This work has been submitted to the IEEE for possible publication. Copyright may be transferred without notice, after which this version may no longer be accessible

Notice: Changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published source:

http://dx.doi.org/10.1109/IVS.2012.6232268
Abstract—IEEE 802.11p is the new standard for inter-vehicular communications (IVC) using the 5.9 GHz frequency band; it is planned to be widely deployed to enable cooperative systems. 802.11p uses and performance have been studied theoretically and in simulations over the past years. Unfortunately, many of these results have not been confirmed by on-tracks experimentation. In this paper, we describe field trials of 802.11p technology with our test vehicles. Metrics such as maximum range, latency and frame loss are examined.

I. INTRODUCTION

IEEE 802.11p is the leading inter-vehicular communications (IVC) technology that has been pushed forward by the IEEE for short-to-medium range communications (up to one kilometre), for both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The 802.11p amendment to the well-known 802.11 standard (WiFi) was adopted in 2010 and non-prototype hardware is now getting available on the market. Contrary to WiFi technologies used in households’ wireless networks, 802.11p uses the 5.9 GHz frequency band and is aimed at the high mobility inherent to vehicular ad-hoc networks (VANETs). Obviously, developing safety-critical systems put certain requirements on the IVC systems that will support them, as they need to guarantee certain levels of performance.

Over the past few years, the performance of 802.11p has been evaluated both in theoretical and simulated studies. Most previous studies [1], [2], [3], [4], [5] used the ns-2 simulator to evaluate the performance of 802.11p. However, the road environment is very complex, always changing, where IVC’s performance metrics are likely to diverge from those studied in theoretical simulations. Multiple effects, ranging from Doppler shift, multipath and shadow fading, etc. can degrade IVC performance. Thus, it is necessary to complement theoretical simulation with field evaluation of the actual IVC performance.

Field performance evaluation of IVC has been ongoing for several years, in many cases as early as 802.11a and b were available [6], [7]. However, we have found that many of the studies aimed at evaluating IVC performances used older versions of 802.11, typically g or g+. For example, Ammoun and Nashashibi [8] evaluated several performance metrics (range, bitrate, etc.) using g+ IVC devices. While such results are interesting, it is fairly straightforward to argue that 802.11g/g+ is no longer relevant to the ITS world. The change in frequency, from 2.4 to 5.9 GHz, means that the behaviour and performance of the IVC device could be fundamentally different, and possibly more in line with results obtained with the older 802.11a at 5.2 GHz.

Nonetheless, a number of recent studies have specifically focused on 802.11p. Böhm et al. [9] studied 802.11p performance in a variety of settings (urban, rural) and road configurations (freeway, straight sections, curves, non-flat sections, etc.); they found that 802.11p was still highly subject to line of sight (LoS) effects and that the direction of movement had a significant impact on range, especially at higher speeds. Guo et al. [10] also explored 802.11p performance and demonstrated that it could be used for average throughput applications at ranges close to the theoretical limit, although the authors make no mention of experimental conditions such as traffic, the surroundings’ density, etc.

Shivaldova et al. [11] have tested 802.11p performance for an infrastructure-to-vehicle scenario focusing on freeway tunnels and their surroundings; they also highlighted the impact of LoS on the communication’s quality. Earlier, both Cheng et al. [12] and Tan et al. [13] found that the 5.9 GHz channels saw an increase in error rates for large packets compared to smaller packets.

Unfortunately, we note that latencies have not been investigated in these previous studies, when they are supposed to be a major improvement brought upon by the amendment. Furthermore, the whole set of possible speed classes have not been investigated in [8], [10], [11] (each study focuses on a precise range such as lower speeds or freeway speeds). Experimental conditions are not very well known [10] or controlled, notably for being in open traffic [9], [11]. Although it is advantageous to measure performance in real road conditions, as they have shown to be very variable depending on the experimental environment, it is important to obtain baseline performance details in more controlled environments first. In this paper we propose a detailed post-processing analysis of performance metrics (latency, range and frame loss), for measurements taken in a controlled, representative freeway-like environment, and using the full range of speeds achieved by motor vehicles.

The remainder of this paper is organised as follows: Section II presents the system’s architecture used for our measurements, while Section III introduces the experimental protocol; Section IV offers a detailed performance analysis;
eventually, we offer conclusions and perspective on future works in Section V.

II. SYSTEM ARCHITECTURE

We performed our field measurements on 2 instrumented vehicles: a Renault Clio 3 and a Citroën C4 Grand Picasso. The vehicles are fitted with powered equipment racks in the boot and several in-cabin screens for HMI. A variety of sensors can be fitted on them depending on the experimental requirements. Our experimental architecture features an IVC device, a host PC, a RTK GPS device and a NTP time server; all are duplicated in each vehicle (see Fig. 1).

The IVC device is an independent computer board fitted with an Atheros 5413 WiFi chipset, the same used in the European CVIS project. We installed the open-source ath5k WiFi driver, which was patched in 2010 for the Grand Cooperative Driving Challenge in order to enable 802.11p channels. Ad-hoc mode and IPv4 are used; note that the dot11OCBEnabled flag is set to false, so that normal 802.11 ad-hoc behaviour is used. Although this option was designed to reduce latency for high-priority safety-related frames, all 802.11p frames need not to use it. Furthermore, it is interesting to evaluate 802.11p latency in a more “classical” 802.11 architecture, so that, with further work, the actual interest of the dot11OCBEnabled flag can be assessed. The IVC device is connected to a roof-mounted 8 dBi gain stick antenna. The chipset’s transmission power is lowered to 20 dBm, so that, accounting for all connectors and cable attenuation (estimated at 2.5 dBm from manufacturers’ data), the effective isotropically radiated power (EIRP) is $20 - 2.5 + 8 = 25.5$ dBm, or 355 mW. This value was chosen in order to: (1) remain under regulation for the concerned frequency band; and (2) allow signal’s natural extinction within line of sight and within 802.11p’s theoretical range (1,000 metres). The frequency used is 5.890 GHz.

A custom Java application hosted on the IVC device was the principle method used to collect data. It sends a UDP frame through a Java datagram socket to the IP address of the target vehicle, at a frequency set by the user; by default, a deterministic timer is used to generate frames at 20 Hz. A typical payload’s size is 20 bytes. The actual frame at the MAC level also includes: 8 bytes of UDP header, 20 bytes of IP header, 8 bytes for LLC, and 28 additional bytes of overheads including the 802.11 MAC preamble and header, as well as the CRC sequence. This adds to a total of 84 bytes. As our research focus is mostly on Emergency Electronic Brake Light (EEBL) applications (see also [16], [17]), we chose to use a frame size in line with EEBL’s requirements. In [18], the recommended payload for EEBL frames is 36 bytes, and includes detailed information on the emitter’s behaviour. Some data fields listed in the cited report can be removed without affecting the application’s usefulness. We believe that 20 bytes is a good compromise for an EEBL frame that can include a vehicle’s ID, location, and timing information. The application computes the latency based on the frame’s emission time recorded in it. A log file is automatically generated containing the frame’s information: computed latency, payload size, received power (signal strength indicator) and reception time. Frame loss and bit rate can be processed from this log file.

A RTK GPS device records positioning data at a 5 Hz frequency on the host computer. Time synchronisation, which is critical for any safety application and for accurately measuring latencies, is performed with Brandywine Network Time Adapters (BTNA), one per vehicle, which distribute accurate timing information from GPS through a NTP architecture. Within the NTP architecture, the BTNA is a stratum 1 time server, as it is directly referenced to GPS satellite-based clocks (stratum 0). As such, the IVC device and host computer are clients of stratum 2. The BTNA is set in broadcast mode, sending timing information to its clients four times a second. This system’s performance has been excellent: most of the time, the offset between the GPS reference time and our devices’ clocks was smaller than one millisecond.

III. EXPERIMENTAL PROTOCOL

The experimental protocol is kept voluntarily simple. We consider vehicle-to-vehicle and no relaying or rebroadcasting. The scenario has a receptor vehicle (usually the Citroën C4) passing by a static emitter (usually the Renault Clio), which is located on the track’s side. It is suggested by previous research and LIVIC’s experience, that the absolute speed of 802.11 emitters and receptors in the environment’s referential does not have much effects on IVC’s quality. On the other hand, the speed difference between the emitter and the receptor is a major parameter. As we consider a static emitter, the speed difference and speed relative to the environment are equivalent. The following speeds were tested: 30, 50, 70, 130 and 170 km/h (approximately 20, 30, 45, 80 and 105 mph).

1www.cvisproject.org

Measurements were performed on Satory’s speed track, isolated from regular traffic. The speed track is a 2-kilometres-long quasi-straight line, with 2 lanes, allowing for 1.4 kilometres of direct line of sight (LoS). The emitter was either located at the track’s eastern end, or near the slight bend, so to have LoS with all the track’s length. The track’s surroundings are largely open, despite a few sections with over-reaching trees. Data were collected on 9 different days spread out from September to December 2011, with a total of over 250 kilometres driven during experiments.

For the remainder of this paper: “closing” will refer to items relevant to when the receptor vehicle is moving toward the emitter; “away” will refer to items relevant to when the receptor vehicle is moving away from the emitter.

IV. PERFORMANCE ANALYSIS

A. Maximum range

The range is the maximum distance at which a frame is successfully received by the receptor vehicle from the emitter; thus what we call the range is actually the transmission range. The range is estimated based on the receptor’s localisation process that uses RTK GPS data.

Fig. 2 gives the average ranges for the main scenario, at all the tested speeds. The significant difference between the closing and away ranges at the same speed is a major phenomenon. Closing range was found to be greater than away range, on some occasions by up to 200 metres. Böhm et al. [9] have recorded a similar phenomenon (at either low or high speed), but their data are reversed compared to ours: away range is greater than closing range. It is difficult to explain this range difference, as one would assume the power-level-based CCA and CSMA/CA mechanisms used in 802.11p would not make any difference regarding the vehicles’ direction of travel. Doppler effects can likely only explain the range reduction with increased speeds.

Setting up a virtual interface working in monitor mode allowed to access management frames and beacons while our measurement application was running. We thus performed additional measurements in the exact same experimental conditions as previously, in order to confirm whether the user transmission on the IP stack had any effect on the results. Our investigation suggests that there is no significant difference between the range for management frames (beacons included) and for applications’ frames. The direction of driving produces the same influence over the maximum range of beacons, which suggests that the difference is due to an actual physical effect.

Consequently, we have investigated the Signal Strength Indicator (SSI) for various speeds. Fig. 3 shows the recorded SSI for one drive at 50 km/h, in both directions. One can clearly see that two “paths” exist: the SSI is consistently lower when the vehicle drives away, compared to when the vehicle drives toward the emitter. We then undertook to examine two factors that could explain such difference: (1) an imperfect omnidirectionality of the antennas (in the horizontal plane), and (2) an influence of the vehicle’s body.

For the first factor, we focused on the receptor’s antenna, as it was the one that would be affecting the most received power during a normal experimental drive. We measured the SSI for 8 orientations of the antenna, rotated 45 degrees from
the previous each time; the emitting antenna remained completely static meanwhile, and the vehicle’s relative orientation did not change. Fig. 4 shows the averaged differences between the overall average SSI and the measured SSI for each angle, demonstrating that the antenna is not perfectly omnidirectional. For example the difference between the 45-225 degrees axis is at least 6 dBm. This would be sufficient to explain the large range difference between closing and away conditions we found in our initial measurements. Indeed, the difference measured on the signal shown on Fig. 3 averages to 5 dBm.

For the second factor, we measured how the SSI behaves when the receptor vehicle is moving either away from the emitter or closing to it, alternatively front and rear-facing, at fixed speed (50 km/h). The antennas’ relative orientation was maintained throughout the whole measurement session, so that the non-omnidirectionality does not affect the experiment. Our measurements show that the vehicle’s orientation (and thus shape) has an influence on the received power of less than 2 dBm.

We performed a third experiment measuring SSI in order to determine whether the direction of driving had a real influence on the range, and if yes what was its strength. The vehicle is moving away from and back to the emitter, but always facing the same direction, controlling for its shape and the antennas’ relative orientation. The measured difference was not significant compared to the other scenarios.

Böhm et al. [9] claim that they measured a difference due to the direction of travel even at walking speed, which allows them to rule out Doppler effects as a possible source for their range difference. Measurements obtained with our set-up at low speeds (<10 km/h) do not show any significant difference between each direction of driving. It is probable that their finding can be attributed to non perfectly omnidirectional antennas. Similarly, the range difference related to the direction of driving that they found, at normal driving speeds, can also probably be explained by non-omnidirectionality.

The largest range for all measurements is 1,046 metres (closing conditions). As specified in Section II, the transmission power was lowered to remain in line with 802.11p specifications. Most of the measured maximum ranges were largely under specifications or ranges measured in other studies. However, in [9], the transmission power was actually slightly lower than ours (17 versus 20 dBm, at the chipset), yet they achieved larger ranges; it is probable that they had lower attenuation in their cables and connectors. Informal measurements with $Tx_{power} = 33 dBm$ suggested no difficulty in systematically achieving kilometic range with larger powers.

B. Latency

We define latency as the temporal delay between the generation of a frame at the emitting device, and its reception at the receptor device. More precisely, we consider the time when the message is generated and sent to the transport layer (UDP) through the socket; similarly, the reception time is set at the instant the frame is read by the application in the receptor vehicle. Thus, latency includes IP, MAC, and physical layers latencies. We have not tried to measure the specific latencies at each layer, as our main interest resides in the application-to-application latency. Indeed, knowing the global latency is essential to design robust vehicular safety applications.

Fig. 5 shows the average latencies measured at 30, 50, 70, 130 and 170 km/h. The average latency is centered around 1.5 milliseconds. The direction of movement does not have any influence on the latencies, as illustrated by Fig. 6, showing data for 70 km/h. In this example, latency is stable within the “useful” range, until 400 metres (where frame loss remains under 50%), and is similar for both direction of movement. For ranges greater than 400 metres, averages are based on fewer measurement points as the number of lost frames increase considerably (see Section IV-C for a detailed analysis of frame loss), thus they are more sensitive to outliers. It is probable that latency is sometimes increased at these large ranges when the underlying management

While the wave propagation latency is likely negligible (a radio signal propagates over one kilometre in about 3.5 microseconds), the time needed to actually emit a frame can be more significant, and depends on the data rate.
processes in 802.11 introduce latencies as they struggle to maintain IBSS (Independent Basic Service Set) membership over a degraded medium link (especially considering we did not use the dot11OCBEnabled option). Indeed, a number of beacons and other management frames have to be exchanged before any useful transmission can take place. At long ranges, IBSS membership can be lost and regained several times, as even management frames have difficulties getting properly transmitted. An application frame can thus be stored in a buffer for a few milliseconds before communication is again possible within the IBSS group.

We can conclude that, according to our results, average latencies are not dependent on the vehicles’ relative speed, either on the transmission range, at least not until extreme ranges where frames start to get missed. Overall, latencies always remained inferior to 4 milliseconds.

C. Frame loss

The last indicator we investigated is frame loss. Frame loss is defined as the percentage of frames that are missed during a certain measurement interval, that we define temporarily and according to range. It is straightforward to deduce the actual bitrate from the nominal bitrate and the measured frame loss. The maximum range is an important indicator, but does not say anything about the quality of transmissions within this range. Typically, one could receive frames up to a thousand metres, yet have 90% frame loss starting as soon as 400 metres away from the emitter. Thus, it is also important to measure the quality of transmission within the transmission range, typically via frame loss.

Fig. 7 shows the compiled results for frame loss, as obtained with our Java application. As per what we found in the range analysis, we classified our results according to the direction of the relative movement between the receptor and the emitter. Maximum transmission range alone is not a sufficient indicator to obtain a good description of the IVC’s performance. For example, at 70 km/h the average transmission closing range we measured was 584 metres (see Fig. 2); this is roughly equivalent to the range at which the average frame loss passed under 50%, as seen on Fig. 7 (closing sub-graph). At this same speed, the largest distance at which a frame was captured is actually around 700 metres.

From Fig. 8, one can note frame loss fluctuations within the transmission range, at all speeds. Some of these can be explained by environmental features that degrade the transmission’s quality (scattering leading to multipath, interferences, degraded LoS, etc.). A typical example are the destructive interferences that build up because of signal reflected from the ground Two-Rays propagation model); the strongest location for these interferences is visible between 100 and 130 metres on most sub-graphs in Fig. 8. Vehicle’s pitch variations can also explain some fluctuations on a not perfectly flat track, as the antenna’s radiation pattern is less omnidirectional in the vertical plane than the horizontal one.

Eventually, changing meteorological conditions should affect the signal’s quality too, even if we have not controlled for them.

V. CONCLUSIONS AND FUTURE WORK

In this paper, the results of field measurements of 802.11p are used to assess the technology’s performance in actual conditions. We have found that latency remains under 4 milliseconds in almost all circumstances, regardless of range and relative speed. We also found that frame loss remains manageable over most of the range, but that it is quite dependent on environmental conditions. Our other results are more pessimistic than existing literature. At the used transmission power, range showed a strong dependency on the relative speed between the emitter and the receptor. We have also found that the vehicle’s shape plays a small role in amplifying or toning down the received signal, partially explaining the range difference related to the direction of driving, when it combines with the imperfect omnidirectionality of the antennas. The range variation depending on speed, antenna orientation and vehicle shape can amount to up to 500 metres.

At high speeds, such as when two vehicles are driving past on opposite sides of a non-segregated trunk road, the large reduction in effective range might reveal to be a problem for safety applications. Indeed, the effective range decreases to a point that IVC are not advantageous any more compared to on-vehicle exteroceptive sensors such as LIDARs or RADARs, with ranges in the 100-200 metres interval. Similarly, a vehicle driving past a RSU on a freeway would be able to maintain connectivity for only 800 metres (with the most generous estimate). Such limitations are very important for the dimensioning of on-vehicle perception systems.

For future work we intend on taking a further look at frame loss by using multiple actual IVC devices on vehicles and on roadside units to simulate a use case that features many emitting nodes at once. Indeed, this scenario can lead to VANET saturation; this scenario has been studied in theoretical simulation, but there is few experimental data.
collection pertaining to it. Overall, we aim at proposing guidelines for the design of efficient safety applications that use 802.11p, taking into account the latter’s limitations.

REFERENCES


