Reliability Analysis of IEEE 802.11p Wireless Communication and Vehicle Safety Applications

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Abstract: In this paper we analyze the performance of IEEE 802.11p vehicular networks used as communication media to warn drivers about hazardous situations on the road. In particular, this paper is focused in three typical active safety applications which are based on the cooperation among vehicles and intelligent elements placed on the road. The reliability of these applications relies on the performance of the radio link among the agents involved in the cooperative scenario, so first we analyze the goodput, Package Delivery Rate (PDR) and delay of this link. Once the behavior of the media is characterized, the kindness of the safety applications is studied. These measures were carried out in real V2V and I2V scenarios using a compliant IEEE 802.11p prototype developed by NEC.

1 INTRODUCTION

Vehicular Ad-Hoc Networks or VANETs have been of particular interest to the communication research area in order to develop a set of applications that could help the driver to avoid or prevent from risky situations. These services are based on the cooperation among vehicles and offer great potential in reducing road accidents and therefore in improving drivers' comfort and efficiency of highways from the traffic management point of view.

But first, to provide these cooperative services a stable and reliable wireless communication system must be deployed on the road infrastructure. For this propose, different technologies have been analyzed in the scenario of infrastructure-to-vehicle (I2V-V2I) and vehicle-to-vehicle (V2V) communications (Wewetzer et al., 2007) (Bazzi and Masini, 2011) (Chou et al., 2009). Table I shows selected characteristics and attributes of a few wireless systems that could be used in a vehicle cooperative scenario (US-DOT, 2004).

Once the communication link is stable then cooperative and warning services could be deployed with the security that all agents involved in a VANET will have the chance of sending and receiving information regarding road events.

According to ETSI TC on ITS a set of applications can be used as a reference for developing cooperative vehicular systems. In the same way, the U. S. Department of Transportation (USDOT) has identified similar applications to be deployed thanks to the potential of DSRC to support wireless data communications between vehicles, and between vehicles and infrastructure.

In this framework, this paper aims to determine if a set of applications based on the description provided by ETSI TC on TC can be deployed in a real VANET using two IEEE 802.11p compliant devices, namely LinkBird-MX communication modules provided by NEC Technologies. In order to determine the reliability of both the communication link and the applications, first the main characteristics of tested cooperative vehicle applications are described at Sections II and III respectively, whereas the scenarios used during this validation process are described at Section IV.The results of this experiments and the analysis about how some safety applications can work in these scenarios are shown in Section V. Finally the conclusions of the paper are presented at Section VI.

2 DSRC AND IEEE 802.11P STANDARD OVERVIEW

Although all systems included at Table 1 provide specific solutions to different connectivity problems, in a mobile environment in which all the nodes must be able to send and receive reliable messages in real-

Table 1: Candidate Wireless Technologies and Atributes

	DSRC	**3G**	**WLAN**
Range	1 km	4-6km	1km
One-way to vehicle	X		
One-way from vehicle	X		
Two-way	X	X	X
Point-to-point	X	X	X
Point-to-multipoing	X		
Latency	200us	1.5-3.5 s	3-4 s

time, DSRC is the only one system that:

- Is dedicated to wireless access in vehicular Ad-Hoc networks 1-hop and multihop communications.
- Provides active vehicle services with Line-Of-Sight (LOS) and Non-LOS (NLOS) link scenarios.
- Is ready to operate in a rapidly varying environment and to exchange messages without having to join a Basic Service Set (BSS), that is, without the management overhead.
- Makes possible low latency in communications among vehicles and infrastructure allowing sharing real-time information.
- Provides unicast, broadcast, real-time and bidirectional communications.

IEEE 802.11p WAVE is only a part of a group of standards related to all layers of protocols of Dedicated Short Range Communications (DSRC) standard (Uzcategui and Acosta-Marum, 2009). In the DSCR 5.9GHz band, FCC (Federal Communications Commission) reserved seven channels (1 Control Channel -CCH- , 4 Service Channel -SCH- , 1 Critical Safety of life Channel and 1 Hi-Power Public Channel) of 10 MHz in a bandwidth of 75MHz for ITS applications while in Europe, ETSI reserved five channel, 1 Control Channel and 4 Service Channel (ETSI, 0 01).

The IEEE 802.11p standard is limited by the scope of IEEE 802.11 which is the definition of MAC and PHY layers, as it is shown at Figure 1 (Jiang and Delgrossi, 2008). At PHY layer, IEEE 802.11p operates in the band of 5GHz, reusing IEEE 802.11a OFDM (Orthogonal Frequency Division Multiplexing) modulation considering 52 subcarriers that can be modulated using BPSK, QPSK, 64-QAM or 16-QAM modulation schemes. Besides, IEEE 802.11p reduces inter symbol interference and the channel throughput (from 3Mbps to 27 Mbps, instead of 6Mbps to 54Mbps commonly used in IEEE 802.11a). This setup allows theoretically a communication range over 1000m (depending on the antennas configuration) and the establishment of communication among vehicles driving up to 200km/h.

At MAC level, in order to speed up the exchange of messages among the vehicles (referenced as On-Board Units) and Road-Side-Units (RSU), IEEE 802.11p standard simplifies initial connection setup used in common IEEE 802.11 networks. The basic MAC layer is based on CSMA/CA improved with IEEE 802.11e EDCA protocol to provide services with priority levels.

Anyway, MAC layer of IEEE 802.11p is a trend research topic in which many alternatives and protocols are being developed (Saeed et al., 0 11)(Bhm and Jonsson,)(Bilstrup et al., 2008)(Han et al., 2012)(Bilstrup et al., 2009).

IEEE 1609.4 defines a time-division scheme for DSRC radios to alternately switch within these channels to support different applications concurrently, that is, it supplements IEEE 802.11 features providing frequency band coordination and management within the MAC layer (Chen et al., 2009). This is possible thanks to the coordinated operation on CCH (using it only for broadcast, high priority and single-use messages) and SCH (for ongoing applications).

Meanwhile, IEEE 1609.3 specifies operation and management of the communications stack, defining the use of UDP transport protocol, coordinating the IPv6 configuration and Logical Link Control (LLC) in VANETs. This standard also manages WAVE Basic Service Set (WBSS), which is required to handle the SCH transmission.

WAVE Short Message Protocol (WSMP) is used by IEEE 1609.3 networking services in CCH and

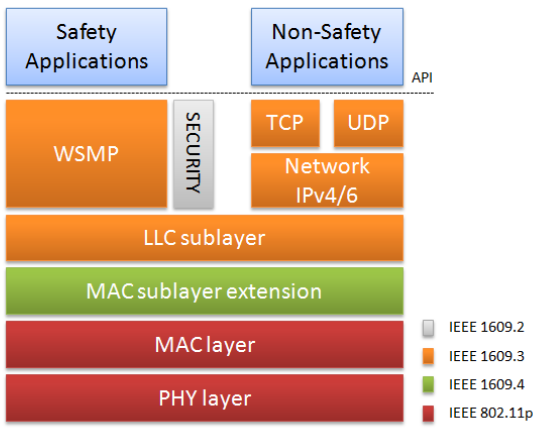

Figure 1: IEEE WAVE/802.11p protocol stack

SCH to enable communications with a maximum payload of 1400 bytes. WSMP allows WAVE-aware devices to directly control physical characteristics (channel number and transmitter power).

Finally, IEEE 1609.2 standard defines secure message formats and the processing of those secure messages in the WAVE system. It covers methods for securing WAVE management and application messages, with the exception of vehicle-originating safety messages.

To sum up, IEEE 802.11p WAVE is only a part of a group of standards related to all layers of protocols for DSRC based operations which concerns to physical and MAC layers. Therefore all the characteristics of the links V2X and the performance of the others DSRC layers depend on the efficiency of IEEE 802.11p standard. For this reason in this paper we will evaluate first the throughput of the IEEE 802.11p link and then the reliability of the applications based on it.

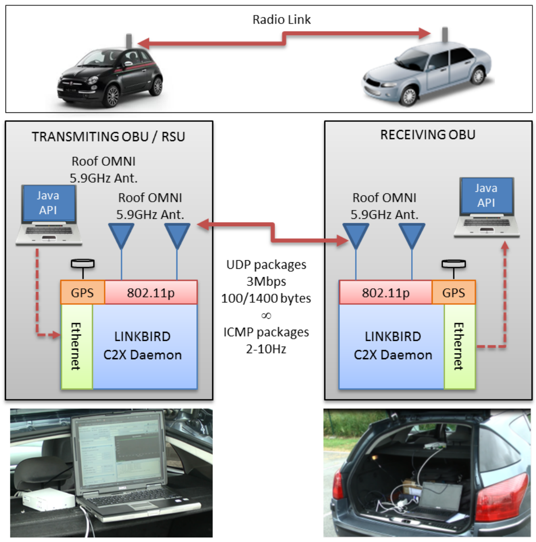

Figure 2: Hardware Setup

3 Cooperative Based Applications

In the field of cooperative ITS services, a huge variety of applications and use cases can be described. Taking into account strategic, economical and organizational requirements, system capabilities and performances as well as legal and standardization requirements, the ETSI TC on ITS has defined a Basic Set of Applications to be used as a reference for developers. These applications are close similar to those described by the US DOT (USDOT, 2004).

In these applications, four types of communicating agents are considered: two mobile entities -OBUs and people- and two stationary entities -the RSUs and the central systems (it could be referenced as a Traffic Management System). These entities are able to run four classes of applications: active road safety, cooperative traffic efficiency, cooperative local services and global internet services. In each class, different applications and uses cases are defined.

Depending on the application and timing restrictions, data exchange among referenced entities can be categorized as:

- Warning messages: these are defined as Decentralized environmental Notification Messages and they can be sent out to each vehicle or RSU.
- Heartbeat messages or beacons: these messages are used by OBUs to report their position, speed and ID to the RSUs. Moreover, these messages are also used to keep updated information about traffic situation. For this, WAVE defines Cooperative Awareness Messages (CAMs), which are broadcasting periodically by each vehicle.
- Non-safety messages: which are used to enhance driver information and comfort: tourism information, Internet access, navigation aid, and so on.

In this paper due to this relevance and likelihood of being deployed in a near future, only three active road safety use cases have been analyzed : intersection collision warning, emergency vehicle warning and Roadwork warning.

4 Scenario Definition

The three applications under test can be deployed both in urban or highway scenario. Moreover to be operative in these environments, cooperative wireless communications must be tested in Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) conditions. For this reason to test the performance of I2V IEEE 802.11p link in an urban LOS and NLOS condition, an industrial area has been chosen. In this location a straight road and intersections with different height buildings are available. The communication zone covered by each RSU is limited to a maximum radius of 1km diameter.

To test the V2V link in a highway under LOS and NLOS conditions two vehicles have been equipped as it is shown in Figure 2. In a real highway both vehicles have been driven at different speeds and with other vehicles (trucks/bus, cars) in the middle of the communication link deployed between them.

Therefore, in both urban and highway scenario the challenges of the described tests are:

- Measuring the throughput, PDR and latency of a

V2X link according to different package size and distance between the entities involved in each scenario.

- According with the results obtained in previous tests, determinate if the three proposed applications are reliable in this context.

4.1 Hardware Setup

In all tests described in this paper, a single omnidirectional radio link is evaluated, either between two OBUs or between a RSU and an OBU. In both entities, the same hardware has been deployed running as OBU or as RSU. The selected hardware is LinkBird-MX which embedded Linux machines based on a 64 bits MIPS processor working at 266MHz. Besides an IEEE 802.11p interface, these modules are equipped with an Ethernet connector that is used to communicate with the Application Unit (the one that runs the applications in a regular PC), a GPS interface and other interfaces as CAN or RS-232. Figure 2 shows the hardware setup used in the tests that have been carried out in the described scenarios.

Although LinkBird allows to select two channel bandwidth, in these tests 10MHz bandwidth has been selected instead of the 20 MHz one usually used by 802.11a devices, in order to minimize multipath delay spread and Doppler effect that appears in mobility and highway scenarios. Moreover, in order to maintain sufficient reliability of the data transfer in a 1-hop scenario, the lowest bit rate has been used, that is 3Mbps (bit rates from 3 to 27Mbps are available at IEEE 802.11p standard), so also the lowest coding rate (1/2) with BPSK modulation has been used to transmit data packets.

Along with the communication modules, two antennas whose characteristics fit well with vehicular applications are provided. One antenna is tuned to the 178 CCH frequency (5.890GHz) and the other one to the 180 SCH frequency (5.9GHz) Technical characteristics of hardware setup are shown at Table 2.

Table 2: IEEE 802.11P Hardware Setup

LinkBird-MX	
Parameter	Values
Frequency	5725-5925 MHz
Bandwidth	10MHz
Tx Power	21dBm
Bitrates	3Mbps

Antenna	
Parameter	Values
Model	ECO6-5500
Frequency	5.0-6.0 GHz
Gain	6dBi
Radiation	Omni-directional

4.2 Applications setup

As it has been mentioned in the introduction, one of the objectives of this paper is to check the reliability of three active road safety applications listed by the ETSI TC on ITS. The goal is to test if the links V2X that are deployed using previous hardware setup satisfy the requirement of these applications. According to (ETSI, 9 06), these requirements are summarized in Table 3.

The SDK provided by NEC with the LinkBird-MX modules includes a set of Java API to interact with the IEEE 802.11p protocol stack. Thanks to these facilities, it is simple to develop applications that send Geographical Unicast, Topologically-Scoped Broadcast, Single-Hop Broadcast and Geographically-Scoped Broadcast or Unicast messages. In this way and according to the applications that we want to test (Table 3), all the packets that will be transmitted in our scenarios will be Single-Hop Broadcast.

To carry out these experiments we have developed a single application in Java in which UDP packages are generated and sent. In this application the payload and transmitted package rate parameters are modifiable as well as the duration of transmission phase. The IEEE 1609.3 standard species that the maximum size of a WSMP message is 1400 bytes. For this reason we have measured the throughput of the V2X links using different payload size, from 100 bytes to 1400 bytes.

In order to measure the latency in the communications between OBUs (V2V) and between RSU and OBU (I2V), we have developed a simple program that sends Internet Control Message Protocol (ICMP) echo request every a configurable time. In this test also the ICMP payload is also configurable in order to know if the latency depends on the package payload.

5 Experimental Results

In this section, the results of measurement campaigns are shown. According with these results, the reliability of the applications under test is analyzed.

Table 3: Requirements of applications under test

	Intersection collision warning	**Emergency vehicle warning**	**Roadwork warning**
Application	Driving assistance Co-operative awareness	Driving assistance Co-operative awareness	Driving assistance Road Hazard Warning
Latency	Less than 100ms	Less than 100ms	Less than 100ms
Message Frequency	10Hz	10Hz	2Hz
Special Needs	Accurate position of OBU	Triggered by vehicle	RSU broadcasts periodic messg.
Link	V2V	V2V	I2V

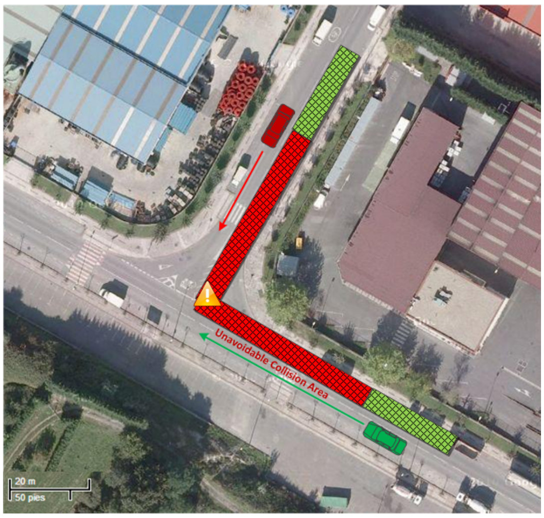

Figure 3: Intersection crossing warning scenario

5.1 Intersection crossing warning

Chosen scenario is shown at Figure 3, where there are two vehicles approaching to the intersection. Although tested scenario is placed at an industrial area, this is a typical situation in urban scenarios where buildings create closed intersections with Non Line-Of-Sight between vehicles. Therefore intersection crossing warning messages is created in order to warn drivers of potential impact when entering an intersection.

The tested scenario recreated the situation where both vehicles approach to the intersection at 50km/h (13.88m/s). While in this scenario a stop bar is in the lane of red vehicle, we consider the worst scenario where this vehicle enters the intersection without stopping and could collision with green vehicle.

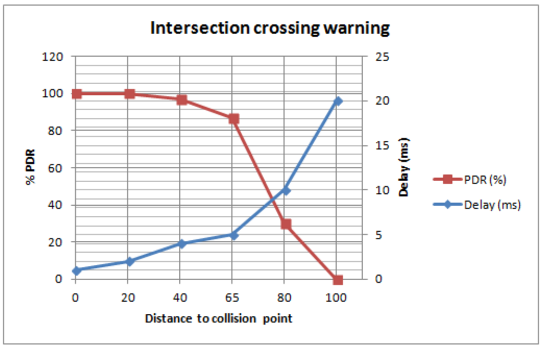

Figure 4: Intersection crossing warning test results

In order to determinate how the IEEE 802.11p system can be used to avoid the collision, first we work backwards from the worst scenario, that is, the collision occurs. Applying kinematic equations to a vehicle in movement, the breaking distance can be calculated using equation 1, where V is the velocity expressed in Km/h, f represents the friction coefficient and i the slope of the road in %. At 50km/h a vehicles requires at least 24m to stop in a flat road. According to (Triggs et al., 1982) (of State Highway and Officials, 2001), drive's reaction time can be from 1.26s to 3s. If we consider an average value of 2.5s, in this time car travels 34m, so in total driver needs 57m to stop the car.

$$D_s = \frac{V^2}{254(f+i)} \tag{1}$$

Hence, in order to avoid the collision and warn the drivers about the presence of each other, the communication link must be reliable and make possible the messages interchange among vehicles before they enter within 57m range, referenced as '*unavoidable collision area*' (in red) at Figure 3.

In this scenario, the results obtained using LinkBirds communication modules are shown at Figure 4. It exposes that in this NLOS scenario, these modules can provide a reliable communication link between both vehicles (speed@50km/h) with a Package Delivery Rate of 95% at a distance of 60 meters from the collision point. Hence the vehicles will be able to interchange awareness messages to inform about their presence near the intersection in order to avoid a collision. Moreover, the measure delay at 60m is 5ms, that is less than the 100ms specified at (ETSI, 9 06) for this application. The links Goodput in this scenario is shown at Table 4.

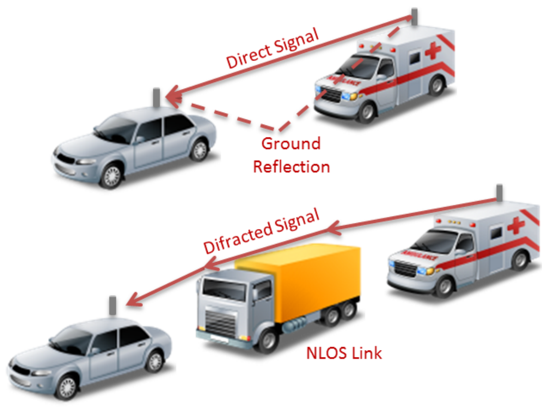

Figure 5: Emergency vehicle warning scenario

5.2 Emergency vehicle warning

In this test, PDR measurements were collected during a trip from Mungia to Portugalete. The distance between both cities is 34kms and the speed limit of the motorway is 100km/h. The goal in this scenario is to validate the communication link from one vehicle to other vehicle where both are in movement at high speed and there are other vehicles like cars or trucks in the line of sight of both vehicles.

During the trip one OBU plays the role of vehicle in emergency sending continuously warning messages to the surrounding vehicles with a period of 1Hz. The other OBU is the receiver and it analyzes the received message. Different situations were recreated (Figure 5): V2V link with direct and reflected paths (ground reflections) and different distances and relative speed between transmitter and receiver and V2V link with vehicle blockage (other cars and trucks) between the OBUs, so it is a NLOS and that it includes a diffracted signal path to the receiver, creating the worst-case performance in this scenario.

Figure 6 gives the results of motorway experiment to measure the PDR for V2V communication link test using packages with a payload of 100bytes.

The results can be analyzed in sections according to the events recorder during the test:

- Events 'A': in both time slots a LOS situation is shown. Both vehicles speed was the same, first 80km/h and then 100km/h and their relative distance was 45 and 60m respectively. In both situations PDR is close to 100% being 98-96% the lowest obtained values.
- Event 'B': in this time slot, vehicles speed was 90km/h and the relative distance was 177m because 3 cars were located between OBUs under test. In this NLOS situation the worst PDR is 78%.
- Event 'C': it reflects the same previous NLOS link but the distance between OBUs was bigger due to the 5 vehicles that were in the middle of the communication link. In this case, the number of low PDR measures is bigger due to the number of obstacles and distance between the OBUs.
- Events 'D' and 'E': these events represent the scenario when a truck blocked the link between OBUs. Here the worst PDR values were obtained being the event 'E' the time slot in which the lowest PDR (29%) was measured. It happened when the distance between OBUs where close to 200m. and truck blocked the communication link.
- Event 'F': during this time slot, only 4 vehicles were between OBUs but it happened at the motorway output ramp, where there is u-shaped bend so it was NLOS link. In this case values of PDR lower than 80% were measured.

Table 4: Intersection Crossing Warning Test Goodput

Payload Size (Bytes)	Goodput (kbps)	PDR (%)
100	244	93
500	1221	94
1000	2468	96
1400	2809	100

5.3 Roadwork warning

To test this safety application, we have recreated a vehicle-to-infrastructure communication between a mobile OBU and a static OBU that plays the role of Road Side Unit (RSU). In this scenario mobile OBU travels at 40km/h (11,12m/s) along a road that has a straight line of 860m (A to B distance) while RSU send warning messages (100bytes of payload) . First we have measured the distance range covered by

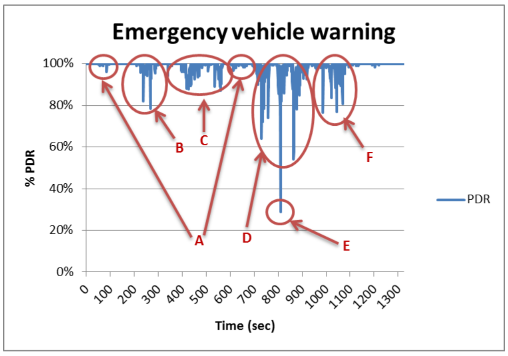

Figure 6: Emergency vehicle warning test results

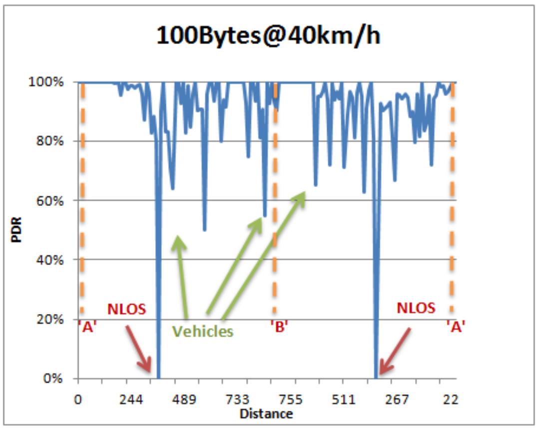

Figure 7: I2V scenario PDR measurements

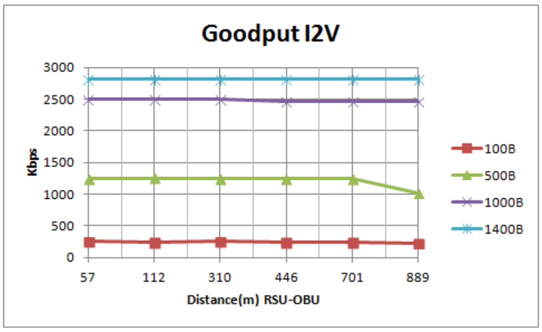

Figure 8: I2V goodput measurements

the RSU using LinkBirds units. The measurements showed at Figure 7 display a two-way trip from A to B when RSU is located at 'A' location and mobile OBU starts the trip close to the RSU, travels until 'B' and comes back to the original position. The obtained PDR is shown in Figure 7, where dash line represents point 'B' where OBU starts come back trip.

During the test link PDR was closed to 0% in some specific locations. It was because the orography of the road due to some 'valleys' in which mobile OBU has not LOS to the RSU. The others low PDR values (around 50%) were caused by some vehicles that obstacle the link between the OBU and the RSU.

The goodput was measured at different RSU-OBU distances and the results are shown at Figure 8. The PHY layer of the IEEE 802.11p transceiver was set up to 3Mbps. The maximum goodput (2.8Mbps) was obtained when the payload is setup to the maximum value of 1400bytes. In this configuration, at the maximum RSU-OBU distance, the PDR was 100% and the average delay was 7ms.

According to these results and considering that RSU is equipped with an isotropic antenna, RSU's radio link cover area can be close to 1700m. In this situation the success of a Roadwork Working safety application depends on two factors: vehicle speed and distance from the end of the covered area by the RSU and the location of roadwork. The limiting cases happen when the OBU receives the warning message at the end of the RSUs covered area and the distance to the roadwork is equal to the distance that the drivers needs to stop the vehicle. Both situations are shown at Figure 9 with the calculations of the security distance according to equation 1.

In case that the roadwork is located in a distance lower than Ds, the driver will not manage to stop the car and a hazard situation could happen. To avoid this situation, two alternatives are suggested:

- Deploy a net of RSUs interconnected by a backbone in order to keep updated all of them with information about the traffic events. Then the whole road (or specific section that could concentrate blackspots) could be covered by the IEEE 802.11p net.
- Combine I2V with V2V communications. In this way OBUs that are inside the RSU covered area could inform about hazardous situations to OBUs that come near to them.

6 Conclusions

The results obtained in these scenarios disclosed useful ideas which can help vehicular networks and active safety applications developers. Regarding the goodput, measured values show that increasing the payload of the messages, high values of goodput are obtained. This is an obvious conclusion, but we have tested at the same time that at distances bigger than 800m (RSU-OBU), the PDR of big payload messages

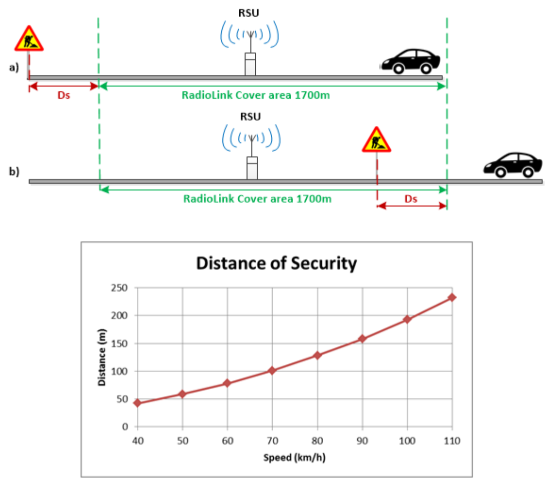

Figure 9: Roadwork warning scenario

(1400bytes) is 100%. Likelyhood warning messages do not need more than 400bits of payload if we consider Basic Safety Message (BSM) as a reference (SAEJ2735, 2009), so it can be settled that in the proposed scenarios, the analyzed applications can work in a correct way. Furthermore, the delay obtained in all the measures is behind the threshold delay specified by the ETSI TC on ITS (ETSI, 9 06).

It also can be concluded that using the proposed hardware configuration, there are not problems in LOS scenarios because high values of PDR and goodput are obtained. However, this configuration presents poor IEEE 802.11p performance in NLOS conditions, so in order to provide full coverage of a given area, the orography and building distribution must be studied and maybe a fixed RSUs network should be deployed.

Before concluding this paper, we want to express that more measurement campaigns should be performed in a near future to complete this study, but it could be considered as a starting point towards better design of active safety applications. Higher distances among vehicles and RSUs should be tested and in these situations problems as handover, beacons delay or channel congestions issued will be tackled.

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