Multi-technology vehicular cooperative system based on Software Defined Radio (SDR)

Nathalie Haziza[1], Mohamed Kassab[2], Raymond Knopp[3], Jérôme Härri[3], Florian Kaltenberger[3], Philippe Agostini[1], Marion Berbineau[2], Christophe Gransart[2], Joëlle Besnier[4], Jacques Ehrlich[4], and Hasnaa Aniss[4]

[1] Thales Communications & Security, Gennevilliers, France,
{nathalie.haziza,philippe.agostini}@thalesgroup.com
[2] Univ. Lille Nord de France, IFSTTAR, LEOST, Villeneuve d'Ascq, France,
{mohamed.kassab,marion.berbineau,christophe.gransart}@ifsttar.fr
[3] EURECOM, Sophia Antipolis, France
{raymond.knopp,jerome.haerri,florian.kaltenberger}@eurecom.fr
[4] IFSTTAR, LIVIC, Versailles, France,
{joelle.besnier,jacques.ehrlich,hasnaa.aniss}@ifsttar.fr

Abstract. Within the scope of the European policy for Intelligent Transport Systems (ITS), the PLATA-PROTON project proposes a multi-technology cooperative Advanced Driver Assistance System (ADAS), based on the integration of Software-Defined Radio (SDR) devices in vehicles. With the choice of significant road-safety related scenarios, V2V and V2I communications have been both implemented and simulated. This paper proposes an overview of the Software-Defined Radio (SDR) platform development and the performance evaluation based on network simulation, performed within this project.

Keywords: Software-Defined Radio, vehicular communication, V2V, V2I, driver assistance application, proof of concept, network simulation, IEEE 802.11p

1 Introduction

Nowadays, the integration of cooperative functions is the main focus of advanced driver assistance systems (ADAS). Following the European policy for Intelligent Transport System (ITS), the cooperative functions are used to enhance road safety, to optimize the traffic and to reduce the impact of transports on the environment. A key potential is the combination of local environment data (exchanged between neighbor vehicles or between vehicles and Road Side Units) and regional traffic data broadcast. In other words, the drivers can get detailed information from immediate surroundings and longer-term forecasts and alerts controlled from a central infrastructure. The communication system associated to such functions must support vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (broadcasting) communications. Several wireless technologies are able to support these communications e.g. WLAN technologies for V2V and V2I and technologies such as Digital Audio Broadcasting (DAB), Digital Multimedia Broadcasting (DMB) and Digital Video Broadcasting (DVB) for broadcasting from the infrastructure. The technologies used for cooperative systems will depend on communication standards and infrastructures defined in each country. Several working groups are active in the field of communications for ADAS. The International Organization for Standardization (ISO) TC204 Working Group 16 [1] produced specifications for the Communications Access for Land Mobile (CALM) [4], providing a reference framework for future implementations. Harmonization at the European level has been provided with C2C-CC (with the European Telecommunications Standards Institute-ETSI [2]), and with the network working group for the IETF and WAVE for IEEE [3]. Among them, the architecture proposed by CALM is particularly interesting regarding interoperability and flexibility. It is based on heterogeneous cooperative communication framework to provide continuous communications to users. The CALM concept is based on the juxtaposition of several communication modems in the vehicles [4]. The need of such heterogeneity is justified by several characteristics of vehicular communications.

As an alternative to several modems to answer to the need of multiple standards, the Software-Defined Radio (SDR) is a wireless system implemented by software routines so that various wireless radios can be supported by the same hardware based on software changes. SDR hardware allows to modify easily the communication technology supported by a terminal in accordance with its environment. The use of SDR allows vehicle manufacturers to adapt communication technologies supported by vehicles to fit to the local standards.

The PROTON-PLATA [9] project lies on a German-French collaboration (Deufrako/ANR agreement) for the development of a common platform, able to deal with various standards, emerging in each country; industrial and academic partners interested in ITS and particularly in vehicular systems were involved. The goal of this project is to show the feasibility and the interest of a cooperative ADAS making use of the SDR technology to enhance communication performances. The main idea is to propose a multi-technology communication infrastructure and to equip On-Board Units by SDR devices that support simultaneously V2V communications, V2I communications and broadcasting (infrastructure-to-vehicle). The scope of the project includes "proof of concept" part and a performance study part. The first one proposes the development of a prototype, including SDR device and driver-assistance applications. The second is a performance evaluation based on network simulation tools.

This paper is organized as follows. In section 2, we propose an overview of research studies related to cooperative ADAS. Section 3 introduces the multi-technology cooperative system designed within the PLATA-PROTON project. In section 4, we describe the prototype development and related experiments. Section 5 propose an overview of results obtained with the simulation based performance study. Concluding remarks are presented in section 6.

2 Related work

Several researches deal with to the enhancement of ADAS to vehicular cooperative systems. These works vary from specification frameworks proposed by international standardization institutes, *e.g.* ETSI, ISO, research projects managed by academic and industrial consortiums and academic works. The research scope is very large from PHY layer to applications, protocols, security, mobility management, communication architecture, *etc.* In this section, we propose a survey of the most interesting works in this area.

Regarding international-wide, three main groups are working on this subject: CALM for the ISO, WAVE for the IEEE and C2C-CC for the ETSI [2].

At the European level, we have identified several key projects related to the enhancement of vehicular cooperative systems.

The Cooperative Vehicle Infrastructure System (CVIS) [5] (2006-2010) is a very well known European research project related to the enhancement of cooperative services based on interaction between vehicles and centralized infrastructure. The goal of the project was to develop an open application framework that enables a wide range of potential cooperative services to operate in vehicles, roadside equipments and centralized management centers. It assumes some diversity in communication technology (802.11p, WiMAX, UMTS, DVB / DAB, *etc.*) and is based on IP network mechanisms (IPv6, MIPv6, NEMO, *etc.*).

The EVITA (E-safety Vehicle Intrusion proTected Application) [6] (2008-2011) focused on the design of an on-board automotive network architecture, to ensure protection against unexpected or unauthorized manipulation, for sensitive data transmission. The CO-OPerative SystEms for Intelligent Road Safety (COOPERS) [7] (2006-2011) concern was about the development of *Co-operative Traffic Management* applications on the road infrastructure with an interaction between vehicles and infrastructure. The approach aims to extend the concepts of in-vehicle autonomous systems and vehicle-to-vehicle communication (V2V) with tactical and strategic traffic information which can only be provided by the infrastructure operator in real time (traffic jam warning and guidance, in-car display and alert of area-specific speed limits, car breakdown/emergency services, *etc*). The SAFESPOT project [8] (2006-2010) considered the combination of the information from vehicles and from the infrastructure, to improve the driver perception of the surrounding vehicles. It focuses on the identification of cooperative solutions that will first be applied to the critical areas, such as the so called *black spots*. Sensing systems on the infrastructure side are proposed in combination with the information coming from vehicles to detect critical conditions and events.

All these projects have contributed to the definition of new applications and services for driving assistance and the specification of cooperative architecture models. The PROTON-PLATA project is a follow up of these works as it focuses on the use of multi-technology architecture and SDR devices to enhance the communication capabilities of ADAS.

3 Multi-technology cooperative system

In this section, we present the main components of the vehicular cooperative ADAS proposed in PROTON-PLATA. We detail the drivers assistance applications and the the communication architecture.

3.1 Driver assistance applications

We have defined four applications that cover several types of services in vehicular environment.

- **GPS position exchange**: This application allows vehicles to exchange their GPS data. Each vehicle broadcasts a message containing its own information: vehicle category (car, truck, motorbike, bike, etc.), geographical position, speed, course and geolocation time. *Geolocation time* is the time given by the geo-location system.
- **Local weather condition**: This application informs the driver about the weather condition where he/she is and according to the travel direction. A centralized server broadcasts information over a given geographic area using a wireless technology.
- **Incident hazard warning**: This application keeps drivers aware of traffic hazards based on information provided by central server, roadside units, road equipment and other vehicles. The hazards that can be supported by this application are multiple such as wrong way driver also called *Ghost driver*, vehicles at a standstill, obstacles on the road, black ice, *etc.* When a vehicle detects a hazard on its way, it sends a message to its environment to share the information with other vehicles. Two versions of this application are defined: *V2V hazard warning* and *V2I hazard warning. V2V hazard warning* is fully decentralized, a vehicle that detects a hazard sends messages to neighboring vehicles via peer-to-peer communications. With *V2I hazard warning*, a vehicle that detects a hazard sends messages to a server located in the management network via a Road Side Unit (RSU). The server forwards the message to appropriate areas using broadcast communications.
- **Speed limit**: This application defines a database for speed limits in a road network. A reference database is located in a centralized server and speed limits are stored on-board the vehicles in a local database. A new edition of the reference database is published at regular intervals. Vehicle on-board systems have to update their local databases periodically. This application defines dynamic and static versions of updating mechanisms. The *Static speed limit* detects and reports any obsolescence of the embedded database by comparing its version number with the reference database. The *dynamic speed limit* is executed when dynamic changes are decided in the center. Updates are sent to vehicle by means of broadcasting transmissions into the related area.

3.2 Communication system

PROTON-PLATA project proposes a communication infrastructure that allows to fully exploit the SDR capacity of the devices in vehicles. The communication infrastructure manages the centralized part of the cooperative system, namely Network-Head (NH). This architecture connects the road traffic management center to two wireless networks. The first one is a wireless access network based on Road Side Units (RSU) along the roads. The second one is a broadcast network based on Base Stations (BS) with large coverage. Figure 1 shows an example of a deployment. The uplink communications between On Board Unit (OBU) and the Network-Head (NH) are supported by the RSUs network, while the downlink communications are supported by both the BS and the RSU.

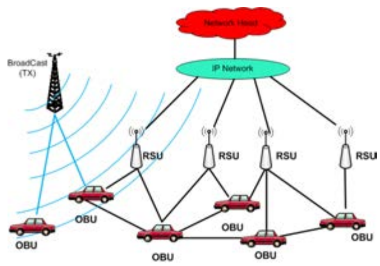

Fig. 1: Communication architecture

The key innovation of the project lies in the design of the multi-technology OBU, which role is to exchange information with the NH (through the RSUs or the BS) and with other OBUs. The OBUs implement different protocol stacks on a *Software Defined Radio (SDR)* device. The SDR is a wireless system implemented by software routines so that various wireless radios can be supported by the same platform based on software changes. SDR hardware allows to modify easily the communication technology supported by a terminal in accordance with its environment and/or needs. The PLATA-PROTON specifications suppose that OBU are equipped with SDR devices that manage V2V communications with other OBUs, V2I communications with RSUs, I2V broadcast reception from BS.

4 SDR Prototype

For the SDR protoype design, the choice of the open-source hardware/SDR DSRC prototype on the *OpenAirInterface* platform [11] has been identified as a real asset, as it answers to the overall aim of the cooperative PROTON-PLATA system, precisely to adapt to standards specific to each country. The standards for the PROTON-PLATA have thus been set to the promising LTE wireless standard associated to the 802.11p vehicular technology.

Figure 2 depicts the software architecture of the OpenAirInterface SDR platform. It is segmented into three parts, the *User Space*, the *Kernel Space* and the *SDR Express-MIMO board*. The user-space contains the code regarding the 3GPP LTE protocol stack and the IEEE 802.11p soft-modem from the OpenAirInterface. It also contains the ITS safety applications that sends IP packets to the PROTON-PLATA virtual interface on the linux subsystem. The kernel-space contains deep linux routines and kernel extensions modules required by PROTON-PLATA. In particular, it contains a hook from the linux subsystem either to the linux wireless subsystem modified to support the IEEE 802.11p (OCB mode) and to a IEEE 802.11p driver, or to the LTE NASMesh device. Finally, the PCI-Express MIMO SDR board is connected via a PCI-Express and an OpenAirInterface firmware to the OpenAirInterface main driver. The salient aspect is that PROTON-PLATA designed it so to be able to support both LTE and 802.11p signals on the same board, and as such shall access to the PCI-Express MIMO board through the same OpenAirInterface driver. Both protocol stacks are capable to work at the same time using different RF chains of the PCI-Express MIMO board.

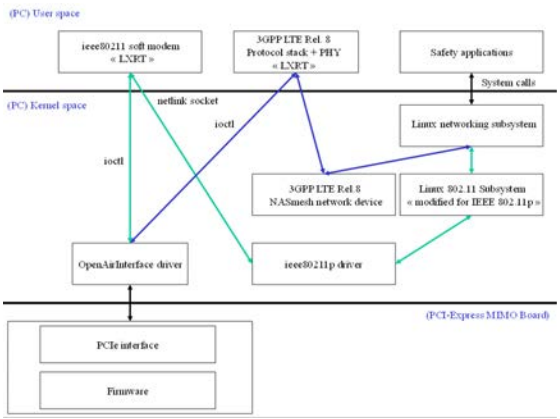

Fig. 2: OpenAirInterface software architecture

4.1 IEEE 802.11p protocol stack

Following Figure 2, the SDR architecture of the IEEE 802.11p protocol stack is composed of three blocks. The upper block contains an extension for IEEE 802.11p of the Linux kernel 802.11 subsystem. This subsystem is composed of *nl80211*, a netlink configuration interface for user-space applications, *cfg80211* which is the Linux wireless configuration interface bridging user-space and drivers and *mac80211*, which offers a framework for driver developers writing soft-MAC wireless devices. The *mac80211* subsystem is the Linux stack for IEEE 802.11.

The second block is the *IEEE 802.11p driver*, which bridges the Linux 802.11 subsystem and the hardware. One major difference with standard architecture for 802.11 systems, is that the IEEE 802.11p driver does not link to the SDR chipset directly, but rather to a *soft-modem* via netlink sockets. We chose this architecture for flexibility in the development and configuration of the low layer functionalities of the IEEE 802.11p stack and to ease the reconfigurability of our radio. The *soft-modem* is the placeholder of all the functionalities of IEEE 802.11p physical layer. Being located out of the chipset, it is totally accessible and reconfigurable. The soft-modem is finally connected to the SDR board via an IOCTL link and a dedicated OpenAirInterface driver, which composes the last block.

4.2 3GPP LTE protocol stack

As for the IEEE 802.11p, the software architecture of the 3GPP LTE rel. 8/9 is composed of three blocks. The upper block is located in the Linux user-space and contains an open-source implementation of the 3GPP LTE rel-8/9 protocol stack, including PDCP, RLC, MAC and the upper PHY. It contains 3GPP LTE rel.8/9 compliant functionalities and a LTE soft-modem. Located in user-space, they are easily extensible to future LTE rel. 10 and beyond features. The second block is the LTE NASMesh device, which is located in the kernel space, due to real-time constraints for low PHY operations. The last block is the OpenAirInterface driver, which acts as interface with the Express-MIMO board.

4.3 SDR Express-MIMO Board

The prototype is based on an Agile Radio Front-end (RF) and ExpressMIMO SDR board. They provide a fully reconfiguration RF and baseband DSP, and include "developper-friendly" tools for real-time hard-modem development and validation. The Express-MIMO board is a FPGA platform on PCI-Express with up to 8 MIMO capacity and providing full SDR descriptions of three air interfaces: *LTE*, *802.11p*, and *DAB/DMB*.

Fig. 3: Express-MIMO SDR Board

4.4 Experimentation

We performed in-situ tests on a dedicated IFSTTAR test-tracks dedicated to road-safety experimentation (Versailles-Satory, France). We equipped two vehicles with the previously described 3GPP LTE/IEEE 802.11p OBU prototype, including an on-board GPS (Figure 4b), and one RSU equipped only with the 3GPP LTE technology. As a test case, we evaluated a *contextual speed warning* application as well as a *ghost driver* applications as specified by the French SCOREF project [10], using V2I communication over 3GPP LTE for the former, and V2V over IEEE 802.11p for the latter. Figure 5 is a screen-shot of the contextual speed warning application, which also depicts the IFSTTAR test track. On that test case, using the 3GPP LTE RSU, vehicles provides to the NH their instantaneous speed and in return the NH provides contextual speed limitations that are displayed on the car HMI.

(a) Integration of the SDR platform on a BMW X5 test vehicle

(b) Warning displayed on the vehicle driving on a wrong direction

Fig. 4: Illustration of the experimental test

Fig. 5: Screenshot of the test-tracks in Versailles/Satory

5 Performance study

In this performance study, we are interested in the communication efficiency of multi-technology cooperative system, and particularly the communication performances experienced by driver assistance applications. This cooperative system is able to balance the traffic generated by V2I communications and I2V Broadcast over two different wireless networks in order to increase the capacity of the system and provide better performances to the applications.
To model communications in the multi-technology cooperative system, we consider the IEEE 802.11 technology for V2V and V2I communications and the DVB-T technology for I2V broadcast. The performance study is based on a simulation framework, developed in the *OPNET Modeler* network simulator, that includes realistic vehicular mobility models [13] and SDR device modeling [12].

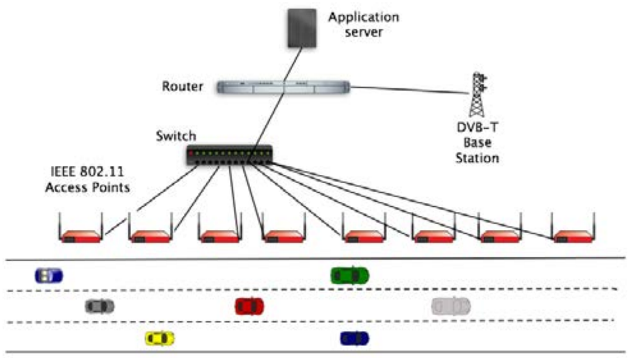

Fig. 6: Simulation scenario for the IEEE 802.11 and DVB-T based architecture

Evaluation context As an evaluation context, we consider a three ways straight road. Two hundred vehicles travel on this road. Vehicle mobility is based on the SuMo tool [13]. The Vehicles are equipped with SDR devices that manage IEEE 802.11 and DVB-T radios [12]. We model the network architectures conforming to the PLATA cooperative system specification 3. We deploy IEEE 802.11 access points along the roadside as RSUs and a DVB-T base station that cover all the road. These wireless networks are connected to a wired network that hosts the application server. Figure 6 shows this architecture. In this architecture, we deploy 35 access points over the roadside, one access point every 300 meters. The access points manage an 802.11 network with a throughput of 54 Mbps and a transmission power of 100 mW. This wireless network is connected to a wired network over a router. Vehicles are equipped with IEEE 802.11 hardwares with a transmission power of 20 mW. The DVB-T base station is broadcasting over the 800 MHz frequency on a 8 kHz bandwidth and a 32 Mbps throughput.

We modeled the driver assistance applications that define V2I communications (*V2I hazard warning* and *Static speed limit*) and I2V broadcasting (*Local weather condition* and *Dynamic speed limit*). In this configuration, data exchanges, defined by the *Static speed limit* and *V2I Incident Hazard Warning*, are carried through the RSUs. Broadcasts, defined by the *Local weather condition* and *Dynamic speed limit*, are sent through the broadcast base stations.

Simulation results The results show that the driver assistance application operates with good performances.

Table 1: Packet Loss

	Sent data (Pkt)	Received data (Pkt)	Packet loss rate
Local weather condition	109654	109654	0
Dynamic speed limit	14	14	0
V2I Incident hazard warning	37438.5	43959.66	0,14
Static speed limit	40536.833	40595.5	0.001

For *static speed limit* response time values vary between 0.11 s and 21.62 s as shown in table 2. Detailed results show the mean response time is about 1.026s with a standard deviation of 3.38. The disparity of response time values is due to the message exchange which consists of four 2-way-handshakes. The obtained values for response time are acceptable, even the highest, considering the nature of this application that aims to synchronize the speed database of the vehicles with the database of the management center. In addition, there is no packet loss for these applications as shown in table 1.

For *V2I Incident hazard warning*, results shows that values vary between 0.001 ms and 9.50s as shown in table 2. The mean response time is about 0.06s with a standard deviation of 0.93. In the case of a vehicle velocity equal to 50 km/h, a delay equal to 3.5 ms enables the information to reach a neighbor vehicle after a move of less than one meter. This value is more than sufficient to get the driver or the onboard system informed in time.

We look to the state of communications on IEEE 802.11 cells (cell load, data dropped and medium access delay) for both architecture. Results in table 3 show that the association of IEEE 802.11 with DVB-T, thanks to SDR in the vehicles, enables an increase of the available bandwidth in each cell.

Table 2: Response Time

	Mean (sec)	Min (sec)	Max (sec)	Stdev (sec)
Static Speed Limit	1.026	0.11	21.62	3.38
V2I Incident Hazard Warning	0.06	0.001	9.50	0.93

Table 3: IEEE 802.11 cell metrics

	Mean	Min	Max	Stdev
Media Access Delay (sec)	0.0002	0.0003	0.0001	0.00002
Cell load (bps)	128354.82	201554.44	0	25930.79
Dropped data (bps)	1055.91	0	26449.99	2142.32

These results open the way for the specification of additional applications that will make use of this bandwidth without disturbing the good operation of the system.

6 Conclusion

Vehicular cooperative systems rely on information obtained from immediate surroundings and longer-term forecasts and alerts controlled from a central infrastructure to offer assistance to drivers. The enhancement of these systems depends closely on wireless communication performances that enable cooperation between vehicles and between vehicles and infrastructure. The communication systems associated to cooperative systems have to support vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (broadcasting) communications. The use of SDR represents an asset to ensure both a wide area coverage and the use of complementary applications to answer to various events on a travel. In this context, the PLATA-PROTON project proposes a multi-technology cooperative Advanced Driver Assistance System (ADAS), based on the integration of Software-Defined Radio (SDR) devices in vehicles. In this paper, we have shown the feasibility and interest of such ADAS through the development of a proof of concept that included SDR and driver assistance application prototypes and a performance study of communications performances, experienced by applications and based on network simulation tools.

Acknowledgment. The PROTON-PLATA research leading to these results has received funding as a Deufrako collaboration from the German *Federal Ministry of Economics and Technology* and the French *Agence Nationale de la Recherche*, with reference ANR-08-VTT-010-01.

References

1. ISO TC 204 working group 16 web page. www.iso.org/iso/iso_technical_committee?commid=54706
2. Car 2 Car communication consortium web site. www.car-to-car.org
3. IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments, IEEE Std 802.11p-2010, pp.1-51, July 15 2010, doi: 10.1109/IEEESTD.2010.5514475
4. TC 204. ISo 21217:2010 : Intelligent transport systems " communications access for land mobiles (CALM) " architecture. Technical report, ISO/ TC 204 (2010)
5. CVIS project web site http://www.cvisproject.org
6. EVITA project web site http://evita-project.org
7. COOPERS project web site http://www.coopers-ip.eu/
8. SAFESPOT project web site http://www.safespot-eu.org/
9. PROTON-PLATA project web site www.proton-plata.fr
10. SCOREF project web site http://www.scoref.fr
11. OpenAirInterface web site http://www.openairinterface.org
12. M. Kassab, M. Berbineau, C. Gransart, M. Wahl: A software defined radio module for vehicular communications. OPNETWORK, Washington D.C. (2010)
13. F. Kaisser, C. Gransart, M. Berbineau: Simulation of vanet scenarios with opnet and sumo. In: 4th International Workshop Nets4Cars/Nets4Trains, LNCS, volume 7266, pages 103"112 (2012)