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Vehicular Communication Networks

An Introduction to VANET and the Cognitive Radio Perspective

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***Abstract*—The development of Intelligent Transport Systems (ITS) supported by Vehicle communication networks studies and experimental implementation done in different type of vehicles, including conventional, cognitive and autonomous vehicles has dramatically increased in latest years. This is mainly caused by the growing industry interest regarding intelligent and autonomous vehicles and its associated efficient communication system. Such research and development activities are been supported by both university research groups, technologically-advanced vehicle design centers spread over the world, and sponsored by some key vehicle and wireless technology consortiums. Under this development model, some communication networks proposals are receiving more attention, preliminary those ones based on the DSRC (Dedicated Short Range Communication) to be used in VANET (Vehicle Ad-Hoc Networks), V-to-X (Vehicle-to-Vehicle, Vehicle-to-persons, Vehicle-to-Infrastructure), HetVNET (Heterogeneous Vehicular Networking) and Smart Radio communication networks based on Cognitive Radio Vehicle (CRV) and SDR (Software-defined Radio) technologies. In this paper, an introduction about state-of-the-art vehicular communications networks based on DSRC and related similar communication schemes based on IEEE 802.11p are described. A particular research and development activity and design flow regarding Cognitive Radio Vehicular Communication Networks is proposed as a R&D project aimed to define a communication architecture using high-level description at system-level and leading to an experimental implementation, based on the concepts of CRV, SDR and adaptive reconfigurable systems.**

Keywords*—Cognitive Radio-enabled Vehicle Communication Networks; Cognitive Radio; Vehicle-to-Vehicle Communications; VANET (Vehicle Ad-Hoc Networks); Software-Defined Radio, ITS-Intelligent Transport Systems; Smart Vehicles

I. Introduction

According to some international health organizations (e.g. WHO-World Health Organization) about 1.25 million people die each year as a result of road traffic accidents. Driving under stressed conditions in increased vehicular congestion in highways and cities is one of the causes as also driving under reduced visibility caused by bad weather conditions, like heavy rain, fog in road or low road-side lighting at night. Therefore if no any action is taken, road traffic crashes are predicted to continuously rising, becoming the 7th leading cause of death by 2030. It is under this type of motivation that some civil organizations and governments around the world started to take some initiatives in order to decrease and control such statistics. On such way, official government organizations, mainly in US and Europe started to elaborate different documents and standards aiming to organize and raise compulsory directions and rules, like those ones by U.S. Department of Transportation (DOT) [1] , ETSI (European Telecommunication Standard Institute) and Car-to-Car consortium in Europe [2]. The DOT and C2C-CC documents aimed to asses and to define some general rules to be used as a reference line for vehicle-to-vehicle communications and are the result of at least a decade of research and dedicated studies. On the other hand, different car-maker and mobile communications associations and mixed consortiums were created walking on the same direction, one proposal is to design driver assistance systems, in order to prevent car accidents, paving the way to the cognitive vehicles[3],[4]. This work aims at least two main objectives, first at all to describe a summary about the present status and advances in updated vehicular communications networks, based on DSRC as well also other technologies like HetVNET, VANET, WAVE and CRV [5]-[7]. And secondly, but not less important, is to establish a baseline to design a vehicular communication network architecture, based on the state-of-the-art of cognitive radio networks and SDR-related technologies [8]-[12].

This paper is developed according to the following structure in sections: (II.A) Vehicle Communications including DSRC protocol for V-to-X paradigm, (II.B) HetVENET, Heterogeneous Vehicular networks, composed by a merge of cellular and DSRC communications, (II.C), WAVE, which it is an extension of basic DSRC vehicular communications and (IV) Vehicle Communications upon the Cognitive Radio Vehicular approach (CRV network). Finally, the conclusions and proposal for CRV-VANET further research is shortly described, including some topics for an experimental study proposal. This is an article mainly based upon a deep review on vehicle communications and cognitive radio vehicular networks, which should be the baseline for a potential research activity to be developed on the LCV group, using the facilities of the LCV/DECOM/FEE, in the University of Campinas.

II. VEHICLE COMMUNICATIONS

This section aims to briefly describe the more relevant communication models proposed so far for the different types of vehicular networking. The V-to-X term connotes the flexible and dynamic environment which involved at least three main actors for transmitter (Tx) and receptor (Rx) ends (see Fig. 1):

- Vehicle-to-Vehicle (V-to-V, V2V)
- Vehicle-to-Infrastructure (V-to-I, V2I)
- Vehicle-to-Pedestrian (V-to-P, V2P)

The simplified diagram in Fig.1 shows a typical scenario with the more important communication paths regarding a vehicle environment, which are characterized by the strongly dynamic nature of its nodes and topology interconnection. Such dynamics causes continuously variable changes in beam directions and energy spectrum, mainly caused by the high mobility of its network components and interconnection complexity. An important issue is related to the variable kind of interferences, caused by external EM radiation sources (e.g. cellular Base Stations, TV transmission, power lines, etc.) and physical objects, like buildings in urban regions and landscape topography, in case of rural or country-side roads and highways.

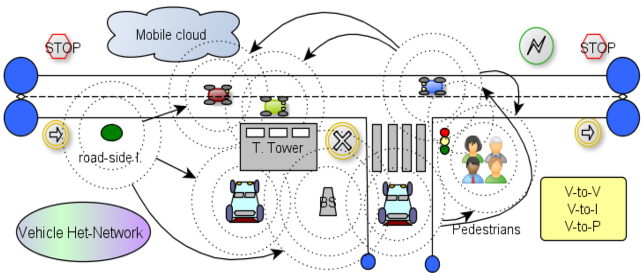

Fig. 1. V-to-X Heterogeneous Vehicular Networking

The different possible paths for V-to-X communication and/or signaling should be: between vehicles (V-to-V), with road side units (infrastructure, V-to-I), to/from pedestrians (V-to-P) and to exchange information with some external networks, in case of Heterogeneous Vehicular Networks (HetVNET), which also should include Base Stations TX/Rx and routing from cell mobile networks.

A. Dedicated Short Range Communications (DSRC)

The DSRC wireless technology presently represents the wider communication option employed by automotive industry both for commercial proposal and conceptual smart cars in vehicle networking. Influent automotive world consortiums are adopting DSRC as a baseline technology for communication in conventional, driver-assistant cars by ADAS (Advanced Driver Assistant Systems) and also for experimental cognitive and full autonomous smart vehicles [4]. DSRC is the result of FCC (the US Federal Communications Commission) proposal and can be considered as an extension of IEEE 802.11p standard. In 1999 the FCC allocated 75 MHz in the spectrum of 5.9 GHz band to be used for ITS-related services (Intelligent Transport Systems).

Primary usage of DSRC is broadcasting of the core state information of every vehicle in a Basic Safety Message (BSM), nominally 10 times/sec, in 360^0 pattern (omnidirectional), according to IEEE 802.11p (Vehicle-to-Vehicle, V2V).

Therefore, upon reception of a V2V BSM, each vehicle in the neighborhood should be able to build a trajectory model of every other vehicle, identifying potential threats to its own mobility pattern, warning the driver through some mechanism in the dashboard or even assuming the powertrain, movement and steering control if such threat is classified as highly severe.

Several classes of messages are defined for V2V, V2I, V2P paths, according to its application, like high priority safety-related or basic infrastructure information. Some V2V-safety examples: FCA (Forward Collision Avoidance), LCA (Lane Change Assist), DNPW (Do Not Pass Warning), BSW (Blind Spot Warning), ICA (Intersection Collision Warning), etc.

Regarding V2I-safety applications, road-side equipment (RSE) enables a suite of messages, which could be classified for different priority usage, like SPaT (Signal Phase and Timing), ex. adaptive dynamic traffic and light signaling, the other use is MAP, related to fixed intersection geometry in urban areas. Additional messages classes are related to traveller and road information, e.g.: men at work next to road, max. curve speed, dangerous driving conditions, height restrictions in highway, foggy environment, slippery road ahead and others. Private and commercial-related V2I information can be also included, like fuel and/or service area available, pay-toll, parking, mechanical maintenance services, etc.

Table 1. DSRC Spectrum, 5850-5925 MHz

f0	f1	f2	f3	f4	f5	f6	f7
Init							End
Reserv	Serv	Serv	Serv	Ctrl	Serv	Serv	Serv
5850-5855	172 Ch.	174 Ch.	176 Ch.	178 Ch.	180 Ch.	182 Ch.	184 Ch.
5 M	10 M	10M	10M	10M	10M	10M	10M
	Ch. 175				Ch. 181		
	20 MHz				20 MHz		
Channel 172		Exclusively designed by FCC for V2V safety					

The Table 1 above shows the frequency band spectrum for DSRC usage, according to FCC specifications, with 75 MHz bandwidth, starting at 5850 MHz (f0, initial band) up to 5925 MHz (f7, end band). Each communication channel has 10 MHz bandwidth, used for different applications and services, with an exception at the f0 reserved channel, with 5 MHz bandwidth and other 2 ones (175, 181) using 20 MHz bandwidth. The f1 highlighted Channel 172 in Table 1 was exclusively designated for safety applications in Vehicle-to-Vehicle communication. According to FCC directions, this channel must be used for collision avoidance and accidents mitigation, safety of life and other related property applications, which needs special and priority processing in high-speed and low latency [1],[13].

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B. Heterogeneous Vehicular Networks (HetVNET)

The integration of VANET (Vehicular AdHoc Network) with cellular network, based on 4G or LTE 5G wireless technologies, will produce a hybrid vehicular networking, known as HetVNET (Heterogeneous Vehicular Network). VANET is particular evolution of MANET (Mobile AdHoc Network), but taken in account the high mobility and dynamics of the vehicular environment and traffic, it could be based on DSRC or other wireless technology like WAVE (see next C section). But although DSRC shows several advantages in terms of cost and performance and presently represents the main option for inter-vehicle communication in commercial products and even for experimental research, some limitations already are presented. In particular, in scenarios with highly congested situations, e.g., highway and streets in big urban areas, some degradation and access issues are reported. On the other hand, wireless cell networks has the singular advantage of high coverage, with an infrastructure already present, normally via 3G, 4G or 5G/LTE wireless networks. But such solution do not guarantee high performance for the most critical safety V2V applications, where high reliability and low latency is crucial for a effective communication. Therefore HetVNET appears as a good option to increase the needed QoS (Quality-of-Service), integrating the advantages of VANET and cellular wireless, by proposing a merged solution. Several architecture options were proposed in [5] and a complete survey on HetVNET solutions is available in [6]. In [5], Zheng et al. presents a good compilation of requirements for safety services and user cases applications, also a base framework for HetVNET is presented.

Table 2. HetVNET/VANET Requirements

Category: Safety wrn	**User cases**	**Comm. mode**	**Min. Freq.**	**Max. Latency**
Vehicle status	Emergency braking, ab-normal cdt	time limit, periodic, broadcast	10Hz, 1Hz	100 ms
Vehicle type	Emergency, slow, bike, motor-cycl	periodic, trigger by vehic. Mod.	10 Hz, 2Hz, 1Hz	100 ms
Traffic hazard	wrong way, stationary v. signal viol.	time limit, periodic, broadcast	10 Hz, 2Hz, 1Hz	100 ms
Dynamic vehicle	overtaking, lane move, pre-crash	V2X cooperative, broadcast	10 Hz, 2Hz	100 ms, 50 ms
Non-safety				
Traffic management	regulatory speed limits	Authoritat. Msg broad.	1 Hz, 2Hz	100 ms
Info for entertain.	commerce, interested pl., media, maps dwnld	duplex comm. RSU-vehic. Internet	1 Hz	500 ms

Table 2 above shows some of the V2I and V2V messages classification for non-safety and safety-related services. As expected, the safety warnings categories are requiring lower latencies (50 to 100 ms) and higher frequency replays.

C. Wireless Access for Vehicular Environments (WAVE)

The WAVE communication technology represents a wider proposal in vehicle network access. The WAVE set is based on a multi-channel concept and it was designed to be used in safety-oriented applications, non-safety, navigation support, as well as multimedia or info-entertainment messages. A performance evaluation based on IEEE 802.11p and MAC (Medium Access Control) was reported in [14]. A survey regarding V2V propagation channels, including simulation results of propagation under different operating condition in WAVE is presented in [15]. For this WAVE version, three standards are integrated in the way illustrated below (Table 3).

Table 3. WAVE Protocol Stack Overview

Layer	**Standard**	**ISO/OSI**	**Data Plane**	
7	SAE J2735 IEEE 1609.1	Application	HTTP	WAVE App Rsrc manager
4	IEEE 1609.2 IEEE 1609.3	Transport	TCP UDP	
3		Network	IPv6	
2b		Data Link	802.2 LLC	
2a			WAVE MAC	
1b	IEEE 1609.4 IEEE 802.11p	Physical	WAVE Physical LCP	
1a			WAVE Physical MD	

The Table 3 shows the protocols stacked and related to the ISO/OSI communication layers and the corresponding IEEE and SAE (Society of Automotive Engineers) standards in WAVE. The 3rd column shows the layer purpose in the ISO/OSI model and its corresponding standard. The 4th column is the data plane: WAVE MAC (Medium Access), PLCP is Physical Layer Convergence Protocol, PMD is Physical Medium Dependent. The associated standards are:

- SAE J2735 It describes message dispatcher defined for cooperative vehicles and safety applications
- IEEE 1609.1 Resource Manager
- IEEE 1609.2 Security Services
- IEEE 1609.3 Networking Services
- IEEE 1609.4 Multi-Channel Operations
- IEEE 802.11p is based on
    - IEEE 802.11a PHY:OFDM modulation
    - IEEE 802.11 MAC: CSMA/CA
    - IEEE 802.11e MAC Enhancement (priority messages)

The SAE J2735 standard defines a basic messages set using DSRC, but in a structured approach with 16 different message frames, 54 different data frames, parameterized through 162 data elements. An additional management plane, not shown in Table 3, can be represented by a column covering layers 1a to 4. The WME (WAVE Management Entity) handles the priority execution of services at all levels/layers.

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III. Cognitive Radio Vehicle Networks

The "Cognitive Radio" (CR) term was coined by Joseph Mitola in 1998 and redefined by himself after a couple of years later [9]. Originally CR aims to represent the integration of computational intelligence, like machine learning, computer vision and natural language processing into a software-defined radio (SDR)[8]. According to the own Mitola proposal [9], a RF-domain intelligent agent allows to CR/SDR user makes some decisions in order to use the radio spectrum available more effectively. Upon this concept, smart radios allows to extract the more relevant information from the radio spectrum, by integrating machine perception into the wireless system, composed by nodes and interconnection topology. In this way the smart radio system is increasingly evolving from aware and adaptive learning towards an ideal cognitive behavior (iCR0).

As described in previous sections, vehicle networking is characterized by high complexity and a continuously variable topology, which causes a high impact on the radio spectrum features available at each time to every user/vehicle. Therefore the use of the CR paradigm for vehicle communications (CRV) emerges as an interesting enabling technology to face the increasing bandwidth demand and the spectrum scarcity [10] of DSRC and VANET applications, based on IEEE 802.11p. Its main feature is based on the opportunistic usage of the radio spectrum available in under-utilized RF bands by primary users (PU), in particular additional bands, like for instance ISDB-T Digital TV, that is, outside of the 5.9GHz band defined by the IEEE 802.11 family. However, the access to such under-utilized band by a secondary user (SU), should not cause an impact on the normal use of the band by the licensed PU.

A. *Opportunistic Networks (ON)*

This is a relevant wireless network peer-to-peer paradigm which supports direct communications between devices in a mobile scenario. Upon this model, the exchange information between highly mobile nodes is limited to decisions made by each node, based on partial or still incomplete knowledge. When applied to vehicle networking ON is attainment through the concept of bridging or hopping V2V communications, i.e., through multiple connection among users (single/multi-hop). Vehicles are normally travelling in physically constrained paths at different speeds, forming clusters, partitioning should be dynamically created by grouping vehicles going in the same direction. In this way messages will be forwarded following a store-carry-and-forward approach over the available dynamic radio links[11],[12]. Such connectivity links are thus exploited in an opportunistic approach inside each cluster of vehicles and also among groups of clusters.

B. *Spectrum Sensing*

Upon CR or CR-VANET networks, the radio spectrum must be accessed in a per-vehicle sensing approach [11]. Several techniques for effective spectrum sensing are proposed in the CR-related literature [10]-[12]. Spectrum access per-vehicle allows reduced cost, however, should be also impacted by the vehicle networks features, mainly caused by the high mobility, physical and EM interferences or other effects (fading, etc.). In this section other complementary techniques are described:

- Geolocation based. Customized databases stored locally in RSUs can supply effective information about several key network features, e.g. exact PUs, specific protection requirements, bandwidths and channels availability, digital maps, etc. However this approach has high cost impact, because of the infrastructure needed.
- Infrastructure BS based. Stationary Base Stations from some cell networks carrier can operate in a cooperative support, which can give ad-hoc information (PU, local spectrum features, traffic density, etc.) to any vehicle passing through the region. The cost should be reduced, compared to geo-location, but this option is strongly dependent on carrier operators and government policy.
- Cooperative between any vehicles in a neighborhood: All the information and characteristics about local spectrum is passed through other vehicles inside the same cluster, external or individually. However, this approach needs information exchange between vehicles to converge fast and effectively, in order to correctly characterize the spectrum in a particular time window.
- Cooperative between selected vehicles: Similar to the previous described option, except that the spectrum-related information is exchanged and broadcasted among a reduced and selected number of vehicles, in order to increase the convergence rate and information reliability.

The Figure below illustrates a Digital TV White band spectrum occupation around NY region in US, obtained from a public database, available by Google [12] .

Such spectrum data in Figure 2 is public, and it is presently available for almost all regions in such country. It is possible to visually verify the higher density of PUs around the urban regions of NY and other cities and a low utilization outside. For other countries, a correct spectrum characterization must be done for each particular region.

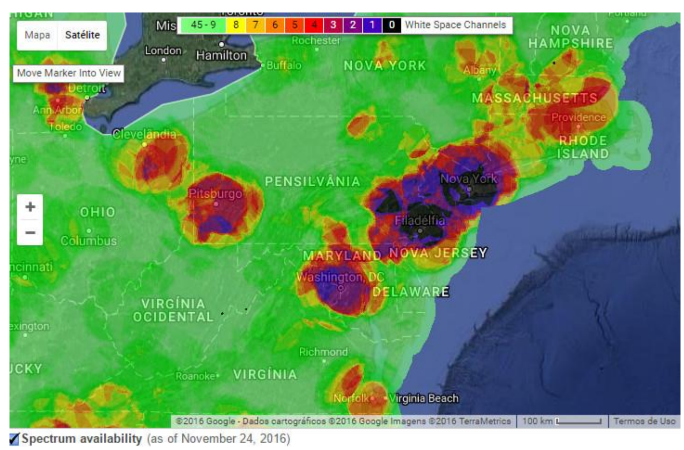

Fig. 2. TV white-band spectrum around NY region (US)

From a CR perspective, such kind of geo-information could be available upon a specific geo-location infrastructure, locally distributed and stored in RSUs (Road Side Units) to be available in specific regions along the vehicle paths.

C. The Cognitive Radio Cycle

The Figure 2 below represents the basic machine learning process in CR [9] and CR-VANET Vehicle communication:

- Spectrum Sensing. Use of some traditional or advanced sensing techniques: matched filter detection, energy, cyclostationary feature detection.
- Select the best frequency/channel to use. Execute rapid characterization of the radio spectrum environment.
- To define the best strategy, coordinating the spectrum access with other users/vehicles in the network cluster.
- Adaptation phase. To adjust the transmission/reception parameters in the SDR/CR system, in adaptive fashion, in order to optimize the communication features (rate, energy, etc.) in a particular time window.

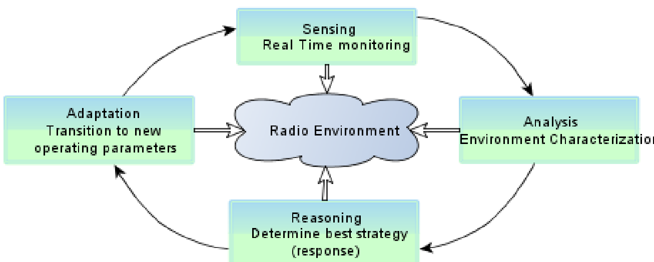

Figure 2. The Cognitive Radio Cycle

Additional results regarding spectrum sensing using several mechanisms in CR-enabled/CR-VANET networks are reported in [16].

IV. CONCLUSIONS

An introduction to vehicle communication networks, with emphasis in VANET (Vehicle AdHoc Networks) and smart communications based on the cognitive radio paradigm (CRV- Cognitive Radio Vehicle networking) was described. Vehicular communications systems based on DSRC proposal were presented, which are already available in some experimental automotive products via concept cars and even in some advanced commercial products. In particular CRV is receiving great attention from R&D groups, both from industry and academy environments. Vehicle communications is surely the next revolution in ITS (Intelligent Transport System), creating a solid base for smart cars and paving the way to the fully autonomous vehicles.

Regarding R&D in CRV-related activities, several issues remain still open, in particular those ones regarding effective spectrum sensing and access in a per-vehicle approach. Some R&D activities using machine learning and neural networks approach, such as deep learning and self-organizing models are under consideration for potential implementation of learning of the Cognitive Radio Cycle, for CR/SDR applied to smart radio and vehicle communications research.

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