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Improving vehicular safety message delivery through the implementation of a cognitive vehicular network

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ABSTRACT

The Wireless Access in Vehicular Environments (WAVE) protocol stack has been recently defined to enable vehicular communication on the Dedicated Short Range Communication (DSRC) frequencies. Some recent studies have demonstrated that the WAVE technology might not provide sufficient spectrum for reliable exchange of safety information over congested urban scenarios. In this paper, we address this issue, and present a novel cognitive network architecture in order to dynamically extend the Control Channel (CCH) used by vehicles to transmit safety-related information. To this aim, we propose a cooperative spectrum sensing scheme, through which vehicles can detect available spectrum resources on the 5.8 GHz ISM band along their path, and forward the data to a fixed infrastructure known as Road Side Units (RSUs). We design a novel Fuzzy-Logic based spectrum allocation algorithm, through which the RSUs infer the actual CCH contention conditions, and dynamically extend the CCH bandwidth in network congestion scenarios, by using the vacant frequencies detected by the sensing module. The simulation results reveal the effectiveness of our architecture in providing dynamic and scalable allocation of spectrum resources, and in increasing the performance of safety-related applications.

1. Introduction

In these last years, wireless systems and technologies for vehicular communication have attracted significant research interests from government, industry, and academia throughout the world. One of the reason of this interest is constituted by the plethora of novel applications and services that can be developed in a vehicular environment, ranging from safety-related systems, collision-avoidance applications, and traffic-monitoring systems to emerging vehicle-to-vehicle communication and multimedia streaming applications, just to cite a few. Due to the high requests of bandwidth needed to support these applications, specific portions of the spectrum have been reserved to enable vehicle-to-vehicle and vehicle-to-infrastructure communication, in both the US and Europe. For instance, the U.S. Federal Communication Commission (FCC) has allocated 75 MHz of Dedicated Short Range Communications (DSRC) spectrum at 5.9 GHz to be used exclusively for vehicle-to-vehicle and infrastructure-to-vehicle communications. The DSRC spectrum is divided into 7 channels with a 10 MHz bandwidth allocated to each one. Six out of these channels are Service Channels (SCH) while the center one is the Control Channel (CCH). The spectrum allocation has been followed by continuous efforts to standardize the entire protocol stack used by vehicular communication. A new amendment protocol of the 802.11 family, i.e., the IEEE 802.11p, has been proposed to regulate the vehicle communication operations at the lower MAC and PHY layers [10], while the network protocol operations between the link and application layers has been regulated by the Wireless Access in Vehicular Environments (WAVE)

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communication stack being standardized by the IEEE 1609 working group. In particular, IEEE 1609.3 covers the connection setup and management [8], whereas IEEE 1609.4 sits right on top of the IEEE 802.11p and enables operation of upper layers across multiple channels, without requiring knowledge of PHY parameters [9]. The IEEE 1609.4 protocol assumes that all vehicles are synchronized, and perform synchronous switches between a control channel interval, and a service channel interval. During the CCH interval, the WAVE device should monitor the control channel, as important safety information may be transmitted. During the SCH interval, the WAVE device can be tuned to any of the six service channel, and transmit data of non-safety related applications. While most of the existing papers on WAVE-related literature have investigated the problems induced by synchronous channel switches on application performance, and have proposed possible enhancement of the 1609.4 multi-channel scheme [35–38], this paper focuses on a less investigated but still fundamental issue to guarantee the correct operations of vehicular applications, i.e. the problem of spectrum allocation and usage in vehicular networks. To motivate our research, some recent results have indicated that the CCH can easily get congested in realistic urban scenarios, thus implying that the 10 MHz channel allocated for safety usage may not be enough [2,19]. To assess the performance of safety applications over the 802.11p protocol, and specifically, the 10 MHz control channel, two parameters are usually studied: *safety message delay* and *packet reception rate*. The former is a crucial factor, since the driver reaction time to traffic signals can be in the order of 700 ms or longer, implying that the safety message delay should be less than 200 ms [7]. With regard to packet reception rate, the system must deliver safety packets reliably, especially that broadcast transmission constitute a key part of a VANET usage [17], and the sender cannot expect acknowledgments and thus cannot tell if a packet was successfully received. As a result, some studies conclude that the probability of message delivery failure in a vehicular network should be less than 0.01 [21]. However, experimental analysis conducted in [13,17] demonstrate that the performance of vehicular applications in medium and high congested scenarios is not acceptable. For instance, the packet reception rate was found to be below 0.6 at zero distance under the Nakagami radio propagation model. Similarly, our results presented in [5] further showed that the message delivery ratio does not exceed 40% under the same conditions. Given these findings, it can be inferred that the 10 MHz CCH cannot provide performance guarantees under congested road conditions, and may therefore render unacceptable system performance for vehicular applications with strict Quality-of-Service (QoS) requirements.

In recognition of the spectrum limitations in the DSRC band, some proposals have been addressed by researchers to enhance the performance of safety-related applications operating on the CCH, while preserving the operations of non-safety related applications. A straightforward approach is to increase the number of message retransmission for safety-related communication, as proposed in [7,13,20]. Although this solution is shown in [13] to increase the probability of reception rate to above 99% in some scenarios, it might easily translate into additional contention on the CCH, and thus it might negatively adverse the problem of spectrum scarcity instead of solving it. Other solutions proposed so far involve the dynamic tuning of WAVE parameters, such as the CCH/SCH interval length [36], or the backoff window size [35].

In this paper, we address the problem of CCH contention and saturation by leveraging the concepts of Cognitive Radio Network (CRN) and Dynamic Spectrum Access (DSA) technologies. CRN [1] constitutes one of the most investigated approaches to increase the capacity of wireless systems, based on the promise to have highly-reconfigurable wireless devices that can modify their transmitting parameters based on the environment characteristics and applications QoS requirements. While several applications of CRN technology have been proposed for wireless mesh, ad hoc and cellular networks, the utilization of CRN principles in vehicular environments is far from being well investigated [25–34]. In this paper, we propose a CRN-based Vehicular Ad hoc NETworks (CRN-VANETs) to alleviate the problem of data contention in the control channel. To this aim, we propose a network architecture, composed of CRN vehicles and Road Side Units (RSUs) that act as repository of information from the moving vehicles. Based on the information received by each vehicle, the RSUs dynamically estimate the CCH contention conditions, and adjust the channel bandwidth, by eventually increasing the DSRC/CCH frequencies with additional spectrum frequencies accessed in an opportunistic way. For this, we propose a Fuzzy-Logic based algorithm to control the spectrum allocation process. Moreover, conversely to most of the existing works on CRN systems that consider the CRN applications in the licensed band (e.g. the UHF-DTV band) [1], we suggest in this paper to extend the DSRC Control Channel (CCH) to the neighboring 5.8 GHz ISM unlicensed band (IEEE 802.11a outdoor channels). This approach can be justified by the fact that Wi-Fi is an inherently short-range service limited by the low power output, and thus the Wi-Fi spectrum on roads and highways is generally minimally occupied. Moreover, the opportunistic utilization of unlicensed spectrum removes the need of protecting the operations of licensed users, and thus it greatly reduces the CRN implementation complexities and costs. Some recent papers investigate the advantages and drawbacks of using CRN-based functionalities on the ISM band, e.g. [31]. Our paper provides three main contributions pertaining to CRN-VANETs: (i) *architectural*: we describe in detail the operations of how a CRN-based architecture might work in practice, including the components (e.g. vehicles, RSU), the data exchanged among them, and the metrics that evaluate the current utilization of the CCH; (ii) *alghorithmical*: we devise novel spectrum allocation and sensing algorithms aimed at implementing a dynamic and on-demand spectrum allocation paradigm on a vehicular environment, and at quickly detecting available spectrum resources in the ISM band; (iii) *evaluation*: we evaluate the proposed architecture and algorithms under both static and varying contention conditions and network loads using computer-based simulations.

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The rest of the paper is structured as follows. Section 2 reviews the existing works on CRN applications for vehicular communication, whereas Section 3 introduces the system model and the proposed CVANET architecture. Section 4 introduces a novel metric to estimate the CCH contention, while Section 5 describes our algorithm for dynamic spectrum allocation, followed by Section 6 that evaluates the proposed system in terms of throughput and delay.

2. Background and related work

Cognitive Radio Networks (CRN) technology constitutes one of the most promising techniques to increase the capacity of wireless systems, thus alleviating the problem of spectrum scarcity caused by the spectrum regulations used so far [6]. In its general definition proposed in [1], the cognition cycle of a CRN node includes an observation stage that merges the previous experience with the current sensed state, and a decision state that acts to modify the radio parameters accordingly. Potentials and issues of CRN have been investigated by several recent papers, addressing spectrum access and sensing techniques, MAC protocols, routing protocols and practical implementation on Software Defined Radio (SDR) devices. At the same time, while CRN has been widely applied to wireless mesh networks and cellular networks, the research on CRN applications in VANETs is still at a preliminary stage, although it is gaining increasing interests in these last years. In the following, we review the main studies and results pertaining to CRN-based vehicular communication. We therefore classify the existing literature into: experimental studies, CRN-related protocols, and CRN-related architectures. An exhaustive survey on generic CRN and CRN-VANETs can be found in [1,25], respectively.

2.1. Experimental studies and results

In [26], the authors take a comprehensive series of spectrum measurements of the TV band from a vehicle traveling along a major freeway near Boston, US. An interesting observation made in this study is that the change in the spectral occupancy is gradual enough to allow for the CRN vehicle to complete the sensing in the TV bands, and to undertake spectrum switching, if needed. These results are also confirmed by the analysis in [27], where the authors investigate the relationship between vehicles' speed, environment characteristics and accuracy of sensing.

2.2. CRN-related protocols

The unique characteristics of the vehicular environment involve the need of designing specific spectrum management schemes (i.e. spectrum sensing, access and mobility) for CRN vehicles. In [28], the authors study the impact of mobility on the performance of spectrum sensing and corresponding tradeoffs between cooperation and scheduling. An interesting result in [28] is that mobility can improve the sensing performance because of spatial–temporal diversity in the received Primary Users (PU) spectrum measurement. Based on this assumption, both [27,29] propose a cooperative sensing scheme, where vehicles collaborate in detecting the presence of spectrum holes in the TV band at their current locations, taking benefit of the predictable nature of vehicular mobility on highways. Once spectrum resources have been identified by CRN vehicles, spectrum decision algorithms select the channel to be used at each location, based on the Quality-of-Service (QoS) requirements of the vehicular applications. For this purpose, the authors of [30] propose and evaluate a range of spectrum selection metrics, based on channel characteristics (i.e. rate and packet error rate) and on PU activity patterns. The channel selection algorithm is integrated with the routing process in the Co-Route algorithm [31]. Similar to our work, the authors of [31] propose to utilize ISM unlicensed spectrum frequencies for opportunistic access by CRN vehicles. However, they do not clarify how the dynamic spectrum access techniques can be integrated into the existing WAVE protocol stack, which, by the way, constitutes an important contribution of our paper.

2.3. CR-related network architectures

Network architecture proposed so far for CRN in VANETs can be roughly classified into: distributed vehicle-to-vehicle frameworks and infrastructure-aided frameworks. In the first class, the network is composed and managed by vehicles, each equipped with CRN functionalities. Even though this solution can provide advantages in terms of network scalability and reducing setup costs, it still poses several challenges on how spectrum coordination can be implemented in practice. For instance, increasing the bandwidth of the CCH of the WAVE stack as proposed in [32] might require that all vehicles synchronize on the correct frequencies to use, in each area. This might be difficult to guarantee in a complete decentralized scenario. On the other hand, infrastructure-aided frameworks deal with periodic interactions between vehicles and RSUs, where the RSUs act as repository of data that is used by subsequently passing vehicles [25]. In our previous work [32], we have proposed a centralized architecture in which CRN vehicles periodically transmit CCH usage information to the RSU. The RSU forward such information to a centralized entity (called LAPU in [32]), that performs data aggregation, and dynamically decides if it should increase the bandwidth of the CCH with vacant TV-spectrum frequencies. In [33], the authors propose a coordination framework, in which the RSU provides sensing instructions to the passing vehicles, which in turn senses the assigned portion of the spectrum, and sends back the result to the RSU. Similarly, a three-pronged approach is proposed in [34]. Here, the authors proposed a cluster-based framework, in which licensed channels are used for inter-cluster communication, and DSRC frequencies are used for intra-cluster communication.

In this paper, we consider a coordinated CRN-based vehicular network, composed of vehicles and RSUs that act as repository of information. Our architecture is similar to [33,34], however, our work introduces the following key distinctions: (i) while [33,34] consider static allocation algorithms in which all the available spectrum resources are utilized by CRN vehicles, we propose a dynamic framework that is able to scale the bandwidth allocation to the effective requirements of safety-related applications; (ii) contrary to most of the CRN systems proposed so far, we investigate the potentials of applying CRN technology in the *unlicensed* band, in order to increase the available bandwidth for vehicular communication and to reduce the implementation complexity and costs; (iii) we integrate the CRN technology with the existing WAVE protocol stack, and more specifically with the IEEE 1609.4 protocol that allows to devise multi-channel VANETs. Moreover, as compared to our previous publications on the topic [32], we provide these novelties: (i) we re-designed several components of the network architecture, including the spectrum sensing and allocation algorithms; (ii) we removed the LAPUs and simplified the overall operations of the CRN network; (iii) we extended the simulation analysis with additional comparisons and evaluations.

3. System model

In the following, we state the system requirements (Section 3.1), describe the components and assumptions (Section 3.2), and present the channel model in use (Section 3.3).

3.1. System requirements

The aim of our proposed system is to mitigate the spectrum scarcity issue in the DSRC Control Channel (CCH) by applying CRN principles. For this, we designed the system in order to meet the following requirements:

- *Self-adaptiveness*. The proposed system should provide an on-demand and dynamic allocation of spectrum resources, based on the actual contention conditions in the CCH. To this aim, it must incorporate (i) network metrics to infer the current state of contention in the CCH, (ii) learning algorithms to identify free parts of the ISM spectrum, and (iii) resource allocation techniques to decide the optimal amount of spectrum frequencies to be used on the CCH, in order to reduce the risk of congestion for safety applications.
- *Robustness*. The proposed system must avoid the presence of single point of failures. At the same time, since the CCH spectrum information must be made available to each vehicle of the scenario, it is fundamental to foresee the presence of *spectrum coordinator units* that are in charge of deciding the available bandwidth in the CCH, and disseminating this information inside the CR-VANET. In our architecture, the spectrum coordination functionalities are implemented by Road Side Units (RSUs).
- *Easy of development*. The employed infrastructure is required to possess modest processing power, in order to make the deployment of the system easy and cost-effective.
- *Preservation of privacy*. The processing units must protect the privacy of drivers' behaviors, in that no driving patterns are to be collected and no profiles of cars and drivers should be maintained.

As shall be described in Section 4, all the above aspects are taken into account in the design of the proposed system.

3.2. Model entities

The system general topology is depicted in Fig. 1. In the following we briefly define the characteristics of each component, while in Section 4 we describe in details the functions that each component implements. As shown by Fig. 1, the proposed system is composed of three main entities:

1. *Vehicles*. Each vehicle is assumed to have an on-board computing unit (OBU) that implements the WAVE standard, previously described and uses an SDR transceiver for wireless communication. It also comprises an on-board GPS, a navigator with its associated maps, a spectrum sensing unit, and an on-board central computer with I/O interfaces. In fact, several of these features are already deployed in present commercial cars, or are expected to be deployed in the near future [3].
2. *Road Side Unit (RSU)*. RSUs are static Access Points (APs) with the ability to communicate simultaneously with multiple OBUs. They are equipped with SDR functionalities, memory capabilities for caching relevant information, modest processing capabilities, and a regular-sized database. RSUs do not participate in the sensing process, but on the other hand, they are involved in the spectrum allocation process.
3. *RSUs interconnection system*. Each RSU is assumed to be connected to its next hop RSUs either via a dedicated wireless link or through the Internet.

While no entity from the ones presented so far is cognitive by itself, the system as a whole is cognitive since learning, adaptation, and reaction will be taking place at different locations and through the various entities, a fact that is depicted in Fig. 2.

3.3. Communication model

The application of cognitive networks in VANETs, especially in DSRC, is enabled by the physical layer that is described in IEEE 802.11p [10]. The modulation scheme adopted for a single channel is OFDM, where the control channel is divided into 64 sub-channels (48 are data) with a variety of modulation and coding rates. The sub-channels are overlapped so that the inter-carrier spacing is 0.15625 MHz and is equal to the bandwidth of a single sub-channel. Actually, this bandwidth is half of that in 802.11a and it is appropriate to combat frequency selective fading and Doppler shifts.

In communication theory, three factors control how fast data can be sent reliably over the channel: (i) available bandwidth, (ii) modulation scheme used, and finally, (iii) channel quality (noise level). Starting with the last factor, controlling noise level is not easily achievable in a dynamic fast varying environment. A valid alternative would consist of increasing the modulation order. However, to conserve reliable transmissions and the same desired Bit Error Rate

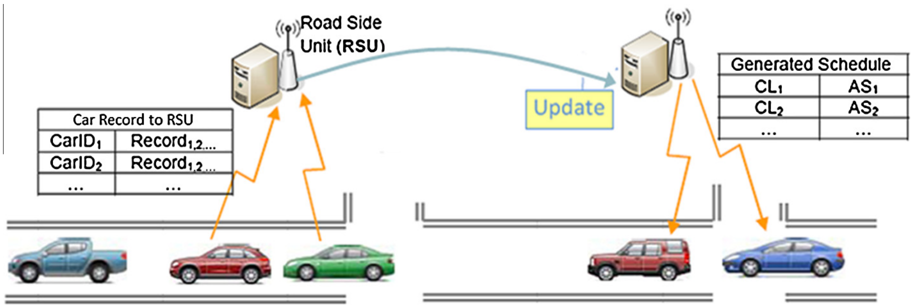

Fig. 1. Proposed system architecture.

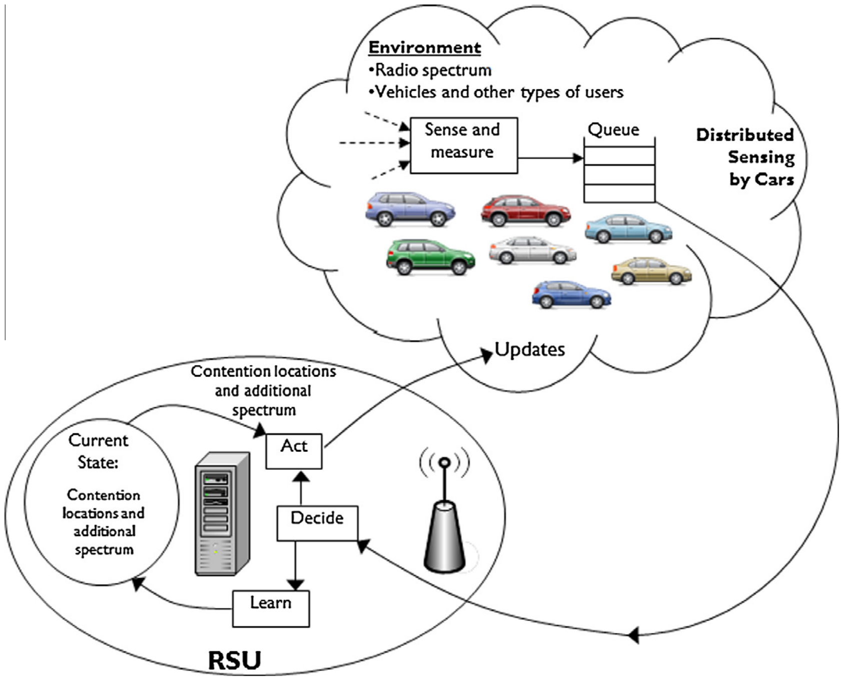

Fig. 2. Network cognition cycle.

(BER), it will become necessary to increase the transmission power above allowed levels according to the WAVE standard. Alternatively, we can increase the maximum achievable capacity by increasing the network available bandwidth through widening the control channel and extending it to the ISM band. More specifically, we propose in this paper to extend the CCH bandwidth by using the neighboring 5.8 GHz ISM unlicensed band (IEEE 802.11a outdoor channels). The utilization of these frequencies can be motivated as follows: (i) they are unlicensed, and thus they can be accessed by CRN vehicles without addressing the need of protecting the operations of PUs, i.e. no fine-grained sensing techniques are required, (ii) they are mainly used by short-range devices (e.g. WiFi transmitters), meaning they are mainly unoccupied in specific vehicular environments, i.e., highways and rural areas, and (iii) they are close in frequencies to the DSRC channels, so that no dedicated antennas should be used by CRN vehicles (as opposed to [32–34] which propose to utilize CRN on TV-spectrum frequencies, and thus need to equip each vehicle with a dual-antenna system). According to Shannon Theorem shown in Eq. (1), maximum achievable capacity C measured in bits/s is proportional to the available bandwidth W, while SNR represents the Signal to Noise Ratio. Using cognitive networks to increase the maximum achievable capacity is translated to an equal or slightly less (depending on the used coding scheme) increase in the used bit rate which positively affects the network throughput and reduces the delay.

$$C = W\log_2(1 + SNR) \quad (1)$$

The newly added spectrum can be divided into sub-channels having the same parameters as those defined in 802.11p (inter-carrier spacing of 0.15625 MHz) while preserving the orthogonality requirement. Hence, the number of available sub-carriers (carrier frequencies of sub-channels) will increase to suit the system's requirements. This allows the bandwidth of the sub-channels to stay constant, and the bit rate to increase but by preserving the modulation order and the coding rate. This form of an OFDM, where the implementation achieves the high data rates via collective usage of a large number of non-contiguous sub-channels, is called non-contiguous OFDM (NC-OFDM) [14], and has been already investigated in previous papers on CRNs [15] as a technique to guarantee the co-existence of primary and secondary users' transmissions. Indeed, when secondary users detect a primary user, the secondary users deactivate sub-carriers that can potentially interfere with it, as proposed in [15]. In our proposed system, we use NC-OFDM techniques to dynamically extend the bandwidth of the CCH by using ISM frequencies. In this paper, we do not investigate the impact of fading effects on RSUs and vehicles communication (a Two-Ray ground model is used in the simulations shown in Section 5), since we mainly focus on the issues of channel utilization and bandwidth allocation. Interested readers on propagation issues on the 5.8 GHz ISM band over urban scenarios can refer to [43].

4. Proposed system

4.1. Overview

In the following, we provide details on how the proposed system works in practice, by distinguishing between the operations performed by vehicles (Section 4.4) and the RSUs (Section 4.5). In brief, we assume a highway or a major road scenario divided into continuous road regions, each of which is referred to as *r*. Each region r is associated with a local RSU (e.g., RSU_r). In each region, vehicles perform channel sensing on the ISM 5.8 GHz band, and report back their measurements to RSU_r. Based on the spectrum information received, RSU_r can determine the *List of Vacant ISM Channels* in region *r*, i.e., LVC_r. The details of the sensing scheme are described in Section 4.2. Moreover, based on the information sent by each vehicle, each RSU estimates the current contention level on the CCH through our network metric that is described in Section 4.3.1. Our proposed metric is a linear combination of two factors: (i) the delay required to transmit a safety message on the CCH, and (ii) the ratio of un-transmitted messages, i.e., the number of events in which a safety-message is discarded by a vehicle because of the expiration of the CCH interval (default length is 50 ms). Based on the contention metric value, RSU_r decides the actual bandwidth of the CCH at region *r* through a Fuzzy-Logic Scheme (FLS) that is defined in Section 4.3.2. The output of the FLS scheme is the actual bandwidth allocation of the CCH (eventually increased with the bandwidth of the channels in LVC_r), and is communicated to all vehicles moving in region *r* through the communication scheme detailed in Sections 4.3 and 4.4.

4.2. Spectrum sensing

The design of a fine-grained and accurate spectrum sensing technique constitutes one of the most challenging issues in cognitive network systems. Several spectrum sensing schemes have been proposed so far, relying on energy-detection, matching-filter, or cyclo-stationary detection techniques [22–24]. Moreover, cooperative techniques have been widely investigated to mitigate the impact of local sensing errors caused by fading phenomena [27]. At the same time, all these techniques have been proposed for an opportunistic network scenario, in which secondary users must be able to detect the presence of a licensed user on the received signal, and vacate the current channel if an ongoing PU activity is detected [22–24]. In our proposed channel model (Section 3.3), we assume that the CRN vehicles will access the ISM unlicensed frequencies at the 5.8 GHz spectrum band, and thus they do no need to vacate the frequencies in case they are found busy by external users (e.g., 802.11a radio transmitters). The CRN vehicles will perform channel sensing during SCH intervals (where CRN vehicles cease transmissions to detect the presence of potential ISM secondary users) in order to infer the occupation pattern of each ISM channel, so as to quickly identify vacant channels and avoid congested ISM channels. We rely on the metric of channel workload defined in our previous paper [39], and assume that each vehicle *c* will sense the ISM spectrum periodically through an energy-detector scheme, and compute the workload of channel *f* (occupancy by 802.11a users) at location r as follows:

$$\omega_r(c,f) = \frac{Number\_of\_busy\_samples\_on\_f}{Total\_number\_of\_samples\_monitored\_on\_f} \tag{2}$$

where a sensing sample is classified as "busy" if the average power perceived is higher than an energy threshold. Based on the channel workload, vehicle *c* can determine the *Residual Capacity RC*(*c*,*f*) of channel *f*, which is defined as follows:

$$RC_r(c,f) = C \cdot (1 - \omega_r(c,f)) \tag{3}$$

where *C* is the maximum achievable capacity of a channel that can be offered by the IEEE 802.11p technology [10] (as described in Eq. (1)). Basically, Eq. (3) provides an estimation of the portion of bandwidth left vacant from the 802.11a users, and thus is usable for opportunistic usage by the CRN vehicles. As shown later in Section 4.5, we assume that sensing information is continuously transmitted from vehicles to the closest RSU that aggregates the received data, and computes the average $\underline{RC}_r(c,f)$ for each ISM channel *f*. By comparing $RC_r(c,f)$ with a threshold value φ (assumed equal to the minimum rate foreseen by the 802.11p technology, i.e., 3 Mb/s), the RSU at location *r* can build the List of ISM Vacant Channels (denoted as LVC_r) that can be potentially used to increase the bandwidth of the CCH through the NC-OFDM technique discussed in Section 3.2. That is:

$$LVC_r = \{channel f \quad | \; \bar{RC_r}(c,f) > \varphi\}$$

4.3. Spectrum allocation

4.3.1. Control Channel contention metric

A major part of our system's operation is to determine the areas along the road that suffer from control channel contention. We define a metric that quantifies contention at each location of the road, where we mean by "contention" data transmission contention at the control channel, and not vehicular traffic contention. We say that the control channel suffers from data transmission contention if the needed bitrate exceeds the offered bitrate (available bitrate). According to the CSMA/CA Distributed Coordination Function (DCF) medium access mechanism of IEEE 802.11, whenever a packet arrives at the MAC from the upper layer, the status of the channel should be checked. If the channel is sensed idle for a period equal to DCF Interframe Space (DIFS), the mobile station randomly selects a backoff counter within a backoff window. The backoff counter is derived from a uniform distribution over the interval [0,*CW*-1], where the Contention Window (*CW*) is a value between [CW_{min},CW_{max}]. The backoff counter is decreased only when the medium is idle, and is frozen (paused) when another station is transmitting. Each time the medium becomes idle, the station waits for a DIFS and continuously decrements the backoff counter. As soon as the backoff counter reaches zero, the station is authorized to access the medium and transmit. Since stations pause their backoff timers whenever the medium is sensed to be busy, this will incur delays that are not modeled in the contention window *CW*. These delays actually infer contention in the medium that ends up affecting the transmission of safety information. In the literature, some metrics are defined to measure the load at the control channel. The "Interferer number" is defined in [20] and the "Communication Density" is proposed in [11]. These metrics however lack the needed practicality for implementation since some of the involved variables are hard to estimate in real time by individual cars, such as vehicular density and interference range.

Therefore, in order to determine contention at a given location, we propose a novel metric $C_r(t)$ to assess the contention level in region *r* at time *t*. We made the contention metric at time *t* rely on $C_r(t-1)$ and on the newly sensed contention C_r so as to account for changes in the contention level and make the system robust to fallacious data. For a given location *r*, the contention is related to the average number of safety packets transmitted plus their average sizes, and the channel capacity as reflected by the achievable bitrate according to the adaptive modulation scheme employed in IEEE 802.11. Thus, if the system accounts for near history (i.e., $C_r(t-1)$) while considering the present contention that is sensed by the cars in region *r*, the new $C_r(t)$ should therefore model actual contention accurately. We model this contention in Eq. (5) using a linear prediction model:

$$C_r(t) = \gamma C_r(t-1) + (1-\gamma)C_r \tag{5}$$

The parameter γ reflects the weight given to history while $(1-\gamma)$ corresponds to the weight of the sensed contention, which in turn depends on the evaluation of data relayed from *n* cars. The correct tuning of γ provides the optimal trade-off between history exploration and dynamic channel variation adaptation, but it is also intrinsically dependent on the characteristics of the vehicular environment which is considered for the network deployment (e.g. its dynamicity). In our analysis, we set $\gamma = 0.6$. The term C_r is a linear combination of two factors, the first being the product of the access delay *D* of safety packets and the channel's offered bitrate *B* divided by the average payload size *S*, while the second factor is the average number of un-transmitted safety packets *U* per total attempted transmissions. The access delay *D* in the context of our system is defined to be the delay between the time when a node (car) decides to send a packet and the time the packet is successfully received at the receiver. With higher contention, *D* increases due to the 802.11 carrier sensing mechanism, where each node pauses its backoff timer during the MAC backoff process whenever it senses a busy channel. Those incurred delays provide a partial contention indication. As a matter of fact, the IEEE 802.11p scheme [10] employs an adaptive modulation scheme that attempts to increase data rates to make use of favorable channel conditions, and reduces the data rate as the channel degrades. Adaptive modulation and coding attempts to maximize average spectral efficiency while maintaining a minimum bit error probability. Given that all cars in the same region are subject to the same channel condition, it is valid to assume that all of them, while employing the same adaptation schemes, will transmit at equal bit rates. It follows that the bit rate used by a certain car at an instance of time *t* in region *r* will indeed represent a lower bound estimate on the maximum achievable channel capacity at *t* and in *r*. The payload size *S* is used to get the average delay per byte. Finally, the number of un-transmitted packets *U* also increases with contention since the control channel interval is limited to 50 ms and the collision avoidance mechanism imposes that certain packets will never be transmitted if contention persists. The result is a unitless sensed contention metric that is calculated as shown:

$$C_r(t) = \alpha \frac{D_r \times B_r}{S_r} + \beta U_r \tag{6}$$

where the symbols D_r, B_r, S_r and U_r are the parameters *D*, *B*, *S* and *U* respectively at region *r*. The first variable in (6) is in effect the achievable channel capacity (*B*) divided by the throughput (*S*/*D*), which we call the inverse of the effective channel utilization (or the normalized delay, i.e., *D* normalized by *B*/*S*).

To derive the optimal value of α and β in Eq. (6), we used a simulation study by modeling the 802.11p vehicular environment through the NS2 extension described in [35]. As was mentioned earlier, the bit rate in 802.11p over the 10 MHz control channel can vary between 3 and 27 Mbps, while the nominal bit rate is considered to be 6 Mbps [12]. When considering a control channel interval of 50 ms and a bit rate of 6 Mbps, the capacity in the control channel interval becomes (6 Mbps × 50 ms)/8 = 37,500 bytes, which is in essence the threshold case. That is, any input to the network that is more than 37,500 bytes during 50 ms will render the network congested. Three scenarios corresponding to three bitrates: 3 Mbps, 6 Mbps, and 12 Mbps were devised. To have a representative sample, the number of cars in each scenario was set to three values: 50, 100, and 200 cars. Table 1 summarizes the parameters for each scenario, including the payload sizes, all of which yield loads that are equal to the channel capacity.

For all the simulations, the values of the access delay divided by the payload and multiplied by the offered bitrate in the channel, $(D_r \times B_r)/S_r$, were plotted against

Table 1
Parameter values for deriving the weights of the contention expression.

Bitrate	3 Mbps			6 Mbps			12 Mbps		
Number of cars	50	100	200	50	100	200	50	100	200
Payload size	375	187	94	750	375	187	1500	750	375

the average number of un-transmitted packets per attempted number of transmitted packets, U_r. The dependent variable is in effect the channel capacity divided by the throughput, which is the inverse of the effective channel utilization. The transmission range was set to 250 m in accordance with the typical values that are discussed in [4,18]. The separation between each two cars was set to 5 m, and the cars were assumed to be in a traffic jam, so that they are relatively stationary, and were distributed equally on four lanes. Each car broadcasts once and randomly within the control channel interval a message to the cars in its transmission range, where the size of the message was determined by the simulated scenario. Each simulation was repeated 100 times for each scenario, and the data from the simulation was then analyzed to compute the different parameters of the system. A linear model relating the inverse of the effective channel utilization and the average number of un-transmitted packets was generated. In this model, the y-value is represented by the first term (i.e., $D_r \times B_r/S_r$) while the x-value is denoted by the second term (i.e., U_r). Hence, using the curve fit that is displayed in Fig. 3, we can relate the two terms with a correlation equal to 0.81 as follows: $D_r \times B_r/S_r = -0.349\ U_r + 0.192$. Next, by realizing that the value of $C_r(t)$ (see Eq. (6)) must hold true for C_{th}, which we normalize to 100, we get: $100 = \alpha(D_r \times B_r/S_r) + \beta U_r$. Finally, using the values of the y-intercept and the slope in the linear regression equation (i.e., 0.192 and -0.349, respectively), we easily compute α as $100/0.192 \approx 520$ and β as $520 \times 0.349 \approx 182$. Eq. (6) now becomes: $C_r(t) = 520(D_r \times B_r/S_r) + 182U_r$. The simulation results plus the computed linear model are plotted in Fig. 3.

4.3.2. Fuzzy-logic based spectrum allocation algorithm

As spectrum is regarded as a scarce natural resource [42], a bandwidth allocation scheme must allocate no more than the needed bandwidth for the operation of our system. In this work, we propose using a simple, yet effective, Fuzzy Logic System (FLS) to render the bandwidth allocation scheme more efficient and intelligent. The proposed FLS allocates the extra bandwidth to the vehicles according to the sensed contention level. This FLS is of the Mamdani type and builds on the fact that network contention can be described using linguistic terms such as the channel utilization and the un-transmitted packets. We will show how these two terms can be used to build rules that describe network contention, and allocate the appropriate bandwidth to relieve the contention. As a result, this FLS-based bandwidth allocation scheme efficiently utilizes the extra spectrum available in the ISM band.

We consider two inputs for the Fuzzy Logic System (FLS):

- *Antecedent 1*: The inverse of the effective channel utilization, denoted as x_1.
- *Antecedent 2*: The average number of un-transmitted safety packets per attempted transmission, denoted as x_2.

A careful examination of the results shown in Fig. 3 reveals the following:

- The station may see a high number of un-transmitted packets that consume channel resources with low inverse channel utilization. Thus, in such scenarios it will appear as if the successfully transmitted packets will render the channel used most of the time. This will cause most of the packets to timeout and not to be transmitted (shown in the right part of Fig. 3).
- The station might be able to transmit most of its packets, so that the un-transmitted ratio will be low, but the delay will be high, thus reflecting a low effective utilization of the channel (i.e., high inverse channel utilization, as shown in the left part of Fig. 3).

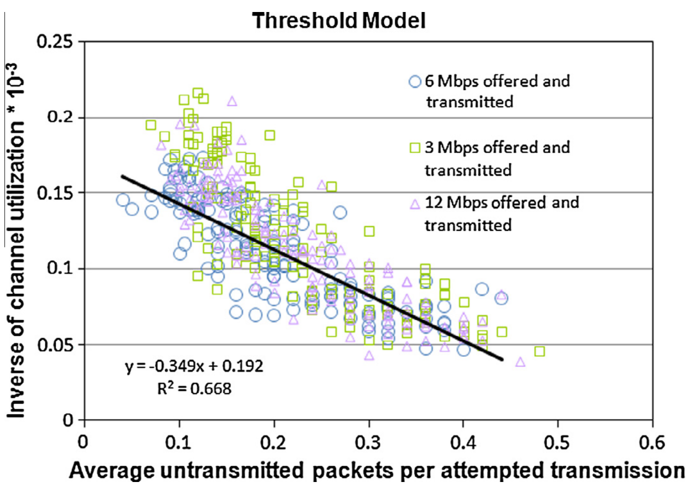

Fig. 3. Threshold linear model.

- The station might be able to transmit a medium portion of its packets with an average delay. This is the middle part of Fig. 3.

Based on the above, the linguistic variances used to represent the inverse of channel utilization and the average numbers of un-transmitted safety packets per attempted transmission are divided into three levels: Low, Moderate and High. The consequence (minimum needed additional bandwidth) is divided into five levels: Very Small, Small, Average, Large, and Very Large. We used trapezoidal membership functions for the edge membership functions and triangle ones for the middle ones. These are shown in Figs. 4 and 5.

From the previous section, we know that we have 2 Antecedents and 3 fuzzy subsets, thus we need $3^2 = 9$ rules for this FLS, which are illustrated in Table 2. These rules are given equal weights and are made consistent with the discussion about data contention in the previous section, specifically based on the observations from Fig. 3. The defuzzifier used in our FLS is the Centroid Defuzzification method (also known as center of gravity) since it is the most prevalent and physically appealing of all the defuzzification methods [40,41]. We chose the min operation for the AND, while for the OR operator, we chose the max operation that was also used for the implication method.

Table 2
Rules used in the FLS design.

Rule #	Antecedent 1	Antecedent 2	Consequence
1	Low	Low	Very Low
2	Low	Moderate	Low
3	Low	High	Medium
4	Moderate	Low	Low
5	Moderate	Moderate	Medium
6	Moderate	High	High
7	High	Low	Low
8	High	Moderate	High
9	High	High	Very High

The input–output characteristic (i.e., surface plane) of our Fuzzy Logic System is shown in Fig. 6, where x_1 and x_2 were defined in the previous section.

4.4. Vehicles' operation

Every x meters, a car initiates the process of information gathering (contention data during the CCH and ISM

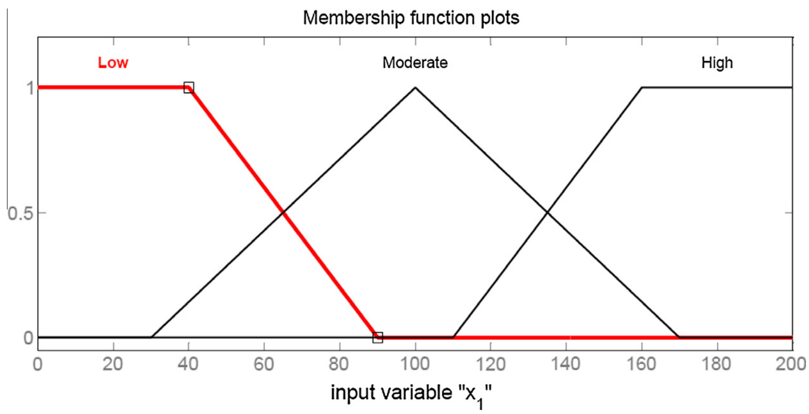

Fig. 4. Membership function of Antecedent 1.

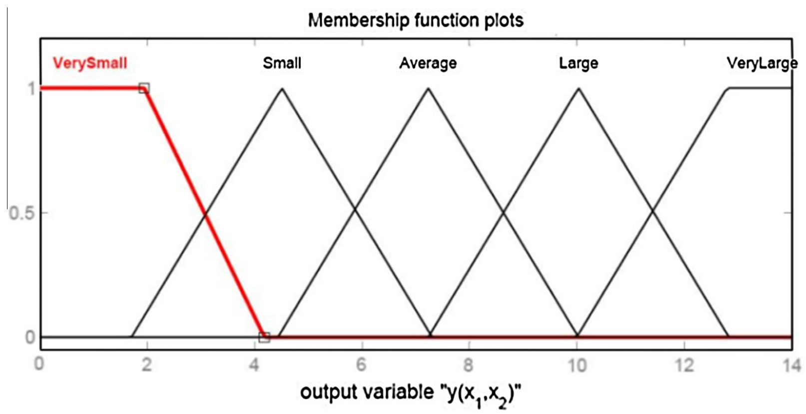

Fig. 5. Membership function of the consequence.

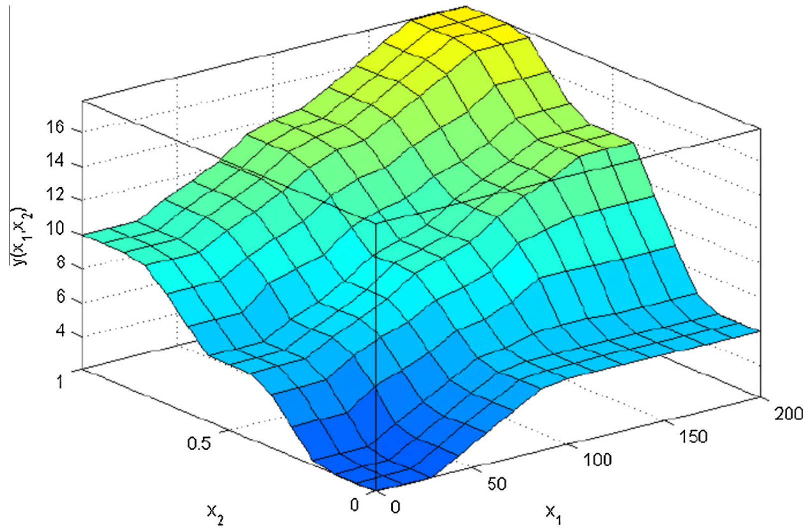

Fig. 6. Input–output characteristics of the Fuzzy-Logic System (FLS).

Table 3
Car gathered data at interval *i*.

$td_{r,i,j}$	Access delay time of each successfully transmitted safety packet *j*
$tx_{r,i}$	Number of sent safety packets at the end of CCH
$rx_{r,i}$	Number of received safety packets at the end of CCH
$s_{r,i,k}$	Payload size of all observed safety packets (sent and received)
$a_{r,i}$	Number of attempted but not transmitted safety packets
$w_r(c,f)$	Workload for channel *f* from the ISM band
$b_{r,i,j}$	Available bitrate at region *r* for each safety packet *j*

channels sensing during the SCH). The value of x is a crucial parameter of our proposed framework. We set it to 50 m, since we can reasonably assume that channel contention does not change significantly at locations closer than 50 m for 802.11p WAVE radio transceivers. The process of information gathering for a specific region r works as follows. Every time the car enters the control channel interval i, it temporarily stores the data shown in Table 3, and then when it enters the service channel interval h, it takes measurements of b ISM channels, where each channel is defined to be 20 MHz in width. It is worthy to note that the car must cease the information gathering process at the end of either the CCH or SCH interval if it exceeds x while in the middle of one of these two intervals.

At the end of the information gathering process that is run each x meters, the car must perform data aggregation in order to minimize the size of the data it sends to the RSU when it later enters its transmission range. It basically has to create a record that summarizes the collected data for the last x meters. In this step the car averages the different information gathered during the preceding N control channel intervals (an estimation of N is presented later in this section) and M service channel intervals. Given that the CCH and SCH intervals occur alternatively, the following relation holds: $M-1 \leqslant N \leqslant M$. More specifically, the car c computes:

- The total number of transmitted packets: $TX_r^c = \sum_{i=1}^{N} tx_{r,i}$.
- The total number of received packets: $RX_r^c = \sum_{i=1}^{N} rx_{r,i}$.
- The total number of non-transmitted packets: $A_r^c = \sum_{i=1}^{N} a_{r,i}$.
- The average number of non-transmitted packets per attempted: $U_r^c = \frac{A_r^c}{TX_r^c + A_r^c}$.
- The access delay: $D_r^c = \frac{\sum_{i=1}^{N}\sum_{j=1}^{tx_{r,i}} td_{r,j,i}}{TX_r^c}$.
- The average payload of sent and received packets: $S_r^c = \frac{\sum_{i=1}^{N}\sum_{k=1}^{tx_{r,i}+rx_{r,i}} s_{r,k,i}}{TX_r^c + RX_r^c}$.
- The average bitrate at r: $B_r^c = \frac{\sum_{i=1}^{N}\sum_{j=1}^{tx_{r,i}} b_{r,j,i}}{TX_r^c}$.
- The residual capacity for channel f from the ISM band: $RC_r(c,f) = C \cdot (1 - \omega_r(c,f))$.

Every x meters, the car goes through multiple CCH intervals. For example, if x is set to 50 m, a car moving at

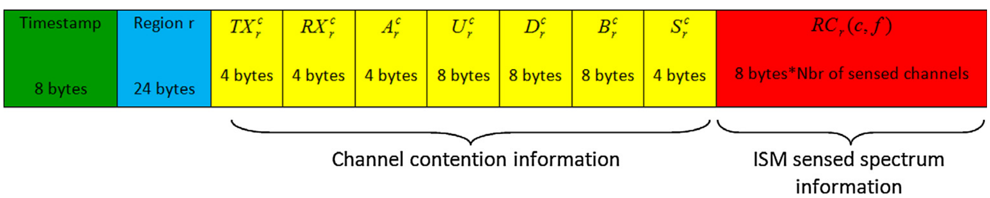

Fig. 7. Format of the record sent by the car to the RSU.

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an average speed of 60 km/h will alternate between CCH and SCH intervals at least 30 times (the sum of CCH and SCH intervals is 100 ms). In this case, the number of CCH intervals visited during the 50 m is about 30. It follows that each record that the car stores for pending transmission to the RSU includes averages of TX_r^c, RX_r^c, A_r^c, U_r^c, D_r^c, S_r^c and $RC_r(c,f)$ for all ISM 802.11a outdoor channels computed from 30 samples collected from the same region. Fig. 7 shows the structure of the record sent by the car to the RSU.

4.5. RSUs' operations

The collection of RSUs within an area represents a distributed computing system that provides spectrum assignment services to the cars. Each RSU provides the service of informing the cars about contention locations along their paths with the associated additional spectrum that they can use. In order to benefit from this service, a car that is in proximity of an RSU, will subscribe to a WAVE Basic Service Set (WBSS) that is generated by the RSU and advertised during the CCH interval. During the next service channel interval, the car will provide the RSU with all the stored records since the last time it passed by a RSU. In addition to this, the car will inform the RSU about the expected next RSU on its path. This information will enable the RSU to provide the car with a table that includes information about the path that the car will follow plus the contention locations and the additional spectrum associated with them. In fact, the RSU stores locally a set of tables, each of which corresponds to a direct next hop RSU. These tables are updated and maintained in the RSU's local memory. Upon the receipt of the next hop information from the car, the RSU forwards the corresponding table, thus enabling the car to extend its spectrum to additional channels at specific contention locations along the way. However, if the car was unable to predict or does not want to share its next hop RSU, it can put a special value in the next hop field of the message sent to the RSU. This will prompt the RSU to send it all the next hop RSU tables and enable the car to have all its possible paths covered with contention locations and available spectrum information. The format of the table is depicted in Table 4. The RSU will also provide the car with a set of ISM channels to be sensed during its journey to the next hop RSU. Each RSU will make sure to provide a number of ISM channels to be sensed per car according to the traffic flow in its region, guaranteeing that the distributed sensing of the whole ISM spectrum does not require a time greater than ΔT_{max}, defined as the maximum delay of relaying the information about the current state of the whole ISM spectrum utilization, such that it does not exceed double the time required by a car moving at an average speed to reach the next RSU.

In order for each RSU to accurately estimate the contention locations along the path between itself and each of its neighboring RSUs, and accordingly find all the available channels in the ISM spectrum, it must exchange with those RSUs records encompassing the parameters discussed previously. Having records collected from cars, either directly or via other RSUs, the RSU groups these records by region. For each region r, with n car records, the RSU calculates the

Table 4
Format of the RSU table forwarded to cars.

Next RSU	
Contention location 1	Additional spectrum 1
Contention location 2	Additional spectrum 2
⋮	⋮
Contention location h	Additional spectrum h

average Residual Capacity $\overline{RC_r}(c,f)$ and the list of vacant channels LVC_r as shown in Eqs. (3) and (4) respectively, in addition to the following metrics:

- The access delay for r: $D_r = \frac{\sum_{c=1}^{n} TX_r^c \times D_r^c}{\sum_{c=1}^{n} TX_r^c}$.
- The average number of non-transmitted packets: $U_r = \frac{\sum_{c=1}^{n} U_r^c \times (A_r^c + TX_r^c)}{\sum_{c=1}^{n} (A_r^c + TX_r^c)}$.
- The average number of payload sizes: $S_r = \frac{\sum_{c=1}^{n} S_r^c \times (RX_r^c + TX_r^c)}{\sum_{c=1}^{n} (RX_r^c + TX_r^c)}$.
- The average bitrate: $B_r = \frac{\sum_{c=1}^{n} TX_r^c \times B_r^c}{\sum_{c=1}^{n} TX_r^c}$.

The RSU next feeds the above aggregated measurements as inputs to the FLS, whose consequence is the minimum needed additional bandwidth to alleviate contention, $C_r(t)$. The RSU generates its estimate of the contention by accounting for the sensed metric and the history component (i.e., Eq. (5)). Finally, each RSU notifies passing cars of the additional bandwidth to use for extending the control channel.

5. Evaluation study

5.1. Simulation methodology

The used approach to evaluate our system integrates ns2 and Matlab, as implied in Fig. 8. We used our extension for 802.11p/1609.4 WAVE in ns2, which is described in [35], to model multi-channel VANETs.

Multiple scenarios of network contention were simulated in ns2 (simulation parameters are shown in Table 5), where the access delay D_r^c, offered bitrate B_r^c, payload size S_r^c and U_r^c were collected continuously from cars. These

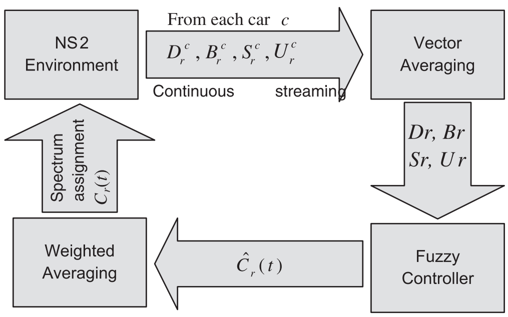

Fig. 8. Simulation methodology used to evaluate our work.

Table 5
Simulation parameters and their values.

Parameter	Value
802.11p data rate	3–6 Mbps
Packet generation rate	10 Packets/s
Packet size	100–1000 bytes
Transmission range	250 m
Communication method	Broadcast
Radio model	Nakagami
Number of lanes	3 per direction
Number of cars/lane/km	10–100

were then fed into a Vector Averaging function that buffers the input data for the last n cars providing measurements for region r, and then calculates the final values of D_r, B_r, S_r, and U_r using simple averaging. The computed averages are next passed as input to the fuzzy inference system (in Matlab). With respect to the message size, it is worth noting that safety-related messages are expected to be relatively large due to the security overhead, as attested by studies like [16] which report numbers between 250 and 800 bytes for the message size. Each simulation was repeated 100 times.

5.2. Simulation results

In this Section, we evaluate the functioning of the proposed CVANET schemes using the simulation environment described in the previous subsection. Unless specified otherwise, we used the simulation parameters described in Table 5 above. We simulate and compare the following two modes in our analysis:

- *CVANET-ON mode*: All components of the CVANET scheme are enabled and the CCH is extended when needed.
- *CVANET-OFF mode*: This is the legacy 802.11p/1609.4 standard described in [9].

We use the following metrics for the evaluation:

- *Message delay*: defined as the average delay to successfully deliver a broadcast message over the vehicular network.
- *Packet Un-Transmitted Risk Index (PURI)*: defined as the probability that a message generated randomly during a CCH interval will not get access to the medium by the end of that same CCH interval.
- *Packet Delivery Ratio (PDR)*: defined as the ratio of messages successfully received by vehicles in the network.
- *Per-vehicle throughput*: defined as the amount of bytes successfully received by a vehicle per-second.

Fig. 9 reveals the results of a simulation scenario performed by varying the number of vehicles, and reports the safety message delay (Fig. 9(a)) and PURI index (Fig. 9(b)) for different payload values. Each car broadcasts one safety message within the CCH interval. Fig. 9(a) demonstrates that the CVANET-ON mode can greatly reduce the end-to-end delay of safety-messages over congested vehicular scenarios, thanks to the spectrum management algorithm implemented by the FLS scheme. Moreover, Fig. 9(a) shows that our scheme is able to meet the QoS requirements of safety-applications, under varying network and load conditions. Similarly, Fig. 9(b) shows that the CVANET-ON mode greatly reduces the ratio of un-transmitted packets over all the configurations considered.

For the same scenario described above, we plotted in Fig. 10(a) the per-vehicle throughput for different payload sizes while varying the number of vehicles. The CVANET-ON scheme significantly improves per-vehicle throughput by the fact that collided and un-transmitted messages have been reduced. In Fig. 10(b), the packet delivery rate is shown to improve in the proposed scheme. This can be also justified by the fact that more packets are able to access the medium and get transmitted successfully.

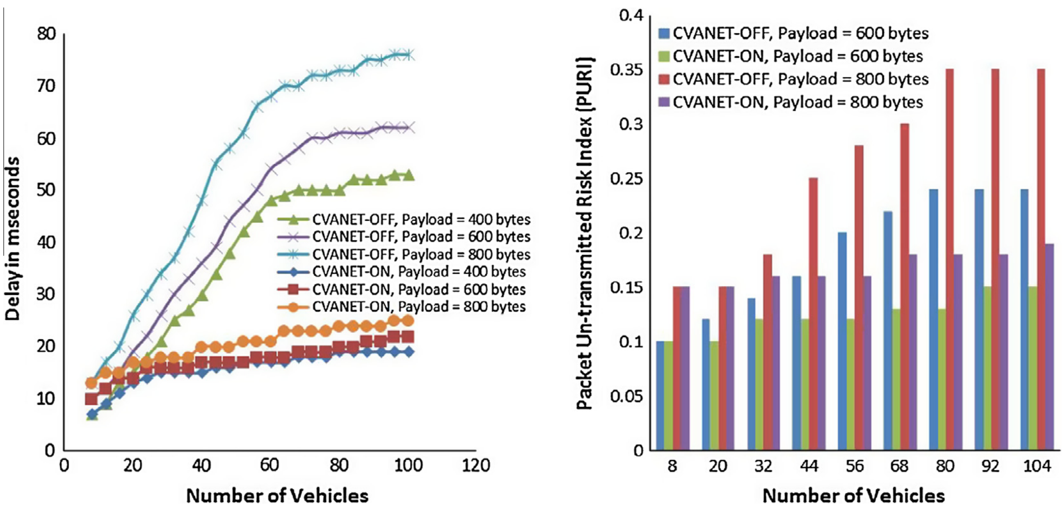

Fig. 9. Safety message delay (a) and packet un-transmitted risk index (b) versus number of cars.

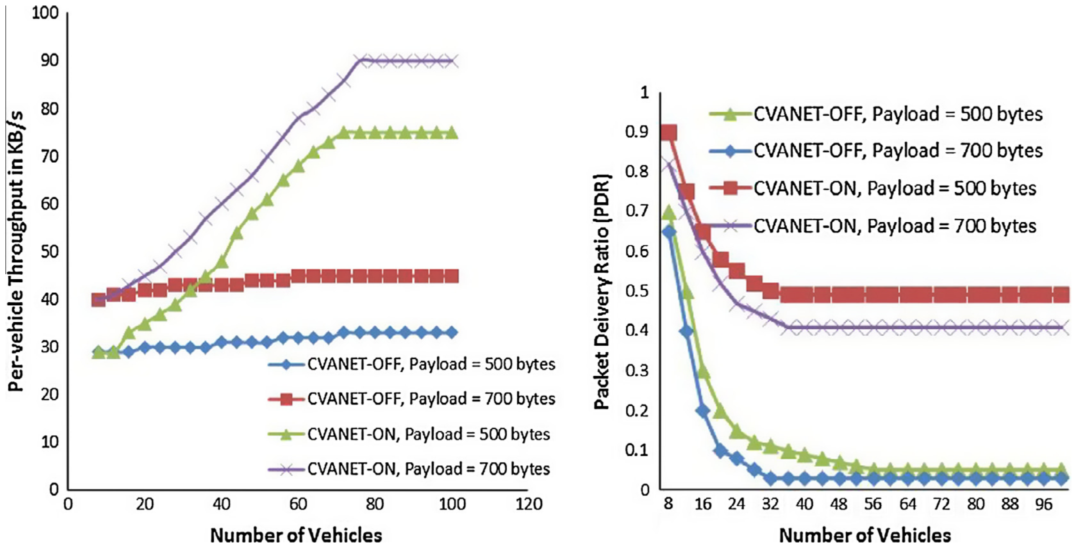

Fig. 10. Per-vehicle throughput (a) and packet delivery rate (b) versus number of cars.

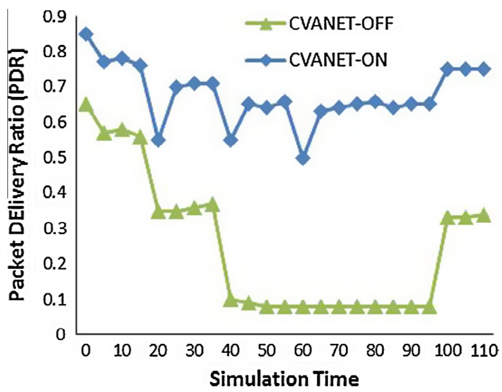

Fig. 11. PDR in case of bursty arrivals.

Finally, the above simulations present a macro-scale view of the proposed system and the improvement reported as compared to the legacy WAVE 802.11p/1609.4 standards. To show the dynamics of the CVANET architecture, we simulate a scenario where the load is increased during simulation time. Packet Delivery Rate (PDR) is reported to visualize the ability of the proposed scheme to cope with increased load conditions and bursty arrivals. At time 20, 40 and 60, we added 25 new vehicles to the simulation scenario, while at time 100, we removed 50 vehicles from the scenario. Fig. 11 shows that the CVANET scheme provides an efficient solution for extreme cases of load increase. The system is able to react fastly to the extra demand for bandwidth, and this avoids the decrease of PDR which occurs in the CVANET-OFF scenario.

6. Concluding remarks

This work introduced a new system that uses cognitive network concepts to extend the spectrum allocated for the control channel in DSRC. The system depends on spectrum sensing provided by cars to yield a distributed measure of contention on the roads and discover white channels in the ISM bands. If contention is detected, free channels from the ISM spectrum are assigned to the cars depending on the severity of the analyzed contention. The NS2 simulations demonstrate the effectiveness of the system in reducing the contention of the CCH, under different load and vehicular traffic conditions. Future works will include the study and comparison of network metrics that reflect the contention conditions of the CCH, and experimental analysis of the spectrum sensing/spectrum allocation framework through small-scale vehicular testbeds.

References

[1] I. Akyildiz, W-Y. Lee, R. Kaushik, CRAHNs: cognitive radio ad hoc networks, Ad Hoc Networks 7 (2009) 810–836.
[2] J. Blau, Car talk: Europe begins testing vehicle to vehicle and vehicle to infrastructure communications systems, IEEE Spectrum 45 (10) (2008).
[3] BMW ILENA Project News, BMW to Develop a New Navigation System that Learns the Driver's Destination of Choice, News Article, February 24th, 2009. <http://www.4wheelsnews.com/tag/bmw-ilena-project-news>.
[4] Q. Chen, F. Schmidt-Eisenlohr, D. Jiang, M. Torrent-Moreno, L. Delgrossi, H. Hartenstein, Overhaul of IEEE 802.11 modeling and simulation in NS-2, in: 10th ACM Symp. Modeling, Analysis, and Simulation of Wireless and Mobile Systems, 2007.
[5] K. Fawaz, A. Ghandour, M. Olleik, H. Artail, Improving reliability of safety applications in vehicle ad hoc networks through the implementation of a cognitive network, in: 17th IEEE International Conference on Telecommunications 2010 (ICT2010), April 2010, Doha, Qatar.
[6] T. Erpek, M. Lofquist, K. Patton, Spectrum Occupancy Measurements, Shared Spectrum Company Report, 2007.
[7] H. Hassanzadeh, Reliable Broadcast of Safety Messages in Vehicular Ad hoc Networks, Master Thesis, Department of Electrical and Computer Engineering, University of Toronto, 2008.
[8] IEEE 1609.3-2010, IEEE Standard for Wireless Access in Vehicular Environments (WAVE) – Networking Services, 2010.
[9] IEEE 1609.4-2010, IEEE Standard for Wireless Access in Vehicular Environments (WAVE) – Multi-Channel Operation, 2011.
[10] D. Jiang, L. Delgrossi, IEEE 802.11p: towards an international standard for wireless access in vehicular environments, in: IEEE Vehicular Technology Conf., 2008, pp. 2036–2040.

[11] D. Jiang, Q. Chen, L. Delgrossi, Communication density: a channel load metric for vehicular communications research, in: IEEE International Conference on Mobile AdHoc and Sensor Systems, 2007, pp. 1–8.
[12] D. Jiang, Q. Chen, L. Delgrossi, Optimal data rate selection for vehicle safety communications, in: 5th ACM International Workshop on Vehicular Inter-Networking, 2007, pp. 1–8.
[13] X. Ma, X. Chen, H. Refai, Performance and reliability of DSRC vehicular safety communication: a formal analysis, EURASIP Journal on Wireless Communications and Networking (2009). pp. 1–13.
[14] J. Poston, W. Horne, Discontiguous OFDM considerations for dynamic spectrum access in idle TV channels, in: 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005, pp. 607–610.
[15] R. Rajbanshi, A. Wyglinski, G. Minden, An efficient implementation of NC-OFDM transceivers for cognitive radios, in: 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2006, pp. 1–5.
[16] M. Raya, J.-P. Hubaux, The security of vehicular ad hoc networks, in: 3rd ACM Workshop on Security of Ad Hoc and Sensor Networks, 2005, pp. 11–21.
[17] M. Torrent-Moreno, D. Jiang, H. Hartenstein, Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks, in: 1st ACM International Workshop on Vehicular Ad Hoc Networks, 2004, pp. 10–18.
[18] M. Torrent-Moreno, P. Santi, H. Hartenstein, Distributed fair transmit power adjustment for vehicular ad hoc networks, IEEE Sensor and Ad Hoc Communications and Networks 2 (2006) 479–488.
[19] Z. Wang, M. Hassan, How much of DSRC is available for non-safety use?, in: 5th ACM International Workshop on Vehicular Inter-Networking, 2008, pp. 23–29.
[20] Q. Xu, T. Mak, J. Ko, R. Sengupta, Vehicle-to-vehicle safety messaging in DSRC, in: 1st ACM International Workshop on Vehicular Ad Hoc Networks, 2004, pp. 19–28.
[21] J. Yin, T. ElBatt, G. Yeung, B. Ryu, S. Habermas, H. Krishnan, T. Talty, Performance evaluation of safety applications over DSRC vehicular ad hoc networks, in: 1st ACM International Workshop on Vehicular Ad Hoc Networks, 2004, pp. 1–9.
[22] G. Ganesan, Y. Li, Agility improvement through cooperative diversity in cognitive radio, in: Proc. IEEE Global Telecomm. Conf. (GLOBECOM '2005), St. Louis, Missouri, 2005, pp. 2505–2509.
[23] D. Cabric, S. Mishra, R. Brodersen, Implementation issues in spectrum sensing for cognitive radios, in: Asilomar Conference on Signals, Systems and Computers, vol. 1, Pacific Grove, California, USA, 2004, pp. 772–776.
[24] T. Yucek, H. Arslan, A survey of spectrum sensing algorithms for cognitive radio applications, IEEE Communications Surveys & Tutorials 11 (1) (2009) 116–130.
[25] M. Di Felice, R. Doost-Mohammady, K.R. Chowdhury, L. Bononi, Smart radios for smart vehicles: cognitive vehicular networks, IEEE Vehicular Technology Magazine 7 (2) (2012) 26–33.
[26] S. Pagadarai, A.M. Wyglinski, R. Vuyyuru, Characterization of vacant UHF TV channels for vehicular dynamic spectrum access, in: IEEE VNC, 2009.
[27] M. Di Felice, K. Chowdhury, L. Bononi, Cooperative spectrum management in cognitive vehicular ad hoc networks, in: IEEE VNC, 2011.
[28] A.W. Min, K.G. Shin, Impact of mobility on spectrum sensing in cognitive radio networks, in: ACM Infocom, 2009.
[29] H. Li, D. K. Irick, Collaborative spectrum sensing in cognitive radio vehicular ad hoc networks: belief propagation on highway, in: IEEE VTC-Spring, 2010.
[30] K. Tsukamoto, Y. Omori, O. Altintas, M. Tsuru, Y. Oie, On spatially-aware channel selection in dynamic spectrum access multihop inter-vehicle communications, in: IEEE VTC-Fall, 2009.
[31] W. Kim, S.-Y. Oh, M. Gerla, K. Lee, CoRoute: a new cognitive anypath vehicular routing protocol, in: 8th International Wireless Communications and Mobile Computing Conference (IWCMC), 2011, pp. 766–771.
[32] A. J. Ghandour, K. Fawaz, H. Artail, Data delivery guarantees in congested vehicular ad hoc networks using cognitive networks, in: 7th International Wireless Communications and Mobile Computing Conference (IWCMC), July 5–8, 2011, Istanbul, Turkey.
[33] X. Wang, P.-H. Ho, A novel sensing coordination framework for CR-vanets, IEEE Transactions on Vehicular Technology 59 (4) (2010) 1936–1948.
[34] D. Niyato, E. Hossain, P. Wang, Optimal channel access management with QoS support for cognitive vehicular networks, IEEE Transactions on Mobile Computing 10 (4) (2011) 573–591.
[35] A.J. Ghandour, M. Di Felice, H. Artail, L. Bononi, Modeling and simulation of WAVE 1609.4-based multi-channel vehicular ad hoc networks, in: 5th ACM International Conference on Simulations Tools and Techniques (SIMUTools 2012), March 19–23, 2012, Sirmione-Desenzano, Italy.
[36] J. Misic, G. Badawy, V. Misic, Performance characterization for IEEE 802.11p network with single channel devices, IEEE Transaction on Vehicular Technology 68 (4) (2011) 1775–1789.
[37] S. Eichler, Performance evaluation of the IEEE 802.11p WAVE communication standard, in: IEEE VTC-Fall, Baltimore, 2007, pp. 2199–2203.
[38] C. Campolo, A. Molinaro, A. Vinel, Understanding the performance of short-lived control broadcast packets in 802.11p/WAVE vehicular networks, in: IEEE VNC, Amsterdam, 2011, pp. 1–8.
[39] W. Kim, A.J. Kassler, M. Di Felice, M. Gerla, Cognitive multi-radio mesh networks on ISM bands: a cross-layer architecture, in: 29th IEEE International Performance Computing and Communications Conference (IPCCC 2010), Albuquerque, USA, 2010.
[40] T. Ross, Fuzzy Logic in Engineering Applications, McGraw-Hill, New York, 1995.
[41] T. A. Runkler, M. Glesner, DECADE—fast centroid approximation defuzzification for real time fuzzy control applications, in: ACM Symposium of Application Computing (SAC'94), Phoenix, AZ, 1994, pp. 161–165.
[42] U.S. Supreme Court, FCC v. League of Women Voters of California, 468 U.S. 364, 1984. <http://laws.findlaw.com/us/468/364.html>.
[43] R.J.C. Bultitude, T.C.W. Schenk, N.A.A.O. den Kamp, N. Adnani, A propagation-measurement-based evaluation of channel characteristics and models pertinent to the expansion of mobile radio systems to frequencies beyond 2 GHz, IEEE Transactions on Vehicular Technology 56 (2) (2007) 382–388.

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