Analyzing the Potential of Cooperative Cognitive Radio Technology on Inter-Vehicle Communication

(Invited Paper)

Marco Di Felice*, Kaushik Roy Chowdhury†, Luciano Bononi*
* Department of Computer Science, University of Bologna, Italy
Email: {difelice,bononi}@cs.unibo.it
† Department of Electrical and Computer Engineering, Northeastern University, Boston, USA
Email:{krc}@ece.neu.edu

***Abstract*—Recent studies demonstrate that Cognitive Radio (CR) technology can increase the spectrum efficiency of wireless systems, provided that the activity of primary users (PUs) must be carefully protected. For this reason, several sensing schemes leverage the cooperation among nodes to increase the accuracy of PU detection. In this paper, we propose to employ the CR principles in the vehicular environment in order to increase the spectrum opportunities for inter-vehicle communication (IVC). We propose a cooperative sensing and spectrum allocation scheme through which vehicles can share information about spectrum availability of TV channels on their path, and dynamically decide the channels to use on each road segment. Moreover, we investigate the role of vehicular mobility in the cooperation process, which might allow a vehicle to know *in advance* the spectrum availability on future locations along its path. Simulation results confirm the ability of our scheme in providing robust PU detection under fading conditions, and analyze the impact of some vehicular networks characteristics into the operations of CR systems.**

***Index Terms*—Cognitive Radio Systems, Vehicular Ad Hoc Networks, Spectrum Sensing, Modeling and Simulation.**

I. Introduction

Recently, Cognitive Radio (CR) technology has emerged as the key solution to support the increasing demand of spectrum for wireless communications, through the implementation of the Opportunistic Spectrum Sharing (OSS) paradigm [1][10]. Following such a paradigm, CR devices are allowed to use all the available spectrum resources, under the constraint that the operations of the licensed users of the bands[1] must not be affected. Most of current research on CR technology has focused on applications to: increase the capacity in backhaul wireless mesh networks, establish reliable communication in emergency networks or favor the bridging of heterogeneous wireless networks [1][9]. In this paper we investigate the application of CR principles on Vehicular Ad Hoc Networks (VANETs), with the goal of increasing the available bandwidth for inter-vehicle communication (IVC). For this purpose, we propose a novel spectrum management framework for cognitive VANETs called *Cog-V2V*, which allows the vehicles to use spectrum holes in the ultra-high frequency (UHF) television (TV) bands in an opportunistic way. *Cog-V2V* includes: a novel cooperative spectrum sensing scheme and an IEEE 802.11p/1609.4-compliant spectrum allocation scheme. Although the integration of CR and IVC systems is still at a preliminary stage [4][8][12], we think there are important observations which might give momentum to the research on this field in the future of telecommunications.

The first observation is that CR technology can effectively alleviate the problem of spectrum scarcity in VANETs. In 1999, the U.S. Federal Communication Commission reserved seven 10Mhz wide channels in the 5.9Ghz portion of the spectrum for vehicular communications [6]. From that, several IEEE working groups have been working on the standardization of the protocol stack for the Wireless Access in Vehicular Environments (WAVE). Among others, we mention here the IEEE 802.11p [14] and IEEE 1609.4 [5] amendments which regulate the Medium Access Protocol (MAC) and its extension for multi-channel operations, respectively. However, despite the usage of dedicated protocols and frequency resources, recent studies show that bandwidth allocation is still a severe problem in VANETs, due to increasing number of users (e.g. vehicles) and applications which might compete for the same channel on the same area [13]. It is demonstrated that the channel bandwidth foreseen by the 802.11p standard might be inadequate to support the severe requirements of VANETs safety-applications in peak hours of traffic [4]. Similarly, there is a risk of spectrum starvation for not-safety applications which scavenge the remaining spectrum resources [12]. At the same time, statistics show that a consistent percentage of TV band in the 400-600 Mhz is left unused in small cities and rural areas of US [8]. Thus, it is reasonable to allow the vehicles to make opportunistic usage of TV-band spectrum channels, also considering that such usage is intrinsically limited in time/space by the vehicles' movement.

The second observation is that the vehicular environment can have a direct impact on CR spectrum management functionalities, which include (*i*) spectrum sensing functionalities, i.e. how to identify *spectrum holes* in the licensed bands and (*ii*) spectrum decision functionalities, how to choose the most suitable spectrum portion for communications. Most of the literature on CR systems has focused on spectrum sensing techniques under static network assumptions, relying on individual or cooperative schemes [3]. Previous results have demonstrated that cooperative spectrum sensing can achieve

[1]In the literature of CR systems, licensed users are commonly referred as Primary Users (PU) of the spectrum.

978-1-4244-9229-9/10/$26.00 ©2010 IEEE

higher detection accuracy in the presence of faded PU signals [10][11]. Here, we highlight that the vehicular environment exhibits some extra characteristics, which must be taken into account by cooperative sensing schemes, i.e.:

- *Duration of spectrum opportunities*. Unlike static CR systems, the spectrum availability can dynamically change over time as a function of PU activity *and* as a consequence of the vehicles' movements. Duration of spectrum opportunity depends on nodes' speed, but it can last few seconds on high mobile scenarios (e.g. highways). As a result, it is crucial for a vehicle to detect spectrum holes as fast as possible, minimizing the overhead of frequency scanning.
- *Planned direction of movements*. Unlike generic MANETs, here the vehicles move along roads with fixed topologies. Given the average speed, current speed, and road trajectory, the future position of a vehicle can be predicted. As a result, each vehicle can be interested in knowing *in advance* the spectrum resources available on its path, so that it can decide the channel schedule to be used *before* accessing a given area.
- *Multiple points of observation*. Individual sensing can be biased as an effect of shadowing, fading and Doppler shifts phenomena on the received signal [9][10]. However, since vehicles move on lanes, they can average multiple samples from different locations in the PU range domain, and hopefully reduce the probability of PU mis-detection.

Benefits of collaborative spectrum sensing schemes on CR-based vehicular systems have been investigated in some preliminary works [4][8][12]. In [4], the authors propose a CR-based architecture in which data sensed by the vehicles are sent to road units that in turn forward the aggregated data to a processing unit. Analogously, [12] introduces a framework for coordinated spectrum sensing, where road units define the set of channels which must be sensed by individual vehicles. However, both [4][12] assume the presence of a road-side infrastructure, and are not suitable for supporting inter-vehicle communication systems. In [8], the authors apply Belief Propagation techniques so that each vehicle can combine different observations coming from other vehicles, considering the spatial correlation of received data. However, the performance of the distributed sensing scheme is analyzed for a three vehicle case only. To the best of our knowledge, an exhaustive study of costs and benefits of cooperative sensing in CR-based VANETs is still missing.

In this paper, we attempt to fill this gap by proposing the *Cog-V2V* framework, through which we address three main contributions. First, we propose a light-weight cooperative sensing scheme for the vehicular environment, through which vehicles can exchange sensing information and detect spectrum holes along their paths. Second, leveraging the vehicular mobility, we show how each vehicle can use the received information to decide in advance the channel to use on future locations, so that spectrum opportunities are better exploited. Third, we discuss how the proposed framework can be integrated into the existing IEEE 802.11p/1609.4 protocol stack. Simulation results investigate the impact of several parameters (e.g. vehicle density, broadcast frequency, etc) on the cooperative sensing, and confirm the ability of *Cog-V2V* in increasing the accuracy of PUs detection over several scenarios and network conditions.

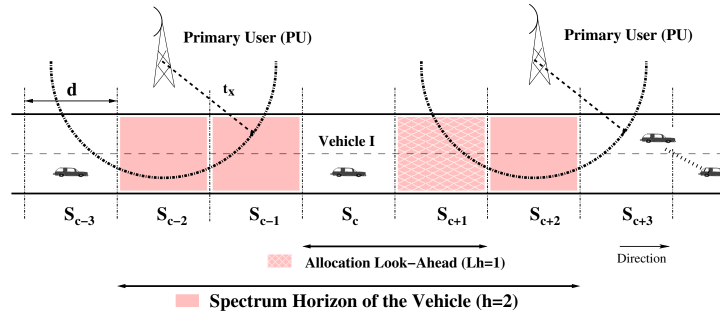


Fig. 1. The highway scenario.

The reminder of the paper is organized as follows. The system model is described in Section II. In Section III, we describe our architecture for cooperative sensing and spectrum allocation, which is evaluated in Section IV. We discuss extensions and future works in Section V.

II. System Model

In this section, we describe the system model of *Cog-V2V*, considering the scenario, the channel and the communication models.

Scenario model. For sake of simplicity, we consider a target scenario of a multi-lane highway, as the one depicted in Figure 1. The extension to the urban environment will be addressed as future work. We assume each vehicle is equipped with a Global Positioning System (GPS) receiver, so that it is aware of its current location. Moreover, we assume the highway to be divided into a set of segments of equal length d. Each segment can be uniquely identified by a couple: $< H_{id}, S_{id} >$ where H_{id} is a number identifying the highway and S_{id} is a progressive number identifying a segment on that highway. We also assume this information is included into the digital maps and shared among the vehicles, so that each vehicle is aware of the current segment S_c where it is moving on. This approach can be easily implemented by identifying a reference point of the highway for all the vehicles of the scenario, and then assigning a progressive number to each segment.

Channel model. In *Cog-V2V*, each vehicle is allowed to use one of the licensed channels in the UHF-TV band. For this purpose, we assume the TV spectrum band to be divided into M channels. Each TV band can be used by a licensed PU (i.e. TV broadcaster) which is fixed, although its position might be unknown to vehicles. Each PU is characterized by a pattern of activity, which is modeled according to the

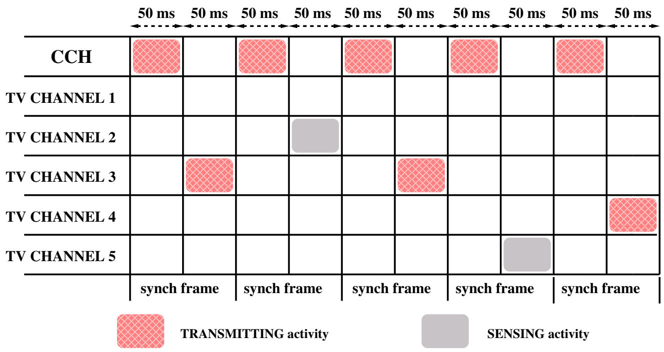


Fig. 2. The channel model for $M = 5$ and T_s=150ms.

exponential ON/OFF model [7]. Moreover, we assume each TV broadcaster has a transmitting range t_x which is $>> d$, i.e. each PU transmission can potentially affect several segments on the highway.

Communication model. We assume each vehicle is equipped with an 802.11p/1609.4 IEEE compliant radio transceiver, which also supports spectrum-agile capabilities and sensing functionalities. Through this radio interface, each vehicle can communicate with other vehicles on its transmission range without the aim of road-side infrastructures. Basically, we are considering here a completely *decentralized* VANET architecture. The spectrum sharing scheme is based on the 1609.4 IEEE protocol [5], which enhances the underlying 802.11p MAC scheme for multi-channel operations [6]. Under such scheme, all the stations are synchronized and cyclically switch between a common control channel (CCH) and a service channel (SCH). The CCH duration is 50 ms, and it is used to transmit control or management information. The SCH duration is also 50 ms, and it is employed for data transmission. Compared to classical 1609.4 IEEE scheme, we introduce two important novelties. First, we allow each vehicle to use any of the M channels in the SCH interval. Second, we assume each vehicle periodically senses the TV licensed spectrum by using an energy-detector scheme [3], in order to detect the spectrum holes. Spectrum sensing is performed every T_s time intervals and occupies a full SCH slot, which can not be used for data transmission. Optimal sensing schedule is out of the scope of this paper, and is addressed in [7]. Without loss of generality, we assume here that sensing frequency is fixed and channel to sense is chosen randomly among the available M licensed channels. Figure 2 shows an example of spectrum sharing operations of a vehicle, for the case of M=5 and T_s=150ms.

III. *Cog-V2V* Architecture: Spectrum Sensing and Allocation

In this section, we describe the rationale of the *Cog-V2V* framework, while the implementation details are provided in Sections III-A, III-B, III-C. Periodically, each vehicle performs energy-detection sensing on a licensed channel, using the model described in Section II. Results from sensing activity are stored in a spectrum availability table (Section III-A), and periodically broadcasted on the CCH with a frequency of T_b time units. When a vehicle receives a sensing message from another vehicle, it updates its table by merging the local and received data through the aggregation scheme of Section III-B. We highlight here that in *Cog-V2V* each vehicle keeps a set of information on spectrum availability for all the road segments included in a *spatial horizon* distance, whose length is a multiple of the segment length d. As we can see from Figure 1, the spatial horizon includes both past and future road segments, so that a vehicle moving in segment S_c can be aware of spectrum availability in segments $S_{c+1}, S_{c+2}, ..$[2] by leveraging the vehicles' cooperation. Based on such a knowledge, and given the constrained nature of mobility on highways, a vehicle can decide in advance the channels to be used for its communication over the segments $S_{c+1}, ...S_{i+L_h}$. The spectrum schedule over the next L_h segments is decided by the allocation scheme described in Section III-C, and is broadcasted on the CCH by the vehicle while in segment S_c. Basically, the L_h parameter governs the frequency of channel allocation in space/time, and for this reason is referred as the *spectrum-lookhead* of our framework. The optimal setting of L_h and its impact on system performance are investigated in the evaluation section (Section IV). Then, the IVC communication is employed by following the same approach of the SSCH-MAC [2] protocol, which implements multi-channel operations on a single 802.11 radio transceiver. If a vehicle A needs to communicate with a vehicle B, it needs to listen to the CCH to receive the spectrum schedule of A. Based on such a schedule, vehicle A tunes its radio to the the same channel of B and performs channel hopping accordingly on each of the L_h segments. Algorithm 1 shows the description of the main functionalities of *Cog-V2V*.

A. Spectrum Availability Table

In *Cog-V2V*, each vehicle collects the results of the sensing activity in a spectrum availability table, which contains a list of entries with this format:

$$< S, f, \overline{P_{S,f}}, n_{S,f}, O_{S,f} > \quad (1)$$

where:

- $S \in H$ is the identifier of a segment in the horizon (H);
- $f \in M$ is a TV licensed channel;
- $\overline{P_{S,f}}$ is the average power measured in channel f and segment S (in dBm);
- $n_{S,f}$ is the number of sensing samples which were averaged in the current estimation of $\overline{P_{S,f}}$;
- $O_{S,f}$ identifies the vehicles which produced the $n_{S,f}$ sensing samples for channel f and segment S (Details are provided in section III-B).

If a vehicle is moving on segment S_c, then the spatial horizon H is defined as the set of segments in range $[S_{c-h} : S_{c+h}]$, where h bounds the horizon size. Figure 1 shows the case with h=2. While moving, the spectrum horizon is dynamically

[2] We are considering the case of a vehicle moving upward from segment S_c to segment S_{c+1}

re-computed, and entries for segments outside the range are automatically removed from the table. It is easy to see that higher values of h translates into higher degree of awareness of the spectrum occupancy in the current environment, but also imposes additional costs in terms of memory requirements and communication overheads.

B. Sensing Data Aggregation

Every T_b intervals, each vehicle broadcasts a SENSE message on the CCH including the content of its spectrum availability table. When a vehicle I receives a SENSE message from vehicle J, it updates the entries corresponding to segments in its spatial horizon, i.e. H_I. The merging rule for segment S and channel f is defined as follows:

$$\overline{P^I_{S,f}} = (1-\alpha)\cdot\overline{P^I_{S,f}} + \alpha\cdot\overline{P^J_{S,f}} \quad (2)$$

where α is a weighting factor. It is reasonable to assume that a vehicle collecting more sensing samples on a given channel/segment can provide higher accuracy on PU detection. For this reason, we define α as follows:

$$\alpha = \frac{n^J_{S,f}}{n^J_{S,f} + n^I_{S,f}} \quad (3)$$

In case of local sensing, we use Equation 2 with α=0.5. In *Cog-V2V*, each vehicle keeps track only of the aggregated value of $\overline{P_{S,f}}$, but not of the sensing samples which produced the average value. Due to the locality of wireless communication, it is possible that the values of $\overline{P^I_{S,f}}$ and $\overline{P^J_{S,f}}$ are somehow correlated because they contain an overlapping set of sensing samples from the same vehicles. For this reason, we introduced a special entry in the table (e.g $O^I_{S,f}$) to identify the vehicles which produced the sensing samples. Before merging the data, vehicle I computes a similarity function f between $O^I_{S,f}$ and $O^J_{S,f}$, and merges data through Equation 3 only if the similarity is lower than a predefined threshold ϕ:

$$f(O^I_{S,f}, O^J_{S,f}) < \phi \quad (4)$$

There are different methods to define $O^I_{S,f}$. In the following, we provide some implementation hints for solving this problem, underlying however that this issue does not constitute the main relevant part of our proposal. A computational-efficient but memory-costly method is to define $O^I_{S,f}$ as the *list of identifiers* of the vehicles which produced the aggregated sensing value. In that case, the similarity function is defined as follows:

$$f(O^I_{S,f}, O^J_{S,f}) = \frac{|O^I_{S,f} \cap O^J_{S,f}|}{|O^I_{S,f}|} \quad (5)$$

An alternative approximated method to define $O^I_{S,f}$ leverages the properties of prime numbers. For this purpose, we assume that each vehicle can randomly select a prime number as pseudo-identifier from a pre-shared table of prime numbers. Due to the unique factorization theorem, each set of vehicles can then be represented as the product of the pseudo-identifiers of the vehicles composing the set, in an unique way. In some cases, this approach can reduce the amount of memory required, although introducing additional complexities on the computation. For space shortage, we omit further details of this approach here.

Instead, we highlight that the *Cog-V2V* aggregation scheme described so far constitutes a simple yet effective cooperative scheme, which can be implemented on top of existing radio technologies. It is worth to mention that more accurate cooperative sensing techniques can be employed when the CR nodes are allowed to share detailed spectrum information, or when statistical methods are used to detect correlation between sensing samples [3][10][11]. However, all these techniques might not be practical for the VANET environment, where radio devices are constrained in computational and communication capabilities, and where spectrum conditions dynamically change because of the vehicles' mobility.

C. Spectrum Data Allocation

Based on the information on its spectrum availability table, each vehicle can determine the presence of TV-spectrum holes in current and future segments along its path. Denoting with $H(S,f)=0$ the hypothesis that PU is active on channel f and segment S, and with $H(S,f)=1$ the hypothesis that the channel is free from PU activity (i.e. it is a spectrum hole), the classification rule for vehicle I can be written as follows:

$$H(S,f) = \begin{cases} 0 & \text{if } \overline{P^I_{S,f}} > \rho \\ 1 & \text{if } \overline{P^I_{S,f}} \leq \rho \end{cases} \quad (6)$$

where ρ is the sensitivity threshold of the PU energy detector scheme. Based on such classification, vehicle I in segment S_c determines the Spectrum Holes List (SHL) for each of the segments S_i in the range $[S_{c+1} : S_{c+L_h}]$:

$$SHL_{S_i} = \{f \in M | H(S_i, f) = 1\} \quad (7)$$

and builds the spectrum schedule Sch by choosing exactly one channel from SHL_{S_i} for each of the next L_h road segments:

$$Sch = \{ < S_i, f > | c+1 \leq i \leq c+L_h, f \in SHL_{S_i}\} \quad (8)$$

When SHL_S contains more than one element for a given segment S, then channel selection should be performed by taking into account additional parameters such as amount of interference from CR users, channel utilization, etc. In this paper, we let each vehicle choose randomly a channel from SHL_S, when multiple choices are available for segment S. We plan to extend the channel allocation scheme with novel selection metrics as future work.

IV. Performance Evaluation

In this section, we evaluate the performance of the *Cog-V2V* framework through an extended version of the NS-2.34 simulator. We consider a multi-lane highway scenario of 8 km length divided into segments of d=100m length. Each vehicle moves at uniform speed v, with $v \in [25:30]$ m/s, and is equipped with an 802.11p radio transceiver. We consider the following channel environment. The licensed spectrum band

Algorithm 1 *Cog-V2V* operations for vehicle I

Broadcast function:
Broadcast SENSE message every T_b interval

Aggregate function:
When receiving a SENSE message from vehicle J:
for each segment $S \in H_I$ **do**
  for each channel $f \in M$ **do**
    compute similarity function f on set of observers
    if $f(O^I_{S,f}, O^J_{S,f}) < \phi$ **then**
      Update $P^I_{S,f}$ through Equation 2
      Update $O^I_{S,f}$ and $n^I_{S,f}$
    end if
  end for
end for

Allocate function:
set schedule list $Sch = \emptyset$
for each segment S_i in range $[S_{c+1} : S_{c+L_h}]$ **do**
  Build the spectrum hole list SHL_{S_i} through Equation 7
  Choose a channel $f \in SHL_{S_i}$
  Sch = $Sch \cup \{< S_i, f >\}$
end for
Broadcast a SCHEDULE message with Sch on CCH

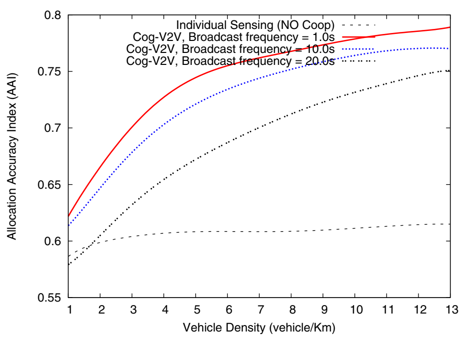


Fig. 3. The Allocation Accuracy as a function of the vehicle density.

is divided into 5 channels (i.e. $M = 5$), and each channel can be occupied by a TV broadcast PU which transmits according to an exponential ON/OFF activity pattern [7]. Without loss of generality, we consider here a static PU case where the PUs are always active (i.e. always ON). The extension to the case of alternate ON/OFF PU activity will be addressed as future works. There are 8 PUs in the current scenario, and each PU transmits up to 1 Km of distance to PU receivers. PU are located at the borders of the highway, so that: *(i)* the activity of a single PU can affect multiple segments of the highway and *(ii)* there is at least one spectrum hole available for IVC on each segment. We consider a Nagakami multi-path propagation model, which allows to take into account the impact of fading on PU sensing activity. Unless specified otherwise, we set the *Cog-V2V* network parameters in this way: $T_s = 0.3s$ (sensing frequency), $h = 5$ (horizon size), $L_h = 1$ (spectrum look-ahead). We investigate the ability of *Cog-V2V* to provide opportunistic usage of licensed bands, while protecting the activity of PUs. For this reason, we consider three main metrics:

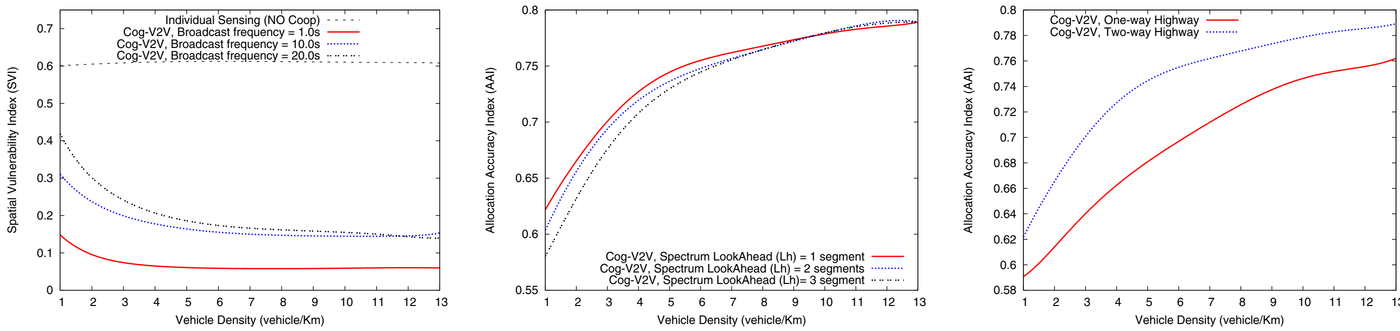
- *Allocation Accuracy Index (AAI)*. This is defined as the probability that a vehicle has chosen a channel which is not used by a PU transmission. Conversely $1 - AAI$ is the probability that channel allocation has incurred in a collision with PU activity.
- *Spatial Vulnerability Index (SVI)*. In case of PU mis-detection on the current channel and segment, this is defined as the ratio of segment length after which a vehicle detects the PU presence on the current channel. More specifically, the SVI metric is defined in this way:

$$SVI = min\{\frac{space\_covered}{d}, 1\} \tag{9}$$

where d is the segment length, and $space\_covered$ is the distance covered by the vehicle from the segment start till the location where the PU was detected on the current segment. If the vehicle traverses all the segment without detecting the PU activity, then we normalize SVI to 1.

We highlight that these two metrics can provide an orthogonal view of the performance of our sensing and allocation framework. With the AAI metric, we test the ability to perform accurate spectrum decision, based on local and received sensing information. With the SVI metric, we measure the responsiveness of the system in case the system allocation incurred in an error due to PU mis-detection. Figure 3 shows the AAI as a function of the vehicle density on the highway. We compare the performance of *Cog-V2V* with those of a non-cooperative scheme, in which each vehicle decides the channel to use based on its local sensing observation only[3]. Moreover, we consider different configurations of the *Cog-V2V* framework for different values of the broadcast interval T_b, i.e. 1.0s, 10.0s and 20s. Basically, T_b governs the rate of spectrum information sent by each vehicle, and thus it reflects the amount of cooperation in the VANET. From Figure 3, we can see that cooperative sensing can greatly increase the probability to detect spectrum holes compared to a non-cooperative approach, due to following reasons. First, cooperative sensing alleviates the impact of fading and shadowing effects on PU detection, since multiple (possible not-correlated) sensing samples might be available at each vehicle for the same segment and channel. Second, cooperative sensing allows a vehicle to quickly collect spectrum information of all the M channels although it can perform sensing on just one channel at the time every T_s time intervals. Moreover, the accuracy of the cooperative sensing scheme improves with the number of vehicles and the level of cooperation among them. At the same time, Figure 3 shows that the performance of *Cog-V2V* become stable when considering high values of vehicle density and broadcast frequency, due to impact of the increasing contention on the CCH, which might cause SENSE messages to be discarded at MAC layer. Figure 4(a) shows the SVI metric as a function of the vehicle density. If a vehicle relies on individual sensing only, it will detect the presence of a PU on the current channel on average only after

[3]This scheme is indicated as "Individual Sensing" in Figures 3 and 4(a)



(a) (b) (c)

Fig. 4. Figure 4(a) shows the Spatial Vulnerability Index (SVI) as a function of the vehicle density. Figure 4(b) and 4(c) show the Allocation Accuracy for different values of the spectrum look-ahead L_h (Figure 4(b)) and different highway scenarios (Figure 4(c)).

having covered 60% of the segment size d (approximately after 60m, since d=100m in our experiments). Based on the vehicle's speed, this spatial overlapping with the activity of PUs might translate into harmful interference to PU receivers over time. Figure 4(a) shows that the SVI decreases to less than 6% in the case of *Cog-V2V*, due to fact that a vehicle can learn the presence of PU on the current segment/channel from other vehicles, and dynamically switch to an alternative channel. In Figure 4(b) we test the ability of *Cog-V2V* to perform accurate allocation in advance, varying the values of the spectrum-lookahead L_h. As described in section III-C, each vehicle moving in segment S_c defines the spectrum schedule over next segments $S_{c+1}, S_{c+2}, ...S_{L_h}$. In Figure 4(b), we consider three configurations of *Cog-V2V* with L_h equal to 1,2,3 respectively, and with T_b equal to 1s for all the configurations. Figure 4(b) confirms the intuitive idea that the allocation accuracy depends on the segment distance and on the amount of spectrum information available by each node. In case of low density of vehicle, the accuracy of the allocation decreases when predicting the spectrum conditions over more than one segment of distance. For values of vehicle density higher than 7 vehicles/km, each vehicle can collect enough samples of the spectrum conditions over next segments in its spatial horizon, so that the allocation over next three segments (i.e. $L_h = 3$) is as accurate as the allocation over next segment only (i.e. $L_h = 1$). Figure 4(c) shows the allocation accuracy of the *Cog-V2V* framework for two different highway scenarios. In the one-way scenario, all the vehicles move in the same direction (e.g. North-South direction). In the two-way scenarios, there are separate lanes for vehicles moving in opposite directions (e.g. N-S and S-N directions). From Figure 4(c), we can see that performance are improved when considering a two-way highway scenario, due to the fact that a vehicle can leverage the information from vehicles which already covered its spatial horizon on the opposite direction.

V. Conclusions

In this paper, we have investigated the application of Cognitive Radio principles to Vehicular Ad Hoc Networks (VANETs) in order to increase the spectrum opportunities for inter-vehicle communication. For this purpose, we have proposed the *Cog-V2V* framework which allows vehicles to make opportunistic usage of TV bands on highways. We have described a novel distributed sensing scheme which leverages the cooperation among vehicles, so that a vehicle can be aware of spectrum conditions on future positions along its path. Simulation analysis has investigated the impact of mobility and cooperation on the sensing accuracy, and has shown that our approach can significantly enhance the performance of non-cooperative schemes under fading conditions.

References

[1] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty. NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey. *Computer Networks Journal*, 50(1), pp. 2127- 2159, 2006.

[2] P. Bahl, R. Chandra, and J. Dunagan. SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-hoc Wireless Networks. In *Proc. of ACM MobiCom*, pp. 216-230, Philadelphia, 2004.

[3] D. Cabric, S. M. Mishra, and R. W. Brodersen. Implementation issues in spectrum sensing for cognitive radios in *Proc. of IEEE ACSSC*, pp. 772-776, Pacific Grove, 2004.

[4] K. Fawaz, A. Ghandour, M. Olleik and H. Artail. Improving Reliability of Safety Applications in Vehicle Ad hoc Networks through the Implementation of a Cognitive Network. in *Proc. of IEEE ITC* , pp. 798-805, Doha, 2010.

[5] IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation. *IEEE Std 1609.4-2006*, 2006.

[6] D. Jiang and L. Delgrossi. IEEE 802.11p: Towards an International Standard for Wireless Access in Vehicular Environments. in *Proc. of IEEE VTC Spring*, pp. 2036-2040, Singapore, 2008.

[7] W. Y. Lee and I. Akyildiz. Optimal Spetrum Sensing Framework for Cognitive Radio Networks. in *IEEE Transactions on Wireless Communication*, 7(10), pp. 3845-3857, 2008.

[8] H. Li and D. Irick. Collaborative Spectrum Sensing in Cognitive Radio Vehicular Ad hoc Networks: Belief Propagation on Highway. in *Proc. of IEEE VTC Spring*, pp. 1-5, Taipei, 2010.

[9] D. Maldonado, B. Lie, A. Hugine, T.W. Rondeau, C.W. Bostian. Cognitive radio applications to dynamic spectrum allocation. in *Proc. IEEE DySPAN*, pp. 597600, Baltimora, 2005.

[10] S. M. Mishra, A. Sahai and R. W. Brodersen. Cooperative Sensing among Cognitive Radios. in *Proc. of IEEE ICC*, pp. 1658-1663, Istanbul, 2006.

[11] I. Unikrishnan and V. Veeravalli. Cooperative Spectrum Sensing and Detection for Cognitive Radio. in *Proc. IEEE GLOBECOM*, pp. 2972-2976, Washington, 2007.

[12] X. Y. Wang and P.-H. Ho A Novel Sensing Coordination Framework for CR-VANETs. *IEEE Transaction on Vehicular Technology*, 59(4), pp. 1936- 1948, 2010.

[13] Z. Wang and M. Hassan. How much of dsrc is available for non-safety use? in *Proc. of ACM VANET*, pp. 23-29, San Francisco, 2008.

[14] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Wireless Access in Vehicular Environment *IEEE Std 802.11p/D7.0*, 2009.