A Hidden Markov Model based Scheme for Efficient and Fast Dissemination of Safety Messages in VANETs

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Abstract—Nowadays, Vehicle to Vehicle (V2V) communication is attracting an increasing attention from car manufacturers due to its expected impact in improving driving safety and comfort. IEEE 802.11P is the primary channel access scheme used by vehicles; however it does not provide sufficient spectrum to ensure reliable exchange of safety information. To overcome this issue, many efforts have been devoted to enhance the frequency spectrum utilization efficiency. To this end, the Cognitive Radio (CR) principle has been applied to assist the vehicles to gain extra bandwidth through an opportunistic use of the unused spectrums in their surrounding. In this paper, we focus on safety messages for which we propose an original scheme that makes their exchange among the nearby vehicles more reliable with a significant reduce in their dissemination delay. This improvement is due to the use of a Hidden Markov Model that enables the prediction of the available channels for the subsequent time slots, leading to faster channel allocation for the vehicles. The obtained simulation results confirm the efficiency of our scheme.

Keywords – VANETs, Safety Messages, IEEE 802.11P, Hidden Markov Model, Kalman Filter.

I. INTRODUCTION

Vehicular Ad Hoc Networks (VANETs) [13] are new paradigm of wireless communications that aim to exploit the recent advances in wireless devices technology to enable intelligent inter-vehicle communication. VANETs are distinguished from other wireless networks by their specific characteristics such as; predictable vehicles movement, high speed, powerful processing units, large storage capacities and new applications scenarios. Additionally, VANETs may ensure wide dissemination of data and safety related information due to the large transmission range of vehicles compared to other wireless devices like sensors and handheld equipments. This wide dissemination is also ensured by the specific routing protocols used, such as GPSR [4], BROADCOMM [6] and GEOCAST routing approach [5].

Compared to Wireless Sensor Networks (WSNs) and Mobile Ad hoc Networks (MANETs), VANETs do not suffer from energetic resources scarcity since the vehicle's battery can provide a long term energy supply. Although, VANETs are unable to ensure connectivity between vehicles in certain circumstances like in rural areas where the network density is low. Moreover, VANETs may not guarantee timely detection of dangerous road conditions due to the high mobility of vehicles.

The main objectives of Inter Vehicles Communication (IVC) are improving drivers' and passenger's safety and comfort (e.g. anticipation of any danger, accident, emergency braking from the ahead vehicles etc), allowing better traffic information, providing driving assistance and Internet connection. Due to the expected results of IVC, this communication technology has recently attracted a lot of attention from the research community aiming at developing more Intelligent Transportation Systems (ITS) based applications that make driving easier and safer. To achieve this goal, we need first to design an adequate medium access protocol that fulfills the requirements of vehicular environment along with the ITS applications demands in terms of bandwidth. To this end, many researchers have focused their efforts on designing such MAC protocol, dubbed IEEE 802.11P which is commonly used for vehicular communication. Moreover, the US Federal Communication Commission has reserved seven 10MHz wide channels in the 5.9GHz band for the Dedicated Short Range Communication (DSRC) to support the proliferation of ITS applications. Six out of these channels are Service Channels (SCH, dedicated to communications and applications) and the middle channel is the Control Channel (CCH, dedicated to safety message broadcast).

It has been demonstrated in recent studies that the channel bandwidth as designed by IEEE 802.11P [8] standard (i.e., 10 Mhz) might be inadequate to support the heavy requirements of VANET's safety applications, especially during rush hours. Therefore, it becomes mandatory to design alternative dynamic frequency allocation schemes to replace the currently used static techniques. Hence, this may ensure a reliable exchange between the increasing numbers of vehicles and increases the achieved data rates. Indeed, the users are more likely to seek for extra bandwidth to know how long congestion lasts or to find entertainment (e.g. Internet access, video streaming, P2P applications etc). To satisfy this need of bandwidth, we present in this paper an original cooperative sensing and spectrum allocation scheme that exploits the strength of cognitive radio technology as well as the hidden Markov model properties to increase the bandwidth share of users and diminish the transmission delay of emergency messages.

The remainder of the paper is organized as follows. Section II gives an overview on IEEE 802.11P. Next, we present the most significant contributions for spectrum frequency allocation in VANETs and highlight their limitations in section III. In section IV, we introduce our scheme. In section V, we present and discuss the obtained simulation results. Finally, we conclude in Section VI.

II. OVERVIEW OF IEEE802.11P

In order to provide an efficient means of communication in VANET and facilitate its integration with other networks, such as WSNs to constitute the so-called Hybrid Sensors and Vehicular Networks (HSVNs) [14], the IEEE 802.11P task group has defined a set of specifications for Wireless Access in Vehicular Environment (WAVE) to fulfill the requirements of such challenging environment. IEEE 802.11P operates in the frequency band of 5.85-5.925 GHZ, within which the DSRC spectrum is divided to seven channels of 10MHZ each. The control channel (CCH) is exclusively reserved for safety related communications like beacons and event-driven messages whereas up to six service channels (SCHs) are used for

non safety data exchange. IEEE802.11P uses the same medium access mechanism of IEEE 802.11e, named Enhanced Distributed Channel Access (EDCA) [7]. In IEEE 802.11P, the channel time is divided into synchronization periods of 100 ms each, consisting of equal-length alternating CCH and SCH intervals. Therefore, the vehicles' devices must switch to the frequency of each channel (i.e., the CCH or one of the SCHs) during its specified interval in order to transmit the type of messages authorized during this period. To make this access scheme more accurate, a period equal to 4ms, called Guard Time, is set at the beginning of each interval to account for the radio switching delay and the timing inaccuracies in the devices. Notice that the coordination between channels is achieved through the use of the Coordinated Universal Time (UTC) offered by a global navigation satellite system.

III. RELATED WORK

Before presenting the most recent works dealing with the spectral frequency scarcity in V2V communication, we first give a brief description of cognitive radio technology.

The cognitive radio is a technology that allows a wireless user to interact with its environment using opportunistic management of spectrum resources and according to its needs in terms of Quality of Service (QoS) and security requirements.

To increase the available bandwidth for V2V communication, particularly over the CCH, the authors of [3] have exploited the TV spectrum holes to increase the available bandwidth for vehicles communication through a cognitive radio based scheme. The key idea behind that is as follows; a vehicle senses the radio spectrum in its surrounding to detect its occupancy and usage based on an energy-detector scheme. Once one or more holes are detected, the detector vehicle selects one of these holes (i.e., the spectrum of the Primary Users (PU)) to communicate over it. Notice that in the rest of the paper we use the term secondary users to refer to the vehicles that might use the PU's spectrum holes.

In [9] the authors have proposed a spectrum management framework for cognitive VANET, dubbed Cog-V2V. In this framework, the vehicles can exchange sensing information and detect spectrum holes through a cooperative sensing technique as described below. Each vehicle shares the gathered information regarding the spectrum availability, then it aggregates each received data from its neighbors to make a decision about the channel to use for its transmission. A vehicle can know in advance the spectrum availability by receiving data from other vehicles ahead in the path. The main advantage of this cooperative sensing scheme is that it mitigates the risk of individual detection error. However, the decision about the channel to use is taken individually without coordination with the nearby vehicles. As a consequence, several vehicles may choose the same channel at the same time (i.e., different communications in the same channel may occur), which is the main drawback of this scheme.

In contrast to the previous framework, the authors of [10] have conceived an architecture that uses the road side infrastructure as a supervisor that manages the PU's channel holes assignment to the secondary users. A road-side infrastructure records the data gathered by vehicles (regarding spectrum holes) when they are in its transmission range. Then, it assigns the available channels, if any, for each passing vehicle to prevent multiple simultaneous accesses to the same channel. The road-side infrastructure computes a metric called contention metric which assesses whether there is a contention in the CCH channel or not. If so, the system will exploit the spectrum holes detected by the CR component of the passing vehicles. The main shortcoming of this architecture is its high dependence on the infrastructure's performance. Moreover, these road-side units are very costly for their deployment and maintenance.

Despite being a promising solution to the lack of bandwidth, cooperative sensing based schemes, as introduced in [9], and [10], suffer from two major concerns, as explained below.

- The sensing accuracy is highly dependent on the density of the vehicles.
- The heterogeneity of primary users' signals makes their detection more difficult; indeed the thresholds of detection differ according to the type of signal (21dB for digital TV, 1dB for analog TV and 12dB for wireless microphone).

As opposed to cooperative sensing schemes, in the stand alone mode the secondary users themselves perform the whole process of sensing and decision making. This category of schemes alleviates the problem of density since the vehicles are independent from each others. Despite this advantage over cooperative sensing schemes, this solution has several drawbacks. Simultaneous accesses to the same channel from several secondary users may occur, which leads to troubles. Furthermore, the detection ability of each vehicle relies solely on its own equipment, which may create unfairness among the secondary users as different vehicles are dotted with different equipments and technologies.

To address this issue, [11] has proposed a novel spectrum sensing coordination scheme that aims at taking the best of both sensing approaches (i.e., cooperative and stand alone) to improve the sensing efficiency and accuracy. Its working principle can be summarized as follows; a coordination node is chosen among the vehicles in the network. This node uses an energy based detection technique to speed up the spectrum holes detection. Once the promising channels have been identified by the coordination node, it assigns a part of the spectrum to a secondary user which in its turn performs an additional stand alone sensing to access the available channels. This scheme leaves some freedom for the vehicle to choose which channel to use. It also diminishes the scope of the master/slave relationship of the architecture proposed in [10], which was one of its main drawbacks.

An alternative solution to [11] is proposed in [12] where cognitive radio is used to increase bandwidth spectrum through a decentralized cooperative sensing scheme. In this scheme, the authors propose to apply a Belief Propagation (BP) algorithm to manage the spectrum holes detection. The key principle of BP algorithm can be summarized as follows; first, each vehicle broadcasts a message to all the secondary users in VANET to inform them about its belief of the presence of a PU. Afterwards, each receiver vehicle combines its local observations with the received belief to generate a new belief. The major drawback of BP based schemes is the slow process of available PU's channels detection, which may affect the efficiency of the opportunistic use of the available spectrum holes.

In the next section, we present an original scheme that uses a hidden Markov model in order to circumvent the shortcoming of the previously discussed schemes and speed up the PU's holes detection and assignment to secondary users, which leads to reliable and fast dissemination of emergency messages.

IV. THE PROPOSED SCHEME

In our scheme, we consider a cognitive vehicular network within which the vehicles are organized in clusters to make communication easier and more efficient. A cluster of vehicles is composed of a cluster-head and cluster members. The cluster-head assigns channels to cluster members upon request. Whenever a vehicle arrives within a cluster, it first checks whether a cluster-head already exists or not. If so, it updates the cluster-head information with the identity of the current cluster-head. Otherwise, it serves as cluster-head as stated in [9].

For data transmission, two types of channels will be used; the exclusive channel (a dedicated bandwidth in DSRC) which is reserved for safety related messages transmission and the shared channel that can be used by both PUs and the other vehicles. These vehicles exploit the inactive time slots (i.e., spectrum holes) of the PUs to opportunistically transmit their messages. Therefore, this increases the offered bandwidth of the exclusive channel and leads to fast transmission of safety messages.

In our scheme, spectrum sensing is performed locally by each cluster member in each time slot. Since a cluster is spatially restricted to a small area, we will have redundancy in each vehicle's sensing. We take advantage of this property to estimate the state of the shared channels in the current time slot (i.e., idle or occupied). The final decision about the state of a shared channel is taken by the cluster-head based on the received observations from the vehicles belonging to its cluster. Subsequently, the detected holes in the licensed spectrum are assigned to the vehicles by the cluster-head. The main feature of our scheme is the decrease of the dissemination delay of safety messages compared to the schemes discussed in section III. This is achieved by computing the probability of the expected state (during the subsequent time slot) of each shared channel based on its current status. This probability indicates to the cluster-head how many observations should receive before making the final decision regarding a given shared channel state. Therefore, in the worst case, the cluster-head will wait till receiving the observations from all the cluster members and thus ensures a comparable dissemination delay to the previous schemes; otherwise, it ensures a lower delay that varies according to the computed probability. Note that this probability is computed based on a Hidden Markov Model (HMM) framework as described hereafter.

Let us assume that the state of the channels is a hidden random variable of a HMM. The cluster-head vehicle will estimate the state of each shared channel through a probabilistic computation , thanks to the sensing observations provided by all cluster members. Now, we define our HMM as follows:

- $X(t)$: refers to a state variable in time slot t.
- $Y(t)$: denotes a given observation in time slot t.
- $X(t) = (x_1(t), x_2(t), ..., x_c(t))$

such that c denotes the number of available shared channels, which varies in time and space. We set the following conventions:

- $x_i(t) = 0$ if the channel i is idle at time slot t.
- $x_i(t) = 1$ if the channel i is busy at time slot t.
- $Y(t) = (y_1(t), y_2(t), ..., y_c(t))$

where $y_i(t)$ is the merged observations of all vehicles in the cluster regarding the channel i.

Notice that our model is based on two fundamental but still reasonable assumptions which state that each state $X(t)$ depends only on the last state $X(t-1)$ (i.e., which refers to the Markovian assumption) and a given observation $Y(t)$ depends only on the hidden state $X(t)$. Additionally, we assume that our model is a Linear State Space Model.

We denote by $Q(t)$ the state transition matrix at time slot t, which describes the inner dynamic of the system and by $G(t)$ the measurement matrix at time slot t, which describes the relationship between the hidden state and the measurement. The states and observations are linked by the following equations that constitute the corner stone of our model.

- State equation

$$X(t + 1) = Q(t)X(t) + \varepsilon(t) \qquad (1)$$

- Observation equation

$$Y(1) = G(t)X(t) + \varepsilon'(t) \qquad (2)$$

Here $\varepsilon(t)$ and $\varepsilon'(t)$ are additive Gaussian Noise which refer to the noise measurement at time slot t. Note that this well known model allows us to estimate the state of the hidden variables $X(t)$ and $X(t+1)$ knowing $Y(t)$. Since we are utilising the Linear Gaussian State Space Model, we can use the so-called Kalman filter, described in [2] and [1], to provide an estimation of the laws of $P[X(t)/Y(t)]$ and $P[X(t+1)/Y(t)]$.

Table I: Example of a state table in a given time slot

	$X(t)$	$X(t+1)$
Exclu-Channel	1	1
Shar-Channel1	1	0
Shar-Channel2	1	1
Shar-Channel3	0	0
. . .		
Shar-Channel C	0	1

Table II: Example of the schedule table

Type of messages	Safety (S)	Data (D)
No. of messages to transmit	2	1

A. Kalman Filter overview

The objective is to estimate the random variable X_k from Y_k in an optimal and recursive manner. To this end, we adopt the standard deviation minimum criterion to estimate the conditional distribution of the random vector $X_k/Y_{0:k}$, such that $Y_{0:k}$ denotes the k first observations received by the cluster-head vehicle. Since we are in Gaussian context it is obvious that the variable of interest follows a Gaussian distribution. Hence, we need only to compute the mean and covariance matrix of the distribution. The conditional mean and the covariance matrix are calculated recursively, as shown in Equations 3 and 4, respectively.

$$\hat{X}_k = E(X_k/Y_{0:k}) \qquad (3)$$

$$\hat{X}_k = E[(X_k - \hat{(X)}_k)(X_k - \hat{(X)}_k)^*/Y_{0:k})] \qquad (4)$$

The Kalman Filter achieves this in a two step process, as described below.

- The prediction step: during which the conditional law of X_k knowing $Y_{0:k-1}$ is computed, thanks to the Equation. 1.
- The update step: during which the recently available observation Y_t is used to correct the prediction. This enables to compute the mean and covariance matrix of the distribution of interest.

Once the channel state is estimated by the filter, the cluster-head vehicle will establish a schedule to gather the states of the channels. Note that the exclusive channel is always available, so we set

$$X_{ExcluChannel}(t) = 1$$

The cluster-head will also collect the requests of communication sent by each vehicle, specifying the type of messages to be transmitted (i.e., data, beacon or safety message) and the number of messages in each type. These requests are saved in the so-called schedule table as shown in Table II.

When the cluster-head builds the communication table, it allocates channels to each vehicle following a weighted scheduling scheme. In our scheme, we assign an increasing weight to safety messages in order to speed up their transmission. In next subsection, we give an example to illustrate the functioning of our scheme.

B. Example

We consider a cluster of three vehicles where vehicles V_2 and V_3 have safety and/or data messages to transmit. The cluster-head (i.e., vehicle V_1) assigns an increasing weight to safety messages in order to indicate their priority. When new messages arrive the cluster-head assigns to them a weight equals to 2, 3 etc.

The cluster-head performs channels allocation based on the information contained in Tables I and III. It assigns first the exclusive channel to safety messages with low weight. Then, if the exclusive

channel is not congested the cluster-head allocates its remaining bandwidth to the messages with high weight. Afterwards, the other messages will be transmitted over the shared channels having a state equals to 1. If safety messages cannot be all transmitted at time slot t, the expected state of the shared channels at time slot $t + 1$ is then used to pre-allocate them in order to reduce the channel allocation time.

The main advantage of our model consists in predicting the state of the channel during the next time slot through a probabilistic computation. Hence, we can allocate the data not transmitted at time slot t to the expected free channels during the next time slot. This will significantly reduce the waiting time for the vehicles and consequently decrease safety messages dissemination delay. Therefore, the cluster-head can complete the allocation table with the pre-allocation data for the time slot $t + 1$.

During the observation collection process performed by the cluster-head, a weight is assigned to each measure provided by the cluster member vehicles. This weight is calculated based on the physical distance between the vehicle and the antenna representing the PU's channels. A higher weight is assigned to vehicles closer to the antenna since their observations are more accurate compared to those provided by a farther vehicles. To this end, it is assumed that the cluster-head knows the GPS coordinates of the antenna and those of each vehicle. Therefore, it is able to compute the corresponding weights.

C. Probability calculation

Here, we will explain in details how we calculate the probability of a channel c being available in next time slot based on its status during the ongoing time slot. This probability is calculated as follows.

$$P(X_c(t) = X_c(t-1)) = \frac{1}{N_v} \sum_{i=1}^{N_v} Y_i \omega_i \qquad (5)$$

where N_v is the number of cluster members that have sent their observations to the cluster-head. Notice that the weight ω_i is calculated according to the distance between the vehicle and the antenna. It varies from 1 to 2.

$$\forall i \in \{1, ..., N_v\} 1 \leq \omega_i \leq 2$$

According to the probability calculated in Equation 5, we determine a threshold that defines the number of required observations to confirm the idle status of a given channel.

$$\lambda_{min} \leq P \leq \lambda_{max}$$

If the probability P is smaller than the threshold λ_{min} then the cluster-head waits for more observations. The number of the expected observations to wait for is calculated as follows.

$$N_{obs} = (1 - \lambda_{min}).N_v \qquad (6)$$

On the other hand, if this probability is greater than λ_{max} then the cluster-head builds a table storing channels states for $T + 1$. This table helps this cluster-head to speed up the free channels assignment during the subsequent time slot as it waits only for N_{obs} regarding each channel before making decision about its status (free or occupied).

Channel assignment to vehicles is performed in two steps as follows. First, the cluster-head vehicle identifies the idle channels following two different mechanisms. Secondly, it establishes an assignment order among the vehicles requesting channel access according to the type and the number of messages to transmit.

The cluster-head considers a channel as free according to one of the two mechanisms described below:

- Mechanism 1: among the N_{obs} received, if the number of observations equal to 1 is larger than those equal to 0, then the channel is free. Otherwise, the channel is considered occupied.

Table III: Example of the communication table

	Vehicle1		Vehicle2		Vehicle3	
Request	S1	D1	S2	D2	S3	D3
No. of messages	0	1	2	0	3	1
Weight	-	3	1	-	2	4

Table IV: Example of the allocation table

	$X(t)$	Messages allocation	$X(t+1)$	Messages pre-allocation
Exclu-Channel	1	S2	1	S3
Shar-Channel1	1	S2	0	-
Shar-Channel2	0	-	0	
Shar-Channel3	0	-	1	D1
Shar-Channel4	1	S3	1	D3
Shar-Channel5	1	S3	1	-

- Mechanism 2: the cluster-head awaits till receiving N_{obs} observations confirming the free status of a given channel. If the first N_{obs} observations received are equal to 1 then the channel is considered idle, otherwise the cluster-head should wait till the number of observations equal to 1 reaches the value N_{obs}. If the whole set of observations is received and the N_{obs} of observations equal to 1 is not reached yet, the cluster-head applies the mechanism 1 for the whole set of observations.

V. SIMULATION RESULTS

In this section, we present and discuss the obtained simulation results that evaluate the performance of our scheme. We have conducted our simulation using MATLAB in which we have implemented our scheme and run simulation for several scenarios under various conditions, as summarized in Table V. It is worth mentioning that at the beginning of each simulation, several time slots are used as a training sequence to calculate the probability values to be used in the subsequent time slot. Therefore, during these time slots no PU's channel assignment is performed.

To highlight the effectiveness of our scheme compared to the existing works, we have chosen to measure the following metrics.

- The Average Number of Mini-time Slots (ANMS) required for assigning an idle PU's channel to a vehicle.
- The Percentage of the Extra Bandwidth (PEB) gained by each vehicle, as a consequence of applying our scheme, to its total acquired bandwidth fair-share in the CCH.

Before discussing the results of these metrics let us first analyze the probability values calculated by our scheme in different scenarios. As depicted in Figure 1, the probability of a channel being free in the next time slot based on its current status varies between 0.4 and 0.8. Its lowest value is 0.44 whereas the highest achieved one is equals to 0.79. We observe from these values and their distribution on the different scenarios for each PU's channel that our scheme ensures efficient prediction of channels status. This is due to the fact that each PU's channel is predicted to be free in the next time slot for at least 1 scenario. Notice that no bar is plotted to represent an occupied channel in a given scenario (i.e., its corresponding probability is equal to 0).

One of the most important metrics for evaluating the effectiveness of channel allocation schemes is the time elapsed between the vehicle request and the channel allocation by the cluster-head. The value of this metric is more critical when we deal with safety related messages, especially in VANETs. In the herein conducted simulation, this metric is measured by the means of ANMS value. Figure 2 compares the ANMS values achieved by our scheme to those of the existing schemes (i.e., the schemes discussed in Section III). The plotted curves show that our scheme (the red curve) outperforms the other schemes (the blue curve) in various scenarios. We observe that

Table V: Simulation scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
No. of vehicles	10	12	17	20	7
No. of channels	8	6	9	7	5
No. of mini-time slots per time slot	10	12	17	20	7
Idle channel identification	Mechanism 2	Mechanism 2	Mechanism 1	Mechanism 1	Mechanism 2
Weight	{1, 1.25, 1.5, 1.75. 2}				
Data rate	{2, 5.5, 11, 18} mbps				
No. of simulation epochs	5				
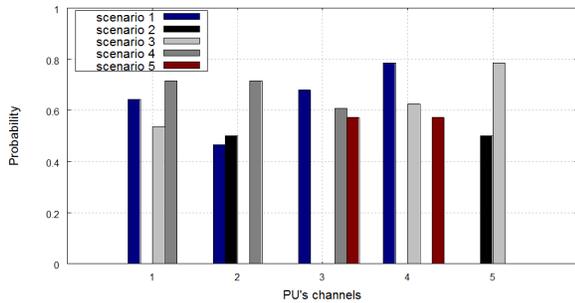
Figure 1: Probabilities of PU's channels being free in the subsequent time slot
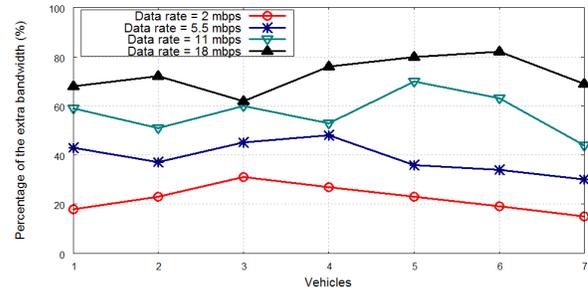

Figure 3: Percentage of the extra bandwidth (PEB) gained by the vehicles under different data rates
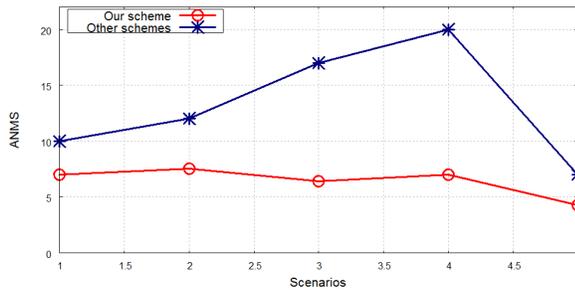

Figure 2: ANMS values achieved by our scheme vs. the other schemes in the literature

VI. CONCLUSION

We have conducted a comprehensive study on the state of the art contributions dealing with bandwidth scarcity issue, caused by the increasing number of ITS multimedia applications, in dense vehicular networks. We have mainly focused on identifying their advantages and limitations. We then proposed a novel scheme to overcome these limitations by applying cognitive radio technology based techniques to increase the available bandwidth and consequently speed up the transmission of emergency messages over VANETs. This scheme uses Kalman Filter to predict the channel state for the subsequent time slot in order to accelerate its allocation to the requesting vehicles, thus the dissemination delay of emergency messages is significantly reduced. For higher accuracy, the observations received from vehicles closer to the transmitting antenna, in which holes are detected, are given higher importance through an adequate weight scheme. Our scheme has been implemented in MATLAB and the obtained results have proven its efficiency.

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the gap between the two curves is important particularly in scenarios 3 and 4 where the channel allocation delay in our scheme is less than the half of that achieved in the other schemes. This is due to the mechanism 1 (see section IV-C) used in these two scenarios to detect the idle status of a channel, which allows significant reduction of the ANMS.

Figure 3 shows the percentage of the extra bandwidth gained by each vehicle (7 vehicles in the case of scenario 5 whose the results are plotted in this figure) when it applies our scheme, under various data rates. We denote that the higher the data rate of the PU's channels is, the larger is the bandwidth acquired by the vehicles. This increase of the bandwidth is justified by the rise of the offered bandwidth at each shared channel. Hence, it is clear that each vehicle will get extra bandwidth even if collisions occur. We also observe that the worst gain achieved by each vehicle under a data rate of 2 mbps (i.e., the lowest data rate in our simulation) is around 20 % of its acquired bandwidth fair share in the CCH, so this confirms the effectiveness of our scheme.

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