Data Delivery Guarantees in congested Vehicular Ad hoc Networks using cognitive networks

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Abstract—**The Wireless Access in Vehicular Environments (WAVE) protocol stack is one of the most important protocols used to allocate spectrum for vehicular communication. In a previous work, we proved that WAVE does not provide sufficient spectrum for reliable exchange of safety information. More specifically, safety message delay is not acceptable and exceeds application requirements. In this paper, we propose a system that provides Data delivery guarantees using Cognitive networks principles in congested Vehicular ad hoc networks. We will refer to our system as DCV. Our goal is to ensure that all safety packets get generated and transmitted during the same interval. The system monitors the contention delay experienced by cars on the control channel where all safety packets should be transmitted. If the sensed contention delay exceeds delay threshold γ, the Road Side Unit (RSU) needs to increase the spectrum allocated to the control channel using cognitive networks. The RSU employs a feedback control design where additional bandwidth is added to drive the contention delay below the delay threshold γ used as reference input for the controller. Analysis and simulations indicate the effectiveness of the system in providing data delivery guarantees in vehicular networks and thus increasing safety measures on the road.**

Keywords- QoS; data delivery guarantees; vehicular networks; congested networks; cognitive networks.

I. INTRODUCTION

A Vehicular Ad Hoc Network (VANET) is a distributed network that does not rely on a central administration for communication among vehicles and between vehicles and fixed road side equipment (also known as Road Side Units, RSUs). In an effort to assign a spectrum for vehicular usage, the U.S. Federal Communication Commission (FCC) has allocated 75MHz 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) and the center one is the control channel (CCH).

The allocation of the DSRC band was followed by an effort to standardize the entire protocol stack used by vehicular communication. The IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) amendment stands for the lower MAC and PHY layers. In the WAVE protocol, it is specified that all devices should be able to monitor the control channel during a common time interval called the CCH interval. Synchronization is used to insure that all devices switch together to the control channel during the same time interval. This is so that all devices can listen to safety and other high priority information.

Figure 1 shows how the CCH and SCH intervals are divided and alternated. The Sync interval is the sum of the CCH and SCH intervals, while Guard intervals are introduced to minimize the effect of timing inaccuracies. The length of the Sync Interval is 100 ms and default values for the control and service channel intervals are 50 ms [11]. At each channel interval, previous MAC activities are suspended and the current ones are started or resumed to ensure that each packet is transmitted on the correct RF channel.

Recent simulations studying QoS requirements (safety message delay and throughput) have shown that the control channel can suffer from large data contention, implying that the 10 MHz channel allocated for safety usage may not be enough [16]. Safety message delays in VANETS should be less than 200 milliseconds to allow proper driver reaction time to traffic signals [9]. In [6], we showed that scenarios where message repetition is used, results in a safety message delay that exceeds 1000 milliseconds, which clearly violates the delay limit.

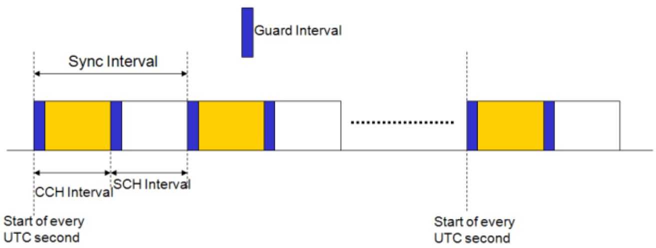

Figure 1: Different intervals in the DSRC spectrum

Due to high delays, some of the safety messages generated in a particular CCH interval will not obtain access to the physical medium by the end of the 50ms interval, and thus are postponed to the next CCH interval. We call these packets the untransmitted packets. Such packets will witness an additional delay $T_{untrans}$ equal to the SCH interval length ($T_{untrans} = 50ms$). This additional delay is unique for

DSRC and is due to the employed time synchronization mechanism. Our goal is to reduce the number of untransmitted packets to zero, and provide data delivery guarantees in environments where the traffic load exceeds the channel capacity. The presented system uses cognitive networking principles to dynamically increase the spectrum allocated to the control channel to effectively reduce the number of untransmitted packets to zero.

II. PROBLEM DEFINITION AND RELATED WORK

To assess the performance of safety applications over the existing 802.11p protocol, we should consider two parameters of the 10 MHz control channel, mainly the safety message access delay and packet reception rate. Safety message delay is defined as the average delay a packet experiences until successfully received at the destination. Packet reception rate on the other hand is defined as the ratio of the number of packets successfully received to the total number of packets transmitted. According to [20], the probability of message delivery failure in a vehicular network should be less than 0.01. Packet reception rate values obtained in the literature and from our results in [6] show that the packet reception rate falls well below the expected value of 0.99. This suggests that the 10MHz allocated to the DSRC control channel cannot provide performance guarantees under realistic road and traffic conditions. Some researchers suggested that non-safety use of DSRC ought to be severely restricted during peak hours of traffic to insure that automotive safety is not compromised [16]. However, such solutions for spectrum scarcity could impact the commercial side of DSRC. Other researchers have proposed some enhancements to the existing safety applications using repetition schemes [9][14][17], whereby the sender repeats the transmission of the safety message several times to increase the reliability of safety communications. It is shown in [14] that such a scheme would in fact increase the probability of reception rate to above 99%, making safety communications reliable over the control channel. However, repetition incurs additional traffic on the control channel, which can cause delays that are greater than 200 ms [6].

Safety message delay can be considered as the sum of the average queuing delay in the higher MAC layer, the average contention delay due to car contention with other cars for channel access, the average transmission delay, and the average propagation delay. It can be safely assumed that the average propagation delay is negligible while the average transmission delay is fixed. Moreover in [18], it is shown that the average queuing delay is determined by both the mean and the variance of the contention delay. It follows that the average contention delay at Node i $E[d_i^c]$ is the dominant delay component. Hence, any QoS-aware protocol needs only to ensure that the contention delay is below the applications' requirements.

Several approaches have attempted to provide data delivery guarantees in ad hoc network. Measurement-based admission control protocols were proposed in VMAC [3] and SWAN [2], but have been proven unsuccessful [19]. The works in [12] and [13] suggest centralized scheduling protocols, but such mechanisms normally incur high message overhead and thus are not feasible in ad hoc networks. Scheduling algorithms that provide delay guarantees by varying contention window sizes have been proposed in [1] and [18]. The authors in [18] who propose the Distributed Delay Allocation (DDA) algorithm argue that the average contention delay is a function of the contention window size. Hence, they designed DDA to allocate different contention window sizes to different flows to ensure that their delay requirements are satisfied. However, when the total requirements of the real-time flows exceed the network capacity, DDA diverges, proving that in such situations no scheduling algorithm can provide QoS guarantees.

Cognitive Radio has been applied in several architectures in VANETs, mainly in [21][22][23][24]. In [21], the authors consider the application of cognitive radio in VANETs to alleviate varying radio channel conditions. They use the CCH to exchange information about the spectrum status at the SCHs. The sender can check the status of the channels at the receiver and decide which SCH to use to improve spatial reusability by having nodes communicating at different channels. The authors in [22] focus on the exploitation of the predictable vehicle mobility to identify spectrum holes of the TV spectrum on the road and use them to extend the channel by exchanging spectrum tables between the nodes. In [23] the authors also propose a distributed vehicle sensing coordination framework that exploits the role of some nodes to guide the sensing. Finally, the authors in [24] apply Belief Propagation techniques to combine different sensing observations coming from other vehicles. However, these approaches do not scale to broadcast scenarios, the integral part of safety message transmission; also they don't adapt extra bandwidth according to channel load which is the main contribution of this paper. In summary there is no work that attempts to provide QoS guarantees for safety messages by applying cognitive radio for DSRC.

III. SYSTEM MODEL

A. Overview of Contention Delay

The contention delay $E[d_i^c]$ is the difference between the time that the packet becomes at the head of the MAC layer queue and when it gains access to the physical medium and starts transmission. The medium access mechanism of IEEE 802.11 specifies that when 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 DIFS, the station randomly selects a backoff timer (time slot) within a backoff window and derived from a uniform distribution over the interval $[0, CW-1]$, where CW is a value between $[CWmin, CWmax]$. The backoff timer is decreased only when the medium is idle: whenever the station senses the medium to be busy, it pauses its timer until the medium is found idle again, after which the station waits for a DIFS and continuously decrements its timer. When the timer expires, the station is authorized to access the medium and transmit.

As we have mentioned, it is shown that the message delay is mostly dependent on the contention delay. An equation for the contention delay is provided in [18]:

$$E[d_i^c] = DIFS + \{E[w_i]\epsilon + E[m_i]T_d\}p_i^b \quad (1)$$

The term w_i is the number of backoff slots and ϵ stands for backoff slot time. m_i is the number of data packets transmitted by the neighboring nodes during the node backoff process (causing pauses of the backoff timer), and T_d is the duration of a successful data transmission. Finally, p_i^b is the probability that a packet at Node i having n_i neighbors sees a busy state upon arrival. This probability is also defined in [18] as follow:

$$p_i^b = \sum_{j \in n_i} \alpha_{j,i} \frac{\lambda_j}{B_j} + \frac{\lambda_i}{B_i} \quad (2)$$

where λ_j is the average packet arrival rate at Node j, B_j is the physical channel transmission rate at Node j and $\alpha_{j,i}$ is a positive discount factor between 0 and 1.

B. Busy State Probability

Algorithms for data delivery in the literature assumes that the network load does not exceed maximum channel capacity: $E[\lambda_i] < E[B_i]$. This assumption does not hold in congested networks such as the DSRC control channel, as we have argued in section II. Our first contribution towards providing data delivery guarantees in congested networks is by introducing changes to formula (2) to account for congested situations:

$$p_i^b = \begin{cases} \sum_{j \in n_i} \alpha_{j,i} \frac{\lambda_j . S}{B_j} + \frac{\lambda_i . S}{B_i} & if\ E[\lambda_i] < E[B_i] \\ \beta & otherwise \end{cases} \quad (3)$$

where Srepresesnts the payload size and is added for unit consistency, while $\beta$is a positive value between 0 and 1.

The probability p_i^b is directly proportional to the traffic in the system, where it can be argued that when $E[\lambda_j] > E[B_j]$, β should be close to 1 since the channel is busy most of the time. However, to decide on an exact value for β, scenarios with two different bitrates: 3 Mbps and 6Mbps were devised. Simulations were based on the network simulation software ns2.34, which includes support for IEEE 802.11p. For each scenario, the number of nodes in the network was increased to generate additional traffic in the system, whereby each node broadcasts one 800-bytes safety message during the CCH interval. Each scenario is repeated 1000 times and average values were taken. The value of p_i^b is plotted against the number of nodes in Figures 2 and 3, where p_i^b was computed as the fraction of medium busy time over total simulation time.

Based on Figures 2 and 3, we can see that the average busy state probability p_i^b tends toward 1 when the system suffers from data contention. Given that the limits in the two cases were approximately 0.96 and 0.94, as one could notice in the figures, we can assign β in equation (3) a preliminary value of 0.95. Actually, this value turns to be accurate when measuring contention delay, as will be shown in the next subsection. However, to get a more accurate value, a mechanism is implemented in our proposed system to adaptively tune β to network conditions, as we will also discuss later.

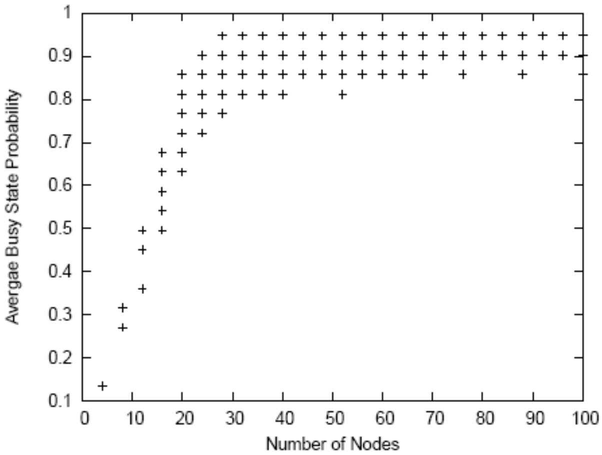

Figure 2: p_i^b versus number of nodes with 3Mbps bitrate

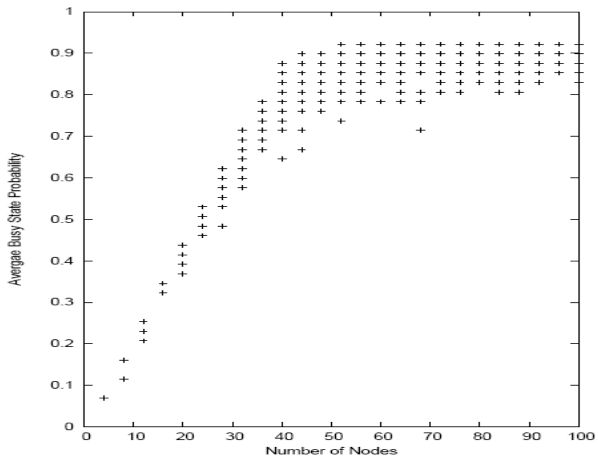

Figure 3: p_i^b versus Number of Nodes with 6Mbps Bitrate

C. Model Verification

With the changes we made to the busy state probability, we need now to prove the correctness of Eq. (1). We modified the implementation of mac-802_11Ext in ns2 to be able to measure the values w_i and m_i and accordingly compute the contention delay. We call this the theoretical contention delay. On the other hand, this delay can be measured in ns2 directly from the packets log file by obtaining the difference of the MAC time and the physical time. We refer to this as the actual contention delay. If the two delay values match, we could claim that equations (1) and (3) can be used to evaluate the revised contention delay model.

We developed a scenario where the payload size is fixed to 800 bytes and the number of nodes is 100 cars. In fact, it is suggested in [15] that the message size would reach 800 bytes after adding security features to it. The considered bitrate values were 3, 6, 12 and 24 Mbps. Again, each scenario is repeated and average values were recorded.

Figure 4 shows the theoretical contention delay while Figure 5 shows the actual contention delay. The plots show almost a perfect match between the theoretical and actual contention delay revealing that the revised model in (3) is accurate. We should note that a similar validation was missing in [18], where the model was assumed valid without proper verification.

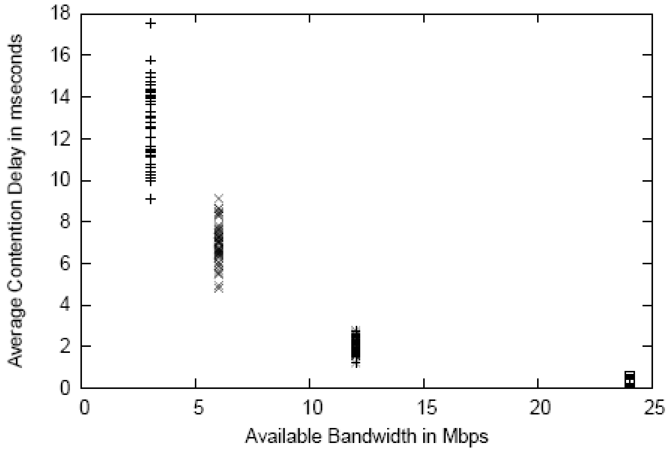

Figure 4: Theoretical Average Contention Delay versus Bitrate.

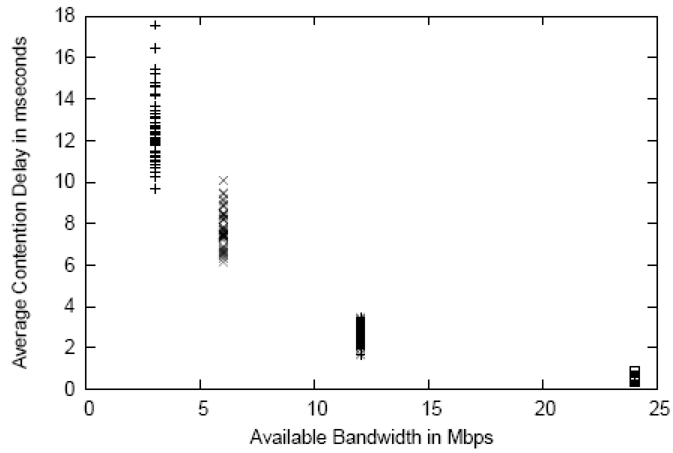

Figure 5: Actual Average Contention Delay versus Bitrate.

IV. DCV

A. Cognitive Networks

In this work we propose DCV, a system that provides Data delivery guarantees using Cognitive networks in Vehicular ad hoc networks. The system extends the control channel bandwidth to the additional white band indicated by the cognitive radio mechanism. A cognitive network inherits its properties from the concept of cognitive radio, which, in addition to its awareness and adaptive capabilities, can use previous knowledge relying on learning and acquired experience to adapt to a non predefined scenario [10]. The cognitive radio technology is based on the notion of utilizing open spectrum in the space, time, and frequency dimensions that until now have been unavailable [8]. The FCC Spectrum Policy Task Force recommended in its report on November 2002 to adopt cognitive radio as a method for additional spectrum access [7]. The main idea of cognitive radio is to periodically sense the radio spectrum, intelligently detect occupancy and usage in the spectrum, and finally make the decision to adjust its radio parameters to opportunistically communicate over spectrum holes of the primary system.

B. System Description

DCV implements a cognitive network to offer cars on the roads additional spectrum from the TV band that is typically underutilized [5]. The TV spectrum primary usage is static by nature as it is limited to licensed transmission towers, which makes it an ideal candidate for usage for safety message. It is highly unlikely that a piece of TV spectrum that has been free for a considerable amount of time on a certain place to be dynamically used by primary users. The increase in the CCH spectrum should reduce delays and cause practically all safety packets to be transmitted during the same CCH in which it was generated. Thus the number of untransmitted packets should also drop toward zero. The overall objective is for making car communication to be more reliable for improving road safety.

The major components of the DCV system are the vehicles and the Road Side Units (RSUs). The system works as follow: A car will be assigned a set of TV channels to monitor their power levels, and every short distance (e.g., 20m) the car will generate and store a record containing the values shown in Table 1, in addition to its location coordinates and a timestamp. When a car enters the transmission range of an RSU, an exchange of information will occur. The car provides the RSU with its next hop RSU along its predicted path, with all the records stored since the interaction with the previous RSU on its path. The RSU maintains updated tables, one for each next hop RSU. Each table contains the id of the next hop RSU, the estimated contention locations along the path till this next hop RSU, and the corresponding additional spectrum allocated. The last two fields are described later in this section. The general format of the table is depicted in Table 2, where a contention location denotes a range covering the distance between two coordinate points on the road.

Table 1. Car gathered data during interval *i* at region *r*.

$w_{r,i,j}$	number of backoff slots for each transmitted safety packet *j*
$m_{r,i,j}$	number of pauses during the transmission of safety packet *j*
$tx_{r,i}$	number of sent safety packets at the end of CCH
$s_{r,i}$	payload size of all sent safety packets
$p_{r,i}^{b}$	busy state probability at region *r* during interval i
$pl_{r,v,h}$	power level measured for TV channel *v* at SCH interval *h*

The RSU determines the next hop RSU received from the car, and accordingly, forwards to this car the corresponding table it maintains whose entries were computed and transmitted by the next hop RSU. This next hop RSU had computed the additional spectrum entries from data relayed from cars that have passed by it. The car will now have the necessary information indicating the predicted data contention locations along its path till the next hop RSU with the associated additional spectrum at these locations. The car will then extend the control channel according to the received information (i.e., additional spectrum at given locations along the way). The car then performs first a fast sensing to guarantee that the additional spectrum is indeed free at the moment of transmission. On the other hand, the car should not worry about other cars not receiving its messages, since all cars possess the same table and should be listening on the same extended control channel at the specified locations which provides synchronization of all vehicles on the additional spectrum.

Table 2. Format of the RSU table forwarded to cars.

Next RSU	
Contention Location 1	Additional Spectrum 1
…	…
Contention Location h	Additional Spectrum h

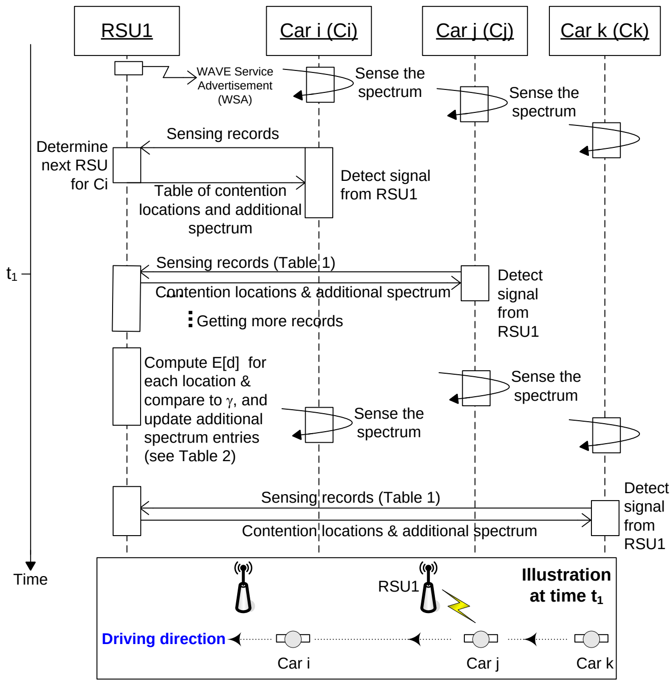

Figure 6: Interaction between vehicles and RSU.

When, an RSU receives contention information from n cars providing measurements for region r, it calculates an estimate for contention delay using equation (1) and generate estimates for free TV spectrum from the power measurements. The RSU basically averages the data relayed by the cars to get an estimate for $E[w_i]$, $E[m_i]$, average payload size S and β and plug them into (1). The sequence diagram in Figure 6 elaborates system functionalities.

If the estimate contention delay $\hat{E}[d_i^c]$ exceeds the contention delay threshold γ (which we will derive in the next subsection), we say that the region r suffers from data contention and additional bandwidth should be added to relieve contention. We should extend the control channel by the amount of bandwidth that guarantees that the contention delay is below γ. The RSU uses a feedback controller to decide on the amount of required additional bandwidth to use.

The output of this process is a table that specifies regions suffering from data contention and the needed additional bandwidth to relieve contention. The passing cars will be able to perform regular operation sending on and listening to the extended control channel.

C. *Contention delay threshold γ*

A main operation of the system is to determine the areas along the road that suffer from data transmission contention. We define a contention delay threshold γ. If the contention delay at a location r of the road exceeds γ, we claim that the region suffer from data contention.

To derive γ, recall that the control channel interval length is 50 ms. The number of sent packets in these 50 ms is:

$$N * \lambda * \frac{50}{1000} = \frac{N\lambda}{20} \ \ packets \quad (4)$$

where N is the number of vehicles in the scenario and λ is the average packet arrival rate in packets per second. For the sake of this derivation, we assume that all the nodes have the same average packet arrival rate and that packet size S and offered bitrates $B_{offered}$ are fixed.

Moreover, if we neglect propagation delay and queuing delay, the total incurred delay in the system will be due to contention delay $E[d^c]$ and transmission delay $E[T_d]$. This delay should not exceed the 50 ms interval. Thus, the following inequality holds:

$$\frac{N\lambda}{20}\left[E[d^c] + E[T_d]\right] \leq 0.05 \quad (5)$$

Transmission delay is equal to the packet size divide by the bitrate since we assume S and $B_{offered}$ are fixed:

$$E[T_d] = E\left[\frac{S}{B_{offered}}\right] = \frac{S}{B_{offered}} \quad (6)$$

Then, we have the following lower and upper bound for contention delay:

$$0 \leq E[d^c] \leq \frac{1}{N\lambda} - \frac{S}{B_{offered}} \quad (7)$$

Let's define γ to be the threshold contention delay that satisfies the upper bound in (7). γ is the maximum contention delay that can be tolerated in the system:

$$\gamma = \max(E[d^c]) = \frac{1}{N\lambda} - \frac{S}{B_{offered}} \ \ seconds \quad (8)$$

As we have mentioned, safety messages have tight delay constraints. If the message is not transmitted during the interval where it was generated and is postponed till the next CCH interval, an additional delay $T_{untrans}$ equal to the SCH interval length ($T_{untrans} = 50ms$) will be incurred. Moreover, packets delayed to the next CCH will encounter a high probability of collisions at the start of the control channel interval due to contention with accumulated frames ready to be sent from other nodes [4].

It follows from this discussion that our objective is to guarantee that all safety packets in vehicular environment are generated and transmitted during the same control channel interval. This objective is achieved if the value of γ is greater or equal to zero and the estimate contention delay $\hat{E}[d_i^c]$ is below γ. To calculate γ, the RSU needs to have knwoldge about the number of nodes in the system, the average packet arrival rate for each node and the payload of each transmitted packet. Thus calculating γ is not practical and may impose additional overhead to the network already congested.

The alternative we use here is the following: A close look to (5) shows us that γ is negative when the time needed to transmitted the packets is greater than then 50 ms. Then to have a total delay less than 50ms, we need a theoretical negative contention delay. For example, if $S = 800\, bytes, N = 100, \lambda = 20\, and\, B = 3Mbps$, the total transmission delay is 213 ms which is much greater than 50ms. In such a situation, $\gamma = -1.63\, ms < 0$ while real contention delay in the system is 12.7 ms and 44% of the packets were untranmitted. However for a scenario with the same parameters but changing $B\, to\, 12Mbps$, $\gamma = -0.033\, ms$ and the real contention delay is 2ms ad the number of untransmitted packets drops to 6%.

We can easily deduce from the above discussion that increasing B leads to increasing γ. When γ approaches zero, the system is able to deliver more and more packets and the number of untransmitted packets decreases dramatically.

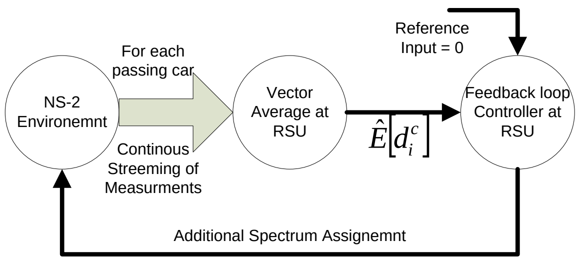

Figure 7: Feedback Loop Controller used to extend the control channel

Thus to achieve our goal of having zero untransmitted packets, we need to drive the estimate contention delay $\hat{E}[d_i^c]$ as much as close to zero. Thus, the delay threshold we need for contention delay is zero ($\gamma = 0$). The estimate contention delay $\hat{E}[d_i^c]$ is compared to zero; if it is greater than zero, we assume the road suffers from contention and additional bandwidth should be added. To decide on how much additional bandwidth to add, the RSU uses a feedback loop controller. The input is the estimate contention delay $\hat{E}[d_i^c]$ and the reference zero. If $\hat{E}[d_i^c]$ exceeds zero, additional bandwidth is assigned to the passed cars incrementally to decrease $\hat{E}[d_i^c]$. The feedback loop controller is shown in Figure 7. The controller assigns the minimum needed additional bandwidth to alleviate data contention in an efficient way that maximizes the utilization of the white spectrum.

V. EXPERIMENTAL RESULTS

To simulate the architecture we suggest in this work, we will assume the following scenario where the bitrate equals 3Mbsp, the payload size is 800 bytes and the number of cars is 100. Each car is broadcasting once during the 50ms control channel interval ($\lambda = 20\, packets/s$). This information is used to describe the channel load. Note that the number of cars is fixed without loss of generality as the channel load is the metric that matters in this context. Channel load can be varied by varying the number of cars, packet size, or transmission frequency. We gathered using ns2 the data in Table 1 that the cars will relay to the RSU. We used these data to calculate $\hat{E}[d_i^c]$ using equation (1). If $\hat{E}[d_i^c]$ is greater than zero, the controller at the RSU assigns additional bandwidth incrementally with steps of 3 MHz. If the contention delay remains high, the RSU assigns additional 6 MHz. Finally, in large data contention, if the previous added bandwidth was not enough, the RSU assigns additional 12 MHz of white TV spectrum. Although the TV spectrum spans 400MHz, and is underutilized [22] [5], it might happen that nodes won't find the needed bandwidth available. Should this rare scenario occur, nodes can resort to service channels that must be free during CCH interval as suggested in [21], or use the system as is on the control channel. Table 3 shows the simulation results for the above described scenario. When the estimated contention delay becomes close to zero, the percentage of untransmitted packets tends towards zero also and thus the RSU stops adding additional bandwidth.

Table 3. System Simulation Result

Offered Bandwidth	Estimate Contention Delay	Percentage Untransmitted	Decision on Additional Band
3 Mbps	12.76 ms	44.18 %	3 Mbps
6 Mbps	6.76 ms	18.78 %	6 Mbps
12 Mbps	0.05 ms	0.44 %	0 Mbps

VI. CONCLUSION

In this paper, we introduced DCV, a system that is able to provide data delivery guarantees in congested VANET. The goal of the system is to guarantee that all packets are generated and transmitted during the same interval. The system detects data contention region in the network using the sensed contention delay. If the contention delay exceeds the delay threshold, the RSU extends incrementally the spectrum allocated for the control channel using cognitive networks principles. Simulations show the effectiveness of our system in reducing the number of untransmitted packets to zero, thus improving safety conditions at the roads. This work is continuing, where near future effort will focus on designing an infrastructureless system that will realize a true cognitive Vehicle Ad hoc Network, where cars communicate directly with each other to measure, process, and adapt to contention conditions by appropriately extending the control channel into white TV channels.

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