# Fuzzy Cognitive Vehicular Ad hoc Networks

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*Abstract*—**The Wireless Access in Vehicular Environments (WAVE) protocol stack is one of the most important protocols proposed to standardize and allocate spectrum for vehicle-to-vehicle and vehicle-to-infrastructure communication. In a previous work, we proved that WAVE faces a spectrum scarcity problem which hinders reliable exchange of safety information. To overcome this problem, we proposed a system that applies cognitive networks principles to WAVE as to increase the spectrum allocated to the control channel (CCH) by the IEEE 802.11p amendment, where all safety information is transmitted. However, the decision making process in our previous work did not utilize the extra spectrum efficiently as it was not allocated according to the contention level experienced by the vehicle. In this paper, we suggest a system that employs a fuzzy logic system (FLS) to dynamically assign additional spectrum from the ISM band to the CCH. This system, which we call FCVANET, assigns the minimum necessary additional bandwidth to relieve the contention. The FLS takes as input 2 parameters, the message delay and the un-transmitted packets and utilizes a feedback loop. Our simulations show that the proposed system allocates bandwidth more efficiently in accordance with the contention level faced by the vehicles. The system succeeds to relieve contention by reducing delay and the number of un-transmitted packets.**

***Keywords-; vehicular networks; cognitive networks; spectrum sharing; fuzzy logic system; ISM band.***

## I. Introduction

Researchers have proposed Vehicular Ad hoc Networks (VANETs) as a distributed network that enables cooperation among vehicles and between vehicles and fixed road side equipment (also known as Road Side Units, RSUs) through multi-hop communications where each vehicle is abstracted as a mobile node. VANETs have enabled various applications to be deployed in the vehicular setting. Needless to say, safety applications are of most importance, as they exploit vehicular communication to alert drivers of potential dangerous situations and consequently could save their lives.

Potential applications of VANETs have led to the initiation of numerous projects in government, industry, and academia throughout the world. In 1999 the U.S. Federal Communication Commission (FCC) 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, each of 10 MHz bandwidth. Six out of these channels are service channels (SCH) while 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) standard defines the operations of the lower MAC and PHY layers [8] of VANETs. IEEE 802.11p, a variant of the 802.11a amendment, uses CSMA/CA as the basic medium access scheme. It operates on channels of 10 MHz and copes with the vehicular environment that is characterized by high error links with fast fading and short connection intervals.

The control channel in DSRC is of high importance, as all vehicles have to broadcast critical safety information to neighboring vehicles to react upon, in addition to periodic beacons and occasional advertisements of private applications that utilize a service channel but are insignificant to the overall channel load [8]. Other applications, advertised on the control channel, operate on one of the service channels and potentially on two of them. Moreover, DSRC utilizes a TDMA scheme to alternate between CCH and SCH. However, recent studies have showed that even though the control channel is limited to safety applications, it suffers from high data contention reflected by an increased message delivery delay and a deteriorated message delivery rate, implying that the allocated bandwidth for the control channel, 10 MHz, to be used for safety usage may not be sufficient [19]. As a matter of fact, our study in [7] further showed that the message delivery ratio does not exceed 40% at zero distance using the Nakagami radio fading model. Given that broadcast scenarios constitute a major part of safety message delivery [14], the deterioration in the message delivery ratio cannot be tolerated. In broadcast scenarios, senders do not expect to receive acknowledgements for the messages they sent, and thus they rely on the underlying mechanisms to reliably deliver the message to the neighboring vehicles.

In our previous work [7], we addressed this problem and identified it as a spectrum scarcity problem. The solution we offered relied on allocating extra spectrum if channel contention was detected regardless of its severity. In this context, decision making was rather simple, and the allocated bandwidth was not appropriate to the channel condition leading to poor spectrum utilization. In this work we introduce a fuzzy logic system (FLS) to replace the decision making process by making it more intelligent. The resulting system, which we refer to as the Fuzzy Cognitive Vehicle Ad hoc Network (FCVANET), dynamically allocates bandwidth to relieve the channel contention. This system decides on the contention region and allocates the appropriate extra bandwidth to the vehicle according to the contention level it is facing. This FLS is of the Mamdani type and makes use of the fact that network contention can be described using linguistic terms by accounting for humanistic and subjective concepts, such as the degree of the delay in the network and the severity of failed transmission. As a result, FCVANET offers several advantages when compared to our previous design. To start with, it efficiently utilizes the extra spectrum available at the ISM band (5.8 GHz ± 75 MHz). Moreover, FCVANET has no additional infrastructure requirements and consequently is more scalable and more feasible to deploy in the future.

In the rest of this paper, Section II elaborates on the problem definition, and surveys some related work. Section III presents our previous CVANET model, while Section IV introduces our new fuzzy based system FCVANET. The simulation results are presented in Section V, followed by a scalability analysis that is described in Section VI. Finally, we conclude the paper in Section VII.

## 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 access delay should be less than 200 milliseconds to allow proper driver reaction time to traffic warning signals [6]. This delay is defined as the average delay a packet experiences between the time at which the packet is generated and the time it is successfully received at the receiver, whereas the packet reception rate is defined as the ratio of the number of packets successfully received to the total number of packets transmitted. According to [21], the probability of message delivery failure in a vehicular network should be less than 0.01.

These two parameters were analyzed widely in literature. In [11], access delay was found to be around 1.2 ms and in [7], the delay was less than 1.5 ms. Packet reception rate values obtained from the literature as well as from our own performed simulations in [7] show that the packet reception rate falls well below the expected value of 0.99. In [14], the probability of reception was found to be less than 0.6 at zero distance under the Nakagami radio propagation model. Similar results were found in [11]. The simulations we produced in [7] were close and showed that the packet error rate is much greater than 0.01. These results suggest 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 in order to insure that automotive safety is not compromised [19], although such solutions for spectrum scarcity could impact the commercial side of DSRC. Other researchers have proposed some enhancements to the existing safety applications using a repetition scheme [6][11][20], whereby the sender repeats the transmission of the safety message several times to increase the reliability of safety communications. It is shown in [11] 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 [7].

A cognitive vehicle ad hoc network system is proposed in [7] to face spectrum scarcity in the control channel, in urban areas. The system extends the control channel bandwidth to the additional white band indicated by the cognitive radio mechanism. 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 [4]. 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. This principle has attracted a great deal of attention from both academia and industry.

The authors of [1] propose a distributed cognitive network access scheme which selects the most suitable access technology depending on the QoS of the application under consideration. The proposed scheme uses Fuzzy logic techniques to gain estimates about the QoS requirements of an application. It does so by processing cross-layer communication quality metrics and by estimating the transport-layer performance. A user wanting to set up a new connection, accesses a shared knowledge base that contains information about the QoS experienced by past and present connections. Performance parameters like throughput, delay and reliability are represented using fuzzy numbers. Finally, Fuzzy Decision making is used to choose the most suitable access opportunity. In the proposed cognitive access scheme, the communication quality expected from each access opportunity is evaluated using fuzzy arithmetic, and the most suitable one is then selected.

## III. CVANET

The CVANET system in [7] implements a cognitive network to offer cars on the road additional spectrum from the TV band that is underused [3], for the purpose of making the exchange of safety messages between cars more reliable and actually faster. The next sub-section presents a description of this system's various components and functionalities.

TABLE 1. Car gathered data during Interval *i*

| | |
|---|---|
| $td_{r,i,j}$ | access delay time of each successfully transmitted safety packet *j* |
| $tx_{r,i}$ | number of sent safety packets at the end of CCH |
| $s_{r,i,k}$ | payload size of all observed safety packets (sent and received) |
| $a_{r,i}$ | number of attempted but not transmitted safety packets |
| $b_{r,i,j}$ | available bitrate at region *r* for each safety packet *j* |
| $pl_{r,v,h}$ | power level measured for TV channel *v* at SCH interval *h* |

### A. System Description

The major components of the CVANET system are the vehicle, the road side unit (RSU), and a local processing unit referred to as the local acquisition and processing unit (LAPU). The system works as follow: A car will be assigned a set of TV channels. Every 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. For detailed explanation, we refer the reader to [7]. When a car and an RSU become within transmission to each other, an exchange of information will occur. The car will provide the RSU with its next hop RSU along its predicted path with all the records stored since the interaction with the last RSU. 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 RSU determines the next hop RSU received from the car, and will accordingly forward the car the corresponding table proactively maintained in its memory. The car will now possess the table 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 to this additional spectrum at these locations and will use it regularly.

When an RSU receives contention information from cars, it relays the data to the LAPU, which aggregates this data to generate estimates of contention locations and free spectrum. The output of this process, which is described in the form of an algorithm in Section III.B, is a contention table that specifies regions suffering from data contention and the needed additional bandwidth to relieve contention. The output is sent by the LAPU to the concerned RSUs to be stored and be used for their interactions with passing by cars. The passing cars will be able to perform regular operation sending on and listening to the extended control channel. The overall cognitive cycle operation is captured in Figure 1.

*B. Network Contention Metric*

A main operation of the system is to determine the areas along the road that suffer from data transmission contention. We defined a metric that quantifies contention at each location of the road. We say that the control channel suffers from contention if the needed bitrate (actual bitrate) exceeds the offered bitrate (available bitrate). The DCF (Distributed Coordination Function) technique for medium access mechanism of IEEE 802.11 incurs delays during a node transmission. According to DCF, whenever a station senses the medium to be busy, it pauses its backoff timer until the medium is found idle again. These delays infer contention in the medium and affect the overall performance, and thus affect the transmission of the safety information.

Therefore, in order to determine contention at a given location, we propose a network contention metric $C_r(t)$ that represents the contention level in region $r$ at time $t$. If this metric is above a certain threshold $C_{th}$, then it is assumed that this region suffers from network contention. We made the contention metric at time $t$ rely on $C_r(t\text{-}1)$ and on the newly sensed contention $\widehat{C_r}$ so as to account for changes in the contention level and to make the system robust to fallacious data. For a given location $r$, the contention is related to the average number of safety packets transmitted and their average sizes, and to the channel capacity in this region as reflected by the achievable bitrate according to the adaptive modulation scheme employed in IEEE 802.11. Thus, if the system accounts for near history that is reflected in $C_r(t\text{-}1)$ while always considering the current sensed results of contention that is conveyed by the cars, the new $C_r(t)$ should model actual contention accurately.

The contention at region $r$ and time $t$ is calculated in Equation (1) using a linear prediction model similar to the approach employed to calculate the Round-Trip Time (RTT) in the TCP protocol [12]:

$$C_r(t) = \gamma C_r(t-1) + (1-\gamma)\widehat{C_r}(t) \quad (1)$$

where $\gamma$ reflects the weight given to history, and $(1-\gamma)$ denotes the weight of the sensed contention.

The sensed metric $\widehat{C_r}$ depends on the evaluation of data relayed from $n$ cars. $\widehat{C_r}$ is a linear combination of two factors, the first being the product of the access delay $D$ of safety packets, and the channel's offered bitrate $B$ divided by the average payload size $S$, while the second factor being the average number of un-transmitted safety packets $U$ per total attempted transmissions. With higher contention, $D$ increases due to the 802.11 carrier sensing mechanism, where each node pauses its backoff timer during the MAC backoff process whenever it senses a busy channel.

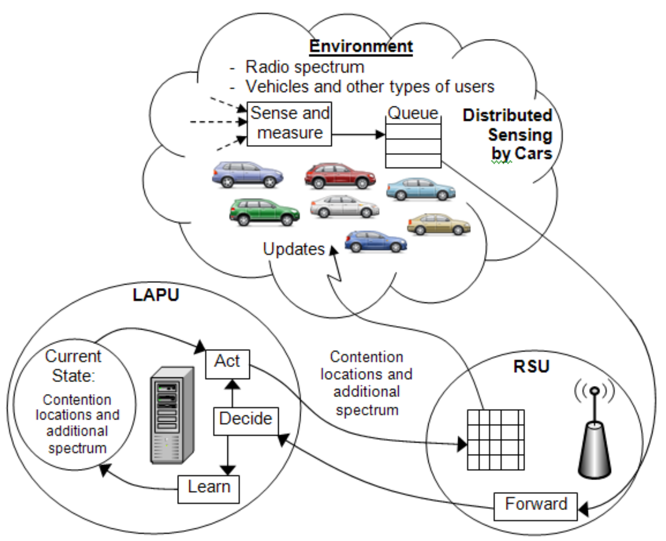


Figure 1. Network Cognition Cycle

Those incurred delays that are actually affected by the channel available bitrate $B$, provide a partial contention indication. The payload size $S$ is used to get the average delay per byte, and finally, the number of un-transmitted packets $U$ also increases with contention since the control channel interval is limited to 50 ms and the collision avoidance mechanism imposes that certain packets will never be able to get transmitted if contention persists. The result is a unitless sensed contention metric that is calculated as follows:

$$\widehat{C_r}(t) = \alpha \frac{D_r \times B_r}{S_r} + \beta U_r \quad (2)$$

The symbols $D_r$, $B_r$, $S_r$ and $U_r$ are the parameters $D$, $B$, $S$ and $U$ respectively at region $r$.

It is worthy to mention that the first variable in equation (2) is in effect the channel capacity ($B$) divided by the throughput ($S / D$), which we called the inverse of the effective channel utilization (or can be seen as normalized delay, i.e. $D$ normalized by $B / S$).

## IV. THE NEW FCVANET SYSTEM

The electromagnetic spectrum is seen more of a critical and scarce natural resource, and as a matter of fact, The U.S. Supreme Court has stated numerous times in the past several decades that the electromagnetic spectrum is a “scarce natural resource” [16]. Related to this, and because the decision making process implemented in [7] does not differentiate between contention levels and does not relate precisely the measured contention to the amount of needed spectrum, which leads to an inefficient utilization of the white spectrum, we proposed an improved version in [17] that attempts to utilize the minimum necessary additional bandwidth to relieve the contention. For example, if the network is suffering from low contention, the system in [17] will assign few Megahertz to mitigate the situation, rather than assigning tens of Megahertz as the system in [7] may do. For this, the approach proposed in [17] quantifies contention into multiple levels of severity using a Fuzzy Logic System (FLS).

The additional white bandwidth used in [17] (and in [7]) is the underutilized TV bands. However, this requires the addition of an extra antenna to the RF system of the vehicles. More critically, since the TV bands are in the Megahertz range (in contrast to the 5.9 GHz used by DSRC), the size of this additional antenna will be prohibitively large, and thus impractical for cars. For this purpose, we suggest to extend the DSRC Control Channel in this paper to the 5.8 GHz ISM band. Accordingly, the new design will only require one antenna in the vehicle, and will therefore not incur any additional cost.

Another major change we introduce in this paper is the removal of the LAPU that is used in both [17] and [7]. The LAPU was used to receive measurements through the RSUs and to compute $C_r(t)$. In contrast, in this proposed system the computations are all done at the RSU level, thus making the design more scalable as discussed in section VI. Thus the execution of the algorithm for computing $C_r(t)$ occurs at the RSU that receives individual measurements from the cars, mainly $D_r$, $B_r$, $S_r$ and $U_r$. The RSU aggregates the measurements from $n$ cars and uses the aggregated values as inputs to the FLS. The FLS consequence is the minimum needed additional bandwidth to alleviate contention, namely $\widehat{C_r}(t)$. Using Equation (1), the RSU generates its estimate of the contention by accounting for both the sensed and the history components. Finally, the RSU forwards the consequence of the FLS to the neighboring RSUs (to accommodate for all traffic directions), which in turn notify the passing cars about the additional bandwidth to use and extend the Control Channel accordingly.

The third major contribution of this paper over its predecessors is the incorporation of an analytical scalability analysis that studies the scalability of the proposed system as the density of cars increases in the area covered by an RSU.

### *A. Designing the Fuzzy Logic System*

We consider two inputs for the FLS:

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

Generally, the methodology used to assess contention is based on comparing the needed bitrate to the offered bitrate in the network. However, we offer a more suitable and linguistic definition for contention. Data Contention is the situation where there is too many stations contending on the wireless channel which ends up affecting the quality of service. From a station’s perspective, its goal in the context of an IEEE 802.11p system, is to send as much packets as it can within the Control Channel interval (50 milliseconds) and with low delay.

To better understand what happens during a contention period, we simulate using the network simulator ns2 a threshold scenario where the needed bit rate is equal to the offered bitrate. NS2 provides a comprehensive support for the IEEE 802.11 set of technologies, and the latest version, ns-2.34, is an overhaul of the previous one and introduces a new architecture and a more up-to-date modeling of the IEEE 802.11 MAC and PHY layers. More importantly to our study, ns2 now includes support for the IEEE 802.11p Dedicated Short Range Communication (DSRC) standard [2], which therefore provides a realistic and accurate simulation of the proposed system.

TABLE 2. PARAMETER VALUES FOR SCENARIO IN FIGURE 2

| Bitrate | Number of cars | Payload size (in bytes) |
|---|---|---|
| 3 Mbps | 50 | 375 |
| | 100 | 187 |
| | 200 | 94 |
| 6 Mbps | 50 | 750 |
| | 100 | 375 |
| | 200 | 187 |
| 12 Mbps | 50 | 1500 |
| | 100 | 750 |
| | 200 | 375 |

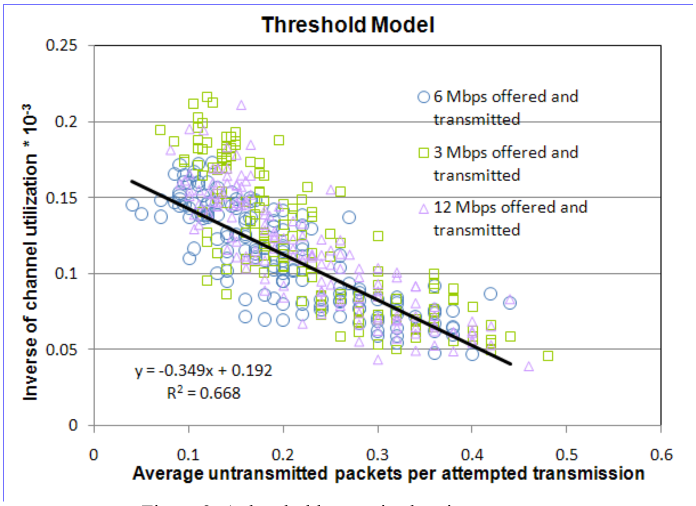


Figure 2. A threshold scenario showing $x_1$ versus $x_2$

The parameters used in the simulation are shown in Table 2 and the results are plotted in Figure 2. A careful examination of the results reveals the following:

- The station might experience a high number of un-transmitted packets, while at the same time the transmitted packets will consume valuable channel resources (low inverse channel utilization). Thus, in contended scenario it will appear as if the successfully transmitted packets will render the channel used most of the time. This in turn will cause most of the packets to timeout and not to be transmitted. This is actually shown in the right part of Figure 2.
- The station might be able to transmit most of its packets, and the un-transmitted ratio will be low, but the delay will be high, thus reflecting a low effective utilization of the channel (high inverse channel utilization as shown in the left part of Figure 2).
- The station might be able to transmit a medium portion of its packets with an average delay. This is the middle part of Figure 2.

Based on the above, the linguistic variances used to represent the inverse of channel utilization and the average number of un-transmitted safety packets per attempted transmission are divided into three levels: Low, Moderate and High. The consequence, the minimum needed additional bandwidth, is divided into five levels: Very Small, Small, Average, Large, and Very Large. We used trapezoidal membership functions (MFs) for the edge membership functions and triangular MFs for the middle ones. These functions are shown in Figures 3, 4, and 5.

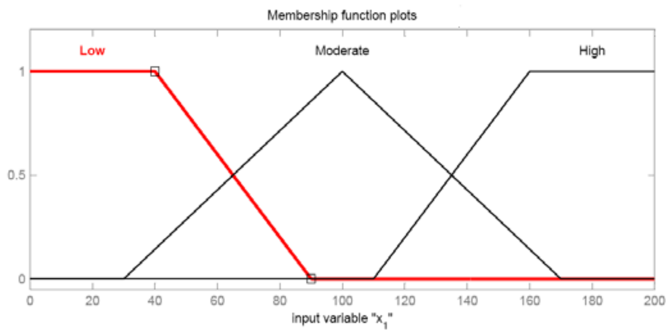


Figure 3. Membership function of Antecedent 1

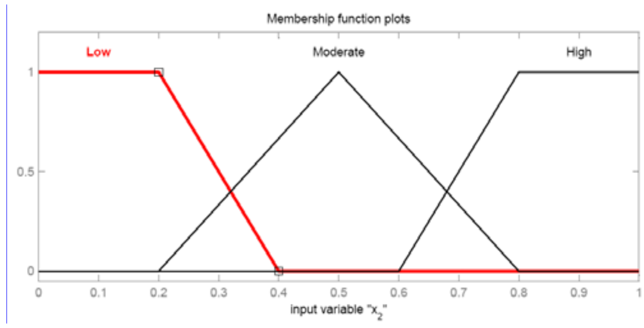


Figure 4. Membership function of Antecedent 2

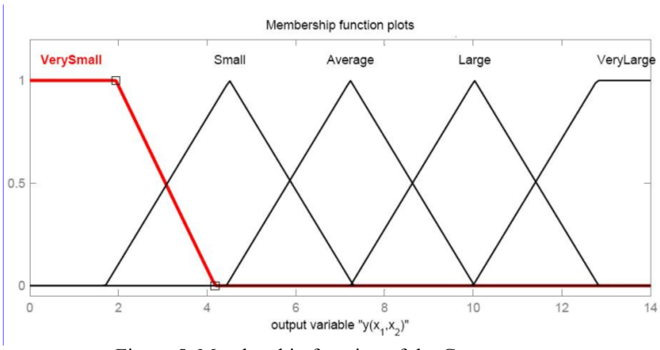


Figure 5. Membership function of the Consequence

From the previous section, we know that we have 2 antecedents and 3 fuzzy subsets, thus we need $3^2 = 9$ rules for this FLS. We choose to make our rules as illustrated in Table 3. These rules are made consistent with the discussion about data contention in the previous section, specifically based on the observations from Figure 2. We give the rules equal weights, and use the Centroid Defuzzification method. For the operators, we chose the min operation for the AND, and the max operation for the OR operator, which was also used for the implication method.

TABLE 3. RULES USED IN THE FLS DESIGN

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

## V. SIMUALTION RESULTS

### *A. Input-Output Characteristic*

The input-output characteristic (i.e., surface plane) of our Fuzzy Logic System is shown in Figure 6. As defined in the previous section, $x_1$ stands for the inverse of the effective channel utilization, while $x_2$ stands for the average number of un-transmitted safety packets per attempted transmission.

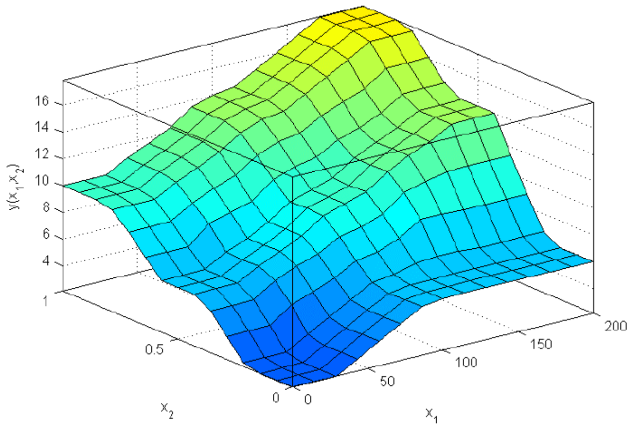


Figure 6. Input-Output Characteristics of the FLS

The output of the FLS, $y(x_1, x_2)$, represents the minimum additional needed bandwidth to alleviate contention in the Control Channel. As one can see, the surface plane is smooth and scalable for the various situations. The extra bandwidth allocation is more appropriate to the contention faced in a specific region. Also, the system is more robust to noisy input due to its approximate nature. This will be made clear in the simulations shown in the following sub-sections.

## *B. Methodology*

The approach used to simulate our fuzzy decision making system integrates ns2 and Matlab. Multiple scenarios of network contention were developed and simulated under ns2. For all the simulations, the values of the access delay $D_r^c$, offered bitrate $B_r^c$, payload size $S_r^c$ and $U_r^c$ were collected for each car. A continuous stream of measurements is created and fed into a vector of averages. The vector buffers the input data for the last $n$ cars providing measurements for region $r$, and then calculates the final values of $D_r$, $B_r$, $S_r$ and $U_r$ using simple averaging. Averaging the input data is necessary to combat fallacious data and measurement errors at the car level. The computed averages are passed as input to the fuzzy logic system developed under Matlab. The FLS has 2 inputs as illustrated in the previous sections: the inverse of channel utilization, $\frac{D_r \times B_r}{S_r}$, and the average number of un-transmitted safety packets per attempted transmission, $U_r$. The output of the FLS is an estimate of the minimum needed additional bandwidth to mitigate contention based on the readings collected from $n$ cars. This output $\widehat{C_r}(t)$ is driven into a weighted average block where equation (1) is implemented. The symbol $\gamma$ reflects the weight given to history, and $(1-\gamma)$ denotes the weight of the sensed contention. This helps reduce oscillations in the system and make smooth transitions in case of abrupt increase in demand for bandwidth. Finally, a feedback loop is used where the allocated bandwidth in the ns2 simulator varies with the output of the weighted average block. The adopted methodology is made clear in Figure 7.

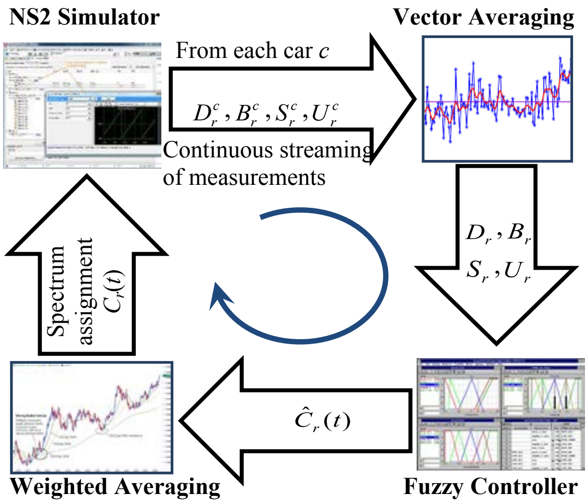


Figure 7. Simulation Methodology used to evaluate our work

## *C. Results*

The first scenario (referred to as Scenario 1) consists of an offered bitrate of 6 Mbps and a needed bitrate of 9.5 Mbps (packetSize × number of cars / 50ms). The adopted simulation parameters are shown in Table 4.

TABLE 4. SIMULATION PARAMETERS OF SCENARIO 1

| Parameter | Value |
|---|---|
| 802.11p data rate | 6 Mbps |
| Packet generation rate | 10 Packets/sec |
| Packet size | 1187, 594, 297 bytes |
| Transmission range | 500 meters |
| Communication method | Broadcast |
| Radio model | Nakagami |
| Number of cars | 50, 100, 200 |

At the simulation startup the additional bandwidth value was set to zero. With the collected readings from cars being collected and passed to the fuzzy logic system, the fuzzy output converged towards 3.5 MHz. We chose to make $n = 10$, meaning that the readings of every 10 cars were averaged together using the Vector Averaging box.

The system clearly suffers from contention based on our definition of contention in previous sections. The output $C_r(t)$ of the weighted average was monitored and plotted in Figure 8, where the expected $C_r(t)$ was 3.5Mbps. The additional bandwidth output line is very close to the expected line, which indicates that the system was able to detect contention and assign as much needed bandwidth in an interesting manner.

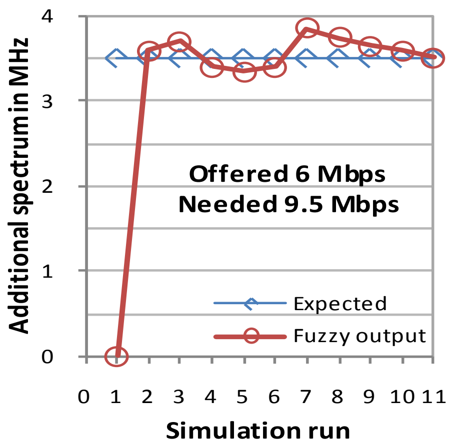


Figure 8. Simulation Output for Scenario 1

It should be noted that the data of the fuzzy output were only fed back into ns2 till the end of the last simulation run. We expected that the addition of this white spectrum will remove contention and lead to a value of zero $C_r(t)$. The fuzzy output in Figure 9 shows that the actual value was close to zero and varies between 0 and 1 Mhz.

Next, we devised a second scenario (Scenario 2) where the offered bit rate is 6 Mbps and the needed bitrate is 13 Mbps. The contention is higher than the one in the first scenario, and we expected $C_r(t)$ to be 7 Mbps. The results in Figure 10 show that the system was also able to identify contention and determine the needed bandwidth to alleviate it.

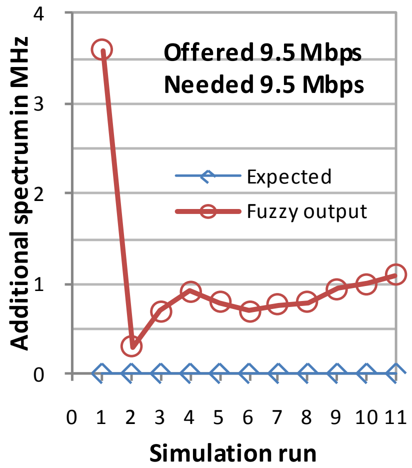


Figure 9. Simulation output with extra bandwidth

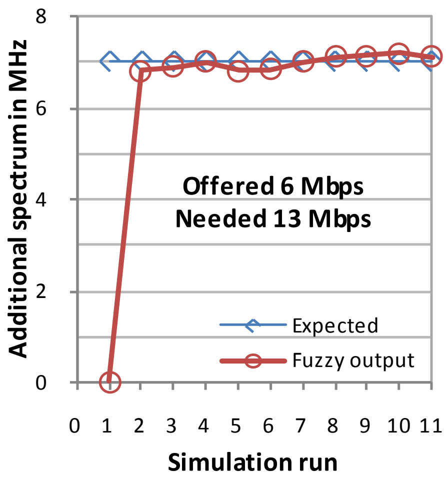


Figure 10. Simulation Output for Scenario 2

The additional bandwidth used to extend the Control Channel should reduce the number of un-transmitted packets, and to verify this, we report the number of these packets before and after extending the control channel in Figure 11, where we clearly notice major reductions and smaller variations.

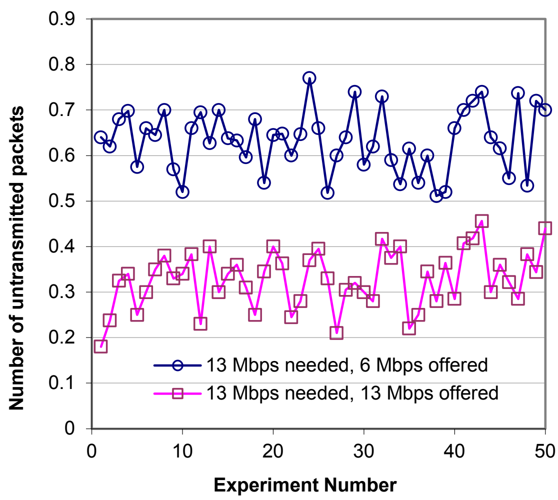


Figure 11. Number of un-transmitted packets before and after

## VI. Scalability Analysis

Normally, the scalability of any system is limited by its most restrictive component. The main components or resources that the proposed system includes are the car's processor and memory, the network connection between the car and the RSU, and the RSU memory and processor. Below, we consider each one separately in order to pinpoint the performance limitations of the system.

1. The car does not provide any type of service to other cars. The only constraint is the memory required to store data when collecting records every 20 meters. Taking an average distance of 10 Km between neighboring RSUs, the size of the data that a car will hold by the time it reaches an RSU is 62 KB, thus implying that the car will not be the bottleneck of the system.

2. The RSU communicates with the cars on the CCH to operate at a particular SCH. Advertisements are sent at periodic control channel intervals, but add insignificant load on the CCH [8]. To understand the added overhead from exchanging records and tables on an SCH, we let the total size of the records to send to the RSU be $I$ and the size of the tables sent by the RSU be $U$. A service channel has a bandwidth of 10 MHz (although two channels can be combined to yield 20 MHz), thus offering a 6 Mbps bitrate $R$. Similar to [10], we consider a scenario where all the cars need to communicate with an RSU located at the side of a $G$-lane road. In this case, the cars adjust their transmission power, thus eliminating the spatial reuse factor and limiting the total one hop capacity in the transmission region, $r$, of the RSU to $R$. With $N$ cars in $r$, the capacity available to the car is at maximum $R/N$. In the following we attempt to find the maximum number of cars that can simultaneously contact the RSU for road contention tables. Assuming the average car length plus the distance between cars is $s_l$ meters, a lane of length $L$ can then hold a maximum of $L/s_l$ cars (referred to as sites or cells in the literature [18][13]). We define the car density $\rho$ as the number of cars in a lane divided by the maximum number of cars that a lane can hold, and use the work in [18] that models the relation between the average velocity and car density. A high car density occurs when $\rho > 1/M$ [18], where $M$ the maximum velocity in sites per unit time, and the average velocity is $1/\rho$-1. Thus, the time the car needs to cross the region covered by the RSU is given by $2r/v_{av}$, where $v_{av}$ is $M$ normalized to m/s. Hence, in high traffic, the number of cars is $\rho \times L/s_l \times G$, and the total size of the data that needs to be exchanged is $\rho \times L/s_l \times G \times (I+U)$. While the car is in the range of the RSU, it can exchange up to $2r/v_{av} \times R$ bits. Therefore, the system will perform acceptably if all the data that need to be exchanged is below this limit. If we apply the above to a realistic scenario, where $G$=4 [5], $(I+U)$=75 KB, $R$=6 Mbps in a 10 MHz SCH [9], $r$=1000m, $s_l$ =7.5m with a time step of 1 seconds [13] (which gives $v_{av}=(1/\rho-1)\times 7.5$ m/s), and finally having $M$=4 (equivalent to 108 km/h or

67 mph [15]), we find that $\rho$>-1.44 by applying the inequality we implied above. Knowing that $\rho$ is lower bounded by ¼ (1/$M$), then all data can be exchanged reliably in high traffic conditions. The average velocity is $\left[M-1+\frac{1}{\rho}-\sqrt{\left(\frac{1}{\rho}-1-M+2f\right)^2+4f(1-f)}\right]/2$ for low traffic [18], where $f$ is the stochastic delay and $0\leq \rho \leq 1/M$. In the worst case, the average velocity is maximum (i.e., $f$=0, and less time in contact with the RSU) and is equal to $M$. Hence, $v_{av}$ is $M\times s_l$, the time to cross the RSU region is $2r/(M\times s_l)$, and the maximum amount of data exchanged will be $R\times 2r/(M\times s_l)$. Given that in the worst case the car density $\rho$ will be $1/M$, the data needed to be exchanged will be $(1/M)\times(L/s_l)\times G\times(I+U)$. Using the appropriate values for the case with the low traffic scenario, the size of the needed traffic is less than the maximum amount, meaning that the system also scales in low density situations.

3. For the RSU processing and memory capabilities, we outline the RSU's main operations:
   a. Receiving the records relayed by the cars
   b. Performing averages for received records
   c. Updating the tables if the number of records for a region exceeds the threshold
   d. Transmitting the table to the neighboring RSUs

   The memory requirements are independent of the increase in number of the cars, suggesting no related scalability issue. However, as the rate of incoming data increases, there is more processing needed to calculate averages, and update the needed bandwidth. It has been stated that a processor utilization of 75% should be the limit [5] in order to leave room for other asynchronous operations. We calculate the processor utilization by dividing the needed number of instructions per second (MIPS) by the nominal MIPS of the processor. Again, we consider a worst case scenario, where the RSU's network interface is working at full bandwidth (54 Mbps – equivalent to two SCHs), which is equivalent to 92 car readings per second, each containing 500 records. Assuming the processing of each record takes 20 instructions, the processor will run 92×500×20=0.92 MIPS. Using the 75% limit, a processor with a rating of 0.92/0.75=1.23 MIPS will then do the job. As to the FLS component, its processing overhead can be approximated by a lookup operation of one record, which is therefore independent of the number of cars, suggesting no scalability issue. In total, the processing load is very modest, since for example the old INTEL Pentium III processor provides 1354 MIPS. Hence, even under worst case data flows, the processing capacity of the RSU will not constitute a performance bottleneck.

## VII. Conclusion

In this paper, we introduced a system that is able to detect and quantify data contention in vehicular ad hoc networks. The system assigns the minimum needed additional bandwidth to alleviate this contention in an efficient way that maximizes the utilization of the white spectrum in the ISM band. Simulations and analysis show the effectiveness of the system in reducing data contention, and thus improving communication reliability.

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