Extending the DSRC's Control Channel using Cognitive Networking Concepts and Fuzzy Logic

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Abstract—**Wireless Access in Vehicular Environments (WAVE) protocol stack is the most important protocol used to allocate spectrum for vehicular communication. The capabilities of WAVE to provide reliable exchange of safety information are questionable. In [6], we suggested a system that employs cognitive networks principles 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 implemented in that work 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. In order to assign the minimum necessary additional bandwidth to relieve the contention, we suggest in this paper a new system that quantifies contention into multiple levels of severity based on Fuzzy Logic and maps additional spectrum correspondingly. Simulations show the effectiveness of the system in allocating the minimum needed bandwidth to relieve contention, without affecting other QoS parameters such as delay and number of untransmitted packets.**

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

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, 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 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).

In the DSRC band, all common safety messages are to be exchanged in the control channel, while non-safety usage in the control channel is limited to occasional advertisements of private applications that utilize a service channel, but it is insignificant to the overall channel load [11]. Recent simulations studying the safety message access delay and packet reception rate have questioned the capabilities of the control channel interval to reliably deliver safety packets, implying that the 10 MHz channel allocated for safety usage might not be enough [17].

This paper presents a fuzzy logic system that dynamically allocates bandwidth to extend the control channel in DSRC, if necessary. We will refer to this system as Fuzzy Cognitive Vehicle Ad hoc NETworks (FCVANET). It is basically a fuzzy version of our previous model CVANET [8] that aims to enhance the decision making capability by accounting for humanistic and subjective concepts such as the degree of the delay in the network and the severity of failed transmission.

The decision making process implemented in [8] 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. Fuzzy logic allows for better estimating the contention severity and efficiently assigning the least needed additional bandwidth to relieve contention. To accomplish this task, we build a new decision making system that quantifies contention into multiple levels of severity using Fuzzy Logic System (FLS) and maps additional spectrum accordingly.

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 [9]. Safety message access delay is defined as the average delay a packet experiences between the time it is generated and when it is successfully received at the receiver, while packet reception rate is defined as the ratio of the number of packets successfully received to the total number of packets transmitted. According to [13][18][19], the probability of message delivery failure in a VANET should be less than 0.01 since broadcast scenarios constitute the key usage part. That is, a sender will not get acknowledgments, and thus cannot tell if a critical safety packet was successfully received.

These two parameters were analyzed widely in literature. In [12], access delay was found to be around 1.2 ms, and in [8] 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 [8] show that the packet reception rate falls well below the expected value of 0.99. In [15], the probability of

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reception was found to be less than 0.6 at zero distance under the Nakagami radio propagation model. Similar results were found in [8][12]. These results suggest that the 10MHz 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 [17], although such solutions could impact the commercial side of DSRC. Other researchers proposed some enhancements to existing safety applications using a repetition scheme [9][12][18], where the sender repeats the transmission of safety messages several times to increase the reliability of safety communications. It is shown in [12] that such scheme would in fact increase probability of reception to above 99%, making safety communications reliable. However, repetition incurs additional traffic on the control channel, which can cause delays that are greater than the 200 ms target [8].

Authors in [3][5][6][10][16] also acknowledge the existence of a congestion problem in DSRC, and attempt to provide solutions to alleviate such problem for safety message delivery. In [5], a feedback scheme based on channel occupancy is proposed to control the message sending rate and broadcast range for the car tracking application. The authors claim that by controlling these parameters, they achieve acceptable message delivery ratio and tracking accuracy. The authors consider the information dissemination rate as a QoS parameter without considering the message delay which is critical in safety scenarios. In [16], two protocols for periodic broadcasts and event driven broadcasts are suggested. The authors show an increased message reception ratio with decreased delay. However, the authors neglect the multichannel operation of DSRC, and the 0.5 duty cycle.

A cognitive vehicle ad hoc network system was proposed in [8] to face spectrum scarcity in the control channel, in urban areas. The system extends the control channel bandwidth to the additional white band using a cognitive radio mechanism. It is based on the notion of utilizing open spectrum in the space, time, and frequency dimensions that until now have been unavailable [7]. The main idea 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.

The authors in [1] propose a distributed cognitive network access scheme which selects the most suitable access technology depending on the QoS of the application under consideration. This scheme uses Fuzzy logic techniques to gain estimates about the QoS requirements of an application by processing cross-layer communication quality metrics and estimating the transport-layer performance. 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.

III. CVANET

In our previously introduced CVANET system [8], we implemented a cognitive network to offer cars additional spectrum from the TV band that is underutilized [4], thus rendering the exchange of safety messages between cars more reliable and actually faster. 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.

A main operation of the system was to determine the areas along the road that suffer from data transmission contention. In that work, 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}, it was assumed that the 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 $\hat{C}_r$ so as to account for changes in the contention level and make the system robust to fallacious data. For a given location r, the contention is related to the average number of safety packets transmitted 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, as reflected in $C_r(t\text{-}1)$, while always considering the current sensed results of contention as measured 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 [14]:

$$C_r(t) = \gamma C_r(t-1) + (1-\gamma)\,\hat{C}_r(t) \qquad (1)$$

where γ reflects the weight given to history, and 1-γ denotes the weight of the sensed contention. The sensed metric $\hat{C}_r$ depends on the evaluation of data relayed from n cars. $\hat{C}_r$ 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 is the average number of untransmitted 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 timer during the MAC backoff process whenever it senses a busy channel.

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 untransmitted 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:

$$\hat{C}_r(t) = \alpha(D_r \times B_r)/S_r + \beta U_r \qquad (2)$$

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. FCVANET System Description

The decision making process implemented in [8] does not differentiate between contention levels and does not relate precisely the measured contention to the amount of needed spectrum, which could lead to an overutilization of the white spectrum. That is, if the network is suffering from low contention, it could be resolved by assigning one TV channel (6 MHz), rather than using several channels as the system in [8] may do. In order to assign the minimum necessary additional bandwidth to relieve the contention, we build a new decision making system that quantifies contention into multiple levels of severity using a Fuzzy Logic System (FLS). The execution of the algorithm for computing $C_r(t)$ occurs at the local acquisition and processing unit (LAPU) that receives individual measures from the cars through the RSU, mainly D_r, B_r, S_r and U_r (see Figure 1). The LAPU 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, $\hat{C}_r(t)$. Using equation (1), the LAPU generates its estimate of the contention by accounting to the sensed metric and the history component. Finally, the LAPU forwards the consequence of the FLS to the previous RSU which notifies passing cars of the additional bandwidth to use to extend the control channel.

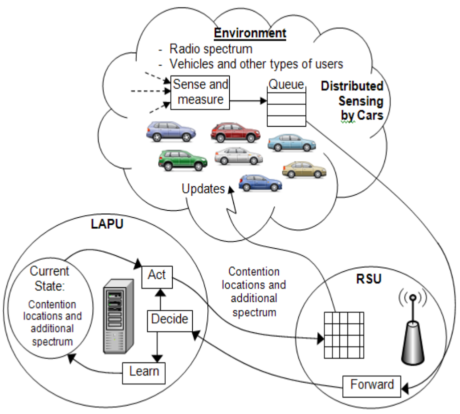

Figure 1: Network Cognition Cycle

A. Designing the Fuzzy Logic System

The design of the system considers 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 ms) and with low delay.

To better understand what happens during contention periods, we simulate using the network simulator 2, ns2, a scenario where the needed bit rate is equal as the offered bitrate. NS-2 provides a comprehensive support for the IEEE 802.11 set of technologies. 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, ns-2 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. The parameters used in the simulation are shown in Table 1, while the results are plotted in Figure 2.

Table 1. Parameter used in the simulation

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

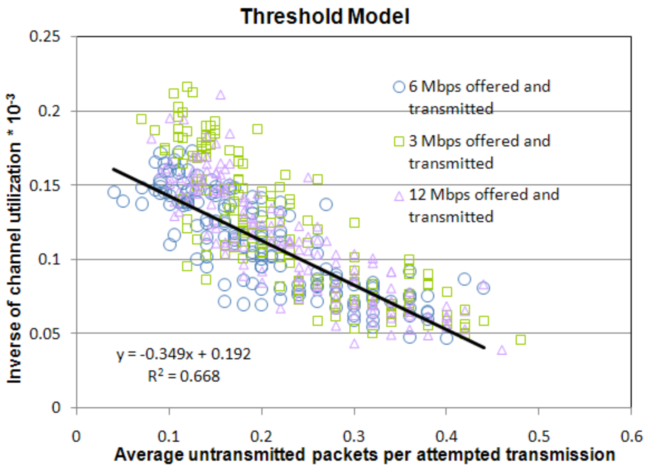

Figure 2: A threshold scenario showing x_1 versus x_2.

A careful examination of the results reveals the following:

- The station may see a high number of untransmitted packets that consume channel resources (low inverse channel utilization). Thus, in contended scenarios it will appear as if the successfully transmitted packets will render the channel used most of the time. This will cause most of the packets to timeout and not to be transmitted (shown in the right part of Figure 2).

- The station might be able to transmit most of its packets, so that the untransmitted ratio will be low, but the delay will be high, thus reflecting a low effective utilization of the channel (i.e., high inverse channel utilization as shown in the left part of 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 (*minimum needed additional bandwidth*) is divided into five levels: Very Small, Small, Average, Large and Very Large. We used trapezoidal membership functions for the edge membership functions and triangle ones for the middle ones. These are shown in Figure 3, 4 and 5.

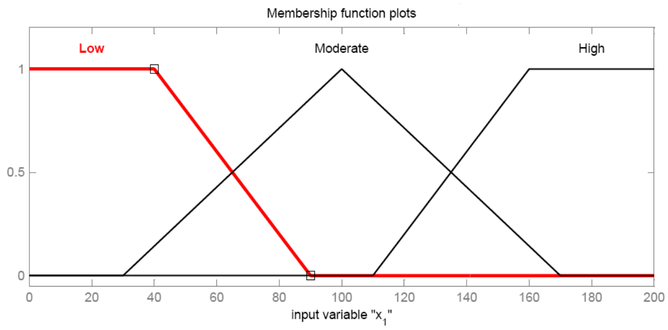

Figure 3: Membership function of Antecedent 1

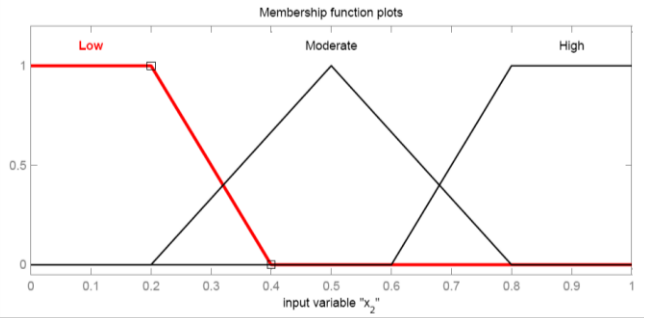

Figure 4: Membership function of Antecedent 2

From the previous section, we know that we have 2 antecedents and 3 fuzzy subsets, thus we need $3^2 = 9$ rules for this FLS, which are illustrated in Table 2. These rules are made consistent with the discussion about data contention in the previous section, specifically based on the observations from Figure 1. Rules are given equal weights. The defuzzifier used in our FLS is the Centroid Defuzzification method. For the operators used, we chose the min operation for the AND, while for the OR operator, we chose the max operation, which was also used for the implication method.

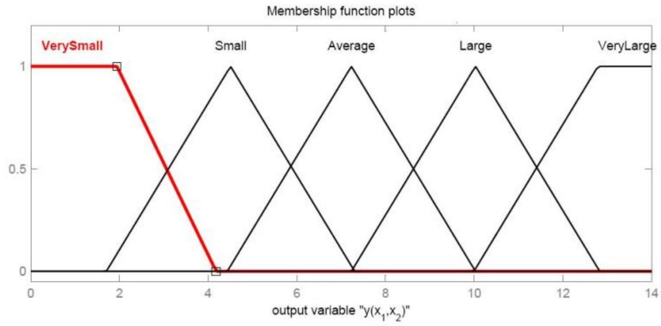

Figure 5: Membership function of the Consequence

Table 2: Rules used in the FLS design.

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

V. SIMULATION 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.

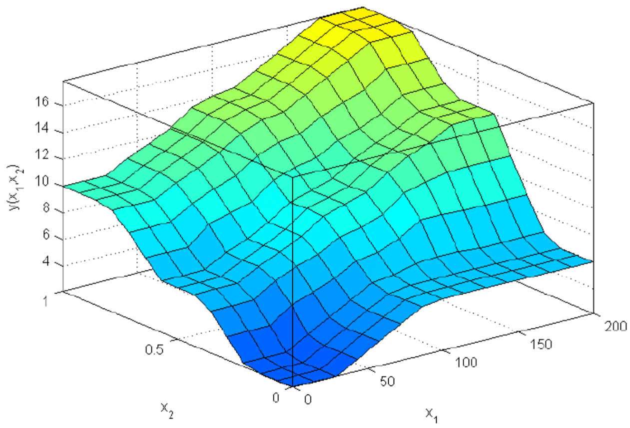

Figure 6: Input-Output Characteristics of the FLS

B. Methodology

The approach we used to evaluate our system integrates ns2 and Matlab, as implied in the diagram of Figure 7. Multiple scenarios of network contention were simulated in ns2 (simulation parameters are shown in Table 4), where the access delay D_r^c, offered bitrate B_r^c, payload size S_r^c and U_r^c were collected continuously from cars. These were then fed into a Vector Averaging function that buffers the input data for the last *n* cars providing measurements for region *r*, and then calculates the final values of D_r, B_r, S_r, and U_r using simple averaging. The computed averages are next passed as input to the fuzzy inference system (in Matlab).

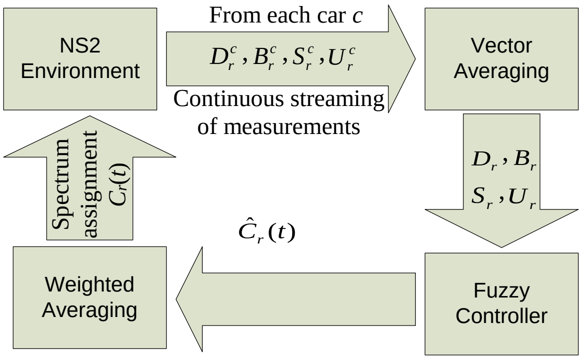

Figure 7: Simulation Methodology used to evaluate our work

Table 4. Simulation parameters

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

C. Results

The first scenario used an offered bitrate of 6 Mbps and needed bitrate of 9.5 Mbps (packet-size×number-of-cars/50ms). The output $C_r(t)$ of the weighted average was monitored and plotted in Figure 9, where the expected $C_r(t)$ is 3.5Mbps. The fuzzy output converged towards the 3.5 MHz expected bandwidth, demonstrating that the system was able to detect contention and assign the needed bandwidth. We set *n* to 10, meaning that the readings of every 10 cars were averaged together using vector averaging. It should be noted that the value of the fuzzy output was only fed-back into ns-2 at the end of the lat simulation run. The addition of this white spectrum is expected to remove contention and lead to a value of zero $C_r(t)$, which is what Figure 8 shows. Finally, we devised a second scenario, where the offered bit rate is 6 Mbps and the needed bitrate is 13 Mbps. Similarly, the results in Figure 9 show that the system was able to identify contention and determine the needed bandwidth to alleviate it.

VI. CONCLUSION

In this paper, we introduced a fuzzy inference system that is able to detect and quantify data contention in vehicular ad hoc networks. The experimental results show the effectiveness of the system in reducing data contention on the roads by assigning the needed bandwidth. Continuing work is focusing on designing a distributed system without requiring an LAPU.

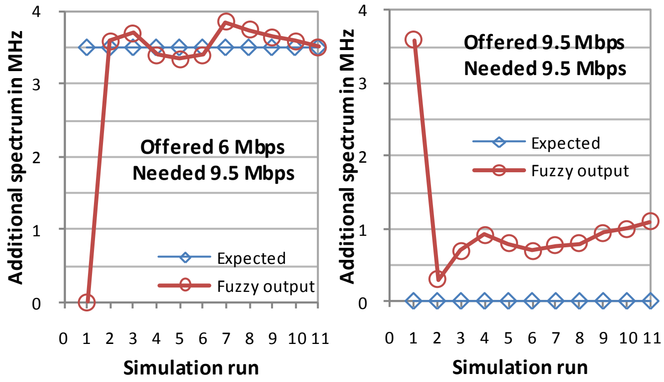

Figure 8: Simulation results of Scenario 1

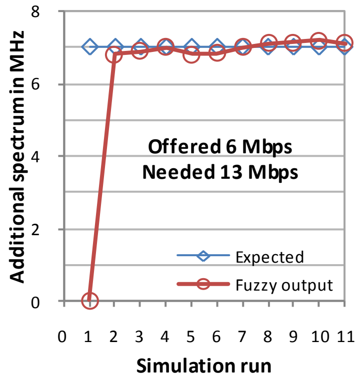

Figure 9: Simulation results of Scenario 2

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