Applying Adaptive QoS-aware Medium Access Control in Priority-Based Vehicular Ad Hoc Networks

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Abstract—This paper proposes a novel, adaptive medium access control mechanism for vehicular ad hoc networks. A simple, effective, and efficient nonlinear control law is built, based on fuzzy logic control principles, which can be easily adopted in different network environments (e.g., vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication). We demonstrate, via simulative evaluation, that the proposed fuzzy control methodology offers inherent robustness with effective control of the system under dense and dynamic conditions, without the need to (re)tune any parameters. The proposed approach offers distinct differentiation among differently prioritized traffic types, thus providing adequate Quality of Service (QoS) in terms of throughput performance, in contrast with the IEEE 802.11p MAC protocol we compared against.

Keywords—vehicular ad hoc networks; medium access control; fuzzy logic control

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) represent a particularly challenging class of mobile (ad hoc) networks that enable vehicles to communicate with each other (vehicle-to-vehicle (V2V) communication) and/or with roadside infrastructure (vehicle-to-infrastructure (V2I) communication). The aim of VANETs is the facilitation of a plethora of applications, such as traffic safety, traffic efficiency and management, as well as infotainment.

The variety of the intended applications implies that the Quality of Service (QoS) required varies from non-real-time, to soft real-time where a timing failure might compromise service quality, up to hard real-time where a timing failure might lead to a disaster. For this, there is ongoing standardization, notably the Wireless Access for the Vehicular Environment (WAVE) standards [1-4],

Moreover, the IEEE 802.11 standard body is currently working on addressing these concerns through a new amendment, IEEE 802.11p [5, 8]. The IEEE 802.11p WAVE standardization process [9] originates from the allocation of the Dedicated Short Range Communications (DSRC) spectrum band [6, 10] to be used exclusively for V2V and V2I communications.

The IEEE 802.11p is based on the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. It uses the enhanced distributed channel access (EDCA) mechanism originally provided by IEEE 802.11e [11] that differentiates traffic types through different static MAC parameters values. An extensive analysis of several CSMA based wireless networking MAC protocols and tuning mechanisms has already been carried out. However, the performance of IEEE 802.11p has not been substantially studied; a number of researchers have given an overview on both the capabilities and the limitations of the technology [12- 15]. Up to date, to the best of our knowledge, IEEE 802.11p has only been evaluated and enhanced (e.g. [16-17]) for specific vehicular environments (e.g. V2V or V2I), using a single class of traffic application.

In this paper, we propose an adaptive, QoS-aware medium access control mechanism to be applied in priority-based vehicular ad hoc networks. With the use of a linguistic model of the system under control, a simple, effective, and efficient nonlinear control law is built, which can be easily adopted in different network environments (V2V and V2I). We show that the proposed mechanism offers significant improvements over the original IEEE 802.11p MAC protocol in controlling access to the medium, under dense and dynamic conditions. Specifically, it provides acceptable QoS, in terms of throughput performance, and effective differentiation among differently prioritized traffic types.

The paper is organized as follows. Section II gives the basic features of the WAVE system, and the IEEE 802.11 MAC protocol in concern. In Section III we present an overview of the related work, and in Section IV, we briefly review some of the properties of fuzzy logic control and its application in network control problems. In Section V, we present our proposed fuzzy logic based MAC mechanism applied in V2V and V2I networks. Then, Section VI discusses the performance of the proposed strategy through simulations, also comparing with the original IEEE 802.11p protocol. Finally, in Section VII we present our conclusions.

II. WAVE SYSTEM

The IEEE has developed the WAVE system architecture [1-4] to provide wireless access in vehicular environments. Collectively, IEEE 802.11p [5] and IEEE 1609.x [1-4] are called WAVE standards because their goal, as a whole, is to facilitate the provision of wireless access in vehicular environments [9].

A WAVE system consists of two main entities:
The IEEE 802.11p standard is based on the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. It uses the enhanced distributed channel access (EDCA) mechanism originally provided by IEEE 802.11e [11] that provide traffic types differentiation through different static MAC parameters values.

As explained in Section I, the IEEE 802.11p is based on the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. It uses the enhanced distributed channel access (EDCA) mechanism originally provided by IEEE 802.11e [11] that provide traffic types differentiation through different static MAC parameters values.

Four applications’ access categories (ACs) are defined in the WAVE standards. The differentiation in priority between ACs for channel access parameters is implemented using the appropriate EDCA parameter set values (see Table I and Table II), which are defined as follows [4]:

- **Contention window (CW):** An interval from which a random number is drawn to implement the random back-off mechanism.
- **aCW**<sub>min</sub> and **aCW**<sub>max</sub>, which are static values (15 and 1023, respectively), as specified in [5].

Note, that the back-off mechanism is used in case the medium is sensed busy, and a back-off time is chosen uniformly at random from the interval [0, CW+1], where the initial CW is equal to the aCW<sub>min</sub>. The interval size gets doubled, until it’s equal to aCW<sub>max</sub>, if the subsequent transmission attempt fails/collides.

A generic system architecture of the MAC is shown in Fig. 1 [4]. The internal contention algorithm, as indicated in Fig. 1, calculates the back-off independently for each AC based on access parameters. The AC with the smallest back-off wins the internal contention, and the winning AC then contends externally for the wireless medium [4].

### III. RELATED WORK

A number of enhancements on the IEEE 802.11p MAC protocol have been proposed; a detailed description and review can be found in [18]. Up to date, to the best of our knowledge, IEEE 802.11p has been evaluated and enhanced (e.g. [16-17]) targeted in specific vehicular environments (e.g. V2V or V2I), using a single class of traffic application.

For example, in [16] two schemes are presented that adapt the contention window, based on the number of transmitting vehicles. The first proposal is a centralized approach that assumes the knowledge of the number of transmitting vehicles. This is however difficult to obtain due to the variability and high dynamics of the environment. The second proposal is a distributed approach: vehicles use local channel information to adapt the contention window size. A linear updating method is used to change the back-off window size based on channel busy measurements; the high dynamics of the environment imply that such a linear updating method is not robust enough.

The evaluation of these schemes (that focused only on V2I communication) has taken into consideration only one application access category for each scenario, ignoring the mixture of prioritized traffic types expected to be present.
A. Fuzzy Logic Control (FLC)

Fuzzy logic is a logical system, which is an extension and generalization of multivalued logic systems [19]. It is one of the family of tools of what is commonly known as Computational Intelligence (CI). The idea of FLC was initially introduced by Zadeh [20] and first applied by Mamdani [21] in an attempt to control systems that are difficult to model mathematically and hence design controllers. FLC [22] may be viewed as a way of designing feedback controllers in situations where rigorous control theoretic approaches are too difficult and time consuming to use, due to difficulties in obtaining a formal analytical model, while at the same time some intuitive understanding of the process is available. FLC has strengths in controlling highly nonlinear, complex systems, which are commonly encountered in product design, manufacturing and control. While FLC based techniques are not a panacea (and it is important to view them as supplementing proven traditional techniques), there is a lot of interest not only from the academic research community (e.g. [23]) but also from the industry, including the telecommunications industry (e.g. [24]), due to its successful deployment in the field, controlling complex, difficult to control systems (e.g. [25]).

The capability to qualitatively capture the attributes of a control system based on observable phenomena is a main feature of FLC. Thus, if the FLC is designed with a good (intuitive) understanding of the system to be controlled, then the limitations due to the complexity the system’s parameters introduce on a mathematical model can be avoided. In contrast, a common approach in classical control theory is to either ignore such complex parameters in the mathematical model, or to simplify the model to such an extent (in order to make tractable and obtain some stability results), which renders the designed controllers and their derived stability bounds overly conservative.

B. Application of Fuzzy Logic in Networks

FLC has been successfully used in a wide variety of applications in many fields, e.g. engineering, science, business, and medicine. A number of research papers using fuzzy logic investigating solutions to congestion control issues in networking, especially in Asynchronous Transfer Mode (ATM) networks, have been published. For example, [23], [26], [27] and [28], since early 90’s, have successfully used concept of FLC for congestion control in ATM, as an alternative to conventional counterparts. FLC was also used in IP world (e.g. [29] and [30]).

V. FUZZY LOGIC-BASED MAC MECHANISM IN VANETS

We present an enhanced, adaptive MAC protocol, based on the IEEE 802.11p, operating under VANET environments. The proposed mechanism is needed to offer QoS-aware wireless access in vehicular environment (both V2V and V2I); taking into account the differentiation of the various traffic applications, those are categorized into different priorities with different basic MAC parameters.

We use fuzzy logic control principles to design a simple, effective and efficient nonlinear control law, in order to offer inherent robustness with effective control of the system. To the best of our knowledge, fuzzy logic is yet to be considered in the development of a MAC scheme in VANETs.

Due to the high mobility and the resulting highly dynamic network environment, the adaptive medium access control mechanism needs to operate in a decentralized and self-organized way, i.e. locally at each VANET node. The new scheme adapts the back-off/contention window parameter for each transmitting node based on the channel traffic occupancy, combined with the access categories the applications belong to, in order to be adaptive to the high environment dynamics. The perspective achievement is the QoS provision in terms of throughput performance, by providing effective differentiation among traffic types that belong to different applications’ access categories. It is expected that the new scheme will give priority/preference to the higher ACs (AC2 and AC3), rather the lower ACs (AC0 and AC1), especially in the case of highly dense conditions.

The system model of the proposed fuzzy logic based MAC mechanism (FLMAC) is shown in Fig. 2, where all quantities are considered at the discrete instant $kT$:

- $T$ is the sampling period.
- $CTO(kT)$ is the channel traffic occupancy, measured throughout the current sampling period, by keeping the amount of time a channel is busy. The record of busy time within each sampling period is achieved by physical layer channel idle/busy indication.
- $CTO(kT-T)$ is the channel traffic occupancy, measured at the previous sampling period.
- $CW(kT)$ is the calculated contention window parameter used in determining the back-off time.
- $SG_{i1,2}(kT)$ are the input scaling gains.
A fuzzy inference engine (FIE) is designed to operate locally at each VANET node, and control the wireless access using linguistic rules that describe the behavior of the environment in differing widely operating conditions. As shown in Fig. 2, the FIE dynamically calculates the contention window parameter, based on two network state inputs: the channel traffic occupancy for two consecutive sampling periods (can be interpreted as a prediction horizon).

In fuzzy control theory, the range of values of inputs or outputs for a given controller is usually called the “universe of discourse”. Often, for greater flexibility in fuzzy controller implementation, the universe of discourse for each process input is “normalized” by means of constant scaling factors [22]. For our fuzzy controller design, the input scaling gains, \(SG_{i1,2}(kT)\) are chosen so that the range of values of \(SG_{i1}(kT)CTO(kT)\) and \(SG_{i2}(kT)CTO(kT-T)\) lie in the real interval \([0, 1]\). Thus, \(SG_{i1,2}(kT)\) is set to be equal to \(1/T\). The range of values of the controller’s output, \(CW(kT)\), lies between \(aCW_{\text{min}}\) and \(aCW_{\text{max}}\), according to the access category the application, run on each VANET node, belongs to (see Section II – Table I and Table II).

Therefore, the contention window parameter is calculated dynamically, based on a nonlinear control law derived by the construction of the FIE, and taking into account the density of the environment. This is in contrast with the basic operation of the IEEE 802.11p, where the contention window is just doubled if the subsequent transmission attempt fails/collides, without taking into account the density of the medium. Further, due to the high variability and dynamics of the system, a nonlinear control law is more efficient to cope with these uncertainties and dynamics, in contrast with a linear control method (e.g. [16]).

There is no accepted systematic procedure for the design of a fuzzy controller [22]. The most commonly used approach is to define membership functions of the inputs and output based on a qualitative understanding of the system, together with a rule data base, and to test the controller by trial-and-error until satisfactory performance is achieved. More sophisticated techniques abound, however, we opt for this simple approach which also yields a simple implementation, and as we show in Section VI is effective. The focus is on the achievement of the design goals of the controller, whilst keeping the design of the controller as simple and generic as possible. Note, that as the fuzzy controller is nonlinear, it is very difficult to examine analytically the influence of certain parameters. Usually, extensive simulation and experimentation are used to investigate its behavior.

The multi-input FIE uses linguistic rules to calculate the contention window parameter. These rules form the control knowledge–rule base of the controller and describe how to best control the system, under differing operating conditions. Hence, linguistic expressions are needed for the inputs and the output, and the characteristics of the inputs and the output. We will use “linguistic variables” (that is, symbolic descriptions of what are in general time-varying quantities) to describe fuzzy system inputs and output. The linguistic variables take on “linguistic values” that change dynamically over time and are used to describe specific characteristics of the variables; such values are generally descriptive terms such as “small”, “zero” and “large”.

The philosophy behind the knowledge base of the FLMAC scheme is that of being aggressive when the density of the channel is very high over the two consecutive sampling periods (where congestion starts to set in and quick relief is required), but on the other hand being able to smoothly respond in the case of low density. All other rules can represent intermediate situations, thus providing the control mechanism with a highly dynamic action. This point can be illustrated by observing the visualization of the nonlinear control-decision surface of the FIE used in the FLMAC scheme (see Fig. 3). It is shaped by the constructed rule base and the linguistic values of the inputs and output variables. A convenient way to list all possible IF-THEN control rules is to use a tabular representation (see Table III). These rules reflect the particular view and experiences of the designer, and are easy to relate to human reasoning processes and gathered experiences. Usually, to define the linguistic values of a fuzzy variable, Gaussian, triangular, or trapezoidal shaped functions are used. Due to computational simplicity, we select triangular shaped membership functions in FLMAC control scheme (see Fig. 4).

Recall that the range of values of the controller’s output, \(CW(kT)\), lies between \(aCW_{\text{min}}\) and \(aCW_{\text{max}}\), as defined in Table I and Table II. Thus we expect, in case of very high density, the constructed FIE to give a very large value of the contention window. As the range of values for the AC2 and AC3 are much smaller than the ranges of the AC0 and AC1, FLMAC will prioritize the higher ACs (AC2 and AC3), over the lower (AC0 and AC1); this effectively differentiates traffic types that belong to different applications’ access categories. Also note, that an identical fuzzy controller is used for each AC; only the range of values of the output is changed, based on the standard (see Table I and Table II).
TABLE III. FLMAC LINGUISTIC RULES - RULE BASE

<table>
<thead>
<tr>
<th>CW (kT)</th>
<th>CTO(kT-T)</th>
<th>Z</th>
<th>VS</th>
<th>S</th>
<th>L</th>
<th>VL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>VS</td>
<td>VS</td>
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<tr>
<td>VS</td>
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<td>VS</td>
<td>VS</td>
<td>S</td>
<td>S</td>
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<tr>
<td>S</td>
<td>S</td>
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<td>S</td>
<td>S</td>
<td>S</td>
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<tr>
<td>L</td>
<td>VL</td>
<td>L</td>
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<td>L</td>
<td>L</td>
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<tr>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
<td></td>
</tr>
</tbody>
</table>

a. table notations: zero (Z), very-small (VS), small (S), large (L), very-large (VL)

VI. PERFORMANCE EVALUATION

In this section, we use simulative evaluation to demonstrate the effectiveness and robustness of the fuzzy logic-based MAC scheme implemented in both V2V and V2I environments. A comparison is also made with the IEEE 802.11p protocol. The performance is evaluated using the NCTUns network simulator [31], a freely available simulator used in other papers regarding VANETS (e.g. in [32]).

We have considered two different environments: V2V and V2I. The common network parameters used in the simulations are:

- The channel data rate is set to 3 Mbps.
- Each VANET node generates CBR traffic with 600 byte packet every 1.5 msec (used in [16]). However, we set different priorities, to create a mixture of differently prioritized types of traffic.
- The total simulation time is 60 seconds.
- The sampling period is set to 20 msec (slightly bigger than the maximum back-off time that could be obtained, by having a contention window parameter of 1023 multiplied by the slot time of 13 μsec).

A. Examination of dense V2V and V2I environments

We investigate the performance of the tested MAC schemes as the number of VANET nodes increase, thus creating a very high dense environment. We use two different environments: V2V and V2I.

TABLE IV. THROUGHPUT COMPARISON IN DENSE V2V

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Original 802.11p</th>
<th>Fuzzy Logic based MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AC0</td>
</tr>
<tr>
<td>4</td>
<td>146</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>65</td>
<td>0.24</td>
</tr>
<tr>
<td>20</td>
<td>42</td>
<td>0.1</td>
</tr>
<tr>
<td>28</td>
<td>32</td>
<td>0.1</td>
</tr>
<tr>
<td>32</td>
<td>30</td>
<td>0.1</td>
</tr>
</tbody>
</table>

TABLE V. THROUGHPUT COMPARISON IN DENSE V2I

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Original 802.11p</th>
<th>Fuzzy Logic based MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AC0</td>
</tr>
<tr>
<td>4</td>
<td>293</td>
<td>6</td>
</tr>
<tr>
<td>12</td>
<td>98</td>
<td>1.4</td>
</tr>
<tr>
<td>20</td>
<td>59</td>
<td>0.7</td>
</tr>
<tr>
<td>28</td>
<td>41</td>
<td>0.6</td>
</tr>
<tr>
<td>32</td>
<td>37</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Five (5) different scenarios are tested using a different number of vehicles. In the V2V environment, we start with four senders transmitting data to other four receivers (i.e., creating four pairs); on the next scenario we create 12 pairs; then we increase to 20, 28 and 32 pairs. In a V2I environment, we have the RSU sending data to 4, 12, 20, 28, and 32 vehicles. In each scenario, we equally split the total number of vehicles into four groups (one for each access category of Table II).

The results are summarized in Table IV and Table V, for V2V and V2I, respectively. It is clearly shown that as the number of vehicles increases, i.e., we have a very high density, the proposed scheme outperforms the 802.11p in terms of throughput, as well as in the differentiation of the prioritized traffic types. Thus our scheme, FLMAC, provides better QoS to the higher priority applications that belong to the AC2 and AC3 categories by providing most of the available bandwidth to them. On the other hand, the original 802.11p fails to provide any differentiation between the different ACs (even though this differentiation is a design goal of the standard). Table VI shows the AC3’s throughput gain of the proposed scheme over the original 802.11p in V2V and V2I. The superiority of the proposed scheme over the original 802.11p is obvious in terms of providing the most wireless access to the higher priority traffic (thus offering the required QoS). Due to lack of space, we show in Fig. 5 the throughput obtained by the highest priority AC3, as the number of vehicles increases, in both V2V and V2I environments.

Figure 4. Membership functions of the linguistic values representing the input and output variables.
TABLE VI. FLMAC GAIN OVER ORIGINAL 802.11p

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>AC3's Throughput Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V2V</td>
</tr>
<tr>
<td>4 pairs</td>
<td>571%</td>
</tr>
<tr>
<td>12 pairs</td>
<td>389%</td>
</tr>
<tr>
<td>20 pairs</td>
<td>296%</td>
</tr>
<tr>
<td>28 pairs</td>
<td>266%</td>
</tr>
<tr>
<td>32 pairs</td>
<td>272%</td>
</tr>
</tbody>
</table>

B. Dynamic changes in V2V and V2I environments

We examine the performance of the tested MAC schemes under dynamic traffic changes. The network conditions apply as indicated in the previous section, however, now half the vehicles appear at the start of the simulation and the rest appear midway through the simulation; this evaluates how the tested MAC schemes adapt to sudden changes.

The results are shown in Table VII (for V2V) and Table VIII (for V2I). We can clearly observe that FLMAC again outperforms the original 802.11p scheme; it provides efficient differentiation to the different prioritized traffic types, whereas the original MAC scheme fails to do so. The throughput gain of the higher priority traffic is again very high; this can be seen implicitly from Table VII and Table VIII.

VII. CONCLUSIONS

It is our view that the use of a nonlinear control in MAC can lead to efficient and effective control laws. Furthermore, due to the high variability and dynamics in VANETs, a robust, effective controller is beneficial to keep the system in a controlled state, under differing conditions.

In this paper, we proposed a novel, adaptive medium access control mechanism in VANETs, based on fuzzy logic control, to enhance the original 802.11p protocol, in terms of providing QoS in different prioritized traffic types. We demonstrated that the nonlinear control scheme we have proposed can be readily applied for both V2V and V2I communication purposes; it significantly enhances controlling wireless access in VANETs under differing operating conditions, without the need for (re)tuning.

Specifically, we have shown that the proposed scheme is able to compensate for a varying number of active VANET nodes, as well as handle dynamic traffic changes. The fuzzy logic-based MAC mechanism outperforms the original MAC mechanism, in terms of throughput performance, while at the same time it provides a highly effective differentiation among the different prioritized traffic types; by giving precedence to the higher priority traffic, it offers such applications the QoS they demand.

The successfully demonstrated application of fuzzy logic in the dynamic calculation of a suitable contention window parameter for each applications’ access category, motivates (as part of future work) the adoption of such methodology in adjusting the potential value range of the contention window, and comparing the performance with the current one.

REFERENCES


