A New Hierarchical and Adaptive Protocol for
Minimum-Delay V2V Communication

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Abstract— The past few years witnessed a great interest in the issues related to transportation efficiency and safety. Intelligent Transportation Systems (ITS) are envisioned to be integrated in vehicles and road-side equipment to alert drivers of hazardous conditions (e.g., slow traffic, pot holes, road construction, lane departure, etc.). Several protocols have been proposed in the literature to achieve Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication. V2I protocols rely on Road-Side Equipment (RSE) to exchange messages between vehicles and the underlying transportation network. Even though V2I protocols can be used to relay messages between vehicles, these protocols result in unnecessary delays as the packets need to be relayed through the RSE. V2V protocols serve to minimize the communication delay through the direct exchange of messages between vehicles and the underlying transportation network. Even though V2I protocols can be used to relay messages between vehicles, these protocols result in unnecessary delays as the packets need to be relayed through the RSE. V2V protocols serve to minimize the communication delay through the direct exchange of messages between vehicles without the need to rely on any road-side infrastructure. Thus, providing an economical solution that does not depend on the deployment of expensive infrastructure. The majority of V2V protocols presented in the literature utilize a combination of controlled access techniques (e.g., TDMA, FDMA, CDMA) to provide prioritized access to the communication medium. While these protocols split the capacity of the communication link to support a maximum number of users with different priority levels, our work utilizes a combination of CDMA and TDMA techniques to increase the number of concurrent users sharing the bandwidth. The proposed protocol provides an adaptive scheme that classifies the vehicle’s messages as “urgent” or “non-urgent” based on its statistical parameters (e.g., speed, acceleration, directional stability) and the state of its neighboring vehicles (e.g., normal or urgent). Furthermore, the proposed protocol achieves intelligent scheduling and allocation of messages and the underlying bandwidth to minimize the end-to-end communication delay and the costs associated with the deployment of Vehicle Infrastructure Integration (VII) without the need for road-side equipment.

I. Introduction

Since the invention of the vehicle, accidents have been taking thousands of lives each year. Till now, no comprehensive solutions have been proposed to solve this problem. One possible approach would involve alerting the drivers of possible dangerous situations before facing them. In this paper we propose a lightweight Medium Access Control (MAC) protocol for communicating messages between vehicles. The proposed protocol strives to deliver alert messages with the minimum end-to-end delay so that drivers can be alerted about urgent or hazardous situations like accidents or traffic congestions. In this work, we represent the network of vehicles as a two-level hierarchy by introducing the concept of master and normal vehicles in a given geographic area. The proposed protocol also adapts to the state of vehicles in a given geographic area by allowing vehicles with urgent messages to communicate more frequently than those with non-urgent messages. The rest of this paper is organized as follows: Section II provides a brief overview of V2V protocols presented in the recent literature. Section III describes the proposed MAC protocol. Section IV describes the mathematical model of the proposed channel allocation scheme. Section V provides the description of the On-Board fuzzy-logic controller that monitors the parameters of the vehicles and the state of the neighboring vehicles to determine their relative priorities. Section VI explains the proposed dynamic channel allocation heuristic that serves to maximize the number of concurrent vehicles accessing the communication bandwidth. Simulation experiments and performance analysis of the proposed protocol under various traffic conditions are described in section VII and VIII, respectively. The conclusions of our study and potential extensions are presented in section IX.

II. Related Work

MAC protocols can be classified as random-access or controlled-access. The later one assigns each node a time-slot (TDMA), a frequency (FDMA), or a code (CDMA). Controlled-access protocols are usually suitable when the utilization of the communication channel is high. On the other hand, in random-access
protocols, channel allocation is not coordinated but is competitive between nodes. This is beneficial when the utilization of the communication channel is low. Further, hybrid-access protocols combine the capabilities of random-access and controlled-access protocols depending on the channel conditions. AGENT [1] is an example of a hybrid-access protocol.

An important reason for introducing Vehicular Ad-hoc NETworks (VANETs) is the concept of public transportation safety. Transportation safety is defined in terms of a set of software and hardware tools designed and implemented to decrease the number of vehicle accidents by making vehicles communicate alerts with the minimum end-to-end communication delay. In general, the amount of data communicated is small but important factors in the design of VANET protocols include the transmission reliability and delay.

One of the biggest challenges in VANETs involves the frequent topological changes due to the mobility of the vehicles. Opposite to their sensor counterparts, VANETs do not suffer from the issues of CPU, memory and power limitations.

The IEEE 802.11p group has been working on defining new standard for vehicle-to-vehicle communication. IEEE 802.11p which is also called WAVE (Wireless Access Vehicle Environment) is most concerned with the concepts of active safety where reliability and low latency are important. WAVE employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the basic medium access scheme and uses the 5.850-5.925 GHz band of the frequency spectrum in North America. By using Orthogonal Frequency Division Multiplexing (OFDM), communication over 1000m distance is achieved for V2V and V2I communication. Operating in 10 MHz channels, it will allow A data payload capabilities of 3, 4.5, 6, 9, 12, 18, 24 and 27 Mb/s, and when using the optional 24 MHz channel, the achievable data rate can reach a maximum of 54 Mb/s [2].

In [3], an evaluation of 802.11p was carried out based on both analytical and simulation studies. In their work, the authors analyzed the capabilities of the proposed standard and demonstrated that WAVE is capable of prioritizing messages. When increasing the number of communicating nodes on AccessClass3, collision probability increases significantly. Also, the study indicated that the WAVE technology cannot ensure the timely delivery of critical messages in large-scale deployment scenarios. In this work, we introduce intelligent channel allocation and messages prioritization schemes to address this limitation.

One of the most popular VANET protocols is the ADHOC MAC, which was conceived in conjunction with the European project CARTALK2000. This protocol uses dynamic TDMA for channel allocation by extending the Reservation-ALOHA into Reliable Reservation ALOHA where each active vehicle need to select its Basic Channel (BCH). Each basic channel is one time slot that is periodically repeated every N successive time frames. The detailed specifications of this protocol can be found in [2]. Other VANET protocols are based on the use of directional antennae where each vehicle transmits in a certain direction, and the transmission space is divided into N transmission directions of (360/N)º each. Directional MAC or DMAC is one of the directional antenna based protocols. It assumes that each vehicle knows its position and its neighbor’s positions using Geo-stationary satellites (e.g., GPS or Galileo).

Comparisons between these two protocols show that the ADHOC MAC solved the hidden terminal problem, and guarantees an acceptable level of QoS which is required for real-time traffic. On the down side, ADHOC MAC does not provide efficient use of the communication medium as the number of vehicles in the service area should be less than the number of available time-slots in the MAC frame. On the other hand, DMAC provides greater network throughput by decreasing the transmission collisions and increasing the medium reuse factor. DMAC relies of the use of expensive hardware that is hard to deploy in large-scale networks. The protocol proposed in this paper does not rely on expensive hardware infrastructure as it does not rely on expensive synchronization devices or road-side equipment for inter-vehicle communication.

Our proposed communication protocol is based on asynchronous CDMA for message transfer between vehicles. In asynchronous CDMA, the codes that are assigned to vehicles cannot be assumed to be uncorrelated. For example if two senders x and y attempt to transmit their messages to destination z and y is closer to z than x, x and y should adapt their power levels to ensure that no transmitter is overwhelming the receiver with its signal. A detailed strategy for power management is presented in a later section of this paper to ensure successful use of asynchronous CDMA.

III. Protocol Specifications

For vehicles to communicate with each other, each vehicle must lease a code from the master vehicle in its service area.
The protocol assumes that each vehicle has a unique ID (e.g., Vehicle Identification Number) and is able to know its current position from a satellite-based positioning system (e.g., GPS or Galileo). Also each vehicle should be able to know its current service area from the digital maps stored in the vehicle On-Board Equipment (OBE).

The proposed protocol is based on three types of messages to achieve V2V communication. These types are as follows:

- **Vehicle Advertisement Message (VAM):** this message contains source vehicle ID, the destination vehicle ID (i.e., the ID of the master vehicle in that region), the current position of the vehicle, the current region ID of the vehicle and the state of the vehicle (i.e., normal or urgent).
- **Code Request message:** will be sent when a vehicle enters a service area and needs to lease a code to communicate with the serving master vehicle. The code request should explicitly declare whether the vehicle is in urgent or normal state.
- **Master claim message:** as each vehicle enters a service area, it sends this message and if there are no master vehicles in the area, the vehicle claims to be the master vehicle.

When a vehicle enters a service area with no master vehicle, it sends a master claim message using the designated code from the code set assigned to the service area. If multiple vehicles enter a given service area at the same time, each vehicle will receive the master claim messages and the vehicle with the highest ID will be assigned as the master vehicle of the service area in question.

The master vehicle divides the codes in each service area into two categories: uplink codes and downlink codes. These are further divided into urgent-uplink, normal-uplink, urgent-downlink and normal-downlink codes.

The master vehicle is responsible for code management in its service area including the assignment of codes to newly entering vehicles, collection and dissemination of VAMs from/to all vehicles in its broadcast range. Also, the master vehicle has the dynamic channel allocation module that analyzes the traffic received from the vehicles in its service area and allocates a set of codes to be used in the uplink and downlink directions for urgent or non-urgent message exchange. The assignment of codes is based on the current states of all vehicles in the service area. The details of the dynamic channel allocation module are provided in Section IV. When the master vehicle leaves its service area, it handoffs all control information about its service area to the vehicle nearest to the centroid of the service area. This serves to decrease the handoff frequency as the vehicle closest to the centroid of the service area is likely to spend more time in the service area compared to other vehicles.

A vehicle that acquires a code to communicate is called an active vehicle. Active vehicles periodically send their VAMs to the master vehicle the corresponding service area. When an active vehicle leaves its service area, it can continue using its code acquired from the previous service area because the code sets used by neighboring service areas are orthogonal. This provides the vehicle a time leeway to acquire a code from the newly entered service area. Also, when a master vehicle stops receiving VAMs from a vehicle that it serves, it assumes that the vehicle has left the service, so it waits for a certain amount of time (i.e., dead-interval) and then it reclaims the code used by that vehicle so that it can be leased by other vehicles.

A vehicle having no code to communicate is called an inactive vehicle. These vehicles periodically send a code request message to the master vehicle until they are assigned a code. If a vehicle sends a code request and does not get a code there are two possibilities:

- The code request collided with other code request messages from other vehicles.
- There is no master vehicle in the service area.

To realize which of these two cases has occurred, the vehicle checks if it is receiving VAMs from the master vehicle service the area. If the vehicle is receiving VAMs, it can be concluded that the vehicle code request message collided with code request messages generated by other vehicle(s). In this situation, the vehicle backs off for a random amount of time and retries to send the code request message after the back off period.

In case where no VAMs are received from the master vehicle, the vehicle assumes that it is in a service area with no master vehicle, so it waits for a small amount of time, and then sends a master claim message claiming to be the master of the region. After sending the master claim message, the vehicle hunts for master claim messages generated by other vehicles. In case of receipt of multiple master claim messages, the vehicle with the highest ID becomes the master of the service area in questions. All other vehicles concede and declare the vehicle with the highest ID as the winner.

Based on the information conveyed in the VAMs of neighboring vehicles, the on-board fuzzy-logic controller determines whether the vehicle VAMs should be sent as
urgent or not. If the module determines that the vehicle VAMS are urgent, the vehicle leases an urgent communication channel from the master vehicle; otherwise, the vehicle leases a normal channel. The operating principles of this fuzzy controller are described in Section V.

Each vehicle continuously receives VAMs coming from the master vehicle in its service area. One of the received VAMs conveys the details of the master vehicle. This VAM contains the current location of the master vehicle in the service area. By calculating the distance between the active vehicles and the master vehicle, the active vehicles can adjust their power transmission level based on the distance from the master vehicle; farther vehicles send using higher power levels and closer vehicles send using lower power levels. This helps to balance the power levels of the signals received by the master vehicle; thus, minimizing the Bit Error Rate (BER) perceived at the master vehicle.

IV. Optimal Allocation of Channels

The performance of the proposed protocol relies heavily on the ability of master vehicles to perform efficient allocation of the available codes to vehicles in their corresponding service areas. In this section, we formulate the optimal channel allocation problem using Integer Linear Programming (ILP). This serves to help the master vehicles determine the optimal number of urgent and non-urgent codes that should be used for communication. The ILP model can be used in conjunction with ILP solvers (e.g., CPLEX) to perform off-line optimization of the available channel resources. Further, this model serves as a baseline of comparison with the real-time heuristic described later in this section. The ILP model for optimal channel allocation is described as follows:

Assume:

- \( V \): The total number of vehicles in a given service area.
- \( N_c \): The number of codes per service area
- \( D_u \): The maximum delay for urgent vehicles
- \( D_n \): The maximum delay for normal vehicles
- \( D_t \): The time slot duration
- \( R_{vol} = \begin{cases} 0, & \text{if a vehicle in normal state} \\ 1, & \text{if a vehicle in urgent state} \end{cases} \)
- \( S_u = D_u / D_t \): the number of time slots per urgent channel
- \( S_n = D_n / D_t \): the number of time slots per normal channel

Given the following variables:

- \( C_{Nc,x1} \): is the set of codes for a region and is defined as
  \[
  C_{Nc,x1} = \begin{cases} 
  0, & \text{for uplink channels} \\
  1, & \text{for downlink channels} 
  \end{cases}
  \]
- \( U_{Nc,x1}^{u} \): is the set of urgent uplink channels and is defined as
  \[
  U_{Nc,x1}^{u} = \begin{cases} 
  0, & \text{other wise} \\
  1, & \text{if the channel is urgent uplink} 
  \end{cases}
  \]
- \( U_{Nc,x1}^{n} \): is the set of normal uplink channels and is defined as
  \[
  U_{Nc,x1}^{n} = \begin{cases} 
  0, & \text{other wise} \\
  1, & \text{if the channel is normal uplink} 
  \end{cases}
  \]
- \( D_{Nc,x1}^{u} \): is the set of urgent downlink channels and is defined as
  \[
  D_{Nc,x1}^{u} = \begin{cases} 
  0, & \text{other wise} \\
  1, & \text{if the channel is urgent} 
  \end{cases}
  \]
- \( D_{Nc,x1}^{n} \): is the set of normal downlink channels and is defined as
  \[
  D_{Nc,x1}^{n} = \begin{cases} 
  0, & \text{other wise} \\
  1, & \text{if the channel is normal downlink} 
  \end{cases}
  \]
- \( A_{V,Nc}^{n} \): is the set vehicles that are using the normal uplink channels and is defined as:
  \[
  A_{V,Nc}^{n} = \begin{cases} 
  0, & \text{if vehicle i is not using normal uplink j} \\
  1, & \text{if vehicle i is using normal uplink j} 
  \end{cases}
  \]
- \( A_{V,Nc}^{u} \): is the set vehicles that are using the urgent uplink channels and is defined as:
  \[
  A_{V,Nc}^{u} = \begin{cases} 
  0, & \text{if vehicle i is not using urgent uplink j} \\
  1, & \text{if vehicle i is using urgent uplink j} 
  \end{cases}
  \]
such that:

\[
0 \leq C_i \leq 1 \quad \forall \quad 1 \leq i \leq N_c
\]

\[
I - C_i \leq U_i^u + U_i^n \leq I - C_i
\]

\[
C_i \leq D_i^u + D_i^n \leq C
\]

\[
0 \leq U_i^u \leq l
\]

\[
0 \leq U_i^n \leq l
\]

\[
0 \leq D_i^u \leq l
\]

\[
0 \leq D_i^n \leq l
\]

\[
0 \leq A_{ij}^u \leq 1
\]

\[
0 \leq A_{ij}^n \leq 1
\]

\[
0 \leq B_{ij}^u \leq 1
\]

\[
0 \leq B_{ij}^n \leq 1
\]

\[
\sum_{i=1}^{V} A_{ij}^u \leq S_u \times U_j^u
\]

\[
\sum_{i=1}^{V} A_{ij}^n \leq S_n \times U_j^n
\]

\[
\sum_{i=1}^{V} B_{ij}^u \leq S_u \times D_j^u
\]

\[
\sum_{i=1}^{V} B_{ij}^n \leq S_n \times D_j^n
\]

\[
D_n(1-R_i) + D_u R_i \geq \sum_{j=1}^{N_c} (A_{ij}^u + B_{ij}^u) (S_u-2) + \sum_{j=1}^{N_c} (A_{ij}^n + B_{ij}^n) (S_n-2)
\]

\[
\forall \quad 1 \leq i \leq N_c
\]

The goal of the proposed heuristic is to minimize the communication delay perceived by all vehicles in the service area. Thus, a greedy heuristic is introduced to handle these dynamics in real-time through sub-optimal channel allocations that are easier to compute.

Fig. 1 illustrates the overall structure of the proposed greedy heuristic.

As indicated in the above objective and constraints, this formulation strives to minimize the overall communication delay for all vehicles in the service area while respecting the delay guarantees of urgent and normal vehicles. Depending on the scale of the vehicular network, it can be computationally expensive to execute this model on the master vehicle in real-time as vehicles join and leave the service area. Thus, a greedy heuristic is introduced to handle these dynamics in real-time through sub-optimal channel allocations that are easier to compute.

Fig.1: Dynamic Channel Allocation Heuristic
V. On-Board Fuzzy-Logic Based Controller

When a vehicle requests a code from a master vehicle in its service area, it should specify its state in the code request message as urgent or normal. A fuzzy-logic based controller installed on-board the vehicle determines whether the vehicle state is urgent or normal. The parameters that affect the decision of the controller are:

1- **Acceleration and Directional Stability**: if the vehicle is accelerating or decelerating, its state will be flagged as urgent. Further, directional stability reflects the behavior of the driver when changing lanes. If the driver changes lanes more frequently, the vehicle state will be urgent. Both Acceleration and Directional Stability are represented by three member functions; namely: Negative, Zero and Positive Acceleration and Directional Stability as illustrated in Fig. 2.

2- **Vehicle Speed**: if the vehicle speed is substantially greater than the speed limit of the road, its state will be urgent. Speed is represented by three triangular membership functions; namely: Slow, Average and Fast Speed as illustrated in Fig. 3.

3- **Neighboring Vehicles State**: if the state of a vehicle is urgent, this means that neighboring vehicles are more likely to be urgent. The state of a vehicle is represented by two membership functions; namely: Normal and Urgent as illustrated in Fig. 4.

The output of the Fuzzy logic controller is embedded in the VAM of the vehicle as a binary value: 0 for Normal and 1 for Urgent.

Five fuzzy rules determine the decision of the On-Board fuzzy-logic controller: (1) If Neighborhood is Urgent then Vehicle State is Urgent (2) If Speed is not Average then Vehicle State is Urgent (3) If (Neighborhood is Normal) and (Speed is Average) and (Acceleration is Zero) and (Directional Stability is Zero) then Vehicle State is Normal (4) If (Acceleration is not Zero) then Vehicle State is Urgent (5) If (Directional Stability is not Zero) then Vehicle State is Urgent.

The initial setup of the On-Board fuzzy-logic controller is illustrated in Fig. 5 where Acceleration and Directional Stability are set to Zero, speed is set to Average and Neighbor State is set to Normal. Based on these inputs and applying the rule set explained above, the output of the On-Board fuzzy-logic controller shows that the vehicle is in Normal state (A state Value of 0.5 which is relatively Normal). By changing acceleration and Directional Stability to positive values, the state of the vehicle changes to almost 0.7 which means that the vehicle is in Urgent states depicted in Fig. 6.
Fig. 6: Acceleration and Directional Stability positive so the vehicle state changes to Urgent.

VI. Simulation Experiments

A simulation model of the proposed protocol was implemented on Quadstone Paramics. Quadstone Paramics is an enterprise-software targeted for the simulation of vehicular and transportation networks. This software provides flexible APIs to realize V2V and V2I protocols by monitoring, collecting and disseminating the parameters of the vehicles on the simulation surface.

The simulation area is a network of streets connected with intersections and roundabouts and can have traffic-lights, bus stops and other ingredients of real-life transportation networks. The network used in our study is generic enough with congested (e.g., downtown) and uncongested (e.g., rural and suburban) areas.

As explained earlier, the proposed protocol uses CDMA to enable V2V communication. In our simulation, all vehicles are assigned orthogonal codes such that no two vehicles in the same transmission range are allowed to have the same code at the same time. The simulation starts by dividing the simulation area into service areas and assigning a set of orthogonal codes for each service area. These codes are then leased by the master vehicles to vehicles that need to initiate V2V communication in their corresponding service areas. In order to guarantee the uniqueness of the used codes in neighboring service areas, the code sets are divided into nine sets which are distributed over the service areas such that no codes are shared between adjacent service areas. In the simulator, vehicles are generated on the simulation surface from areas called zones. Before releasing vehicles from these zones, the number of vehicles to be released from each zone must be specified in the demands file that contains the number of vehicles to be released from each zone during the simulation time. This file determines the traffic intensity in each part of the simulation area so numbers in the demands files are chosen carefully to reflect the traffic patterns encountered in real-life transportation networks.

VII. Performance Evaluation

In this section we present the results obtained from two experiments. The first experiment aims to study the relationship between the service area size and the frequency of handoffs performed by the master vehicles in the service area.

The simulation results show that increasing the service area size decreases the number of handoffs, which increases the number of vehicles in a certain service area. For the small number of codes assigned to that service area, this results in increasing the number of inactive vehicles in that area. This also increases the frequency of code request message collisions in that area because many vehicles try to lease a code at the same time. Thus, decreasing the utilization of the codes in the service area due to the high competition on the available non-used codes. Fig. 7 depicts the relationship between the service area size and the frequency of handoffs.

Fig.7: Frequency of Handoffs vs. Service area Size.

In our second experiment, we study the relationship between the service area size and the number of times vehicles we unable to communicate because of the lack on codes in their service area. The results obtained from this experiment show that decreasing the service area size increases the frequency of handoffs because master vehicle tend to spend less time in the service area. This also contributes to decrease the number of inactive vehicles in the service. Fig. 8 plots the relationship between the number of lost VAMs due to packet collisions vs. the service area size.
The results show that increasing the number of codes in a service area decreases the number of inactive vehicles and increases the code length for each vehicle. Thus, increasing the bandwidth needed for communication.

VIII. Conclusion and future work

The majority of V2V protocols presented in the literature utilize a combination of controlled access techniques (e.g., TDMA, FDMA, CDMA) to provide prioritized access to the communication medium. While these protocols split the capacity of the communication link to support a maximum number of users with different priority levels, our work utilizes a combination of CDMA and TDMA techniques to increase the number of concurrent users sharing the bandwidth. The proposed protocol provides an adaptive scheme that classifies the vehicle’s messages as “urgent” or “non-urgent” based on its statistical parameters (e.g., speed, acceleration, directional stability) and the state of its neighboring vehicles (e.g., normal or urgent). Furthermore, the proposed protocol achieves intelligent scheduling and allocation of messages and the underlying bandwidth to minimize the end-to-end communication delay and the costs associated with the deployment of Vehicle Infrastructure Integration (VII) without the need for road-side equipment.

We plan to extend our simulation study by evaluating the performance on the proposed protocol in large-scale vehicular networks. Further, we plan to implement the proposed protocol on single-board embedded systems and evaluate the performance of the protocol in terms of end-to-end delay in live vehicular networks. Finally, we plan to incorporate authentication and privacy to deliver safe and secure vehicular communication.

X. References


