Dynamic Channel Reservation to Enhance Channel Access by Exploiting Structure of Vehicular Networks

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***Abstract*—VANET protocols need to exploit the special structure of vehicular networks. This structure includes the one-dimensional nature of roads, the structure of lanes, the group mobility of vehicles, and the communication patterns of the envisaged applications. It is therefore of interest to examine how to specifically tailor VANET protocols to exploit all the above properties. In this paper, motivated by the goal of providing significantly better application level QoS, we study the MAC problem, and examine to what extent one can improve the performance of the mechanism employed in the IEEE 802.11p protocol. We design a dynamic channel reservation (DCR) protocol which leverages the special structure of VANET, and provides greater predictability in channel access, simplifying QoS provision. The key idea, in light of the periodic communication pattern of VANET applications, is to transform the per-packet channel contention mechanism of 802.11p into a per-vehicle one in DCR. We implement the protocol on NS-2 for a comparative evaluation against 802.11p under realistic VANET scenarios. DCR demonstrates lower packet loss probability and higher throughput over 802.11p, and the simulation results appear promising enough to develop a complete protocol specifically for vehicular networks.**

I. Introduction

One of the goals of the intelligent transportation system (ITS) built on the foundation of vehicular ad hoc networks (VANET) is reduced road accidents and casualties. Researchers and car manufacturers have proposed a range of applications to be provided by ITS: cooperative collision warning, automatic emergency brake, lane change assistance, road hazard notification, and even automatic driving in the future. Standardization bodies in North America and Europe have defined protocol layers of VANET as well as its management and security services. The various standards are currently being actively studied and revised in the community through network simulations and pilot experiments.

A key focus of ITS is to support safety applications. A typical safety application makes use of *periodic* broadcast for beaconing. In cooperative collision warning, each vehicle is to periodically broadcast its position, velocity, acceleration, etc., to neighboring vehicles to avoid potential collisions. In road hazard notification, a beacon is set up to notify approaching vehicles of potential danger. To ensure stringent performance of reliable safety services to drivers, good *quality of service (QoS)* of the underlying network which supports such periodic beacons is essential. Application designers require a specified level of QoS, in terms of packet loss probability, throughput, delay, etc., in order to provide guarantees. The QoS provided to the application layer is ultimately determined by the performances of all the layers below it.

However, IEEE 802.11p, the standardized MAC layer of VANET, has been shown to perform poorly in broadcasting [1], [2]. The weakness is due to the fundamental lack of feedback from the network on congestion level. In 802.11p broadcast, no ACK is sent back to the transmitter indicating transmission success or failure, due to the multiple receivers. When the network is congested, broadcast packets collide with each other undetected. There is neither retransmission of them, nor exponential backoff. The random access nature of 802.11p also poses challenges in providing QoS guarantees. Thus, 802.11p fails to provide reliable broadcast support in a congested highway. Reference [3] provides a detailed discussion. It can be foreseen that the enrichment of VANET applications will be problematic for 802.11p except when the network is lightly loaded.

Researchers have been investigating how to fix the 802.11p protocol for improving its broadcast performance, but significantly greater attention needs to be paid to exploit the specific *structure* of VANET in handling the problem. The characteristics of VANET and its applications are not generic but are rather very special, and VANET is much more structured than an ordinary mobile ad hoc network (MANET). In VANET, wireless nodes are vehicles moving with specific patterns in a constrained roadway. On a highway, the mobility is intrinsically *one-dimensional* and shows *group behavior* among different flows of traffic (in sharp contrast, for example, to the random waypoint mobility model in MANET). Moreover, the *periodic* communication pattern induced by VANET applications prompts a more *structured access of* the channel rather than the random access employed in CSMA schemes, such as IEEE 802.11p.

Motivated strongly by providing improved application level QoS, we examine the potential for a *dynamic channel reservation* (DCR) protocol for medium access in VANET. In

This material is based upon work partially supported by The R C Lee Centenary Scholarship, NSF under Contract Nos. CNS-07-21992 and CNS-0626584, and USARO under Contract No. W911NF-08-1-0238.

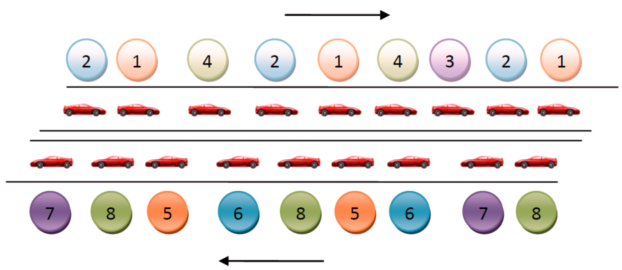

Fig. 1. Vehicular network seen as "moving channel sequences."

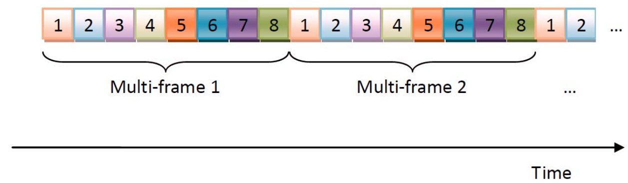

Fig. 2. Multi-frames and channels.

DCR, we divide the medium temporally into periods of fixed duration. Each period is then further divided temporally into a fixed number of "*channels*." The channel sequence repeats in each period; thus a vehicle, or a particular safety application of the vehicle, that gains a channel is ensured of a time slice for transmission in each period. Thus, each vehicle only needs to contend, not at the lower level of time slot *for each packet* to be transmitted, but at the higher, and more *infrequent* level, for one of the channels, which will then ensure that it can periodically broadcast its beacons. The channel contention procedure in DCR is hence on a *per-vehicle* and *per-channel* basis. Notice that each channel can be reused spatially by multiple vehicles when there is enough distance separation between them. The VANET formed can thus be seen as a sequence of channels carried by vehicles moving in a constrained fashion, as depicted in Figure 1. The group mobility structure of vehicles ensures that the topology formed on one side (i.e., direction) of the roadway is relatively stable, and hence vehicles do not need to change their channels frequently. For vehicles on the other side of the roadway, they can use a different set of channels to ensure no interference occurs.[1] The whole scheme is made possible by the availability of GPS in each vehicle which provides position and time synchronization information. The channel-based access is more structured than the per-packet random access scheme in 802.11p, and eases the provisioning of QoS. We elaborate on the details of the DCR protocol in the next section.

The DCR protocol shares ideas with previous works in its building blocks, but the design concept is fundamentally different. R-ALOHA [4] is the earliest scheme which DCR resembles, with both schemes allowing nodes to reserve a time slice for transmission in each fixed period. R-ALOHA is however designed for single-cell networks. Among works designed for multi-cell ad hoc networks, DCR borrows the idea of attaching a "bitmap," as in TDMA/TDD [5], [6], or a "frame information," as in Reliable R-ALOHA [7] and its later version, ADHOC-MAC [8], with each packet, for vehicles to exchange information about detected collisions and channel occupancy. Yet, all the above three schemes are designed without significant explicit consideration of the specific structure of roadways and vehicle mobility. DCR however thoroughly takes care of and exploits the structure of VANET in its design. We have implemented DCR in packet-level detail on the NS-2 simulator to provide, to the best of our knowledge, the first comparison between such a scheme and IEEE 802.11p. This paper thus addresses the broadcast challenge in VANET, to improve the performance characteristics of its channel access schemes, by exploiting the context of the network itself.

[1] In this paper, we do not treat channel access at intersections; that is intended to be the subject of a future paper.

II. Details of the Dynamic Channel Reservation Protocol

The Dynamic Channel Reservation protocol is a dynamic TDMA protocol with memory, with enabling features for it to work in a multi-cell ad hoc network, tailored to exploit the specific structure of vehicular environment. We specify the details of the protocol in this section. Qualitative treatment is given in the following paragraphs. Pseudocode for implementation is given in Algorithm 1 to 3 at the end of this section, in which normal packet processing operations not related to the DCR protocol are omitted.

A. Basic Elements of a Dynamic TDMA Protocol

In DCR, we divide the time into periods called "*multi-frames*." Each multi-frame is subdivided into "*channels*," as illustrated in Figure 2. The length of each multi-frame matches the beaconing period of VANET applications, typically 100 ms. The length of each channel is a system parameter. It should be set such that each channel is long enough to transmit one beacon packet, typically 100-200 bytes, and the number of channels thus permissible in a multi-frame must be large enough to accommodate vehicles within an interference range, in which channels cannot be reused. The channels are numbered and repeated in each multi-frame. Each vehicle which owns the channel can thus use it for periodically broadcasting its beacons.

B. Channel Contention Procedures

When a vehicle is started up together with the VANET safety applications installed, it contends for a channel for transmitting the beacons required. It must only contend for a channel which is not already occupied by other vehicles within its interference range, to avoid packet collisions. Hence, a mechanism for determining channels as available or occupied is needed, and will be described later. After determining a channel as available, a vehicle may request it by broadcasting a "*probe*" packet. If this probe packet is correctly received by other vehicles in the sending vehicle's transmission range without causing collisions, then the channel can be properly used by the vehicle. Hence, we again need a mechanism to detect collisions, which is not trivial in a wireless medium. In the following, we describe both the mechanisms for classifying channels and for detecting collisions, and will then complete the description of the procedure for contending for a channel.

C. Classification of Channel Status

To correctly classify channels, a vehicle must know which channel is being used by other vehicles within its interference range. For channels already being used within its transmission range, the vehicle should be able to receive beacons on those channels sent by its neighbors, and it can simply mark those channels as "occupied" on its "*channel availability bitmap*." For channels used outside its transmission range but within its interference range, such information must be communicated through its neighbors. Thus, we require every vehicle to attach its own channel availability bitmap to every packet it sends. Hence, each vehicle will be able to know the channel usage situation in its two-hop neighborhood. A channel is then classified as "available" if it is detected as available by the vehicle itself, and is marked as available in every channel availability bitmap it receives. The channel is classified as occupied otherwise.

D. Collision Detection

Collisions in a wireless medium cannot be detected by the sender but only by the receivers. Each vehicle is capable of detecting collisions on channels it is not transmitting in, and is able to notify such collisions to the sender if it is within its transmission range. (If the sender is not in its transmission range, then the receiver itself is not in the sender's transmission range either and is not a target receiver of the packet. There is therefore no need for it to notify the sender of the collision.) Thus, in DCR, each vehicle will monitor for collisions on all channels, and mark such collisions on its "*channel collision bitmap*." This bitmap (together with the channel availability bitmap) is to be piggybacked on each packet the vehicle sends. In this way, every vehicle can determine if collisions have happened on a channel in which it transmits packets. A collision happens if one or more collision bitmaps it receives marks the channel as collided. Note that at the beginning of each channel in a multi-frame, each vehicle should reset the collision bit of the corresponding channel.

Now we return to the procedures for a vehicle to contend for a channel. When a vehicle is started up, it should listen to the medium for a time equal to an entire multi-frame, so that it may classify each channel as available or occupied through its own observation and channel availability bitmaps from other vehicles. Then it may randomly pick an available channel and request it by sending a probe packet on that channel. After the probe packet is sent, it should listen for an entire multi-frame for collision bitmaps from other vehicles so as to determine if the probe packet is correctly received or whether it causes any collision. If all such received collision bitmaps indicate that there is no collision, the probe succeeds and the vehicle obtains the ownership of the channel. Otherwise, the vehicle randomly picks an available channel again and repeats the probe process.

The mechanisms for channel contention, channel classification, and collision detection in DCR borrow techniques from the corresponding mechanisms in TDMA/TDD [5], [6] and ADHOC MAC [8], and we assume a symmetric wireless channel.

E. Channel Status Change in a Vehicular Environment

Due to vehicle mobility and failures in information exchange, classification and ownership of channels needs to be reviewed by each vehicle from time to time to ensure proper operation. For example, a vehicle A may mark a channel as occupied since it is used by another vehicle B within its transmission range. Vehicle B then speeds up and leaves the transmission range of A. Vehicle A should then mark the channel as available. In another example, Vehicle A probes to request a channel and it causes collision at Vehicle B. However, when Vehicle B sends its beacon and piggybacks its channel collision bitmap to indicate the collision, the beacon itself gets collided. Vehicle A may fail to detect the collision after one multi-frame and wrongly takes the channel as owned. There should be procedures for Vehicle A or B to give up the channel owned.

To facilitate the correction of channel status, we impose the following rules for each vehicle:

1) For a channel marked as occupied in the channel availability bitmap of the vehicle under consideration, if no packet is received on the channel for three consecutive multi-frames, mark the channel as available.
2) For the channel that the vehicle already owned, if collision is detected for three consecutive multi-frames, give up the channel (and re-contend for one).

We change the status of a channel only after an anomaly is detected for three consecutive multi-frames. This is to avoid frequent changes of channel status due to vehicles on the edge of each other's transmission or interference range moving in and out.

F. Channel Partitioning for Opposite Direction of Movement Traffic

Vehicles moving along different directions of the roadway experience rapid change in the network topology. If their channels are not logically separated, frequent encounters of vehicles using the same channel on different sides of the roadway will happen, causing recurring collisions and rapid change in channel status. This is a prime example of a situation where the specific structure of vehicular movement in VANET, in this case direction of movement, should be fully exploited to enhance performance. DCR thus partitions the channels into two groups, one for each side of the road. With GPS information, vehicles may identify their direction and use channels allocated to their side of the road. Most collisions will then be due to mobility of vehicles on one side of the roadway only, for which the change in topology is moderate. Note that only the channels are partitioned into two groups;

the network itself remains connected and vehicles on both sides may communicate. As a first step, DCR statically allots an equal number of channels to both sides of the road. It is possible to extend the protocol to dynamically adapt the partition according to the traffic demand of each side, which will be described in a future paper.

Algorithm 1 Operations at the start of each channel

```
if this channel was probed at the last multi-frame then
  if #channel collision bitmaps (CCB's) received since last probe > 0 and no collision for this channel was marked in any CCB then
    take this channel as owned
    mark this channel as "occupied" in my channel availability bitmap (CAB)
if I do not own this channel and this channel is marked as "occupied" in my CAB and no packet is received on this channel for 3 consecutive multi-frames then
  mark this channel as "available" in my CAB
if I own this channel and collision for this channel is marked in received CCB's for 3 consecutive multi-frames then
  give up the ownership of this channel
  mark this channel as "available" in my CAB
reset the collision bit for this channel in my CCB
if 1 multi-frame has passed since I started up and I do not own a channel and I did not send a probe packet in the last multi-frame then
  for all channel i do
    if channel i is marked as "available" in my CAB and all received CAB's in the last multi-frame then
      classify channel i as "available"
    else
      classify channel i as "occupied"
  if #channels classified as "available" > 0 then
    randomly pick 1 of these channels
    prepare a probe packet to be sent on this channel
if I own this channel or this channel is picked to be probed then
  start the packet sending routine
```

Algorithm 2 Packet sending routine

```
if this channel is to be probed then
  send probe packet piggybacking my CAB and my CCB
else {I own this channel}
  send data packet piggybacking my CAB and my CCB
```

Algorithm 3 Operations at the reception of a packet

```
if the reception is collided then
  set the collision bit for the current channel in my CCB
  return
if I receive a data packet and the current channel is marked as "available" in my CAB then
  mark this channel as "occupied" in my CAB
store the CAB and CCB piggybacked by the received packet
```

III. Comparative Evaluation of DCR and IEEE 802.11p

We have implemented the DCR protocol on the NS-2 simulator so that we can evaluate its performance fairly against the IEEE 802.11p protocol under standardization. The simulation is run under realistic VANET scenarios with vehicle mobility patterns generated from the VanetMobiSim engine [9]. This is the first comparative evaluation of its kind as, to the best of our knowledge, previous works which propose dynamic TDMA schemes rely on self-developed network and mobility simulators, and do not include the 802.11p protocol in their study. We implement the whole DCR protocol described in the previous section, except the adaptive partition of the channel set for the two sides of the road. In the following, we only study one-way traffic, as two-way traffic is a simple stack of two one-way traffic systems when channels are statically partitioned between them.

TABLE I
Parameters used in the NS-2 simulations

Phy/WirelessPhy	CSThresh_	3.162e-12 W
Phy/WirelessPhy	Pt_	41.50e-3 W (16.18 dBm)
Phy/WirelessPhy	freq_	5.9e9 Hz
Phy/WirelessPhy	L_	1.0
Phy/WirelessPhy	RXThresh_	5.01e-12 W (-83 dBm)
Phy/WirelessPhy	Bandwidth_	6.0e6 bps
Phy/WirelessPhy	CPThresh_	10.0
Mac/DCR	bandwidth_	6.0e6 bps
Mac/DCR	ChannelTime_	0.0005 s
Mac/DCR	NumChannels_	200
Mac/802_11	CWMin_	15
Mac/802_11	CWMax_	1023
Mac/802_11	SlotTime_	0.000013 s
Mac/802_11	SIFS_	0.000032 s
Mac/802_11	ShortRetryLimit_	7
Mac/802_11	LongRetryLimit_	4
Mac/802_11	PreambleLength_	60 bits
Mac/802_11	PLCPHeaderLength_	60 bits
Mac/802_11	PLCPDataRate_	6.0e6 bps
Mac/802_11	RTSThreshold_	2346 bits
Mac/802_11	basicRate_	6.0e6 bps
Mac/802_11	dataRate_	6.0e6 bps

Here we detail the simulation environment. We simulate a straight 4-lane highway with one-way traffic which consists of 200 vehicles. Each vehicle broadcasts a packet of 200 bytes in payload every 100 ms to simulate VANET safety applications [10]. We measure the packet loss probability due to collisions and the goodput at the application layer.

The mobility pattern is generated by the VanetMobiSim simulator, using the Intelligent Driving Model with Lane Changing [11]. Each vehicle is 5 m long, and maintains a headway safe time of 1.5 s from the vehicle in front. We vary the average speed of the vehicles in our simulation runs, from 15 mph to 85 mph. In each simulation run, vehicles travel at a speed within a ± 5 mph range from the average.

We use NS-2.33 for network simulation. The "Propagation/TwoRayGround" model is used for simulating radio propagation; we do not use the more detailed "Propagation/Shadowing" model. The "Mac/802_11" module is adopted for simulating IEEE 802.11p, with parameters tuned according to the 11p standard. We implement the DCR protocol in the simulator with respect to the way the "Mac/802_11" module simulates the wireless medium, particularly, the way in simulating collisions, so that the comparison is fair. Parameters set in the simulation are listed in Table I.

Due to the limitations of the simulators and computational power, each simulation run simulates the scenario for 60 sec. Figures reported below are averages of 3 runs.

The simulation results plotted in Figure 3 show a relatively large performance advantage for the DCR protocol over IEEE 802.11p in terms of packet loss probability due to collisions. The metric is measured at the receiver side, by dividing the number of packets which could be received but are lost due to collisions, by the total number of packets reaching the receiver side. When we decrease the average speed of the vehicles, the

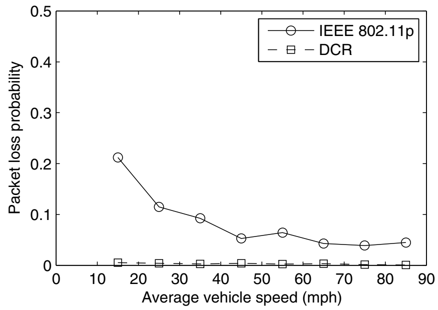

Fig. 3. Performance comparison: packet loss probability.

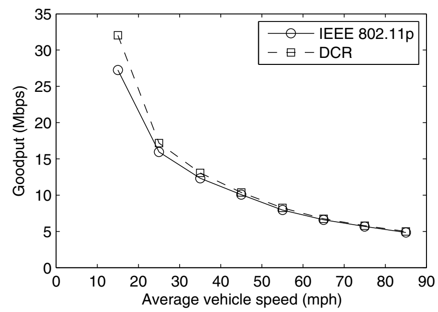

Fig. 4. Performance comparison: goodput.

spacing between vehicles decreases, as they maintain a fixed headway safe time of 1.5 s. Hence at lower speed, the vehicles are more closely packed and there are more vehicles within an interference range. The results confirm previous works [1], [2] that 802.11p collapses at moderate to high node densities. At an average speed of 25 mph, which is typical in urban areas, 802.11p suffers from an 11% packet loss probability. At an average speed of 15 mph, it incurs a 21% packet loss. The high packet loss probability will not satisfy the QoS demand of advanced VANET safety applications such as automatic driving [3]. For initial applications aiming to assist drivers, it also decreases their reliability. The DCR in contrast performs well across a wide range of vehicle densities with less than 1% packet loss probability in all scenarios. The reason for the large performance gap is because of the structured access of the medium by DCR, in contrast to the random access of 802.11p without congestion feedback.

Figure 4 shows the corresponding performance in terms of goodput. By *goodput* we mean the throughput perceived at the application layer of the receivers, excluding overhead at the layers below. Since the packets sent are broadcast to multiple receivers, the goodput is in general higher than the raw data rate of the medium. The results show that DCR performs consistently better than 802.11p in terms of goodput as well. This is important as DCR requires start-up time for vehicles to contend and settle in a channel before transmitting beacons, while 802.11p does not. Results show that the channel contention procedure of DCR is efficient, and its structured access of the medium does lead to a higher goodput. Indeed, the channel contention procedure of DCR is on a *per-vehicle* basis, while for 802.11p it is on a *per-packet* basis and is therefore inefficient when the traffic is periodic. In particular, in our experiments, vehicles typically settle in a channel within 3 multi-frames, i.e., 300 ms, after it is started up. This delay is acceptable for general VANET usage. The settling time is related to the number of channels provisioned and the number of vehicles present in an interference range.

IV. Concluding Remarks

The IEEE 802.11p protocol has been chosen for the standard at the phase 1 development of VANET for its availability and flexibility. However, it is well known that the protocol specifically has performance deficiency in broadcast, which is a common requirement for VANET applications. In handling the broadcast challenge, the context and structure of vehicular networks are often neglected. In contrast, this research and paper propose a solution of the problem based on exploiting the structure of VANET. We have therefore developed the Dynamic Channel Reservation protocol taking into specific consideration the roadway and vehicle mobility characteristics of vehicular networks, as well as the periodic communication pattern presented by typical VANET safety applications. Simulation results on NS-2, with vehicle mobility pattern generated by VanetMobiSim, for specific applications, show that DCR potentially provides a large performance benefit over IEEE 802.11p in terms of both packet loss probability and throughput. This research demonstrates the advantages of thoroughly designing VANET protocols specifically to exploit the structure of vehicular environments.

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