An Adaptive Collision-Free MAC Protocol Based on TDMA for Inter-Vehicular Communication

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***Abstract*—Inter-Vehicular communication is considered to be a promising way to improve traffic safety. Among this, it is a key technology to delivery urgent messages and periodical beacons to neighbors successfully. In this paper, we propose an Adaptive Collision-Free MAC (ACFM) protocol tailored to vehicular networks, based on dynamic TDMA mechanism. In our protocol, RoadSide Units (RSUs) are exploited to schedule time slots assignment and disseminate control information, while the data are spread among vehicles. Each RSU maintains a dynamical slots assignment cycle for vehicles in its coverage adaptively. A cycle consists of N frames, where N varies from 1 to 5 according to the number of vehicles. Under the scenario of light traffic, ACFM controls the excessive increase of unassigned slots through shrinking slots assignment cycle frame by frame. When there are a mass of vehicles on roads, ACFM provides more available slots by expanding cycle which ensures the fairness of channel access for every vehicle. Channel utilization and fairness can be achieved together in ACFM. We implement the protocol on NS-2 for a comparative evaluation against conventional protocols under realistic VANET scenarios. Simulation results show that the ACFM scheme outperforms the conventional protocols in terms of packet loss ratio and delay.**

***Index Terms*—Vehicular networks, MAC protocol, dynamic TDMA, Collision-Free.**

I. INTRODUCTION

VANET, which is one type of intelligent transportation systems, is invented not only to improve driving safety, but also to meet public needs for colorful application services, especially for internet based multi-media services. The Federal Communications Commission (FCC) has allocated 75 MHz spectrum for vehicular applications [2]. Usually, the frequency allocated for public safety can be divided into two categories. One is named control channel and the other is called service channel. Those safety-related messages are sent through control channel and entertainment data are conveyed in service channel. Based on the method of triggering the sending of control messages, control messages can be subdivided into event-driven messages and periodic messages. In this paper, we focus on periodic messages. Vehicles in the contention area of a roadside unite (RSU) periodically broadcast their vehicle IDs, velocity, accelerated velocity and so on, while road side unites periodically broadcast their control messages to onboard unites (OBU), the vehicles. Due to the high mobility of vehicles, fast changing topologies, and fluctuation of node densities, it is still a challenging issue to ensure that messages among and between RSU and OBU are delivered correctly.

In real scenarios, high transmission reliability and low delivery latency are critical optimization objectives. Many research efforts have been done to make full use of MAC level characteristics and medium efficiency towards those goals. For instance, IEEE 802.11p [1] has been approved as the standard MAC layer protocol for vehicular communication. However, when it comes to fast changing topology or high traffic node density, IEEE 802.11p performs not so well as usual [3-6]. Due to the lack of acknowledge schedule in 802.11p, it is hard for RSU to know whether or not the control messages are correctly delivered. What's more, influenced by the random feature of 802.11p, it is hard to guarantee the fairness of services, thus a vehicle might be served after an unbearable delay. To the best of our knowledge, it is still an open research direction to guarantee reliable and collision-free transmissions.

In this paper, based on Time Divided Multiplexing Access (TDMA), we propose an Adaptive Collision-Free MAC (ACFM) protocol, a novel approach to avoid collision as well as guarantee QoS in considerate of fairness. According to simulation results, the MAC protocol ACFM demonstrates a satisfactory performance in considerate of both average delay and packet loss ratio.

The rest of the paper is organized as follows: in Section II, various MAC protocols are compared and discussed. The details of ACFM protocol can be found in Section III. We evaluate the performance in Section IV and finally conclude the paper in Section V.

II. RELATED WORK

In vehicular networks, the wireless communication medium between vehicles is shared by neighbors. When one vehicle is transmitting messages in the channel, all the other neighbors have to wait until the medium is released. Therefore, it is quite urgent for a vehicle to be informed whether the channel is occupied or not. In vehicular networks, it is much more difficult with high node mobility and fast changing topology.

One way of the above problem solving technique is Carrier Sense Multiple Access (CSMA) [7], which is adopted by 802.11p. In 802.11p [8], the distributed coordination function is responsible for the medium access based on CSMA with Collision Avoidance (CSMA/CA), which utilizes the request-

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to-send/clear-to-send mechanism to exchange packets and is fully distributed so that it does not need RSU messages. However, 802.11p, in terms of the performance of packet loss rate, collision probability and latency, can hardly meet the QoS needs for Inter-Vehicular communication, especially taking the changing topology and high traffic node density into consideration[14].

Another approach is TDMA-based protocols, which divide time into several frames and each frame could then be subdivided into tiny time slides for vehicles. Thanks to the collision-free nature of TDMA, it has been widely used and become the foundation of other TDMA based protocols [5, 9] for vehicular networks. R-ALOHA [10] was the earliest dynamic channel reservation scheme, which allows nodes to reserve a time slot for transmission in a fixed period. ADHOC-MAC [11] is a completely distributed scheme, but its correctness depends on the assumption that the network topology remains static when the transmission schedules are used. In [12], a DCR protocol with GPS information was designed. However, both of them are based on the hypothesis that the traffic load is light. Frequency divided multiplexing access and code divided multiplexing access are also used in [5, 7], but the performance are constrained.

The proposed ACFM protocol originates from the idea of dynamic TDMA according to traffic load on roads, which not only utilizes RSUs to maintain tiny time slots assignment, but also take advantage of vehicle-to-vehicle communication. What's more, channel utilization and fairness are achieved as additional contributions.

III. Details of ACFM Protocol

A. *Overview*

ACFM is a cooperative dynamic TDMA protocol, tailored to vehicular networks. Each RSU and the vehicles under its coverage form an Ad-hoc subnet, where the RSU schedules slots assignment for all vehicles dynamically cycle by cycle. After being allocated for an available slot, a vehicle will broadcast its beacon to neighboring vehicles. However, the number of vehicles in a subnet varies along with vehicles moving on roads at high speeds. Therefore, our proposed protocol ACFM adjusts slots assignment cycle dynamically with the vehicle's number in a subnet. When the traffic in a particular subnet is light, ACFM will shrink slots assignment cycle frame by frame, to avoid the appearance of massive unassigned slots. In contrast, if there are excessive vehicles in a subnet, ACFM could expand assignment cycle frame by frame (up to five frames at most), where additional unassigned slots are increased to ensure the fairness of channel access for every vehicle.

We make the following assumptions regarding the VANETs context in which our ACFM operates:

- Vehicles and RSUs keep perfect timing. The global time is available to every vehicle and RSUs which are equipped with GPS.
- Neighboring RSUs use two different frequencies which are orthogonal and have no interference with each other.
- Each vehicle is equipped with dual antennas, which is available and inexpensive with the evolution of electronic technique.
- Vehicles and RSUs within a subnet work in the same frequency.
- The only reception error is caused by packet collision.
- When multiple packets arrive at a vehicle or a RSU simultaneously, all of them are destroyed and dropped.
- Each vehicle or RSU has a unique ID.

In this section, we will explain the specific parts of ACFM.

B. *The networks architecture*

As a special type of mobile ad hoc network, VANET has some unique features. First, as vehicles move at high speeds, the density on the road changes rapidly. Second, VANET is more structured, where vehicles moving with specific patterns in a constrained roadway along which there could be many RSUs. The specific structure and features are still open challenge in this filed. In our work, we take advantage of the features above.

1) *The density of moving vehicles.*

In our protocol, a RSU can assign DS (which abbreviates Data Slots to be explained in Section III.C) time for 180 vehicles in a cycle at most, which is competent to most traffic scenes. Under a light traffic load, our protocol works well as the delay of beacons reaches around 20ms, which is much lower than 100ms. Then we consider an extremely dense traffic scene, a RSU can cover 300 meters (CL) [2] of a 4-lane road (LR), the average vehicular length (VL) is 4 meters, the average distance (VD) between two neighboring vehicles is 3 meters. The total number of vehicles being under a RSU's coverage simultaneously are given by:

$$N = \left(\frac{CL}{VL + VD} + 1 \right) \times NR \tag{1}$$

So there are 156 vehicles in this dense traffic scene, which are lower than the number of DS (180) in the longest cycle. And the delay of a beacon can reach up to a maximum of 100ms. That is, in most cases, ACFM has enough DS to allocate to each vehicle by adjusting the cycle length adaptively according to the density of vehicles.

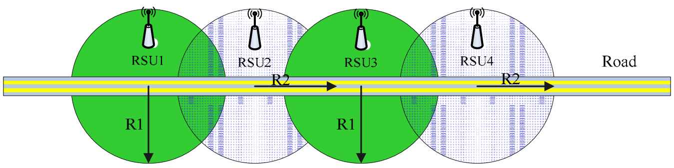

Figure 1. Frequency Coverage of RSUs

2) *The coverage of RSUs.*

Within an urban road scenario, we assume that most roads are always in the coverage of one or more RSUs which work in different frequencies. In fact, we can prove that it just needs two orthogonal frequencies to divide the entire road into different segments which don't interfere with each other. Each RSU and vehicles in its coverage form an Ad-hoc subnet, where they communicate with each other using the same frequency selected by RSU. As illustrated in figure 1, a road is covered by four RSUs: RSU_1, RSU_2, RSU_3 and RSU_4. RSU_1 and RSU_3 work in the same frequency, so do RSU_2 and RSU_4. We denote the frequencies of RSU_1 and RSU_3 as S_A and S_B, respectively, where S_A and S_B are orthogonal with each other. For two neighboring RSUs, they have no interference for orthogonal frequencies although there is an overlapping space. For RSU_1 and RSU_3, they don't interfere either because they aren't in a competitive area, even though they work in the same frequency. For simplicity, we assume that the entire road is covered alternately by two orthogonal frequencies: S_A and S_B. OBUs scan for two kinds of RSU beacons which work in S_A and S_B. For every RSU, OBU will select the best one based on RSSI(Received Signal Strength Indication). If two kinds RSUs above respond, it means the vehicle is in the overlap of the two kinds RSUs.

As illustrated in figure 2, there is an Overlapping Area (OA) between two subnets. So the coverage area of each RSU can be divided into 3 sections: two OAs (LOA and ROA) on the edges and a Free Area (FA) in the middle. The length of OA is only a small part of FA, due to the locations of RSUs. Vehicles in OA must know adjacent nodes in both two subnets. Dual antennas are needed for vehicles with ACFM to communicate with adjacent vehicles from two subnets using different frequencies, even though only one antenna is at work in FA, either in S_A or in S_B.

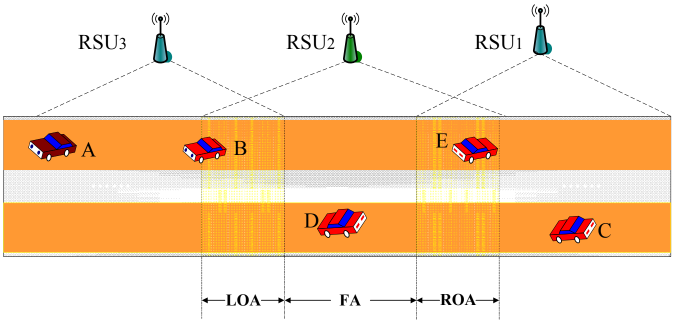

Figure 2. Road architecture

C. TDMA frame structure

As illustrated in figure 3, time is divided into periods called "frames". Each frame is constituted by a fixed number of "slots". Every RSU maintains a cycle schedule which consists N Frames, where N is a variable from 1 to the maximum 5. Therefore, the cycles of RSUs could be different. And the maximum period of a cycle is not more than 100ms which matches the beaconing period of VANET application, typically 100ms. Each Frame includes a RSU slot (RS) and 36 data slots (DS). So there are 5 RS, and 180 DS per cycle at most.

In our protocol, every frame is divided into two segments named: RSU segment and vehicle segment. The RSU segment is reserved for RSU to broadcast control messages to the vehicles under its coverage. The control message includes DS assignments schedule called "DS assignment map" and time synchronization information whose packet is larger than beacon data. According to the U.S. standards within IEEE, we set the guard time G as 100µs between two adjacent slots and transmission rate S to 4Mbps given in[12]. Therefore, the maximum packet size of a RSU control message transmitted in a RSU segment can be given by:

$$S_{Control} = \frac{1}{8}(T_{RS} - G) \bullet R \tag{2}$$

Where RSU segment time T_{RS}=2ms, transmission rate S= 4Mbps, and the guard time G= 100µs. Obviously, the length of a RSU control packet can reach up to 950 bytes which is enough to transmit the control message in a frame.

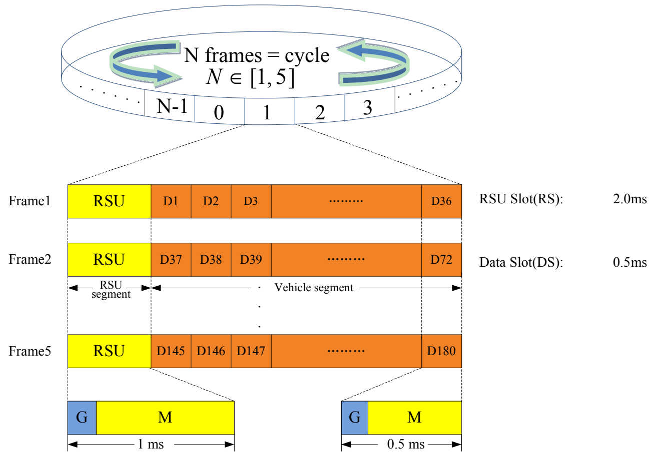

Figure 3. TDMA frame structure

Similar to the RSU segment, the vehicle segment is consisted of 36 DS time slots, each of which is a short time reserved for a vehicle to broadcast its beacon data to neighboring vehicles. Once a DS is assigned to a specific vehicle, the vehicle won't release it until the slot is reallocated. The length of DS in our protocol is a system parameter which should be set such that each DS is long enough to transmit one beacon packet completely. The DS time is given by:

$$T_{DS} = \frac{P \times 8}{S} + G \tag{3}$$

Where the vehicular data packet size P doesn't exceed 200 bytes, transmission rate S can reach up to 4Mbps and the guard time G is still set to 100µs given in[15]. So a DS time allocated to a vehicle is 500µs or 0.5ms.

For a specific RSU, it broadcast the control message every 20ms repeatedly. The control message includes a particular DS assignments schedule which ensures a vehicle to deliver its beacons to neighboring vehicles without collisions. However, there could be a few different frames in a specific cycle, that is, RSU changes its cycle dynamically from one frame to five frames according to the vehicle's number under its coverage. So a vehicle gets a DS in a dynamical way, along with the RSU's cycle ranging from 20ms to 100ms at most.

D. Specification of DS assignment and collision map

In our work, control messages from RSU mainly include DS assignment and collision map information.

1) DS assignment map

DS assignment map is a particular DS assignment schedule for vehicles in a frame that ensures a vehicle to deliver its beacons to neighboring vehicles without collisions. RSU is always receiving beacons from vehicles in the subnet. Owing to GPS messages and received signal strength indicator (RSSI) from vehicles, RSU is able to precisely locate vehicles' positions and allocate DS base on the global insight. i) For a RSU, if there are packets received from a vehicle in a particular DS, RSU will mark this DS as occupied and attach vehicle ID to the DS on the DS assignment topology map. ii) if no packet is received in a DS for three consecutive cycles, mark the DS as idle and remove the vehicle ID from the subnet. According to the rules above, RSU is able to complete the DS assignment topology map cycle after cycle.

2) Collision map

After listening for a complete frame or a cycle, a vehicle which tries to gain a DS is thus aware of the entire DS availability. If there are more than one free DS, the vehicle will occupy one randomly. In our work, RSU is responsible for the completion of a "collision map" for all DS. If more than one vehicle choose the same DS simultaneously, they can't detect the collision. However, this can be supervised by RSU. Then RSU marks this DS in the "collision map" and sends the map to all vehicles in the next frame or cycle. In this way, vehicles will be able to determine if collisions have happened and choose another free DS in the next frame or cycle to avoid further collision.

E. DS selection mechanism

1) New vehicle joins

A vehicle must listen to the media for some time before it joins in the network. Generally, this will last one frame's time until the vehicle receive a RSU broadcast packet. Thus the vehicle will know whether there are idle DS in the frame. If there were, it could select one randomly to send its message. Otherwise, it should wait until the next RSU broadcast packet. This process can last one cycle time (100ms) at most, so the maximum distance of the vehicle movement is 1.7 meters before it joins in the network, where we assume the vehicle speed is 17m/s in urban area.

A vehicle joins in the network in two cases:

a) In FA.

For vehicle D shown in figure 2, when it starts, it can only scan for one frequency over the threshold. After receiving a RSU broadcast packet, the vehicle can find the ID of RSU_2 . So the vehicle knows it is in FA of RSU_2, and it starts to works only in subnet RSU_2.

b) In OA .

For vehicle E in figure 2, when it starts, it receives two different frequencies over the threshold. The vehicle can simultaneously monitor two frequencies due to dual antennas and multiple data caches. But it can only use one frequency at a time to send messages in a DS since there is only one processor inside a vehicle. So the vehicle has to work in two subnets, using two frequencies in two different DS allocated by two cooperative RSUs, they are RSU_1 and RSU_2 in figure 2. Note that, a vehicle in OA will not interfere with adjacent vehicles in subnet RSU_1 because of the orthogonal frequency used between neighboring RSUs.

The details of the procedure of new vehicles' join in a subnet are shown in TABLE I.

TABLE I. NEW VEHICLE JOIN ALGORITHM

Algorithm 1: Vehicle join in the network

```
vehicle beacons
repeat
  while RSU broadcast message is not received
    vehicles spend one cycle to listen to the channel
     if (Only one strength of received radio frequency >
     minimum reorganization frequency)
     Vehicle locate in FA
  else
     Vehicle locate in OA
RSU beacons
  if there are idle time slots in the slot frame
     select one randomly and prepare to send
     if RSU receive the beacons from vehicle successfully
         RSU allocate a time slot to the vehicle and send it in
         the next RSU slot (RS)
        thus a vehicle join in the network
     break;
  else vehicle wait for one or max to five frames' time and
retry
until a time slot is assigned
```

2) Areas switch mechanism

As illustrated in figure 2, there are Left OA (LOA), Middle FA (MFA), Right OA (ROA), three different areas for each RSU in total. In our ACFM, RSUs are both wired connected and cooperative, so the performances of time synchronization and vehicles status information(including vehicle velocity, position, etc.) sharing are efficient. Therefore, each RSU knows the vehicle number in its three areas depicted above. We denote the number of vehicles in LOA, MFA, ROA as LN, MN, RN, respectively. Each RSU is responsible for DS allocation of a subnet. In our work, after a new vehicle's selecting an idle DS randomly, the corresponding RSU of the subnet will re-adjust the DS assignment map before next round of broadcasting according to vehicles' particular positions. Vehicles in FA use different DS from vehicles in OA. Assume M is a particular boundary of DS numbers in a frame, which can be calculated from equation (4):

$$M = \left\lfloor \frac{LN + MN + RN}{DN} \right\rfloor + 1 \tag{4}$$

Where LN, MN and RN are the number of vehicles in LOA, MOA and ROA, respectively. DN equals to 36 in our protocol which is the total number of DS in a frame. We assume that every DS has a unique id and let $IdleSet$ denote the set of all idle DS to be allocated. A vehicle is assigned an idle DS according to its position following rules below:

- If a vehicle is in LOA, we randomly select a DS from the set A given by:

$$A = \{ DS | DS \in IdleSet, DS.id > M, DS.id \quad is \quad odd \} \tag{5}$$

- If a vehicle is in FA, a DS selected randomly from the following set B will be provided for it.

$$B = \{ DS | DS \in IdleSet, DS.id \le M \} \tag{6}$$

- If a vehicle is in ROA, a DS from the following set C will be supplied.

$$C = \{ DS | DS \in IdleSet, DS.id > M, DS.id \quad is \quad even \} \tag{7}$$

Vehicles in different areas use different DS. The movement of a vehicle is actually a switch process between different areas and subnets. All these switches are under the control of RSU, the details of the procedure are shown in TABLE II.

TABLE II. AREAS SWITCH

Algorithm 2: Areas switch

```
while true
RSU listens to the media and monitor all vehicles in its coverage
  if a vehicle's data packet is received
    locate the vehicle's position and deal with the data packet
    if the vehicle enters FA from OA
      select an unused time slot N < M
      change the Nth element of DS_allocation Array to the vehicle's ID
      the vehicle uses 2 different frequencies at 2 different time slots and works in 2 different subnets simultaneously
    else if the vehicle enters OA from FA
      if OA on the left edge of RSU
        select an unused time slot N > M, N is an odd
      else
        OA must be on the right edge of RSU
        select an unused time slot N > M, N is an even
      change the Nth element of DS_allocation Array to the vehicle's ID
      the vehicle uses a same frequency as the RSU and works only in a subnet
    else
      the vehicle's area is not changed, do nothing
  if RS time is reached
    RSU broadcasts the control message with DS_allocation
    foreach vehicle V in the coverage of RSU
      V receives the message and synchronizes the time
      V detects whether its time slot is changed
      if the time slot is changed
        V marks it and uses the time slot according to RSU
```

3) *Cycle length expansion and shrinking*

In our protocol, each RSU expands or contracts the cycle length adaptively according to the vehicles number in its coverage. The cycle length changes from one frame to five frames dynamically. If there is no enough DS for current vehicles to be allocated, a RSU will increase its cycle length by one frame, where 36 additional idle DS are created. However, the total length of a cycle can't exceed five frames at most. In contrast, a RSU will shrink its cycle frame by frame when vehicles leaves off its coverage. Otherwise there will be many redundant idle DS in a cycle, which could lead to a lower channel utilization and a higher communication delay. In our work, not only can each vehicle be serviced instantly but also the number of idle DS be reduced by adjusting cycles, respectively.

IV. PERFORMANCE EVALUATION

In this section, simulation results are demonstrated regarding performance of our proposed protocol. In our simulation experiments, we compare the performance of our protocol with 802.11p and pure 3G transfer protocol, in terms of average delay and packet loss ratio.

A. *Simulaiton Evironment*

We have implement ACFM protocol, 802.11p, and pure 3G transfer protocol (P3G, in which all messages are sent by 3G channel) on the NS-2 [17] network simulator so that to compare the performance of these protocols fairly. The simulation is run under realistic VANET scenarios with vehicle mobility patters generated from the VanetMobiSim [13].

In our simulation scenario, a 500m×340m rectangle road network with a straight 4-lane highway is created. Each vehicle broadcasts a beacon packet of 200 bytes every 20ms, in order to evaluate the efficiency of our ACFM protocol fully, not adopting the 100ms generally used in VANET safety applications [16]. During our simulation, each vehicle possesses two orthogonal frequency radio antennas in a transceiver with two independent caches. There are 200 vehicles in the simulation, and simulation time is set to 1000s in each simulation case. Here, we define network density as the number of vehicles in the coverage area of a roadside unit, not the ratio between the number of vehicles and the size of coverage area. Therefore, the network density of a subnet varies from 0 to 200 at most. As given in[12], we set the bandwidth for channel to 4Mbps in our simulation. Other configuration are listed in TABLE III.

TABLE III. SIMULATION PARAMETERS

Parameter	***Value***
Number of lanes	4
Number of vehicles	200
Bandwidth for channel	4Mbps
Beacon interval	20ms
Simulation time	1000s
Vehicle velocity	0~25m/s
Vehicle Max Deceleration	$10m/s^2$
Vehicle Max Acceleration	$10m/s^2$
Packet Size	200bytes

B. *Simulaiton Results*

Figure 4 shows the average delay of the three MAC protocols in different network density scenarios. 802.11p has the smallest delay at first, but its delay grows logarithmically with the density increases. The delay of P3G possesses the largest delay in most cases. Taken both sparse and dense scenarios into consideration, ACFM, whose delay is not more than 100ms in most scenarios, has the best performance.

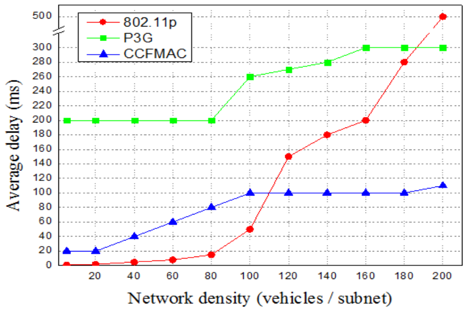

Figure 4. Performance comparison: average delay

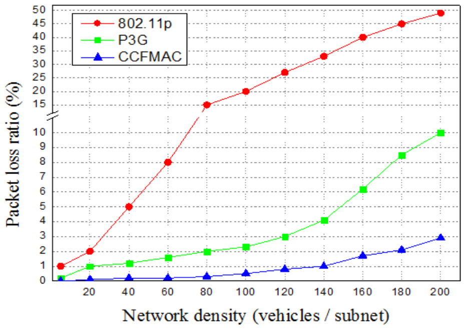

Figure 5. Performance comparison: packet loss ratio

The packet loss ratio is depicted in figure 5. It is obvious that, the packet loss ratio rises in accordance with the network density . ACFM has clearly the lowest packet loss ratio. On the contrary, 802.11p has the highest loss ratio. When there are 200 vehicles in a subnet, nearly 48% of the packets are lost in 802.11p. What's more the packet loss ratio of ACFM is less than 3% in all cases.

V. CONCLUSIONS

In this paper, we propose a collision free ACFM protocol, tailored to vehicular networks based on dynamic TDMA scheme. In our ACFM protocol, a RSU and vehicles in its coverage form a Ad-hoc subnet, where the RSU schedules slots assignment and disseminates control information for all vehicles dynamically cycle by cycle. Each cycle maintained by a RSU consists of N frames, where N varies from 1 to the maximum 5 according to the vehicle's number in a subnet. When the traffic in a particular subnet is light, ACFM will shrink slots assignment cycle frame by frame to avoid the appearance of massive unassigned slots. In contrast, if there are excessive vehicles in a subnet, ACFM could expand assignment cycle frame by frame (up to five frames at most), where additional unassigned slots are increased to ensures the fairness of channel access to every vehicle.

In order to evaluate the feasibility and efficiency of ACFM, we compare the performance of 802.11p, the pure 3G transfer protocol with ACFM through a mass of simulations. The results demonstrate that our proposed ACFM has a clear advantage over 802.11p and the pure 3G transfer protocol in terms of packets loss ratio and average delay. In the future, we will introduce various kinds of messages with priorities into the protocol to meet QoS needs of realistic safety-related applications in VANETs.

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