FINE-GRAINED TDMA MAC DESIGN TOWARD ULTRA-RELIABLE BROADCAST FOR AUTONOMOUS DRIVING

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ABSTRACT

In the autonomous driving era, V2X communication is essential since it enables rapid message dissemination via periodical beacon exchange (broadcast communication), which contributes to better situation awareness and maneuvering cooperation. However, designing a MAC protocol for reliable V2X broadcasting is challenging, as minimal beacon delivery delay and collision avoidance should be achieved simultaneously. In this article, we design a fine-grained TDMA-based MAC protocol to support ultra-reliable broadcast for autonomous vehicles. Specifically, three critical issues are first identified: mobility-caused time slot collision, time slot shortage, and stiff beacon rate limitation. Accordingly, three fine-grained solutions are provided to tackle those issues: mobility-aware time slot assignment, beacon rate adaption with safety awareness, and flexible beacon rates support. Moreover, a case study on mobility-aware time slot assignment based on road topology and lane distribution is presented, with simulation results' verification. Finally, we elaborate the steps to implement the fine-grained MAC protocol in autonomous driving environments.

INTRODUCTION

With growing on-road traffic, the daily commute has become a big concern to urban residents due to increasing car accidents and traffic jams. It seems impossible even for experienced drivers to avoid all potential driving dangers induced by night driving, aggressive drivers, and distracted or drowsy driving. To liberate humans from these heavy and complex driving tasks, both the research community and industry have paid tremendous efforts toward autonomous driving in recent years [1]. Generally, autonomous vehicles are equipped with various onboard sensors to detect static obstacles, track other vehicles, and locate themselves relative to a high-definition (HD) map, based on which driving decisions are made in real time by artificial intelligence (AI) techniques. Even though sensor-based automation has been demonstrated in many field tests, it still suffers from several inherent drawbacks. First, the perception range of sensors is limited, and objects and road conditions outside their vicinity cannot be sensed. Second, extracting useful information from raw sensing data, especially for video contents from cameras, is time consuming, whereby any outage situations or delayed outputs may result in irreparable dangers. Third, autonomous vehicles are unable to collaborate with each other to perform efficient and complicated transportation tasks.

Vehicle-to-everything (V2X) communication shows great potential in addressing the above issues by providing real-time communication capabilities [2–4]. For instance, instead of processing similar sensed data repeatedly on different vehicles, vehicles can send out their status information via V2X connections, which not only extends sensing ranges but also helps to relieve the intensive computing pressure. In addition, through V2X communications, vehicles can obtain a comprehensive view of their surroundings, which is beneficial to decision making. To support autonomous driving, *broadcast* communication is essential, in which vehicles and roadside units (RSUs) periodically broadcast safety beacons called cooperative awareness messages (CAMs) to their neighbors. With real-time CAMs, autonomous vehicles are empowered with additional sensing capability and high-efficiency cooperative swarm intelligence. However, achieving such high-performance broadcast communication poses great challenges to medium access control (MAC) design. First, to keep CAMs up to date, the *broadcast frequency* of each vehicle and RSU is as high as 10 Hz (i.e., every 100 ms), which inevitably overloads the limited V2X channel [5, 6]. Second, as those CAMs are related to driving safety, *message collisions* should be carefully avoided. Third, as there is no global central unit in vehicular environments, vehicles have to negotiate the channel access in a fully *distributed* way.

In the literature, there have been several MAC protocols proposed for broadcast paradigm in traditional vehicular ad hoc networks (VANETs). Our focus is on time-division multiple access (TDMA)-based MAC techniques in the autonomous driving era due to their efficiency of delay guarantee in supporting periodic broadcast [7–11]. However, adopting TDMA-based MAC in autonomous driving is quite different from that in traditional VANETs. Specifically, as all real-time driving deci-

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sions are made based on up-to-date information, any delayed transmissions or reception failures would result in biased and dangerous decisions; therefore, *ultra-reliable* broadcast communication at the MAC layer (i.e., without message collisions) is essential. On the other hand, various onboard sensors and the use of high-definition (HD) maps at autonomous vehicles can provide rich environment information, which can be utilized in MAC design to enhance the broadcast reliability.

In this article, we consider the concept of *fine-grained* MAC design, which leverages the precise sensing information of autonomous vehicles to provide ultra-reliable broadcast for autonomous driving. We first identify three important issues in vehicular environments, which will impair the efficacy of TDMA-based MACs in providing periodic broadcast. Specifically, as vehicles move, multiple respective independent vehicle sets that originally have collision-free time slot assignments merge together and then cause time slot collisions. In addition, vehicle densities in urban areas vary dramatically over time, where the broadcast channel can easily be congested when the vehicle density becomes very heavy. At last, vehicles may have different safety threats, which calls for different beacon rates, while current TDMA-based MACs only support the stiff beacon rate (i.e., all vehicles have the same beacon rate), making medium resource allocation out of tune. To tackle these issues, we then present three possible techniques:

- Mobility-aware time slot assignment: assigning disjoint time slot sets to those vehicles that are about to merge
- Safety-aware beacon rate adaptation: adapting beacon rates according to vehicles' safety demands
- Supporting flexible beacon rates: allowing vehicles with different beacon rates to negotiate the medium access

Before investigating the TDMA-based MAC, the preliminaries of its main methodology are introduced in the following section. Moreover, a case study regarding the mobility issue is also provided after elaborating the fine-grained design, in which time slots are assigned based on the road topology and lane distribution. Finally, we give the implementation steps to achieve the fine-grained MAC, and conclude the article in the final section.

Preliminaries of TDMA-Based MAC

In this article, we focus on the control channel of dedicated short-range communication (DSRC) [12], which supports the dissemination of the crucial CAMs.

Time-Slotted Channel Medium

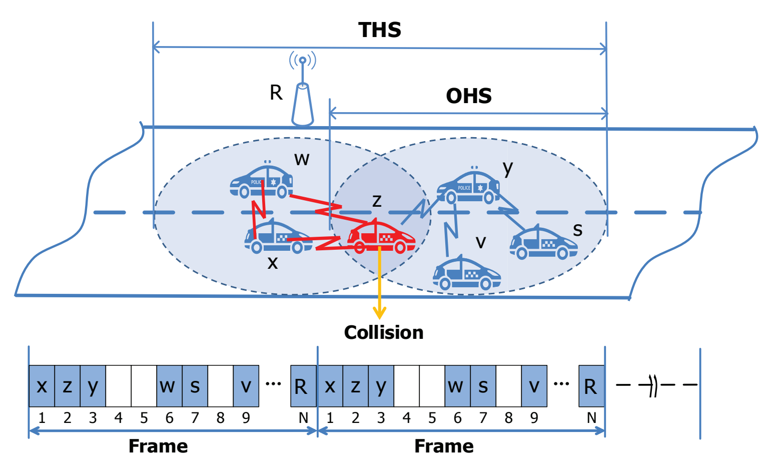


FIGURE 1. Frame structure of a typical TDMA-based MAC.

In TDMA-based MAC protocol, the channel medium is represented by distinct time slots. As shown in Fig. 1, time is divided into consecutive frames, and each frame contains *N* equal time slots. Every node (i.e., vehicle or RSU) synchronizes the index of time slots with each other and transmits messages by accessing vacant time slots. For periodic broadcast, each node can apply for a unique time slot and broadcast at the same time slot in consecutive frames. To avoid concurrent transmissions, nodes within interference range should be assigned distinct time slots. As shown in Fig. 1, neighboring nodes in the communication range of vehicle *x* constitute its one-hop set (OHS), and all nodes in the same OHS have to select different time slots. In addition, to overcome the hidden terminal problem, nodes in the same two-hop set (THS), which is the union of two overlapped OHSs, should also choose different time slots. Particularly, the OHS of vehicle *x* overlaps with the OHS of vehicle *y* as vehicle *z* is located in both OHSs; the reception collision would happen at receiver *z* if vehicles *x* and *y* broadcast in parallel since they cannot hear each other. The time slot assignment in the figure is a valid example, in which nodes within one THS have been assigned different time slots for broadcasting.

Slot Access and Collision Detection

Broadcasting Additional Frame Information: To access time slots in a distributed way, additional information exchange among neighbors is needed. In each beacon, in addition to application data, the vehicle (say vehicle *i*) should also broadcast the information of $I(j)$ and $T(j)$ for $\forall j \in N_{cch}(i)$, where $I(j)$ and $T(j)$ are the vehicle IDs, and the time slot index acquired by vehicle *j*, and $N_{cch}(i)$ is the OHS of vehicle *i* (including *i* itself). In this way, each vehicle can perceive time slot acquisitions within its THS (i.e., interference range).

Accessing Time Slots: To access a time slot, first, a vehicle (say vehicle *k*) has to listen to the channel for *N* successive time slots to obtain $T(j)$ for $\forall j \in N^2_{cch}(k)$, where $N^2_{cch}(k)$ is the THS of the vehicle *k*. After that, the vehicle can randomly choose a time slot from the free time slot set, that is, $\mathcal{N} - T(j)$ for $\forall j \in N^2_{cch}(k)$, where $\mathcal{N}$ is the whole time slot set. Once the vehicle successfully acquires a time slot, it can use the same time slot in all subsequent frames unless a time slot collision is detected.

Detecting Time Slot Collisions: Due to network topology variation, multiple vehicles may access the same time slot, leading to massive transmission collisions. To detect a time slot collision, at the end of every frame, each vehicle has to check the frame information received during the previous *N* time slots. Specifically, for a vehicle *i*, if all beacons received from *j* for $\forall j \in N_{cch}(i)$, indicating that $i \in N_{cch}(j)$, it means no concurrent transmissions happen during time slot $T(i)$; otherwise, vehicle *i* may collide with another vehicle in its THS. Once

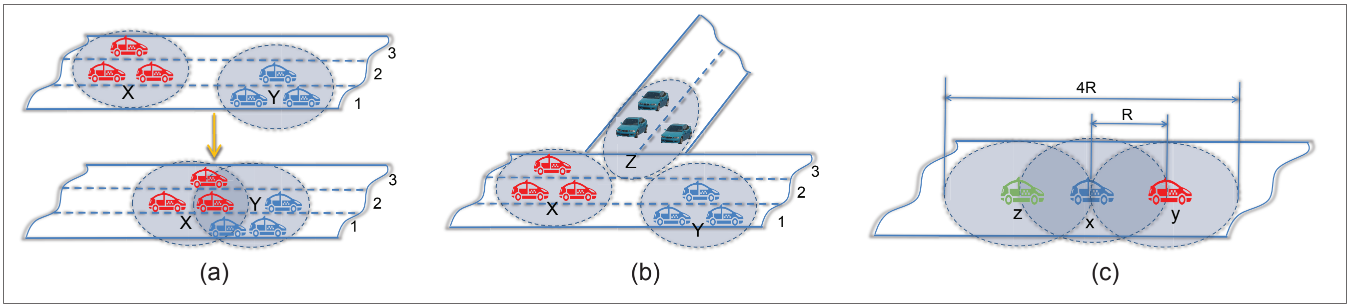


FIGURE 2. Problems causing message collisions in TDMA-based MAC: a) vehicle merging in different speed-limited lanes; b) vehicle merging at road intersections; c) the maximum interference range of vehicle x.

a collision is detected by a vehicle, it has to release its original time slot and try to acquire a new time slot.

Problems in Widely Employing TDMA-Based MAC

In this section, we identify several critical issues induced by inherent vehicular features, which are impediments toward ultra-reliable broadcast.

Massive Time Slot Collisions Caused by Mobility

Due to dynamic mobility, the efficacy of current TDMA-based MACs can be deteriorated by massive time slot collisions when multiple separate vehicle sets merge. As an example, in Fig. 2a, vehicles are moving on a multi-lane road, in which each lane has different speed limits. At the beginning, vehicles in respective sets X and Y have been guaranteed distinct time slots, and the two sets are separate from each other. As the vehicles in set X move faster and eventually catch up with the vehicles in set Y, the two sets overlap with each other, leading to time slot collisions. This merging phenomenon is common, especially on highway roads where frequent overtaking happens and network topologies vary dramatically. Figure 2b shows another time slot collision case happening at an intersection. Specifically, when vehicle set Z arrives at the intersection, it will overlap with vehicle set Y from another road segment, and thus time slot collisions could happen. Even worse, if there is a red traffic light, vehicle set Z will stop at the intersection and interfere all sets traversing the crossing (e.g., vehicle set X). Contradictorily, it is intersections that require the highest level of reliable beacon exchange to enhance driving safety.

Time Slot Shortage Problem

Another important feature of vehicular environments is the density variation. Specifically, the vehicle density in suburbia is normally light, while in urban and highway scenarios, the vehicle density can become very heavy. In addition, even at the same location, the vehicle density could also vary dramatically over time. Those unbalanced traffic densities call for dynamic medium resource management to avoid medium underutilization or frequent channel congestion. In this article, we focus on the latter case since it directly affects reliable broadcast communications at the MAC layer. Considering the following practical example where the size of each beacon is about 500 bytes [13] and DSRC radios adopt a moderate transmission rate of 6 Mb/s [12] for reliable transmission, the data transmission requires about 0.67 ms. To provide periodic broadcast every 100 ms, the length of each frame lasts at most for 100 ms; then the size of N in each frame should be smaller than $100/0.67 \approx 150$. Figure 2c shows the interference range of a particular vehicle x where vehicles y and z are at the edge of its communication range R. As hidden terminals for x may exist in respective communication range of vehicles y and z, the maximum interference range of vehicle x could reach up to four times R. According to the DSRC experiment study [12], the reliable communication range of DSRC can reach above 300 m in an urban area. Therefore, 150 slots have to be shared by vehicles within the interference range of 1200 m. In practical scenarios like urban intersections or bidirectional eight-lane highways, vehicles will heavily aggregate at peak time and time slots can easily run out. Then the *time slot shortage problem* would arise, in which the number of time slots N is far from adequate and the channel will be severely congested.

Stiff Beacon Rate Limitation

In current TDMA-based MACs, all vehicles are assumed to have the same beacon rate (i.e., 1 beacon/frame). However, in real driving situations, vehicles may have different danger threats to the transportation system, calling for flexible beacon rates. Specifically, in [14], vehicles are required to broadcast with diverse beacon rates to support different intelligent safety applications. For example, intersection collision warning and visibility enhancement applications require broadcast frequency of 10 Hz and 2 Hz, respectively. This stiff beacon rate limitation makes the medium resource allocation out of tune. On one hand, if adopting aggressive beaconing rates, the channel will be easily saturated. On the other hand, if adopting moderate beaconing rates, the received beacon information may be out of date, leading to wrong driving decisions or delayed reactions. Therefore, it is essential to support flexible beacon rates at the MAC layer such that the medium resources are efficiently allocated on demand.

Fine-Grained Solutions to Achieve Ultra-Reliable TDMA-Based MAC

Mobility-Aware Time Slot Assignment

To avoid potential time slot collisions, one possible solution is to assign disjoint time slot sets to those vehicle sets that are going to merge [8]. Unlike other types of mobile ad hoc networks in which nodes have random and unrestricted mobil-

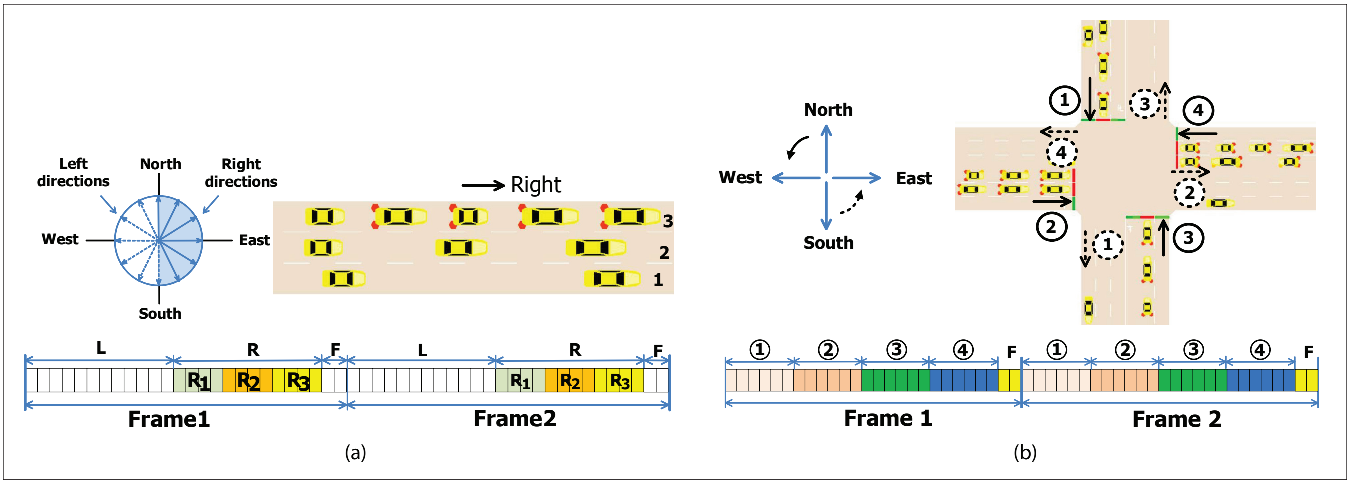


FIGURE 3. Mobility-aware time slot assignment: a) assigning disjoint time slot sets on a multi-lane road; b) assigning disjoint time slot sets at an intersection

ity, vehicle mobility is subject to road topology and layout, as well as road signs and traffic lights. However, the vehicle topology in different lanes would vary dramatically; for example, vehicles in fast lanes will constantly catch up with vehicles in slow lanes. To cope with it, we can leverage the sensing information at each autonomous vehicle that can precisely tell the current lane layout and to which lane it belongs, to facilitate mobility-aware time slot assignments. Specifically, when vehicles move on multi-lane roads, as shown in Fig. 3a, in each frame, time is first partitioned into three disjoint time slot sets (*L*, *R*, and *F*), which are associated with vehicles moving in in theleft direction, vehicles moving in the right direction, and RSUs, respectively. As vehicles in different lanes are also likely to merge, the time slot sets *L* and *R* are further divided into disjoint subsets, that is, L_1, L_2, L_3 and R_1, R_2, R_3, respectively. On the other hand, vehicles from different road segments will inevitably merge at the intersection. As shown in Fig. 3b, when vehicles arrive at an intersection, the time slot sets will be partitioned according to the intersection topology. As merging situations mainly happen for vehicle sets from road segments entering the intersection (defined as *inbound* road segments), vehicles from those segments should be assigned with disjoint time slot sets. To this end, given an *n*-way intersection, we divide the full time slot set into $n + 1$ disjoint subsets, that is, ①, ②, ,... , ⓝ, and *F*. Subset *F* is allocated to RSUs, while subset ⓚ, $k \in [1, n]$, is associated with the *k*th inbound road segment counted anticlockwise from the north direction. As vehicles from the inbound road segment may also collide with vehicles leaving the intersection (defined as *outbound* road segment), the subset ⓚ, $k \in [1, n]$, is also associated with the *k*th outbound road segment counted anticlockwise while from the south direction. Figure 3b gives a time slot assignment at a four-way intersection, and the assignment scheme can also be applied to other three-way or five-way intersections.

Beacon Congestion Control with Safety-Awareness

When the channel is saturated, beacon congestion control is needed; meanwhile, safety demands of each vehicle should also be guaranteed. Therefore, congestion control strategy is of great importance, while traditional max-min or equal fairness control schemes are no longer suitable due to the lack of driving safety consideration. For instance, if a particular vehicle is sacrificed to achieve maximized system-level throughput, nearby vehicles would be unable to perceive its existence and thus result in potential dangers. To achieve a safety-aware beacon control scheme, the danger threat of each vehicle (induced by moving status including velocity, relative distance, acceleration, etc.) should be taken into account.

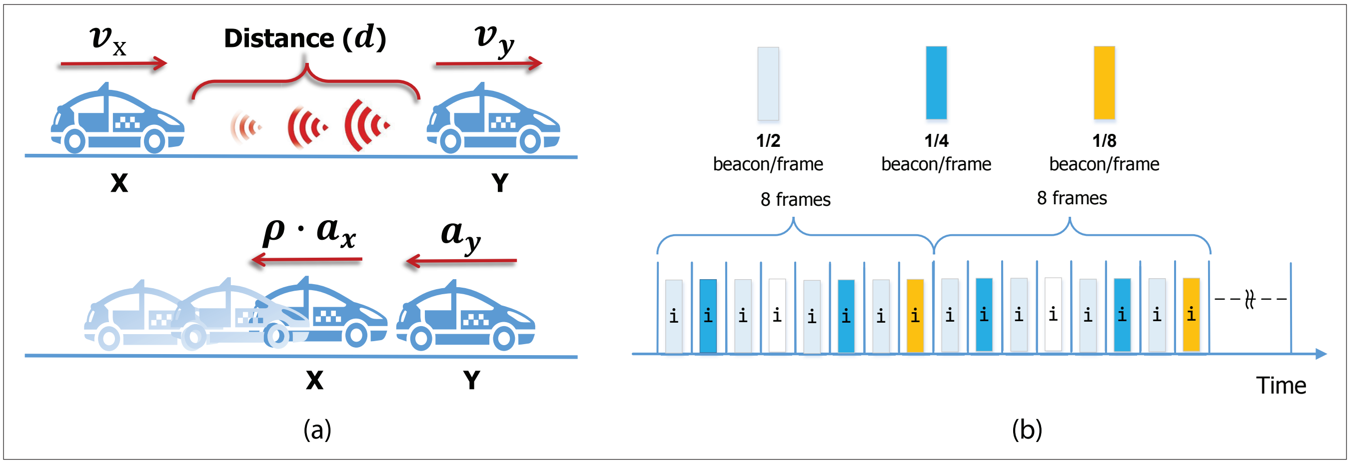
Safety Awareness Perception: We study a rear-end crash model to characterize the relationship between the beaconing activity and danger risk. Figure 4a illustrates an example, in which the behind vehicle *X* originally moves after the ahead vehicle *Y* with a following distance *d*, and their speeds and accelerations are V_x m/s, V_y m/s, and a_x m/s^2, a_y m/s^2, respectively. There is a rear-end collision risk when vehicle *Y* brakes at the maximum acceleration suddenly. Vehicle *X* can react to the situation after receiving the beacon from vehicle *Y* with a delay of $1/\beta_y + t_{\text{reaction}}$, where β_y is the beacon rate of vehicle *Y* and t_{reaction} is the reaction time of the autonomous driving system. The danger risk can be captured by how hard vehicle *X* should brake. Therefore, we define a danger coefficient ρ to capture the danger risk; specifically, vehicle *X* has to take $\rho \in (0, 1]$ of its maximum acceleration to brake in order to avoid hitting vehicle *Y* in this situation. Kinematic relations of two vehicles can be expressed as follows:

$$V_x\left(\frac{1}{\beta_y}+t_{\text{reaction}}\right)+\left(\frac{V_x^2}{2\rho a_x}-\frac{V_y^2}{2a_y}\right)=d, \tag{1}$$

and the danger coefficient ρ can be then calculated as

$$\rho=\frac{V_x^2}{2a_x\left(d-V_x\left(\frac{1}{\beta_y}+t_{\text{reaction}}\right)+\frac{V_y^2}{2a_y}\right)}. \tag{2}$$

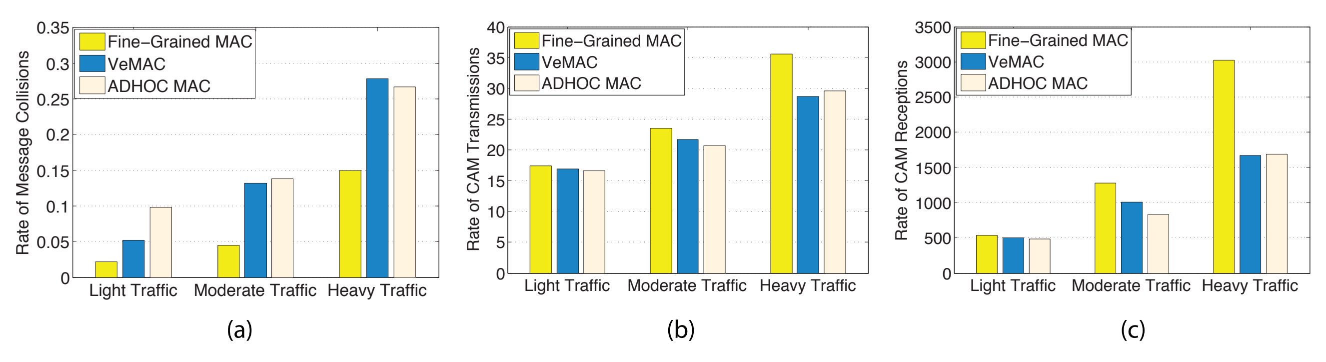
With exchanged CAMs and sensor information, each vehicle can calculate its danger coefficient



(a)

(b)

FIGURE 4. Fine-grained solutions: a) perceiving safety awareness; b) multiple vehicles share a time slot.



(a)

(b)

(c)

FIGURE 5. a) Average rate of message collisions; b) average rate of CAM transmissions; c) average rate of CAM receptions.

ρ in real time, which can be an effective indicator to describe the required beacon bandwidth with respect to such danger risk.

Beaconing Medium Constraint: To relieve the channel congestion, the beaconing medium should be allocated under the channel capacity constraint. Specifically, within the interference range of a particular vehicle, there are N time slots as the beaconing medium in each frame; if a vehicle broadcasts every frame, its beaconing item size can be treated as 1; if it broadcasts every two frames, the size can be treated as 1/2, and so on. The total beaconing item size of all vehicles within the interference range should be kept lower than the value of N. By receiving beacons, each vehicle is able to perceive the number of vehicles within its interference range and their beacon rates, which together can determine whether the channel is congested. Once a channel congestion event is detected, beacon rate adaptation is required.

Safety-Aware Beacon Rate Adaptation: Under the beaconing medium constraint, beacon rates can be adapted intelligently in accordance with the estimated danger coefficient. In addition, according to the safety application report [14], the beacon rate can range from 1 Hz to 10 Hz which limits the beacon rate range between $[\beta_{min}, \beta_{max}]$. The maximum beacon rate prevents those vehicles with high danger coefficients to be assigned excessive beaconing medium while the minimum beacon rate helps those vehicles with low danger coefficients to keep a certain level of situation awareness. To this end, given the channel capacity, the ρ-weighted beacon rate adaptation within $[\beta_{min}, \beta_{max}]$ can be conducted when a channel congestion event is identified.

Supporting Flexible Beacon Rates

As broadcasts are periodic, it is beneficial to make multiple vehicles alternately broadcast on the same time slot under fine-grained coordination [11]. As an example, in Fig. 4b, a singe time slot i, $i \in [1, N]$, can be shared by three vehicles with the respective beacon rates of 1/2, 1/4, and 1/8 beacon/frame; in addition, there is still space left in time slot i to support another vehicle with the beacon rate of 1/8 beacon/frame. To share a time slot, beacon rates of vehicles have to comply with a precondition. Particularly, for two vehicles with the beacon rate of $1/\alpha_i$ and $1/\alpha_j$ beacon/frame (i.e., broadcast a beacon every α frames, $1 < \alpha_i \leq \alpha_j$), respectively, if $\alpha_j = n * \alpha_i, \forall n = 1, 2, 3, \ldots$, those two vehicles can share a time slot well; otherwise, two vehicles would collide with each other. For example, in Fig. 4b, if the beacon rate of the vehicle (in blue) changes from 1/4 to 1/3, it will continuously collide with other vehicles at time slot i. Each vehicle has to be aware of the information of time slot-occupation and beacon rates of vehicles in its interference range, which can be obtained through beacon exchanges. To this end, vehicles with different beacon rates can cooperatively share a time slot with well-matched neighbors.

Case Study

In this section, we present a case study of mobility-aware time slot assignment, in which time slots are divided according to the lane distribution and road topology.

Methodology

Simulation Setup: To simulate a real driving scenario, we construct a typical urban road topology over the Simulation of Urban Mobility (SUMO), in which four bidirectional six-lane road segments converge at the center and form a four-way intersection. At the intersection, traffic lights are set at each inbound road segment with the duration of red state, green state, and yellow state being 20 s, 20 s, and 5 s, respectively. For each road segment, the length of road lasts for 4 km, and each of three lanes in one direction is given the speed limit of 50 km/h, 60 km/h, and 70 km/h, respectively. In addition, we assume that the vehicle arriving pattern in each lane follows a Poisson process with parameter λ. To emulate different traffic densities, we generate three types of traffic, that is, light, moderate, and heavy, with λ being 0.05, 0.1, and 0.3 (in each lane), respectively, and each simulation lasts for 1500 s. In all simulations, the duration of each frame is set to be 100 ms and the number of time slots within one frame is set to be 150, and we set the transmission range R to be 300 m. Note that as we study the performance of MAC protocol, transmissions are considered successful within communication range when there is no time slot collision, and we implement the MAC simulation system by Python with about 480 lines of code.

Benchmark Protocols: We compare the fine-grained TDMA-based MAC with the following two state-of-the-art TDMA-based MACs.

VeMAC [7]: In VeMAC, time slots are divided into two disjoint slot sets (i.e., L and R) for vehicles moving in opposite directions.

ADHOC MAC [9]: In this MAC, time slots are not divided, and all vehicles compete for unique time slots from a full time set.

Performance Metrics: We define the following three metrics to evaluate their performance:

- Rate of message collisions: that is, the number of transmission collisions per frame per THS.
- Rate of CAM transmissions: that is, the number of successful CAM transmissions per frame per THS. A transmission is labeled as successful when it is sent out, within the THS, and no concurrent transmission happens at the time slot.
- Rate of CAM receptions: that is, the number of successful CAM receptions per frame per THS. A reception is labeled as successful when no concurrent packet arrives.

Performance Comparison

Figure 5a shows the average collision rates in different traffic densities, and we make two major observations. First, in all traffic conditions, the fine-grained solution can achieve the best performance for number of collisions. Second, with heavier traffic, the rate of collisions increases in all three MACs. However, even in the heavy traffic scenario, the fine-grained MAC can still effectively work with the average collision rate about 0.15, whereas this rate can reach above 0.27 in other two MACs, that is, with more than 40 percent of message collision avoidance. Figures 5b and 5c show the average rate of CAM transmissions and receptions under different traffic conditions, and two similar observations can also be made. First, the fine-grained MAC outperforms the other two MACs in terms of CAM transmission and reception rates in all traffic conditions. Second, traffic density is a major factor that could impact the other two MACs greatly. For instance, in heavy traffic conditions, the average transmission rate is about 30 in the other two MACs while the value can be enhanced to 36 by our solution. This advantage can be better demonstrated in the metric of reception rate since one transmission collision only impacts one vehicle's transmission rate but can affect various vehicles' reception rates. Specifically, in heavy traffic conditions, the average reception rate is no more than 1700 in other two MACs while ours can reach above 3000, that is, with about 76 percent performance improvement. These results demonstrate that the fine-grained MAC can work robustly in all traffic densities, whereas the benchmarks will be inefficient when meeting heavy traffic conditions.

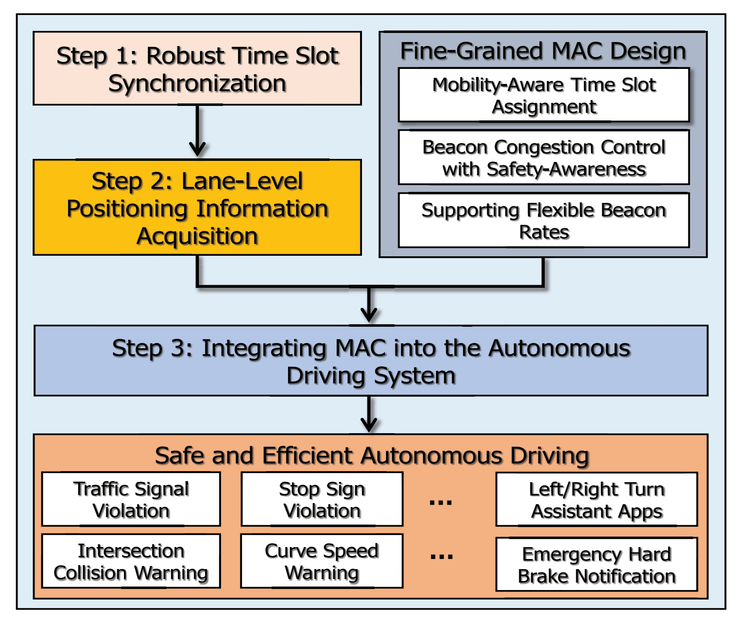


FIGURE 6. Implementation steps for the fine-grained MAC.

Implementation Steps

With the fine-grained MAC design, different levels of safety applications can be simultaneously supported by well negotiating the time-slotted channel. In addition, as the MAC takes different mobility patterns into consideration, no matter where the vehicle moves, it can achieve the collision avoidance time slot assignment. Besides, the MAC has the congestion control capability and can work reliably no matter when the density increases dramatically. In this section, we present the implementation steps to achieve the fine-grained MAC in autonomous driving,

By leveraging the precise sensing-information of autonomous vehicles, we have designed a fine-grained TDMA-based MAC protocol to support ultra-reliable broadcast in the autonomous driving era. In particular, we have first identified three critical issues that may impair the efficacy of the TDMA-based MAC, and to resolve those issues, we have integrated three fine-grained solutions in the proposed MAC protocol.

and Fig. 6 shows three major implementation steps.

STEP 1: ROBUST TIME SLOT SYNCHRONIZATION

To access the time-slotted channel, high-precision time slot synchronization among vehicles is required. Specifically, considering each frame with a duration of 100 ms and the number of time slots larger than 100, the time synchronization should guarantee an accuracy within 100 ms. Normally, time synchronization can be performed by using the Global Positioning System (GPS) along with the pulse per second (PPS) signal. In particular, the satellite signal can provide a global time reference for GPS receivers at all vehicles; the local computer timekeeping is then performed by referring to the PPS signal provided by each GPS receiver. The PPS signal is a square wave with stable frequency, which can be used as a time reference. It provides less than 100 ns synchronization accuracy, which is adequate for recognizing all slot boundaries. However, in urban environments, it is possible that the satellite signals get blocked by high-rise buildings. In the case of a temporary loss of GPS signal, the synchronization among vehicles can still be maintained within a certain time duration, which depends on the stability of the local oscillator at each GPS receiver.

STEP 2: LANE-LEVEL POSITIONING INFORMATION ACQUISITION

To enable autonomous driving on public roads, localization must be precise within the range of a few centimeters to perceive in which lane the vehicle is moving. An HD digital map is needed to achieve such lane-level positioning, in which static models including lane marking, road properties (curvature, slope, heading, etc.), traffic signs, and so on are marked clearly. Relying on the set of readings from vehicle sensors, its position can be estimated on the map by using dead-reckoning techniques [15]. However, an HD map is relatively large and has to be provided in real time by RSUs, which is impossible to guarantee all the time. As identifying to which lane the vehicle belongs is a classification problem rather than a positioning problem, when there is a temporary HD map shortage, such information can be retrieved from existing road infrastructures (via RSUs), such as closed-circuit cameras, vehicle loop detectors, and RFID techniques; alternatively, individual vehicles can actively obtain the lane information through onboard sensors such as cameras and inertia sensors.

STEP 3: INTEGRATING MAC INTO THE AUTONOMOUS DRIVING SYSTEM

To fully unleash the potential of the MAC, it is better to integrate it into the autonomous driving system. For instance, by adopting the MAC, the emergency hard brake notification system can be enabled, in which the system can give an early notification of hard brakes from preceding vehicles to following vehicles even with limited visibility; the information could be integrated into the control unit and trigger a brake command immediately. In addition, the curve speed warning system can help the computing unit to calculate appropriate speeds to follow curves by proactively collecting the information of curve location, curvature, curve speed limits, and so on. The left/right turn assistant application can provide information about oncoming traffic, which contributes to safer turning decision making. In this way, the autonomous driving system can achieve additional sensing information at the earliest time, which is valuable for complicated driving tasks with safety and efficiency requirements.

CONCLUSION

In this article, by leveraging the precise sensing information of autonomous vehicles, we have designed a fine-grained TDMA-based MAC protocol to support ultra-reliable broadcast in the autonomous driving era. Particularly, we have first identified three critical issues that may impair the efficacy of the TDMA-based MAC, and to resolve those issues, we have integrated three fine-grained solutions in the proposed MAC protocol:

- Mobility-aware time slot assignment
- Beacon rate adaptation with safety awareness
- Flexible beacon rates support

A case study is also presented to verify the effectiveness of the proposed TDMA-based MAC protocol. To shed light on the practical application of the proposed protocol, the implementation steps are also elaborated.

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