Chapter 4

An Infrastructure-Free Slot Assignment Algorithm for Reliable Broadcast of Periodic Messages in VANETs

Contents

4.1 Introduction

Improving road safety is among the main objectives of VANET design as we have seen in the previous chapter. This objective can be achieved by using efficient safety applications which should be able to wirelessly broadcast warning messages between neighboring vehicles in order to inform drivers about a dangerous situation in a timely manner. To insure their efficiency, safety applications require reliable periodic data broadcasting with low latency and while minimizing the number of collisions. In this chapter, we present a novel **D**istributed **T**DMA based **MAC** protocol, named DTMAC, developed specifically for a highway scenario. DTMAC is designed to provide the efficient delivery of both periodic and event-driven safety messages. The protocol uses the vehicles' location and a new slot reuse concept to ensure that vehicles in adjacent areas have a collision-free schedule. Simulation results and analysis in a highway scenario are presented to evaluate the performance of DTMAC and compare it with the VeMAC protocol.

4.2 DTMAC assumptions

A VANET in a highway scenario consists of a set of vehicles moving in opposite directions and under varying traffic conditions (speed, density). DTMAC is based on the assumption that each vehicle in a VANET is equipped with a GPS or a GALLILEO receiver that also allows it to obtain an accurate real-time three-dimensional geographic position (latitude, longitude and altitude), speed and exact time. Moreover, synchronization between vehicles may be performed by using GPS timing information. Each road is divided into small fixed areas (see Figure 4.1). Note that the area size depends on the transmission range of the vehicles (around $310m$). Moreover, we assume that the vehicles are equipped with digital maps to determine which area they are in. In the following, we detail the slot scheduling mechanism in DTMAC and we show how this protocol can provide an efficient time slot utilization for the participating vehicles, while minimizing transmission collisions caused by the hidden node problem.

4.3 DTMAC: Distributed TDMA-based MAC protocol

4.3.1 DTMAC preliminaries

We propose a completely distributed and infrastructure free TDMA scheduling scheme which exploits the linear feature of VANET topologies. The vehicles' movements in a highway environment are linear due to the fact that their movements are constrained by the road topology. Our scheduling mechanism is also based on the assumption that each road is divided into N small fixed areas, denoted by $x_i, i = 1, \ldots, N$ (see Figure 4.1). Area IDs can be easily derived using map and GPS Information.

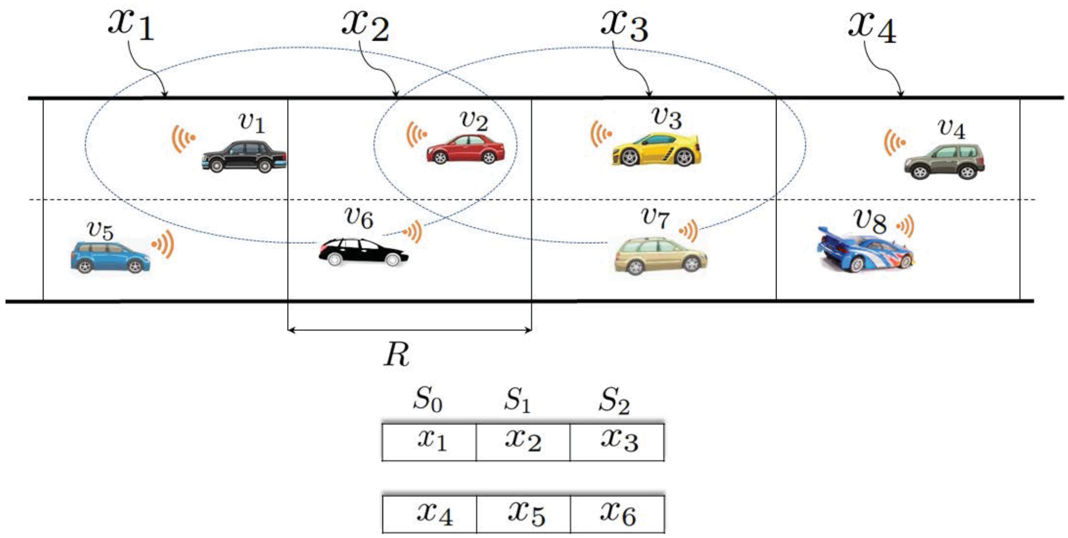

Figure 4.1: TDMA slots scheduling principle.

The time slots in each TDMA frame are partitioned into three sets S_0, S_1 and S_2 associated with vehicles in three contiguous areas: x_i, x_{i+1} and x_{i+2}, respectively (see Figure 4.1). Each frame consists of a constant number of time slots, denoted by τ and each time slot is of a fixed time duration, denoted by s. Each vehicle can detect the start time of each frame as well as the start time of a time slot. In the VANET studied, all the vehicles are equipped with a GPS and thus the one-Pulse-Per-Second (1PPS) signal that a GPS receiver gets from GPS satellites can be used for slot synchronization.

To prevent collisions on the transmission channel, our TDMA scheduling mechanism requires that every packet transmitted by any vehicle must contain additional information, called Frame Information (FI). The FI consists of a set of ID Fields (IDFs) of size equal to the number of time slots per frame, τ. Each IDF is dedicated to the corresponding time slot of a frame. The basic FI structure is shown in Figure 4.2. Each time slot is dynamically reserved by an active vehicle (the vehicle whose communication device is transmitting) for collision-free delivery of safety messages or other control messages. The VC_ID field contains the ID of the vehicle that is accessing this slot. Each vehicle is identified by its MAC address. The SLT_STS field contains the status of each slot which indicates whether the slot is Idle, Busy or in Collision. Finally, the PKT_TYP field indicates the type of packet transmitted by the vehicle, i.e. periodic information or event-driven safety messages.

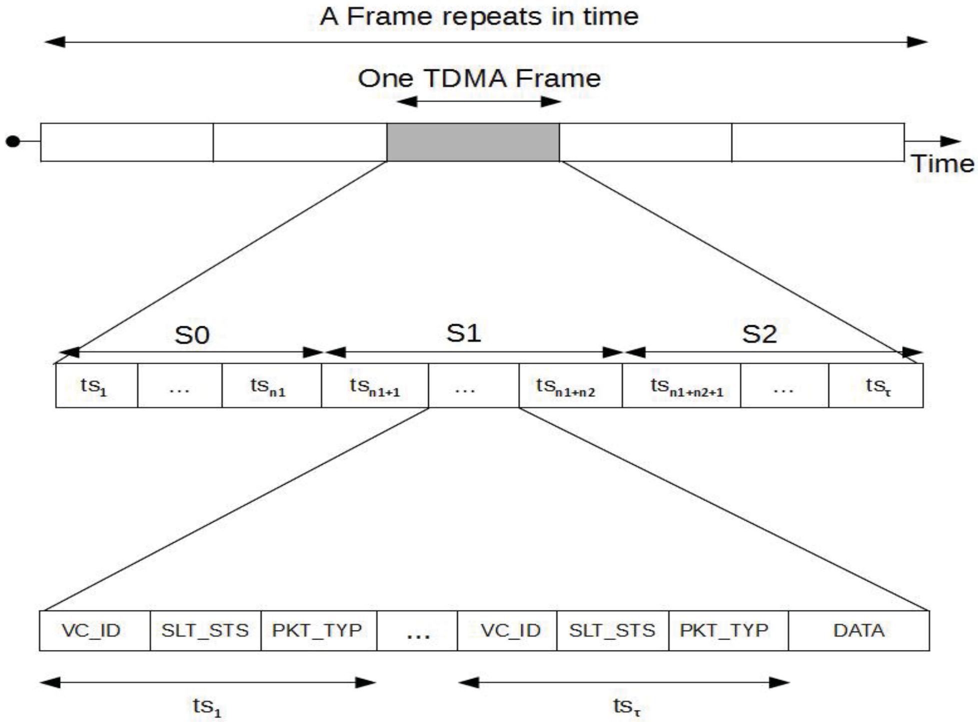

Figure 4.2: Frame information (FI) structure.

4.3.2 TDMA slot scheduling mechanism

Our distributed TDMA scheduling mechanism uses vehicles location and slot reuse concept to ensure that vehicles in adjacent areas have collision-free schedule. The channel time is partitioned into frames and each frame is further partitioned into three sets of time slots S_0, S_1, and S_2 of size equal to $n1, n2$ and $n3$, respectively. These sets are associated with vehicles moving in the areas x_i, x_{i+1}, and x_{i+2}, respectively. As shown in Figure 4.1, by dividing the time slots into three sets, vehicles v_1 and v_3 that are moving within the two areas x_1 and x_3, respectively, can not transmit simultaneously to vehicle v_2 because they are accessing disjoint sets of time slots. Therefore, our TDMA scheduling mechanism can decrease the collisions rate caused by the hidden node problem. In each area, the vehicles access the time slots associated to their locations with the same probability. In the rest of this chapter, we adopt the following notations:

- $S_j(v)$: The set of time slots associated to the area in which the vehicle v is traveling.

- $N(v)$: The set of neighbors[1] of vehicle v on the transmission channel.

Every active vehicle in the network should be allocated a fixed slot in the frame for safety messages or other control packet transmissions. It is obvious that a vehicle's slot cannot be used by any neighboring vehicles within the same area or in adjacent areas, otherwise collisions will occur. The goal of this work is to propose an efficient slot reuse algorithm without having to use expensive spectrum and complex broadband mechanisms such as FDMA or CDMA. In fact, the three subsets of time slots will be reused between neighboring areas in such a way no vehicle in different adjacent areas can access the channel at the same time, and thus no interference will occur.

Let us suppose that an active vehicle v moving within the area x_i needs to acquire a time slot on the transmission channel. Vehicle v starts listening to the channel during the set of time slots reserved for the area in which it is traveling, let $S_j(v)$, where $j = (i + 2)\ mod\ 3$.

- Each vehicle that hears exactly one node transmission in a time slot reserved for its location, will set the status of the slot to "busy" and record the ID of the vehicle accessing the channel in this time slot in the corresponding VC_ID field.

- If a vehicle does not hear anything during a specific time slot, it will set its status to "free" in the FI.

- If a vehicle can not decode the data during a specific time slot, it will set its status to "collision" in the FI.

- When a vehicle A has sent data in a given slot, it looks in the field information of the next slots to discover whether its neighbors have correctly received its data. If a neighbor of A reports collision for this slot (in the FI) or even if this slot is reported to be "busy" but being sent by another node (say B in the VC_ID), A considers that its transmission has led to a collision[2].

[1] The set of neighbors is the set of vehicles that are moving within the same area.

[2] Actually a node A considers that its transmission is a success if and only if all its neighbors report a success in the FI of their slots specifying that the data was sent by node A.

At the end of the frame the vehicle v can determine the set $N(v)$ and the set of busy slots in $S_j(v)$ used by each vehicle $u \in N(v)$, denoted by $B(v)$. In order to avoid any collision problem, this set of time slots can not be used by any neighboring vehicles. Therefore, vehicle v can determine the set of available time slots $F(v)$ and then attempts to select one of them at random, say time slot k.

Algorithm 2 FI formation

Input

$S_j(v)$: the set of time slots that the vehicle v can reserve.

α_j, β_j: are the indexes of the first and the last slot of the set $S_j(v)$, respectively.

for each slot index $k = \alpha_j$ to β_j **do**
    if only one vehicle u is heard in the slot k **then**
        $FI[k].VC\_ID \leftarrow u$
        $FI[k].SLT\_STS \leftarrow Busy$
    else
        if more than one vehicle is heard in the slot k **then**
            $FI[k].SLT\_STS \leftarrow Collide$
        else
            $FI[k].SLT\_STS \leftarrow Free$
        end if
    end if
end for

Algorithm 2 outlines the details of how the frame information is built. In the algorithm, i is the index of the area in which a vehicle is traveling. If no other vehicle moving in the same area as vehicle v attempts to acquire a time slot k, no access collision occurs. In this case, the attempt of vehicle v is successful and all nodes $u \in N(v)$ add vehicle v to their sets $N(u)$ and record that vehicle v is using time slot k. However, if at least one node within the same area as vehicle v accesses time slot k, then all the transmissions fail and the time slot k is not acquired by any of the contending vehicles. In this case, vehicle v will discover that its attempt was unsuccessful as soon as it receives a packet from any node $u \in N(v)$ indicating that vehicle $v \notin N(u)$. Vehicle v then attempts to access one of the time slots in $F(v)$, and so on until all nodes $u \in N(v)$ indicate that node $v \in N(u)$ and announce that the time slot has been allocated to vehicle v. However, when an access collision occurs among the vehicles that are moving in the same area, the probability of access collision in the next reservation is increased since the choice of available slots will be restrained in the new set $F(v)$. In order to ensure channel access continuity, each vehicle should determine the expected available time slots on the set of time slots associated with the next area before leaving the area in which it is currently traveling. In fact, when a vehicle is using a given time slot in the set S_j, it should acquire an available time slot in the set $S_{(j+1)\ mod\ 3}$ as its future time slot before leaving its current area. Algorithm 3 outlines the details of the slot reservation mechanism. It is executed by each vehicle v which needs to reserve a time slot.

Algorithm 3 Slot reservation

```
Determine the area ID x_i.
Determine the set of time slots S_j associated with the area x_i.
Determine the available time slots F in the set S_j.
if V ≠ {∅} then
    Randomly reserve an available time slot k.
end if
if All the received FIs in the next frame indicate that slot k has been reserved
by vehicle v then
    Successful ← 1
else
    Successful ← 0
    Release the time slot k
    Go back to 4
end if
```

4.4 Access collision probability

In this section, we present a model to compute the average access collision probability. We assume that the VANET scenario taken into account is a two-way highway of length equal to L. We assume that every area of the road has a unique index number such as $1, 2, \ldots, N$. The probability with which the vehicle in the $i-th$ area decides to access the available $j-th$ time slot reserved for its location is denoted by p_{ij}. For instance, the probability of the vehicle in the fourth area accessing the 7-th slot is denoted by p_{47}. First of all, we calculate the access collision probability when a vehicle tries to access an available time slot.

- A_i: actual number of active vehicles in a given area x_i.
- P_{aci}: the access collision probability of the vehicle in area x_i accessing the channel.
- α_i, β_i: the indexes of the first and the last time slots reserved for the area x_i.

For DTMAC, the probability of accessing an available time slot j by a contending vehicle v in the area i is $p_{ij} = \frac{1}{(\beta_i - \alpha_i) - N_{succ_i}(v)}$, where $N_{succ_i}(v)$ is the number of vehicles in the area i which have successfully acquired a time slot as derived from the framing information received by vehicle v. Therefore, the access collision probability of a vehicle in area x_1 can be evaluated as:

$$P_{ac1} = 1 - P_{nac1} \qquad (1)$$

$$P_{nac1} = \sum_{j=\alpha_1}^{\beta_1} p_{1j} * \prod_{k=2}^{A_1} (1 - p_{1j}) \qquad (2)$$

where P_{ac1} denotes the access-collision probability in area x_1 and in a given time slot, while P_{nac1} denotes the non access-collision probability in area x_1 and in a given time slot.

Based on the above derivation, the expression of the total access collision probability of the vehicles in all locations can be given by:

$$P_{act} = 1 - P_{nact} \qquad (3)$$

$$P_{nact} = \sum_{i=1}^{N} P_{naci} = \sum_{i=1}^{N} \sum_{j=\alpha_i}^{\beta_i} p_{ij} * \prod_{k=2}^{A_i} (1 - p_{ij}) \qquad (4)$$

where, P_{act} represents the total access-collision probability of the vehicle accessing the channel, P_{nact} represents the total non access-collision probability of the vehicle accessing the channel.

$$P_{aver-ac} = \frac{1}{N} * P_{act} \qquad (5)$$

$P_{aver-ac}$ represents the average access collision probability of the vehicle accessing the channel.

4.5 Simulation results and performance evaluation

4.5.1 Simulation scenarios and performance metrics

In our work, we have used VanetMobiSim [114] to generate the mobility pattern of vehicles. We simulate different traffic conditions by varying the speed deviation and the vehicles density. We consider a VANET in a two-way highway scenario of size $2000m \times 20m$, where vehicles are moving along the highway in opposite directions. The parameters of VanetMobiSim consisted of the maximum number of vehicles, the starting and destination positions of each vehicle and the number of lanes per direction. During simulation time, each vehicle moves at a constant speed, and the number of vehicles on the highway remains constant. Then the traffic traces generated by VanetMobiSim were used in the ns2.34 simulations, as shown in the Figure 4.3. The simulation parameters used in our experiments are summarized in Table 4.5.1.

We have used a parameter, called the area occupancy (AO) [79], equal to $\frac{N_v \times R}{L_h \times T_s}$ in a highway scenario, where N_v is the total number of active vehicles, R is the communication range, L_h is the length of the highway, T_s is the number of slots reserved for each area.

Table 4.1: *Simulation parameters*

Parameter	Value
Highway length	2 km
Lanes/direction	2
Vehicle speed	120 km/h
Speed standard deviation (σ)	30 km/h
Transmission range	300 m
Slots/frame	100
Slot duration	0.001 s
Simulation time	120 s

DTMAC is evaluated based on the following metrics:

1. The access collision rate: is defined as the average number of access collisions per slot per area.

2. The merging collision rate: is defined as the average number of merging collisions per slot per area.

3. The broadcast coverage ratio: is defined as the average of the total number of vehicles that successfully receive messages to the total number of vehicles within the communication range of the transmitter.

4. The packet loss rate: is defined as the average of the total number of vehicles that do not successfully receive messages to the total number of vehicles within the communication range of the transmitter.

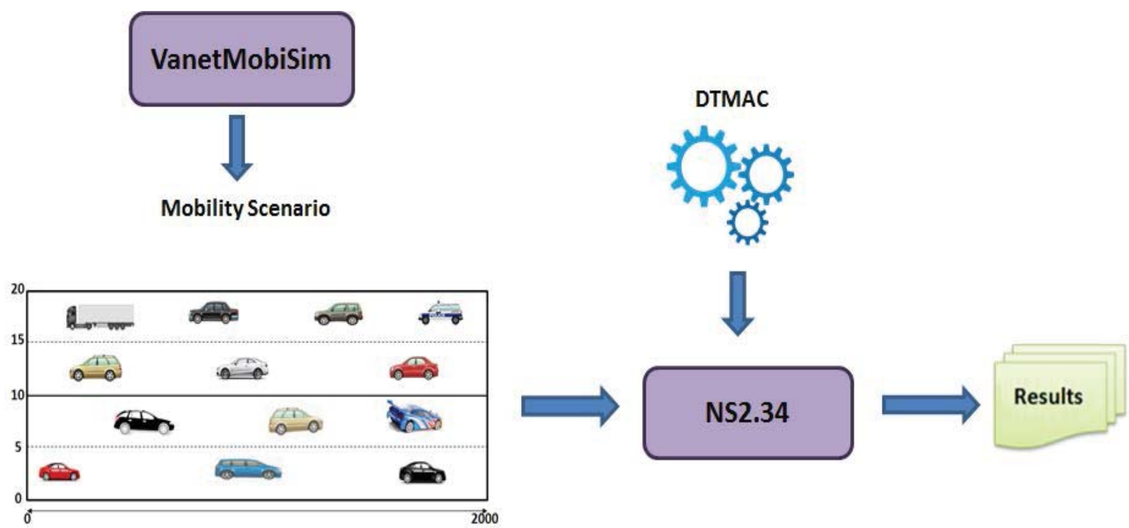

Figure 4.3: VANET mobility scenario

4.5.2 DTMAC performance evaluations

The performance of DTMAC depends on the sizes of the three sets of time slots $n1, n2$ and $n3$ that determine its behavior. An optimal tuning of these parameters can improve the QoS of DTMAC. For this, we evaluated several configurations in different speed scenarios (by varying the speed deviation σ between 20, 30 and 50 km/h) with different area occupancy values to find the optimal values of these parameters. Figures 4.4 and 4.5 shows the average access collision probability under various traffic conditions for σ equal to 20, 30 and 50 km/h, respectively. The experiments were carried out for different values of $n1, n2$ and $n3$. It is clear from these three figures that the first configuration when the three sets of time slots have the same size equal to $\tau/3$, is the best configuration that minimizes the probability of access collision under different traffic conditions.

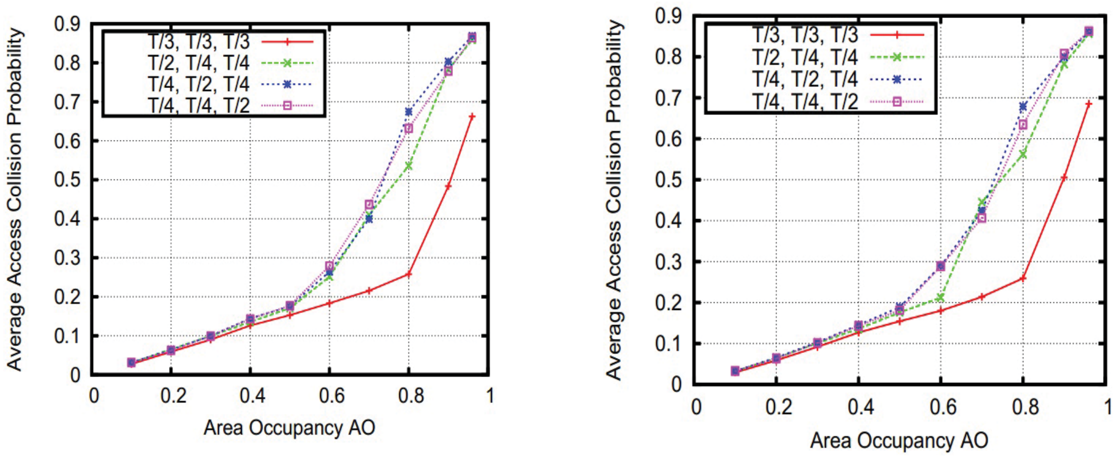

Figure 4.4: The access collision probability for $\sigma = 20$ (left) and $\sigma = 30$ (right).

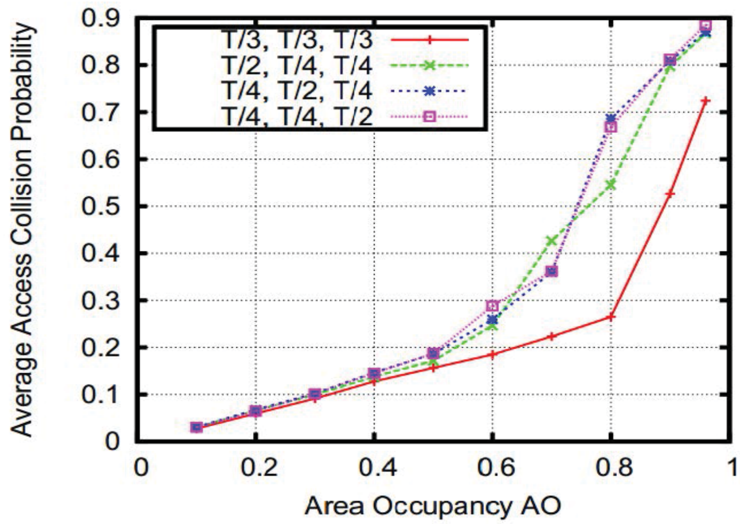

Figure 4.5: The access collision probability for $\sigma = 50$.

Fig 4.6 shows the rate of merging collisions for DTMAC and VeMAC protocols when varying the Area Occupancy (AO). DTMAC[3] prevents more merging collisions than VeMAC even for a high AO since it assigns disjoint sets of time slots to vehicles moving in adjacent areas. However, in VeMAC, the vehicles that cannot access a time slot from the set of slots reserved for its direction, will attempt to access any available time slot reserved for vehicles moving in the opposite direction. Moreover,

[3]In principle, the DTMAC algorithm prevents any merging collision. However when errors at the physical layer lead to a reception error (the FI is not coherent with the transmission), a node may consider that its transmission is a collision even if it has been the sole transmitter within its zone in the slot. Thus, if this error is not on the first attempt of the node to acquire a slot, we consider that it is a merging collision.

the available time slot sets are allocated by the contending vehicles without considering their speed deviations. Therefore merging-collisions occur frequently in VeMAC when traffic density is high as well as when vehicles driving toward each other and at high relative speeds. It should be noticed that, in principle, the algorithm prevents any merging-collision for DTMAC.

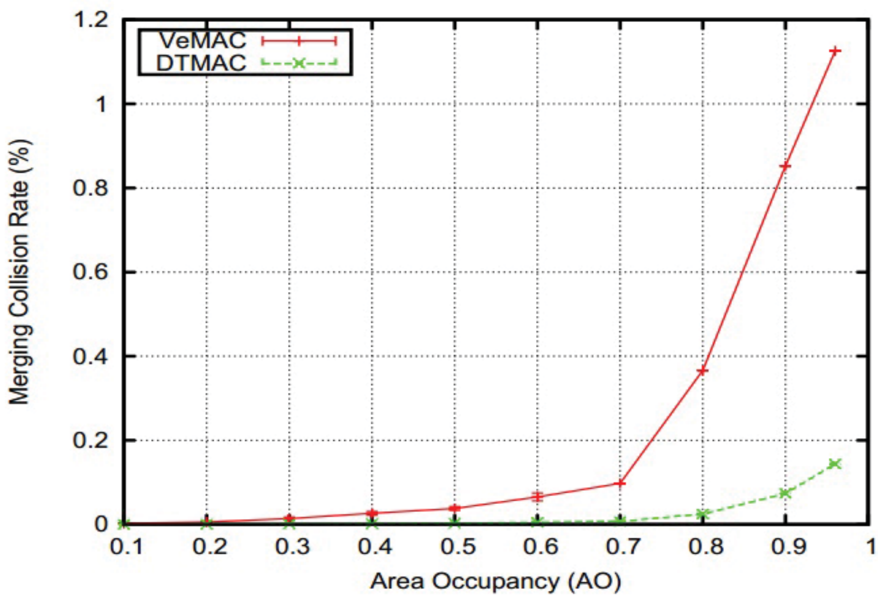

Figure 4.6: The rate of merging collision.

Figure 4.7 shows the access collision rates of the two TDMA based MAC protocols. As shown in this Figure, DTMAC achieves a considerably smaller rate of access collisions than VeMAC, especially for a high AO (≥ 0.7). For instance, at a $AO = 0.96$, the DTMAC protocol achieves an access collision rate of 0.849%, in contrast to VEMAC which shows a rate of 1.598% (i.e. approximately 88.22% higher than DTMAC). These results can be explained by the fact that VeMAC has achieved a higher rate of merging collision compared to DTMAC. Indeed, upon detection of merging-collisions, the nodes in collision should release their time slots and request new ones, which can reproduce access-collisions.

The packet loss rates of the two MAC protocols under consideration are shown in Figure 4.8. For a $AO \leq 0.7$, the DTMAC and VeMAC protocols have almost the same packet loss rate, while for a $AO > 0.7$, DTMAC starts to perform better than VeMAC. It can be seen that our MAC protocol has the lowest packet loss rate, especially for a high AO, due to its ability to handle the merging collision problem.

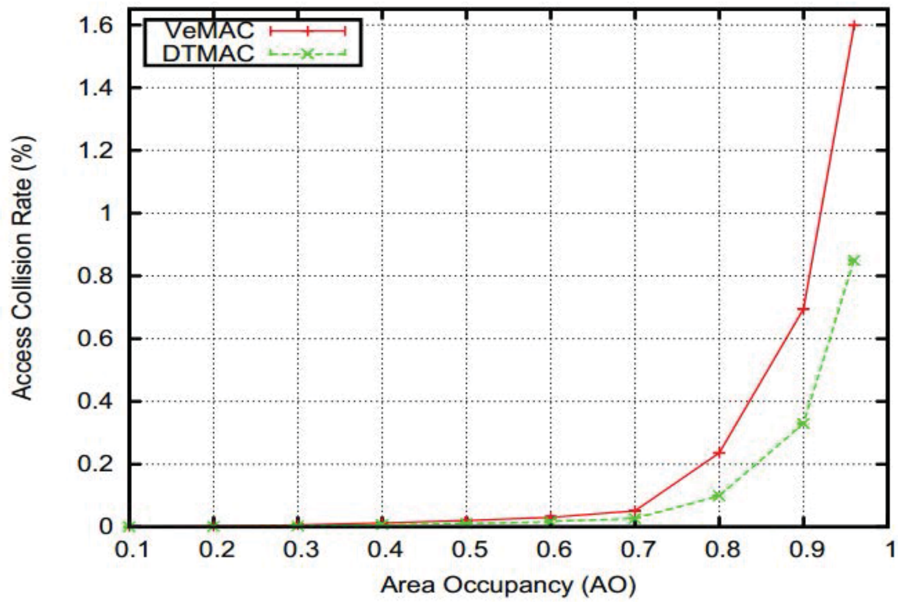

Figure 4.7: The rate of access collision.

For instance, at a $AO = 0.96$, the VeMAC protocol shows approximately 58.23% higher rate of packet loss than the DTMAC protocol.

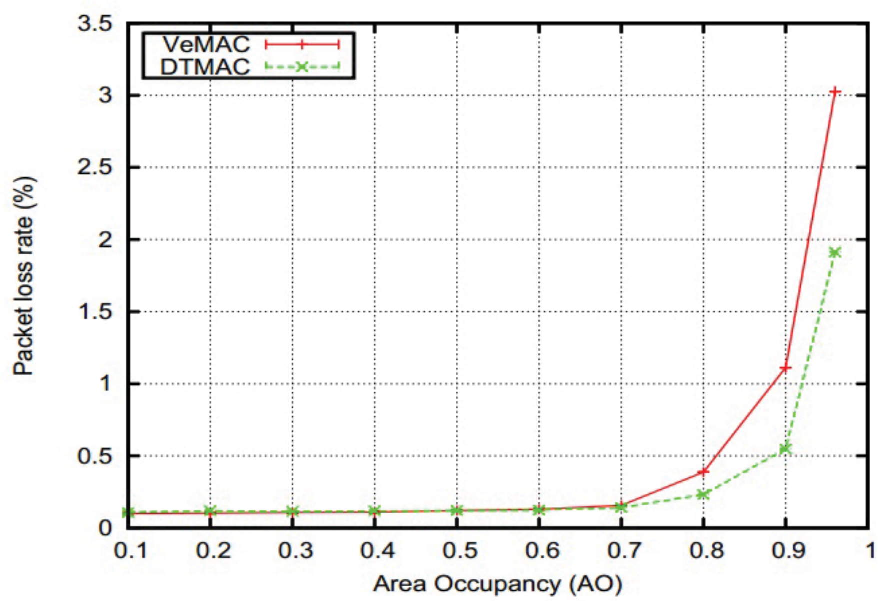

Figure 4.8: The rate of packet loss under various traffic densities.

The broadcast coverage rate is shown in Figure 4.9. It is clear that the two TDMA schemes achieved the same coverage ratio for low AO values. Note that for a high

AO, DTMAC performs much better and the broadcast almost reached full coverage (i.e. 99.45% and 98.06% for *AO* equal to 0.9 and 0.96, respectively).

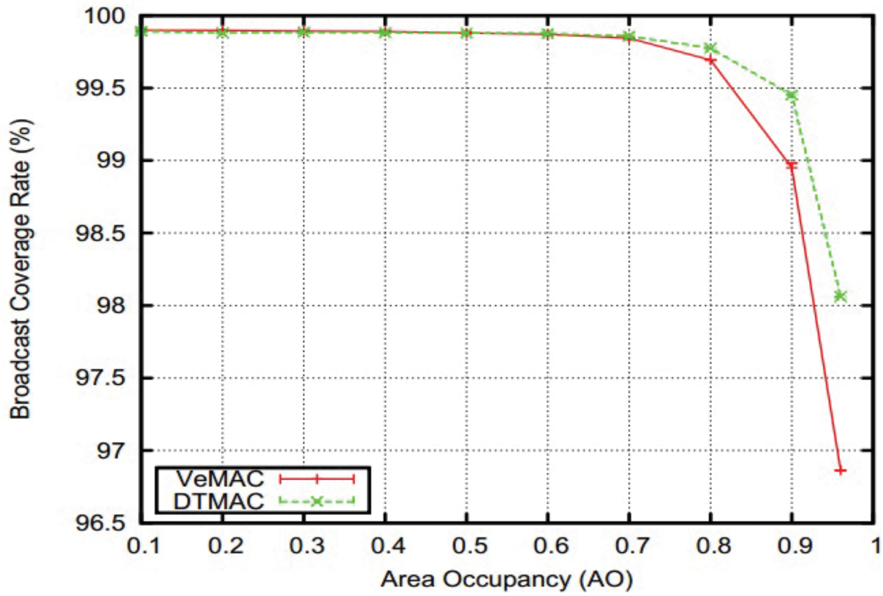

Figure 4.9: The coverage broadcast ratio under various traffic densities.

4.6 Conclusion

Applying VANETs to reduce the number of accidents and enhance driver and passenger safety requires a fast and reliable broadcast service. MAC protocols play a primary role in providing efficient delivery and while avoiding data packet loss as much as possible . Although TDMA-based MAC protocols can provide deterministic access times without collisions, the scheduling mechanisms of these protocols must be able to dynamically adapt to changing network topologies. In this chapter, we propose a completely distributed and infrastructure-free TDMA scheduling scheme, named DTMAC which exploits the linear topology of VANETs. The way that slots are allocated and reused between vehicles is designed to avoid collisions caused by the hidden node problem. The analytical model of the average access-collision probability is proposed. The simulation results show that, compared to VeMAC, DTMAC provides a lower rate of access and merging collisions, which results in significantly improved broadcast coverage.

We focused on the periodic broadcast of safety messages between vehicles and their direct neighbors. However, a safety message can be transmitted over a long