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Connectivity-aware Medium Access Control in Platoon-based Vehicular Ad Hoc Networks

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Abstract—Because of the space and time dynamics of moving vehicles, network connectivity is an important performance metric to affect packet delivery in Vehicular Ad Hoc Networks (VANETs). Grouping vehicles into platoons in VANETs can improve road safety, change the network connectivity, and even reduce channel access collisions. Unfortunately, network connectivity is often ignored in the design of exiting MAC protocols for VANETs. In this paper, we analyze the connectivity probability and present a connectivity-aware Medium Access Control (MAC) protocol for platoon-based VANETs. A multi-priority Markov model is presented to derive the relationship between the connectivity probability and the system saturated throughput. Based on variable traffic status and network connectivity, a multi-channel reservation scheme is adopted to dynamically adjust the length of the Control CHannel (CCH) interval and the Service CHannel (SCH) interval for the improvement of the system performance, in terms of network throughput and the priority packet transmission opportunities for platoons. As a result, some important observations to the design and analysis of such communication systems are provided.

Keywords—Vehicular Ad Hoc Networks; platoon; connectivity; medium access control

I. INTRODUCTION

In recent years, vehicular Ad Hoc Networks (VANETs) have been developed rapidly to support safety-related and non-safety-related applications among vehicles. Safety applications have strict requirements on communication reliability and delay. On the other hand, non-safety (service) applications are more throughput-sensitive [1]. According to the IEEE 802.11p [2] and the IEEE 1609.4 [3] standards, one CCH and six SCHs in the 5.9GHz band have been allocated for VANET communications. A Coordinated Universal Time (UTC) scheme is adopted to coordinate the channel access, where the channel access time is divided into Sync Intervals (SI) each consisting of a CCH Interval (CCHI) and a SCH Interval (SCHI). All nodes tune to the CCH during the CCHI for exchanging safety packets and other control packets like WAVE Service Announcement (WSA) packets. Nodes might switch to one of six SCHs to exchange service packets during the SCHI. Based on these standards, some other access control protocols [4-6] have been discussed to provide efficient communications in VANETs and Smart Grid. Moreover, an efficient response

scheme [7] was adopted in MAC protocol design to ensure the security of the packets.

Network connectivity is an important performance metric to indicate the quality of the network and the user's satisfaction [8]. Network connectivity has been studied a lot for conventional VANETs. The study in [9] developed a distributed connectivity improvement strategy to improve the connectivity of VANETs to a desired level while minimizing the energy consumption and signal confliction. The authors in [10] presented a new analytical framework for determining the connectivity requirements such as the minimum spatial node density and the minimum required transmission range for distributing traffic information in VANETs. It is observed that most of the studies focused on the connectivity of the VANETs. None of them has considered the relationship between the connectivity and the MAC protocol design. However, connectivity has direct influence on channel contention and vehicle communications since it might be difficult to transfer messages to other vehicles in the case of disconnections. The efficiency of channel access is also affected by the connectivity. Consequently, a connectivity-aware MAC protocol taking into account the connectivity and the corresponding number of active nodes in the network can optimize the system performance in a VANET.

Moreover, platooning has turned into an important topic in the research area of VANETs. A platoon is a train of vehicles composed of a leading vehicle and a number of followers travelling at highway speeds with only a few meters between them [11]. In a platoon, the leading vehicle (normally a truck) is driven by a human, while the followers either automatically maintain the velocity of the leading one, but their direction is still controlled by the driver, or follow the leading one in a fully automatic manner [12]. From the viewpoint of moving behavior and packet delivery, a platoon can be regarded as a special vehicle in VANETs rather than an ordinary vehicle or a simple combination of vehicles. Furthermore, we found that the connectivity probability will increase when there are platoons in the network [11]. The influence of the connectivity on the MAC design will be more complex, and interesting for a platoon-based VANET.

In this paper, we focus on the connectivity-aware MAC

Fig. 1. The platoon-based VANET model

protocol design for platoon-based VANETs. The major contributions of the paper are listed as follows.

- A connectivity-aware MAC protocol, with multi-channel features of the IEEE 802.11p/1609.4 standard, is designed for platoon-based VANETs.
- A multi-priority Markov model is derived for the MAC protocol to investigate the relationship between the connectivity probability and the system saturated throughput.
- The MAC protocol is enhanced with a multi-channel reservation scheme with the possibility to dynamically adjust the CCHI and SCHI for the improvement of the system throughput according to the current traffic status and network connectivity.

The rest of the paper is organized as follows. A platoon-based VANET model is derived in Section II. Section III analyzes the connectivity probability of VANETs. Section IV describes the details of the connectivity-aware MAC protocol together with theoretical analysis. Performance evaluation is presented in Section V. Section VI concludes the paper.

II. PLATOON-BASED VANET MODEL

The VANET model in this paper is considered as an unidirectional and uninterrupted one-way vehicle traffic highway. As shown in Fig.1, the VANET consists of N vehicles, which are randomly distributed along the highway segment with 2000m length. It is assumed that there are K ordinary vehicles and M platoons. Each platoon is regarded as a single vehicle in this context. In each platoon, platoon members are connected with each other and can communicate with their leading vehicle directly. All the platoon members firstly transmit their safety and non-safety packets to the leading vehicle, and then the leading vehicle on behalf of the platoon competes to access the CCH. Let p denote the ratio of the platoon in the network, which means the probability that a moving object on the highway segment is a platoon. We have

$$p = M/N = M/(K + M) \quad (1)$$

Then, we can find that the probability that a moving object on the highway segment is an ordinary vehicle is $1 - p$.

Let R_1 and R_2 , ($R_1 < R_2$), denote the transmission ranges of the ordinary vehicles and the platoon leaders, respectively. In addition, it is assumed that R_2 is large enough to cover all the platoon members in a platoon, and the length of a platoon is smaller than $R_2 - R_1$.

We consider the network scenario where the vehicles are distributed on the highway following a Poisson distribution

and all the vehicles are under the transmission coverage of a Road Side Unit (RSU). Let ρ be the traffic density in terms of vehicles per meter. Hence, the probability that k vehicles are found in a distance of x meters is expressed by

$$f(k, x) = \frac{(\rho x)^k e^{-\rho x}}{k!}, k \geq 0 \quad (2)$$

Let X represent the inter-vehicle distance between two consecutive vehicles. We can obtain the probability that the distance between two vehicles is smaller than x , which also means that there is at least one vehicle in the interval with length x . The probability is given by

$$\Pr\{X \leq x\} = h(x) = 1 - e^{-\rho x} \quad (3)$$

Then, we can find that X is independent identically distributed (*i.i.d*) and obeys an exponential distribution.

III. ANALYSIS OF THE CONNECTIVITY PROBABILITY

In Fig.1, let X_i ($i = 1, 2, \dots, N - 1$) represent the random variable denoting the inter-vehicle distance between two consecutive vehicles. In this scenario, the VANET will be connected if there is a path connecting any pair of vehicles. This means that the distance between any two consecutive vehicles should be smaller than the transmission range of the vehicles R , i.e., $X_i \leq R$. Let P_c be the connectivity probability of the VANET. Then, we have

$$P_c = \Pr\{X_1 \leq R, X_2 \leq R, \dots, X_{N-1} \leq R\} \quad (4)$$

Since X_i is *i.i.d* random variable, we have

$$\begin{aligned} P_c &= \prod_{i=1}^{N-1} \Pr\{X_i \leq R\} \\ &= \prod_{i=1}^{N-1} [(1 - p) * \Pr\{X_i \leq R_1\} + p * \Pr\{X_i \leq R_2\}] \end{aligned} \quad (5)$$

Formula (5) describes the relationship between the key parameters, i.e., the connectivity probability (P_c), the transmission range of the vehicles (R_1 and R_2), and the ratio of the platoon in the network (p). When the vehicles are distributed on the highway following a Poisson distribution, according to formula (3), the connectivity probability of the platoon-based VANET is given by

$$P_c = [(1 - p)(1 - e^{-\rho R_1}) + p(1 - e^{-\rho R_2})]^{N-1} \quad (6)$$

Based on (6), we have

$$p = \frac{1 - e^{-\rho R_1} - P_c^{\frac{1}{N-1}}}{e^{-\rho R_2} - e^{-\rho R_1}} \quad (7)$$

Then, according to formula (1), for a given total number of the vehicles (N), the number of platoons (M) and the number of ordinary vehicles (K) in the network can be derived. These two parameters can be used in the following MAC protocol design to get the optimal system performance.

IV. CONNECTIVITY-AWARE MAC PROTOCOL AND ANALYSIS

In the Connectivity-aware MAC protocol, based on the UTC channel access scheme, the CCHI is further divided into SAFETY Interval (SAFI), WSA Interval (WSAI) and ACK Interval (ACKI). As shown in Fig.2, for the reliability and low delay requirements of the safety packets, platoons and ordinary vehicles in the platoon-based VANET firstly broadcast safety packets during the SAFI at the beginning of the CCHI. Then, during the WSAI, vehicles that act as service providers contend to access the channel for broadcasting the WSA packets, piggybacked with service information, i.e., the channel identities of SCHs to be used and other information [3].

Furthermore, the WSAI is divided into several time slots, and service providers attempt to transmit WSA packets at the beginning of a time slots if the channel is idle. When the ACKI starts, vehicles having received the safety packets or being interested in the service announced by the WSA packets will respond with ACK packets sequentially. Besides, to avoid repeated response, if the foregoing nodes have responded to a certain safety packet or service provider, the latter nodes will not repeat the same response. For the sake of fairness, the order of the nodes sending ACK packets is randomly assigned in every ACKI. Through the interaction between the WSA packet and the corresponding ACK packet, a channel reservation mechanism is proposed and the transmission channel identities and the transmission time of the service data on SCHs will be determined. At the end of the CCHI, the vehicles that have made successful reservations will tune to the specific SCHs to perform service transmission without packet collision.

In our model, since all the WSA packets from platoon members should be delivered by its leading vehicle, the leading vehicle on behalf of the platoon must contend the wireless channel and broadcasts the WSA packets to other vehicles. From the viewpoint of fairness, we consider the WSA packets broadcasted by the Platoons (WSAP) should have higher priority than the WSA packets delivered by the Ordinary vehicles (WSAO). The numbers of the platoons and ordinary vehicles in the network can be found from formula (7) based on the network connectivity requirement. A multi-priority Markov model of the WSA packets is proposed to derive the relationship between the connectivity probability and the throughput and get the optimal system performance of the network according to the dynamic network status.

Fig.2 shows the framework of the connectivity-aware MAC protocol. In the protocol, the CCHI and the SCHI can be

Fig. 2. The framework of the connectivity-aware MAC protocol

adjusted dynamically according to the traffic conditions. Furthermore, the lengths of SAFI (T_{SAFI}) and ACKI (T_{ACKI}) are proportional to the total number of vehicles in the current network (N). The optimal length of the WSAI (T_{WSAI}) can also be got from the multi-priority Markov model of the WSA packets. Then, based on the locally collected information, each RSU periodically calculate the optimal duration of the CCHI ($T_{CCHI} = T_{SAFI} + T_{WSAI} + T_{ACKI}$) and SCHI (T_{SCHI}), and broadcasts a CA packet to the vehicles under its radio coverage. Finally, these vehicles will adjust the T_{CCHI} and T_{SCHI} accordingly. The optimization of the CCHI and SCHI is able to maximize the system throughput.

A. Analysis of the Markov Model

In order to optimize the length of the WSAI, a multi-priority Markov model is proposed by setting different values of the Arbitration Inter-Frame Space Number (AIFSN) of different priority WSA packets and formulating the backoff parameters. Then, according to the dynamic traffic condition, the optimal value of T_{WSAI} can be obtained towards the maximum throughput in a multi-priority network.

From Section III, it can be found that there are M platoons and K ordinary vehicles that will transmit WSA packets in the network to satisfy the current network connectivity requirement. We consider $AIFSN(WSAP) = 2$ and $AIFSN(WSAO) = 3$ in our model. Moreover, the model adopts the following assumptions. 1) the channels are ideal; 2) nodes are always in a saturated traffic condition, i.e., every node has WSA packets available after a successful reservation during the WSAI; 3) the transmission probability of packets and the collision probability are independent.

Let $s(i, t)$, $b(i, t)$ and $v(i, t)$ be the random variables at time slot t that represent the backoff stage, the value of the backoff timer, and the active state of the backoff procedure for a packet of class i ($i \in 1, 2$), corresponding to WSAP and WSAO, respectively. Let L_i be the maximum backoff stage for packets of class i , and $W_{i,m}$ be the Contention Window (CW) size of the m th backoff stage, where $s(i, t) = m$, ($0 \leq m \leq L_i$) and $b(i, t) \in (0, W_{i,m})$. We consider that the backoff procedure is in the freezing state when $v(i, t) = 0$, and the BC (Backoff Counter) remains unchanged. The state is active and the BC is subtracted by one at an idle slot when $v(i, t) = -1$. Then,

the three-dimensional process $\{s(i, t), b(i, t), v(i, t)\}$ can be modeled as a Markov chain with different states (i, j, k) .

Fig. 3. The Markov chain model of the WSAF transmission

Fig.3 shows the Markov chain of the WSAF, where the BC is subtracted one at each time slot, so $v(i, t) = -1$ at all time. Let p_1 denote the collision probability. The one-step transition probabilities are given by

$$\begin{cases} Pr\{(j+1, k, -1) | (j, -1, -1)\} = p_1/W_{1,j+1} + 1, \\ \quad 0 \leq j \leq L_1 - 1, 0 \leq k \leq W_{1,j+1}; \\ Pr\{(j, k-1, -1) | (j, k, -1)\} = 1, \\ \quad 0 \leq j \leq L_1, 0 \leq k \leq W_{1,j}; \\ Pr\{(0, k, -1) | (j, -1, -1)\} = (1-p_1)/(W_{1,0} + 1), \\ \quad 0 \leq j \leq L_1 - 1, 0 \leq k \leq W_{1,0}; \\ Pr\{(0, k, -1) | (L_1, -1, -1)\} = 1/(W_{1,0} + 1), \\ \quad 0 \leq j \leq L_1, 0 \leq k \leq W_{1,0}. \end{cases} \quad (8)$$

Fig. 4. The Markov chain model of the WSAO transmission

The Markov chain of the WSAO is shown in Fig.4, where the backoff procedure will experience the freezing state

$(j, k, 0)$ with unchanged BC and $v(i, t) = 0$. Let p_2 , $p_{2,idle}$ and $p_{2,0}$ be the probability that a WSAO was not successfully transmitted, and the probabilities that a WSAO encounters an idle slot or a busy slot, respectively. The one-step transition probabilities of WSAO are expressed as formula (9).

$$\begin{cases} Pr\{(j+1, k, 0) | (j, -1, -1)\} = p_2/(W_{2,j+1} + 1), \\ \quad 0 \leq j \leq L_2 - 1, 0 \leq k \leq W_{2,j+1}; \\ Pr\{(j, k-1, -1) | (j, k, -1)\} = p_{2,idle}, \\ \quad 0 \leq j \leq L_2, 0 \leq k \leq W_{2,j-1}; \\ Pr\{(j, k, 0) | (j, k, -1)\} = 1 - p_{2,idle}, \\ \quad 0 \leq j \leq L_2, 0 \leq k \leq W_{2,j-1}; \\ Pr\{(j, k, 0) | (j, k, 0)\} = p_{2,0}, \\ \quad 0 < j \leq L_2, 0 \leq k \leq W_{2,j-1}; \\ Pr\{(j, k-1, -1) | (j, k, 0)\} = 1 - p_{2,0}, \\ \quad 0 < j \leq L_2, 0 \leq k \leq W_{2,j-1}; \\ Pr\{(0, k, 0) | (j, -1, -1)\} = (1-p_2)/(W_{2,0} + 1), \\ \quad 0 \leq j \leq L_2 - 1, 0 \leq k \leq W_{2,0}; \\ Pr\{(0, k, -1) | (L_2, -1, -1)\} = 1/(W_{2,0} + 1), \\ \quad 0 \leq j \leq L_2, 0 \leq k \leq W_{2,0}. \end{cases} \quad (9)$$

Then, by solving the transition equations shown in formula (8) and formula (9) with the normalization condition of the two Markov chains, the steady-state transmission probability of WSAF (p_i) and the steady-state transmission probability of WSAO (p_j) can be given by

$$\begin{cases} p_i = \frac{1-p_1^{L_1+1}}{\sum_{j=0}^{L_1} w_{1,j}/2 * p_1^j (1-p_1) + 2(1-p_1^{L_1+1})} \\ p_j = \frac{1-p_1^{L_2+1}}{\sum_{j=0}^{L_2} w_{2,j}/2 * p_2^j (1-p_2) + 1-p_2^{L_2+1}} \end{cases} \quad (10)$$

B. The optimal value of the CCHI and SCHI

It is clear that the maximum system throughput can be obtained when the average duration of the idle state $E[idle]$ equals the average duration of the busy state $E[coll]$ in a virtual transmission procedure on the wireless channel with multi-priority packets [13]. That is

$$E[idle] = E[coll] \Rightarrow p_{idle} * T_{idle} = p_{coll} * T_{coll}, \quad (11)$$

where p_{idle} , p_{coll} , T_{idle} and T_{coll} denote the probability that the channel is idle, the probability that a channel collision occurs, the duration of an idle slot and the duration of a packet collision on CCH, respectively. Let p_{busy} and p_{succ} denote the probability that the channel is busy and the probability that the packets are successfully transmitted and $p_{coll} = p_{busy} - p_{succ}$. Then, we have

$$\begin{cases} p_1 &= 1 - (1-p_i)^{M-1} * (1-p_j)^K \\ p_2 &= 1 - (1-p_i)^M * (1-p_j)^{K-1} \\ p_{idle} &= (1-p_i)^{M-1} * (1-p_j)^{K-1} \\ p_{busy} &= 1 - p_{idle} = 1 - (1-p_i)^{M-1} * (1-p_j)^{K-1} \\ p_{succ} &= M * p_i * (1-p_i)^{M-1} * (1-p_j)^K \\ &\quad + K * p_j * (1-p_i)^M * (1-p_j)^{K-1} \end{cases} \quad (12)$$

Let T_{SAF_pkt} , T_{WSA_pkt} , T_{ACK_pkt} , and T_{SIFS} denote the time period for transmitting a safety packet, transmitting a WSA packet, transmitting an ACK packet, and Short Inter-frame Space (SIFS), respectively. For simplicity, we adopt T_{coll} as the largest collision time duration when the last bit of one WSA packet conflicts with the first bit of the successive WSA packet. Then T_{idle} , T_{coll} and T_{succ} can be expressed by

$$\begin{cases} T_{idle} = aSlotTime \\ T_{coll} = 2 * T_{WSA_pkt} + T_{SIFS} \\ T_{succ} = T_{WSA_pkt} + T_{SIFS} \end{cases} \quad (13)$$

Consequently, based on formula (10)-(13), the optimal value of the transmission probabilities p_i and p_j can be solved.

Let T denote the time interval between two consecutive successful transmissions of WSA packets in WSAI. Then, the average value of T is given by

$$E[T] = T_{idle}/p_{succ} + p_{coll} * T_{coll}/p_{succ} + T_{succ} \quad (14)$$

Let Q , and $E[serv]$ denote the number of WSA packets that successfully reserve the SCH channels, and the average successful transmission duration of a service packet on the SCHs, respectively. Then, we have

$$\begin{cases} T_{CCHI} + T_{SCH} = 100 \\ T_{CCHI} = T_{SAFI} + T_{WSAI} + T_{ACKI} \\ T_{SCH} = Q * E[serv]/6 \\ T_{WSAI} = Q * E[T] \\ T_{SAFI} = N_{SAF} * (T_{SAF_pkt} + T_{SIFS}) \\ T_{ACKI} = N_{ACK} * (T_{ACK_pkt} + T_{SIFS}) \end{cases}, \quad (15)$$

where N_{SAF} and N_{ACK} are the number of nodes sending safety packets and the number of nodes sending ACK packets, respectively. Both of them are assumed to be proportional to the total number of nodes in the network (N).

Based on formula (11)-(15), the optimal length of the WSAI (T_{WSAI}) can be derived, and accordingly, the optimal length of the CCHI and the SCHI are achieved. Moreover, let P_{WSA_pkt} denote the payload of the WSA packets. Then we can get the throughput of the system S on the CCH during WSAI as

$$\begin{cases} Q = T_{WSAI}/E[X] \\ S = Q * P_{WSA_pkt} \end{cases} \quad (16)$$

V. PERFORMANCE EVALUATION

In this section, the performance of the proposed connectivity-aware MAC protocol is evaluated by both analytical results and simulations via the simulator NS-2.34. The analytical results of the connectivity probability and the optimal intervals according to the current network condition are presented. Moreover, the theoretical analysis and simulation results of the throughput are illustrated. TABLE I lists the system parameters used in both the theoretical analysis and the simulations.

Fig.5 shows the connectivity probability of the network with different numbers of ordinary vehicles (K) when $R_1 = 200m$

TABLE I
SIMULATION PARAMETERS

Parameters	Default value
Data rate of each channel	6 Mbps
L_1	32
Slot time	20 us
SIFS	10 us
DIFS	50 us
PHY header	192 bits
MAC header	256 bits
Safety packet data length	80 bits
WSA packet data length	160 bits
ACK packet data length	112 bits
Service packet data length	1000 bytes
Highway segment length	2000 m

and $R_2 = 800m$. It is clear that the connectivity probability increases with the increase of either the number of platoons (M) or the number of ordinary vehicles (K). Moreover, the network will nearly be fully connected ($P_c = 1$) when the number of vehicles is larger than 80.

Fig. 5. The connectivity probability of the network

Fig.6 shows the optimal intervals in terms of different number of vehicles corresponding to the connectivity probability shown in Fig.5. It can be found that our proposed MAC protocol can provide sufficient transmission opportunities for safety packets by providing larger SAFI, ACKI and CCHI as the number of vehicles increases. Moreover, the WSAI and SCHI decrease with the increase of the number of nodes, which means that intervals for service reservations on the CCH and service packet transmissions on the SCHs decrease to ensure the sufficient transmission time for safety information. Therefore, under different traffic loads of the network, the proposed MAC protocol is able to adjust the channel intervals to provide the proper bandwidth.

We also present simulation results that confirm the accuracy of the analysis. Fig.7 shows the system throughput on the CCH during WSAI in terms of different numbers of ordinary

Fig. 6. The optimal channel intervals ($M = 10$)

Fig. 7. The throughput on the CCH during WSAI

vehicles. It is clear that the simulation results match well with the analytical results. When the number of ordinary vehicles increases, the connectivity probability will increase as shown in Fig.5. It can be found that the throughput increases with the connectivity probability. However, when the number of ordinary vehicles is larger than 60, the throughput will decrease, whereas the connectivity probability increases. This is because the channel contention is aggravated by numerous nodes in the network. Moreover, when there are more platoons in the network, the throughput will be improved since the connectivity probability of the network increases. These results can help to control the traffic on the highway to reach satisfied network connectivity and improve the whole system saturated throughput.

VI. CONCLUSION

In this paper, the relationship between the connectivity probability and the number of vehicles has been explored for platoon-based VANETs with different traffic densities. This relationship is adopted in the design of the MAC protocol

to ensure the priority packet transmissions for platoons while enhancing the network performance. Furthermore, a multi-priority Markov model is derived to investigate the change of the system throughput with the connectivity probability. Theoretical analysis and simulation results show that the throughput increases with the connectivity probability, however when the connectivity probability is large, the throughput will decrease due to numerous channel contention. Moreover, based on the road traffic density, the optimal channel intervals can be automatically chosen towards the improvement of network throughput by applying a multi-channel reservation scheme.

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