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Joint Power and Contention Window Adaptive Control for Reliable and Efficient Broadcast of Safety-related Services in VANETs

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Abstract. Vehicular Ad Hoc Networks (VANETs) employ broadcasting way to support safety-related services, which have strict performance requirements, such as high reliability, low delay and scalability, etc. However, due to ever-changing vehicle density and the stringent requirements of safety applications, efficient and effective broadcasting of safety messages faces many challenges. In this paper, we propose a joint transmission Power and Contention Window (CW) size Adaptive Control (PCAC) scheme to improve the performance of safety-related services in VANETs. The transmission power dynamically adapts according to the local vehicle density estimation to solve conflict between transmission range and interference. The zero CW and minislot combined with based-receiver implicit acknowledgement mechanism are used, and the preemptive priority and reliability transmission of emergency messages are thus ensured. Coarse adjustment combined with fine adjustment approach is adopted to tune CW size of basic safety messages, which is based on the collision rate estimated from packets received from neighbor nodes, and thus the system throughput is improved. The PCAC scheme works in a distributed way and without extra communication overhead. Extensive simulation results demonstrate that the proposed PCAC scheme can significantly improve the performance of the safety-related services in terms of delay, packet delivery ratio and throughput.

Keywords: broadcast, Contention Window (CW), minislot, safety-related services, transmission power adaptation, Vehicular Ad Hoc Networks (VANETs)

1 Introduction

Vehicular Ad Hoc Networks (VANETs) are dedicated for Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications, and their goals are to improve the road safety. VANETs are a major part of Intelligent Transportation System (ITS), which enable moving vehicles to quickly and accurately collect real-time road traffic information and notify neighboring vehicles of potential dangerous situations [1-2]. It is worth noting that most safety applications work in broadcast fashions. Therefore, safety information can be beneficial to all vehicles around a sender. In order to provide traffic safety, vehicular network uses emergency messages (event-driven) and Basic Safety Messages (BSMs) (periodic) [3]. On the one hand, each vehicle periodically broadcasts BSMs including Media Access Control (MAC) address, speed, position, direction and other relevant information to inform its neighbors. These BSMs can be used to perform cooperation collision avoidance in the Cooperative Vehicle Safety Systems (CVSSs) [4] or Cooperative Active Safety Systems (CASSs) [5-6]. On the other hand, dangerous situations like car accidents or emergency brake will trigger emergency messages to be disseminated, which have highest priorities.

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However, broadcasting safety-related messages to certain regions of interest or particular regions for improving road safety faces many challenges.

Firstly, it is widely known that, due to high-speed mobility, V2V and V2I communication links tend to be short lived. Moreover, rapid changes in traffic density from sparse to heavy may incur the shared channel promptly to be saturated and congested, and thus ***scalability*** issues arise. Secondly, in VANETs, the emergency messages such as traffic incident and emergency brake need ***timely*** and ***reliably*** to be transmitted to neighboring vehicles, so that the drivers can make decisions. Thirdly, in CVSSs or CASSs, accurate tracking is the basis which depends on BSMs' Information Dissemination Rate (IDR), also called broadcast throughput [5]. Therefore, in safety-related applications of VANETs, ***scalability***, low delay***, high reliability*** and high throughput (***efficient***) are the most critical factors.

One strategy increasing duration of communication links in VANETs is by increasing the transmission power to improve the transmission range. However, increasing the transmission power may generate high levels of disruptive interference and high-network ***overhead*** under dense traffic conditions. It is a critical requirement that dynamically adjusting power according to changing traffic density.

To achieve ***timely*** and ***reliable*** transmission of emergency messages, IEEE 802.11p [7] standard for VANETs exploits Enhanced Distributed Channel Access (EDCA) 802.11e [8] to support Quality of Service (QoS) for different applications. According to 802.11e specification that different priority levels can be assigned to various traffic-related messages according to their criticalities for the vehicle's safety. Differently priorities are identified by channel access parameters, including Contention Window (CW) size and Arbitration Inter Frame Space (AIFS). However, current IEEE 802.11p MAC is not able to provide predictable QoS for high-priority safety services with the proposed EDCA [9]. Under the emergency situations, considering the driver reaction time to traffic warning signals can be on the order of 700 ms or longer, the emergency messages must be send out in less than 500 ms [9-10]. According to the requirement of ***reliability***, the emergency messages should have a high Packet Delivery Ratio (PDR) [11]. Thus, the none zero CW size and without Acknowledgment (ACK) mechanism (due to broadcast way) cannot meet ***timely*** and strictly ***reliability*** requirements of emergency messages, especially in high traffic density conditions.

In CVSSs or CASSs, BSMs are transmitted on a shared channel in broadcast way, and they can lead to the high probabilities of transmission collision when multiple nodes within the same communication range are simultaneously trying to broadcast. Moreover, due to no collision detection frame such as Clear To Send (CTS) and ACK [12] for the broadcast service, when collisions happen among BSMs, the CW sizes are not doubled. In fact, on the one hand, ideal CW value should be large enough, and thus the probabilities that multiple nodes derive the same number of time slots are sufficiently small. On the other hand, the CW value should be small enough to avoid excessive delay [13]. Therefore, it is very necessary to dynamically adjust the CW size of BSMs according to changes in vehicle density.

Based on the problem evaluation, we are motivated to propose a flexible approach to control the transmission power and CW size of the safety-related message. We classify the safety-related messages in VANETs into two categories: emergency messages (event-driven) and Basic Safety Messages (BSMs) (periodic). The emergency messages occur only occasionally, but they must meet the requirement of quick and guaranteed delivery. On the other hand, in CVSSs or CASSs, the vehicle nodes periodically broadcast BSMs to the neighboring nodes to improve the tracking accuracy, higher IDR or broadcast throughput are thus needed. Therefore, a joint Power and CW size Adaptive Control (PCAC) scheme is proposed. The PCAC scheme consists of two stages: Stage one is transmission power adaptation, which is used to adjust the transmission power according to estimated vehicle density; Stage two is CW size adaptation. At stage two, each vehicle adopts zero CW and minislot to transmit emergency messages, and dynamically adjusts BSMs' CW according to its statistic collision rate. The aims of proposed PCAC scheme are to improve ***scalable, timely, reliable and efficient*** transmission for safety-related messages under different network conditions. The contributions of this paper are three folds:

(1) First, a scheme of joint adjustment transmission power and CW size is proposed to solve conflict between transmission range and interference, conflict between throughput and channel overload, and thus ***scalable*** data transmission can be ensured.

(2) Second, a preemptive priority and a receiver-based implicit ACK mechanism are proposed to improve the ***timely*** and ***reliable*** transmission of emergency messages. A coarse adjustment combined fine adjustment method is presented to improve the BSMs throughput.

(3) Third, PCAC scheme works in a distributed way and has no extra communication ***overhead***.

The rest of this paper is organized as follows: Section 2 reviews related works. Section 3 describes the proposed PCAC scheme in detail. Section 4 an adaptive algorithm is described. Simulation evaluation is given in Section 5. Finally, Section 6 concludes this paper.

2 Related Works

There are an increasing number of researchers from both academic and industrial communities tackling the challenges as discussed in Section 1. To ensure the performance of active safety-related services, the authors in [14] proposed a Distributed Fair transmit Power Adjustment algorithm for VANETs (D-FPAV) to reduce packet level interference and improve VANETs performance. D-FPAV maintains the beacon load to meet the timely requirement of the emergency messages. In order to ensure the maximum network connectivity and the fairness among beacon transmission, based on a multiple regression equation and a recursive Kalman filter, Mo et al. [15] propose a channel load forecasting algorithm KF-BCLF. In KFBCLF, based on the forecasted channel load, each node pre-adjusts its power to make the channel load under a predefined range, and thus the robustness and stability of beacon dissemination are improved. However this algorithm increases the storage space and computational intensity requirement. An algorithm which utilizes periodic beacon to piggyback the required data for power control is proposed in [16]. The nodes adjust transmission power to reduce the probabilities of message loss according to the piggybacked information from the feedback beacon. The above three schemes all need information from neighboring nodes, and thus the convergence of systems is slow and the performance is affected by the communication quality. The study in [17] only observes its own speed to estimate local vehicle traffic density, and based on the estimation density, the vehicle changes transmission power to adjust the transmission range. Therefore, this scheme can maintain the link life time between the high speed vehicles. Finally, the connectivity issues in sparse and dense traffic environment are solved. However, the vehicle density estimation in [17] is based solely on the vehicle's movement and may not always give a good estimation [18], thus the network connectivity may not always give good performance. Based on fuzzy logic, the work in [19] proposes a model namely the BRAIN-F (Beacon Rate AdaptIoN based on Fuzzy logic), to adjust the beacon transmission rate. The BRAIN-F depends on three parameters including traffic density, vehicle status and location status, and it can reduce the channel congestion and increase the information accuracy. In order to improve the broadcast reception rate of beacon messages, the work [20] proposes a backoff algorithm to adjust the minimum CW size. The backoff algorithm is based on the differential size between the number of expiration beacons and preset threshold. However, both the work in [19] and [20] only consider beacon messages without considering different requirements of two kinds of messages (emergency messages and BSMs) with different priorities. Moreover, both the work in [19] and [20] have higher computation complexity. In [21], the CW is dynamically varied according to the times (deadlines), which the vehicles are going to leave the Road Side Unit (RSU) range, and the urgency level of the message. The CW for high speed vehicle and vehicle with emergency data is varied slowly, which gives quick access the channel. However, the scheme in work [21] is only suitable for working in scenarios with RSU, and it may not work well in some remote areas without RSU. In addition, the scheme in [21] has no acknowledgement mechanism, and the reliable transmission of emergency messages cannot be guaranteed. The work [22] presents a self-adaptive backoff algorithm, which selects a suitable CW according to transmission time and network busy degree. The simulation results have verified that the proposed algorithm can decrease the packet lost rate. However, the algorithm employs a Request To Send (RTS)/CTS mode, which incurs an extra communication overhead, and has thus higher transmission delay.

In VANETs, the safety-related applications need to satisfy strict performance requirements such as low delay, high reliability and scalability under different network conditions [9, 23-27]. To achieve these goals, three key parameters can be adjusted: transmission power of the physical layer, CW of the MAC layer and beacon generation rate of the application layer [18, 28-29], so it is a cross-layer approach. The study in [5] proposes a joint rate-power control scheme to broadcast itself information for neighboring tracking, and it adjusts transmission power and transmission rate according to the tracking accuracy to increase the performance of CVSSs. Rawat et al. [18] proposed a joint power and the size of CW adjustment scheme to improve VANETs performance. This scheme changes the power and CW size according to the locale vehicle density estimation and the instantaneous collision rate. Simulation results demonstrated that the scheme in [18] can significantly improve the throughput and decrease the end-to-end delay. However, transmission power and CW adjustment are hard to meet the safety requirement [27]. This is because that the paper [18] assigns nonzero CW for emergency message and the emergency message still needs backoff, and thus this scheme cannot guarantee the transmission delay of emergency messages within a determine duration. The detailed comparison of different schemes is given in Table 1.

Table 1. Comparison of different schemes

Scheme	Emergency messages/BSMs	TPA/TRA	Zero-CW for emergency messages	CA/FA CW for BSMs	ACK mechanism	ECO needed [1]	Complexity [2]	PDR calculated	PAD calculated	Throughput calculated	Year
Torrent-Moreno et al. [14]	✓/✓	✓/x	-	-/-	✓	✓	higher	✓	✓	x	2009
Mo et al. [15]	x/✓	✓/x	-	-/-	x	✓	higher	x	x	x	2015
Guan et al. [16]	x/✓	✓/x	-	-	✓	x	higher	✓	x	x	2007
Soleymani et al. [19]	x/✓	x/✓	-	-/-	x	x	higher	✓	x	x	2016
Zhao et al. [20]	x/✓	x/x	x	✓/x	x	x	higher	✓	✓	x	2016
Hussain et al. [21]	✓/✓	x/x	x	✓/✓	x	x	lower	x	x	✓	2017
Zhang et al. [22]	✓/✓	x/x	x	✓/✓	✓	✓	higher	✓	✓	✓	2018
Fallah et al. [5]	x/✓	✓/✓	-	-/-	x	✓	higher	x	x	✓	2011
Rawat et al. [18]	✓/✓	✓/x	x	✓/x	✓	x	lower	x	✓	✓	2011
Proposed scheme	✓/✓	✓/x	✓	✓/✓	✓	x	lower	✓	✓	✓	2018

Note. TPA/TRA: Transmission Power Adjustment/Transmission Rate Adjustment, CA/FA: Coarse Adjustment/ Fine Adjustment, ECO: Extra Communication Overhead, PDR: Packet Delivery Ratio, PAD: Packet Average Delay.

3 Transmission Power and Contention Window Adaptation Control Mechanism for Enhancing Performance of Safety-related Applications

We assume that each vehicle is equipped with On Board Unit (OBU) for V2V and V2I communications. The transmissions of safety-related services are on the shared control channel. Each vehicle knows its location, speed and moving direction through an installed Global Positioning System (GPS). Vehicles broadcast two safety related messages: emergency messages and BSMs. The emergency messages usually contain notifications such as accident, emergency brake and road hazards. While the BSMs are typically for cooperative awareness goals such as cooperative collision avoidance and vehicle changing lanes, etc.

In this paper, our objective is to prevent an oversaturation of the channel and improve the performance of emergency message and BSM transmission under vehicular environments. Our focus is to achieve the following objectives: scalability, timeliness, reliability, efficient and minimized overhead.

Firstly, to achieve ***scalability*** objective, our approach addresses congestion problem of control channel under high traffic density environments. Secondly, for the ***timeliness*** and ***reliability*** objective, our specific goal is to ensure the emergency messages to reach full one-hop network coverage under short delay. Thirdly, we utilize coarse adjustment integrates with fine adjustment method to improve ***throughput*** of BSMs, and ***efficient*** goal is thus achieved. Finally, ***minimized overhead*** objective, which means to adaptively adjust transmission power and CW size without any extra communication ***overhead***.

The way to achieve above objectives includes: (1) A transmission power adaptation method is used to mitigate the adverse effects of high-transmission power under a high density environment, while under a low density environment, to increase the duration of the communication link. (2) A preemptive priority and a dynamic receiver oriented implicit ACK method are proposed to enhance the ***timely*** and ***reliable*** transmission of emergency messages. (3) Coarse adjustment combined with fine adjustment way is utilized to adaptively adjust BSMs' CW size to improve ***throughput*** based on collision rate estimated from packets received from neighboring nodes. (4) Local vehicle density estimation, implicit ACK and packets collision rate estimation are implemented by normal broadcast of emergency messages or BSMs without additional communication ***overhead***.

[1] ECO metric has a negative effect on system performance.

[2] Complexity metric includes time complexity or space complexity.

3.1 Transmission Power Adaptation

Rawat et al. [18] proposed a joint dynamic adjustment of transmission power and CW size. According to the estimated local vehicle density, the Transmission Range (TR) can be calculated by following expression derived from [17]. Note, the transmission range value refers to the transmission radius.

$$TR = \min\{L(1-K), \sqrt{\frac{L\ln L}{K}} + \alpha L\}. \quad \textbf{(1)}$$

where

- α is a constant depends on the traffic flow theory [17].
- L is the length of the road segment over which the vehicle estimates its initial local vehicle density.
- K is the local traffic density for a given vehicle, and is calculated as the ratio $K = \frac{AN}{TN}$ of the Actual Number (*AN*) of vehicles on the road within its current transmission range over the Total Number *(TN)* of vehicles that can be accommodated on the road for current transmission range [18].

Based on the value which is obtained using Equation (1), TR can be mapped to a real transmission power value. By extensive simulations of basic wireless propagation models for different VANETs environments. A lookup table in Table 2 which is different from the table in [18] is given. Each node can use Table 2 to obtain power values of the different transmission range. As the lookup table approach is without computations, thus it is faster.

Since the above approach [18] does not introduce significant network ***overhead*** and is without computations, and it is thus a faster method. In this paper, we use it to adjust the transmission power based on the estimated number of the neighboring nodes.

Simply increasing power will just make the channel conditions worse and will not contribute to the original goal of improving road traffic safety [14]. To improve the ***timely***, ***reliable*** and ***efficient*** transmissions of safety-related messages under various scenarios, especially in high traffic density, the PCAC scheme joints transmission power, preemptive priority and CW adaptive mechanism to transmit the safety-related messages.

Table 2. Lookup table for transmission power corresponding to a given transmission range

Transmission Range TR (m)	Transmission Power (dBm)
0-19	-20
20-89	-7
90-199	4
200-299	11
300-399	16
400-509	20
510-609	23
610-719	26
720-819	28
820-909	30
910-1000	32
>1000	N/A in DSRC

Note. DSCR: Dedicated Short Range Communications.

3.2 Contention Window Adjustment Mechanism

There are two categories of safety-related messages in VANETs: emergency messages and BSMs. Emergency messages are event-driven messages which include vehicle crashes and emergency brake, etc, and their communications only occasionally happen but must meet the requirements of quick and reliable delivery [1-2]. BSMs include vehicle MAC address, position, and direction are essential for collision avoidance, cooperative collision warning, etc, and require high throughput. Therefore, for these two different messages, we propose two CW adjustment methods: preemptive priority and receiver-oriented implicit ACK method for emergency messages, coarse adjustment combining with fine adjustment method of CW size for BSMs.

3.2.1 Preemptive Priority and Receiver-Oriented ACK for Emergency Messages

The IEEE 802.11p employs prioritized EDCA protocol to provide differentiated access for four Access Categories (ACs) by a set of distinct channel access parameters, including AIFS and CW range. The highest priority is given to emergency messages and we employ a preemptive priority setting approach to transmit these messages. Zero CW size and minislot in Distributed Inter Frame Space (DIFS) are for the emergency message transmission. Nonzero CW size is for the periodic BSMs service. By utilizing the concept of minislot in [9, 30-32], we divide a DIFS interval into a number of minislots, and the preemptive priority transmissions of the emergency messages can be thus ensured.

- **minislot:** the length of a minislot is set l_m :

$$l_m = 2\varphi + t_{switch}. \tag{2}$$

where φ is the maximum signal propagation delay in the transmission range *TR*, and t_{switch} is the radio switch delay between the reception mode and the transmission mode.

- **mini-CW:** mini-CW is used to avoid emergency message collisions when multiple senders try to access the channel simultaneously for transmitting emergency messages, and it is represented as cw_m :

$$cw_m = \left\lfloor \frac{T_{DIFS}}{l_m} \right\rfloor. \tag{3}$$

where T_{DIFS} and $\lfloor \cdot \rfloor$ denotes a DIFS duration and a floor function, respectively.

Once a node with an emergency message wants to transmit, when it senses channel idle for l_m, and then it random chooses a waiting time t_m from [0, cw_m−1], that is $l_m \le t_m \le T_{DIFS}$. A node with zero backoff window size will immediately access the channel once the message is ready to transmit. This mechanism ensures that the nodes with emergency messages can access the channel before the nodes with BSMs. This is because even if the backoff timer of the node with BSMs is zero, the node still has to wait for T_{DIFS} before dissemination. On the other hand, the mechanism adopting minislot within DIFS can reduce access channel time for emergency messages, and thus end-to-end delay can be reduced. In addition, the minislot mechanism can reduce the possible collisions caused by simultaneous transmissions of the emergency messages. The minislot technology can coexist with the DIFS in the current IEEE 802.11p [9, 30]. We can find that $t_m \le T_{DIFS} \le T_{AIFS[AC]}$, given $T_{DIFS} = T_{SIFS} + 2\delta$ and $T_{AIFS[AC]} = T_{SIFS} + AIFSN[AC] \cdot \delta$, $AIFSN[AC] \ge 2$, where T_{SIFS}, $T_{AIFS[AC]}$, $AIFSN[AC]$ and δ denote the duration of Short Inter Frame Space (SIFS), the duration of AIFS for AC, AIFS number for AC and a time slot, respectively. Therefore, the preemptive priority mechanism can ensure the transmission delay of emergency messages is lower than that of BSMs, and the real-time transmissions of emergency messages can thus be guaranteed.

According to the IEEE 802.11p [7], the vehicles broadcast safety messages to the surrounding vehicles without RTS/CTS handshake or ACK. In this case, the senders cannot ensure the successful transmission of the safety messages. The reliable transmission of safety-related messages, especially emergency messages, is crucial for VANETs. However, adverse VANETs environments such as high mobility and fading channel can further reduce the successful transmission probabilities of emergency messages, and it becomes necessary to design an effective ACK scheme to perform the reliable transmission of the emergency messages and to help to enhance PDR.

We propose receiver-oriented implicit ACK mechanism to overcome the above advert factors. In VANETs, vehicles periodically broadcast BSMs to their one-hop neighboring, which include vehicle node's MAC address, direction, speed and position. By this information, nodes can easily calculate the distance from the sender. On the other hand, on the headers of both emergency message and BSM contain 12-bit sequence number [8], thus, each node can identify which is the newly generated packet and which is the copy of the broadcasted packet. Once a vehicle sends an emergency message, the neighbor vehicles receiving this message will contend to forward it. A distributed way is employed to select forwarding node from neighboring nodes. The forwarding node selection follows two metrics: distance from the sender and Received Signal Strength Indication (RSSI). Through received broadcast packets, neighboring nodes calculate the distance with the sender and know the received signal strength.

Due to the remote node potentially covering a wider area and higher RSSI meaning the emergency packets can be successfully decoded. Let t_{AD} denote an Accessing Delay (AD) timer value, we have

$$t_{AD} = T_{\max}(\omega \cdot (1 - \frac{d}{TR}) + (1-\omega) \cdot (1 - \frac{P_{Thresh}}{P_r})). \quad \textbf{(4)}$$

where d is the distance between the node and the sender, TR is the communication range of the sender in Equation (1), P_{Thresh} is the reception threshold, P_r is the received signal power, ω ($\omega \in$ [0, 1]) is a weight factor and T_{max} is the maximum AD interval allowed. The value of P_{Thresh} is based on received power, and the packet cannot be successfully decoded when the received power is lower than this value. The weight factor represents the preference for distance and received signal power. In the simulations, through trial and error, we set this value to 0.7. Normally, T_{max} is less than the lifetime of an emergency message. All vehicles that have successfully received the message will trigger the AD timer in term of Equation (4). The one whose timer is due first forwards the received emergency packet after a short waiting time t_m. In other word, when the sender in a specified time received the forwarding repetition of the emergency packet, it considers this repetition as an implicit ACK to indicate that its emergency packet is successfully received by its neighboring vehicles. Otherwise, the sender will retransmit emergency packet if the lifetime of the packet has yet not to expire. The implicit ACK mechanism has not extra communication ***overhead***, and it can alleviate adverse influence due to a collision caused by the hidden terminals and / or an erroneous channel. Therefore, the successful probabilities of dissemination of emergency messages can be greatly improved, and the reliable transmission of emergency messages can be guaranteed.

In PCAC scheme, when an emergency situation occurs, the multiple vehicles might send out their emergency messages for the same event, leading to concurrent transmissions. Although the concurrent transmissions can be alleviated by the proposed minislot with zero CW mechanism, the collisions still occur due to the limited cw_m, especially under high vehicle density environment. However, the proposed receiver-oriented implicit ACK mechanism can further mitigate this adverse effect. Since when a sender cannot receive the implicit ACK in a specified time, it will retransmit the emergency message in a relatively short period of time (in a T_{DIFS}). Therefore, the concern of collisions caused by both concurrent transmission of emergency messages and minislot with zero CW mechanism should not be severe.

3.2.2 Contention Windows Size Adaptation for BSMs

BSMs are dedicated to cooperative awareness, and thus the throughput is a crucial performance metric. As BSMs are periodically generated and transmitted by all the vehicles in VANETs, they account for most of the network traffic [33]. As the vehicle density increases, the growing number of BSMs simultaneous transmissions incurs strong signal interference and frequent packet collisions, and thus a long time for accessing control channel is necessary, which further degrades the throughput. On the contrary, in a light density vehicular environment, each vehicle has faster speed, and a long period of time without awareness the other neighboring vehicles is very dangerous. Therefore, the fixed CW is ***inefficient***. To improve the throughput, the dynamic adaptation CW size according to the network state is essential. In our propose scheme, the CW size of BSM may either increase or decrease, the regulating mechanism includes: coarse adjustment and fine adjustment.

The local state of network is determined by calculating collision rate as in [34]. In a given certain time, according to received packets, each node utilizes the records of sequence numbers of the individual vehicles to find the lost sequence numbers of each node, and thus the collision rate or the percentage of lost frames is calculated. Based on these statistics, each vehicle can determine the traffic condition and uses it to adjust CW size. The regulating mechanism integrates the fine adjustment into coarse adjustment. When the collision rate is very high ($p > \eta_2$) or very low ($p < \eta_4$), the CW is doubled or is reduced by half, where p denotes the packet collision rate. Thus, the nodes can rapid alleviate channel congestion condition and decrease packets collision, or reduce delay and improve the throughput. When the channel contention is moderate, the method of linear increment or a linear gradient is adopted, as illustrated in Algorithm 1.

Algorithm 1. To set vehicle's parameters according to the local vehicle density and the network conditions

```
Initial setup
   TR_c ← R_max
   α ← 0.25
   W_bc ← W_min
for every T s do
      Stage 1: Transmission power adaptation;
        Estimate the local vehicle density K;
        if K < η_1 or emergency message then
           TR_c ← R_max ;
        else
           Calculate TR_c using Equation (1);
        end
        Assign the suitable transmission power corresponding to calculated
        transmission range TR_c using look up Table 2.
        Stage 2: CW size adaptation
          // Emergency messages transmission.
        if sender has emergency message then
           Adopt zero CW and minislot to send by using the approach mentioned
           in section 3.2.1;
           Relay node forwards the repetition of the emergency message
           according cording to Equation (4) as implicit ACK for sender;
           end
        if (the sender not received implicit ACK) and (the lifetime of
            emergency message is not due) then
           The sender rebroadcast emergency message;
        end
           // CW size adaptation for BSMs.
        If p > η_2 then
           W_bc ← min(2W_bc; W_max) ;
           if η_3 < p ≤ η_2 then
              W_bc ← min(W_bc · (1+β), W_max)        β ∈ [0,1] ;
              if η_4 ≤ p ≤ η_3 then
                 W_bc ← max(W_min, W_bc · (1−γ))      γ ∈ [0,1]
              else
                 W_bc ← max(W_min, W_bc / 2) ;
              end
          end
        end
end
```

The adaptation of CW can lead to high throughput. We also note that this method does not introduce any extra network communication ***overhead*** since it exploits periodic BSMs, which are specified in DSRC enabled systems [35].

4 The Adaptive Algorithm

According to the previous section discussed, there are many conflicting parameters which can influence the VANETs performance. Keeping these parameters with fixed values will result in undesired performance, particularly in a harsh vehicular scenario where the density on the road is changing very frequently and erroneous channel. Therefore, each vehicle has to change its transmission power, CW size based on the situation on the road to increase the ***scalability***, ***reliability*** and ***efficient*** of VANETs.

Algorithm 1 describes individual vehicles periodically adjust their parameters according to the network conditions and the local vehicle density K, pertaining to the assumptions as follows:

(1) The maximum transmission range (transmission power) is set to R_{max}, and the minimum transmission range is set to R_{min}, which is used in the jam environment.

(2) The CW size W_b for BSMs takes the values in the range [W_{min}, W_{max}], where W_{min} and W_{max} represent the minimum CW and maximum CW, respectively, which are 15 and 1023 [8].

(3) The current used vehicle transmission range and the CW size of node transmitting BSMs are denoted as TR_c and W_{bc}, respectively.

Each vehicle executes the algorithm every T s. Initially, individual vehicle starts with maximum transmission power (maximum transmission range R_{max}) and listens to information from neighbor vehicles. At first stage, according to the received packets, each vehicle analyzes the MAC address and counts the number of neighboring vehicles. Then the K is derived, and then the TR value can thus be obtained according to Equation (1). Based on TR, each vehicle dynamically adjusts transmission power according to Table 2, so as to mitigate the interference of high-transmission power and increase the duration of the communication link in case of low traffic density. At the second stage, vehicles adopt zero CW and minislot to preemptive send emergency messages, and an implicit ACK ensures transmission ***reliability*** of emergency messages. Each vehicle dynamically adjusts the CW size of the BSM according to its statistic collision rate, so that high throughput is achieved. Consequently, this algorithm ensures the transmissions of the emergency messages and BSMs with high packet delivery ratio, low delay and high throughput. We note that the threshold values $\eta_1, \eta_2, \eta_3, \eta_4, \beta$ and γ play significant roles in the algorithm, and may be dynamically adjusted periodically according to the local vehicle density, the network conditions and on the threshold history for a given vehicle.

Now, we analyze the complexity of the proposed algorithm. The algorithm ***overhead*** mainly includes four parts: (a) Estimating vehicle density K and calculating transmission range TR_c according to Equation (1). (b) Looking up the transmit power values based on TR_c from Table 2. (c) Calculating access delay t_{AD} according to Equation (4). (d) Estimating collision rate p by analyzing the received sequence numbers at MAC layer. The complexity of each part is as follows:

(a) Each node utilizes the 12-bit sequence number on the headers of received BSM to estimate the vehicle density K. This method does not introduce significant network ***overhead*** since it exploits the periodic message in DSRC enabled systems. The time complexity of estimating vehicle density is $O(n)$, where n represents the number of neighboring nodes. On the other hand, each node calculates TR_c according to Equation (1), the time complexity of Equation (1) is $O(1)$.

(b) Each node keeps a Table 2 that stores the transmit power values corresponding to different transmission ranges, the space complexity of Table 2 is $O(e)$, where e denotes the number of entries. Nodes require approximately $e/2$ time to look up this table to obtain the transmit power value based on TR_c, the time complexity is therefore $O(e)$. On the other, each node needs to store packets from the neighboring nodes to compute collision rate p, and the space complexity thus is $O(n * m)$.

(c) The time complexity of Equation (4) is $O(1)$.

(d) The time complexity that is used to estimate collision rate is $O(n * m)$, where m represents the average number of received packets from each neighboring node.

Based on the above analysis, the time complexity and space complexity of Algorithm 1 are both $O(n * m+e)$. The time complexity and space complexity are quiet low, and they do not impose much computational cost and space cost on the nodes. It is noteworthy to mention that the proposed PCAC scheme is implemented by normal broadcast of emergency messages or BSMs, and thus it does not require additional communication ***overhead***.

5 Simulation and Numerical Results

We have carried out extensive simulations to verify our proposed PCAC scheme. Traffic flows are generated using the VISSIM [36] and simulation experiments are conducted in a network environment by using NS-3 [37]. The proposed PCAC scheme was evaluated under different traffic densities to guarantee ***scalability***, ***reliability*** and ***efficiency***. We compare the performance of PCAC scheme with the following schemes:

- The fixed value scheme [8]: It is a default EDCA scheme, which has fixed power and CW for different ACs. In this paper, emergency message with the highest priority and BSM with the lower priority which belong to AC_0 and AC_2, respectively.
- The reference paper [18]: It is a well-known joint adjustment of power and CW to achieve high throughput and low end-to-end delay. The reference paper [18] adjusts transmission power and CW size according to local vehicle density and the network conditions, respectively, and we consider this scheme as a benchmark.

5.1 Simulation Scenario

The simulation scenario is on the highway with 1-km length and 2-lane in each direction as shown in Fig. 1. The vehicles follow a Poisson process with different densities on the road. The speed of vehicles is between 60 km/h and 120 km/h, and every vehicle has a GPS and a single-radio DSRC communication device. All nodes can act as both service providers and service users. The generated emergency packet arrives at the MAC layer in a Poisson manner and BSM packet periodically broadcast with fixed frequency. According to Vehicle Safety Communications Consortium (VSCC) and U.S Department of Transportation (USDOT), BSM frequency for collision warning is defined as 10 Hz [38]. Considering the emergency messages are event-driven messages and happen only occasionally [39], and hence, we set the ratio between emergency messages and BSMs is 0.1. Since long time will bring about a lot of expired nodes, while short time will cause frequent updates, we set the algorithm execution cycle T be 0.5s. Lower transmission data rate leads to lower packet errors. The parameter p determines the local state of network, which is obtained according to the method in [34], and p only presents packet collision rate. In order to calculate p value without being affected by packet errors, we set the transmission data rate to 3Mbps. On the other hand, p value also represents the degree of channel congestion. When p value exceeds 0.5 (between 0.5 and 0.3), it means that the channel is quite congested (a little congested) [40], and the CW size should increase rapidly (slowly). Therefore, we set η_2 and η_3 to 0.5 and 0.3, respectively. We follow the reference paper [18], traffic constant α and threshold η_1 are 0.25 and 0.5, respectively. Simulation time is 2 minutes and the final result is the mean of each simulation result. All configuration parameters are in the Table 3.

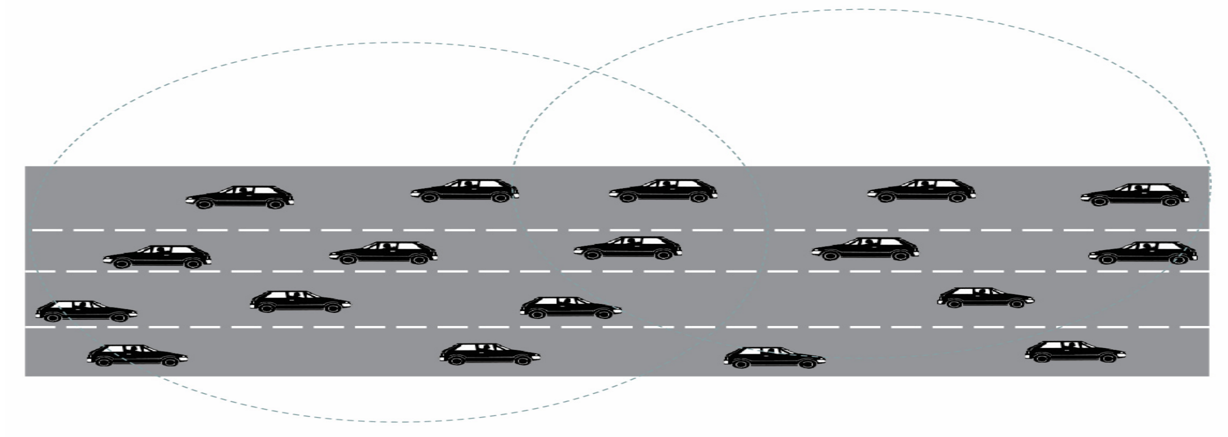


Fig. 1. The highway scenario with 2-lane in each direction

Table 3. Simulation parameters

Parameter	Value
The transmission data rate	3Mbps
Number of vehicles	[10,150]
Vehicle speed:[V_{min}, V_{max}]	[60,120]Km/h
Emergency messages generation	Poisson distribution
The payload of the emergency messages	200Bytes
The payload of the BSMs	512Bytes
Physical-header+MAC-header	56Bytes
Traffic constant α	0.25
Load segment L	1000m
Road configuration	2 lanes in each direction
The transmission frequency of the BSMs	10Hz
Algorithm execution cycle T	0.5s
T_{max}	10ms
T_{DIFS}	60μs
t_{switch}	3μs

Table 3. Simulation parameters (continue)

Parameter	Value
φ	1μs
δ	13μs
Threshold η_1	0.5
Threshold η_2	0.5
Threshold η_3	0.3
Threshold η_4	0.2
ω	0.7
β	0.2
γ	0.2

5.2 Performance Metrics

In this section, we describe the performance metrics in the simulations. Our goal is to support ***scalable***, ***timely***, ***reliable*** and ***efficient*** transmissions of messages by controlling channel congestion to minimize the transmission delay and to maintain higher PDR and higher throughput. Therefore, we give the following metrics:

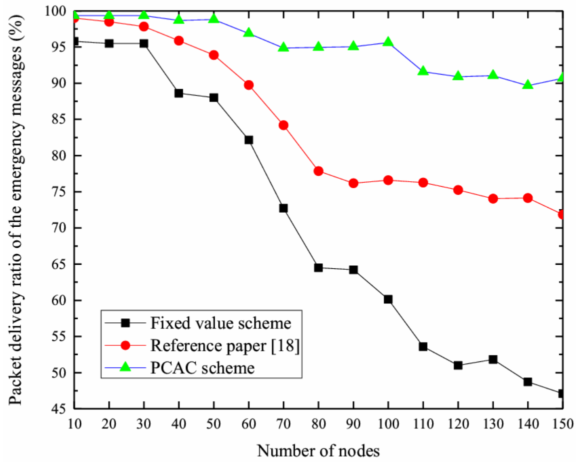
- *Packet Delivery Ratio (PDR)*: which measures the percentage of packets that successfully received by all vehicles in the transmission range of the senders [11]. It is achieved by dividing the number of successful received packets M_{succ} by all vehicles within the transmission range of the senders by the total number of packets transmitted. Assuming there are N vehicles and each vehicle sends M packets. We have

$$PDR=\frac{M_{succ}}{N\cdot M}. \tag{5}$$

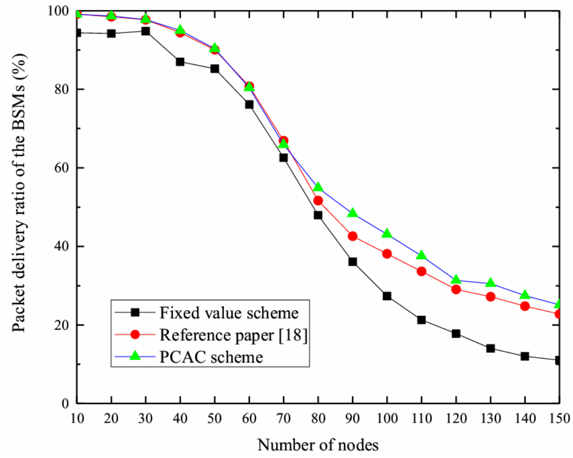
- *Packet Average Delay (PAD):* which measures the transmission timeliness. It contains two parts: queueing time and service time. The queueing time is the duration from the time instant when a packet arrives at MAC queue to the time instant when it becomes the head of MAC queue. The service time is the duration from the time instant when the packet becomes the head of MAC queue to the time instant when it is successfully disseminated.
- *System Throughput (ST):* which measures number of successful received packets within a certain period of time and with the unit of Mbps (million bits per second).

5.3 Simulation Results

Fig. 2(a) and Fig. 2(b) show the PDR of the emergency messages and the BSMs versus the number of nodes, respectively. The PDR decreases as the number of nodes increases. This is because that the collision probability increases with N increasing. It can be seen that the PDR of emergency messages and BSMs in PCAC and the reference paper [18] scheme are higher than that of the fixed value scheme. This is because that in the fixed value scheme, each node uses constant transmission power and CW, while each node in the other two schemes can adjust the transmission power and CW according to the vehicle density and network traffic conditions. In addition, when the emergency messages are disseminated in PCAC scheme, due to employing implicit ACK mechanism, the PDR performance of the emergency messages of the PCAC scheme is better than that of the reference paper [18]. On the other hand, when the BSMs are transmitted, due to coarse adjustment combining with fine adjustment method to tune CW size in PCAC scheme, the PDR of the BSMs in PCAC scheme is higher than that of the reference paper [18]. For example, compared with the fixed and the reference paper [18] scheme, under high density conditions (e.g., N = 150), the PDR of the emergency messages of PCAC scheme improves by 94% and 27%, and the PDR of the BSMs of the PCAC scheme improves by 129% and 11%, respectively.



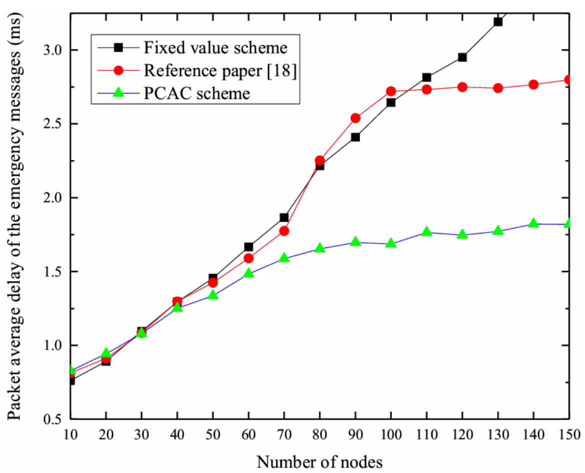
(a) Emergency messages



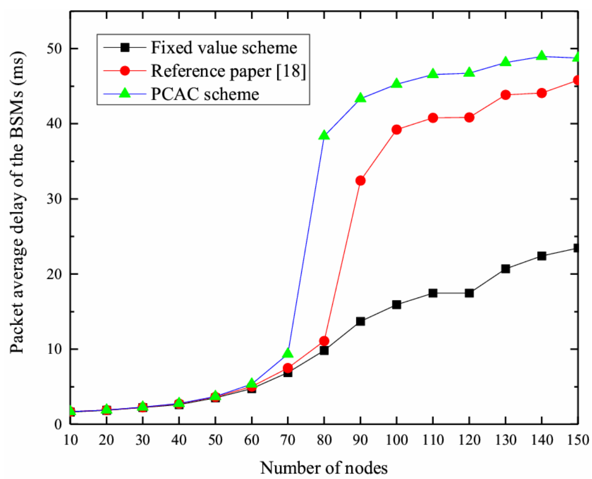
(b) BSMs

Fig. 2. The packet delivery ratio versus the number of nodes

The PAD versus the number of nodes is considered in Fig. 3. From the figures, we can find that the simulation results have increasing trend when *N* increases. This is an expected behavior because when *N* raises, the contentions among nodes become more intense. The backoff timer grows up for two types of messages in both the fixed value and reference paper [18], while the number of retransmission increases for emergency messages in PCAC scheme, which will incur higher PAD. It can be seen from Fig. 3(a) that our proposed PCAC scheme has lower PAD of emergency messages than that of both fixed value and reference paper [18]. This is because that the zero CW and minislot are adopted in PCAC scheme, and the preemptive priority can be ensured. Thus, the proposed PCAC scheme can meet the ***timely*** transmission requirement of emergency messages. At the same time, we also note that in PCAC scheme, the preemptive priority of emergency messages can lead to higher PAD of BSMs than that of the other two schemes, as shown in Fig. 3(b). Considering that in safety-related applications, the emergency messages require to be ensure ***timely*** and reliable transmissions, while the BSMs require higher throughput [4]. Therefore, the PCAC scheme can satisfy the requirement of safety-related applications.



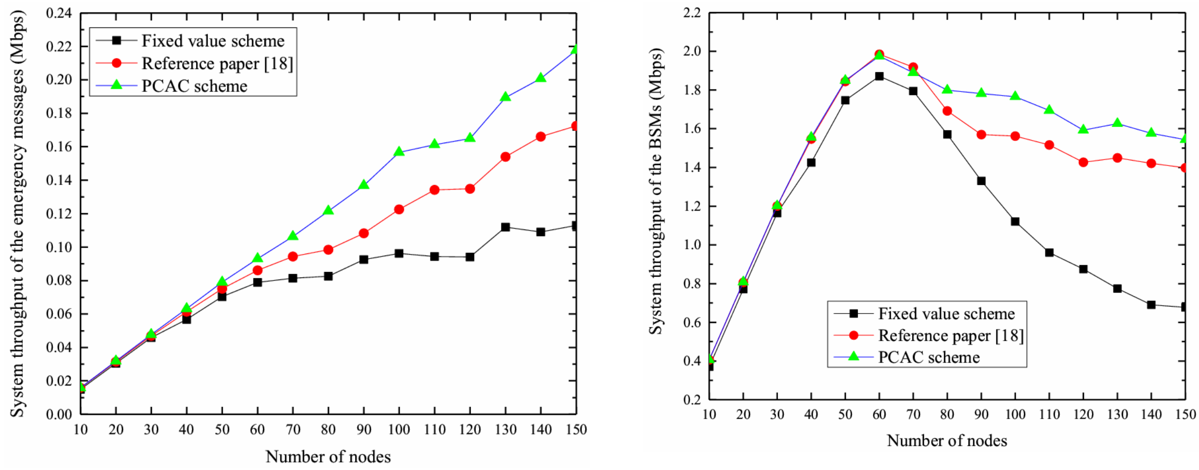
(a) Emergency messages



(b) BSMs

Fig. 3. The packet average delay versus the number of nodes

In order to investigate the effect of the number of nodes on the system throughput. The simulation results are demonstrated in Fig. 4. As seen in the Fig. 4(a), the system throughput of the emergency messages increases with *N* increasing. This is because that, compared with the BSMs, the number of the emergency messages is smaller, and nodes with the emergency messages have smaller CW (for both the fixed value and the reference paper [18] scheme) or zero CW (for PCAC scheme). Therefore, the nodes have more opportunities to transmit the emergency messages. On the other hand, the system throughput of emergency messages in PCAC scheme is higher than that in the two other schemes. For example, when $N = 150$, the system throughput of emergency messages in the PCAC scheme is higher by 93% and 26% than that in the fixed value and the reference paper [18], respectively. The reason is that, in PCAC scheme, the nodes with emergency messages can dynamically adjust the transmission power and utilize zero CW, minislot and ACK mechanism, and thus the ***timely*** and reliable transmission of emergency messages can be ensured. On the other hand, as BSMs account for a large proportion in network traffic, in both the fixed value and the reference paper [18], when the N increases, the channel experiences a process from unsaturated to saturated and then oversaturated conditions, and thus the throughput increases first then decreases. Since in addition to the transmission power of dynamic adjustment, the PCAC scheme also uses coarse adjustment and fine adjustment method, and thus system throughput curve of BSMs in PCAC scheme generally keeps a rising trend and higher than that of the other two schemes. When $N = 150$, compared with the system throughput of BSMs in the fixed value and the reference paper [18], the system throughput of BSMs in the PCAC scheme improves by 128% and 10%, respectively.



(a) Emergency messages (b) BSMs

Fig. 4. The system throughput versus the number of nodes

6 Conclusion and Future Work

In this paper, we propose a joint Power and Contention window Adaptive Control (PCAC) scheme for ***scalable***, ***timely***, ***reliable*** and ***efficient*** broadcast of safety-related services in VANETs. The PCAC scheme dynamically adjusts transmission power based on local vehicle density to achieve ***scalability*** goal. A zero CW, minislot and imply ACK mechanism to ensure the ***timely*** and ***reliable*** transmission for emergency messages. Coarse adjustment and fine adjustment mechanism is to guarantee to achieve the high throughput for emergency and BSMs and improve transmission ***efficiency***. Simulation results manifest that the PCAC scheme can ensure ***reliable*** and ***timely*** transmission of emergency messages and improve the system throughput of two kinds of messages.

In our future work, the compatibility of PCAC scheme with IEEE 802.11p protocol will be considered. We will investigate to improve the performance of safety-related messages and non-safety messages under the multichannel environment.

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