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Channel-Aware Congestion Control in Vehicular Cyber-Physical Systems

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ABSTRACT In vehicular cyber-physical systems, cars are connected to create a mobile network called a vehicular ad hoc network (VANET) to perform various functions, including improved awareness of the surrounding environment. Moving vehicles continually broadcast beacon signals containing information such as position, heading, acceleration, steering angle, vehicle size, and accident notification. However, channel congestion in dense traffic conditions adversely affects network performance. To resolve congestion in VANETs, several works in the literature have studied congestion control. However, they have considered packet loss only as an indication of channel congestion regardless of channel condition. In this paper, we present a channel-aware congestion control algorithm (CACC) that controls the transmission power and data rate. We take into account the received signal strength (RSS) when diagnosing packet loss to determine channel conditions, such as severe fading or channel congestion. In the case of severe fading, we decrease the data rate for a more robust modulation and coding scheme. Additionally, we adjust the transmission power to maintain a desirable packet error rate. Our simulation results show that CACC significantly outperforms other distributed congestion control algorithms by reducing the packet loss rate and increasing the packet delivery ratio.

INDEX TERMS Congestion control, channel-aware protocol, mobile cyber-physical systems, packet loss, vehicular ad hoc networks.

I. INTRODUCTION

A vehicular ad hoc network (VANET) in a vehicular cyber-physical system (CPS) is a technology that uses cars as nodes to build a mobile network. Most vehicle-to-vehicle (V2V) safety applications typically broadcast vehicle information, such as position, heading, acceleration, steering angle, and vehicle size, which provides greater awareness about their surrounding environments. The status information is transmitted at a minimum beacon rate depending on the application. For example, safety-related applications require 10 beacons/s [1]. Using received vehicle information, modeling a context-aware driver assistance system can greatly assist in the development of cars and improve drivers' behavior and decision-making processes to ensure safety and reduce car collision rates.

For this purpose, VANETs have two major standards: the intelligent transport systems (ITS) standard, established by the European Telecommunication Standards Institute (ETSI), and the SAE J2945/1 standard, established by the Society of Automotive Engineers (SAE) [2], both of which uses IEEE 802.11p for Medium access control (MAC) and physical layers. The wireless channel in VANETs becomes congested with a high density of vehicles because V2V safety applications rely on the periodic broadcast of vehicle status information. Packet loss due to collision affects V2V situational awareness and makes it difficult to track surrounding vehicles or to hear vehicle crash warnings from others.

To alleviate channel congestion in V2V, a number of standards and algorithms have been proposed to reduce packet collision, where each vehicle dynamically adjusts its transmission parameters, such as message rate and transmit power, according to the channel condition. However, many algorithms always consider packet loss as an indication of network congestion regardless of the channel condition.

In fact, packet loss results not only from congestion but also from a weak signal or bad channel.[1] Furthermore, the reaction should be the opposite in the two cases: When congestion

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[1] Here, we interchangeably use "weak signal" and "bad channel."

occurs, each vehicle should tune its parameters so that it becomes less aggressive in terms of communication. In contrast, when the channel is bad, each vehicle should adjust its parameters to become more aggressive to overcome the bad channel. Consequently, we need an effective congestion control algorithm that can distinguish the cause of packet loss and react to each situation in a different manner to provide the required communication performance in VANETs.

In this paper, we propose a channel-aware congestion control (CACC) algorithm that can consider the received signal strength (RSS) when diagnosing packet loss. CACC decreases the transmission power to reduce the transmission range, thereby decreasing the number of packet collisions. If the transmission range is smaller, then there are fewer hidden nodes and fewer nodes overall. When a desirable packet collision rate (PCR) is reached, CACC also decreases the data rate and uses a more robust modulation and coding scheme to overcome the bad channel. The higher the data rate, the higher the signal-to-interference-plus-noise ratio (SINR) threshold (dB) required for packet reception. Therefore, the packet delivery ratio (PDR) can be increased by reducing the data rate.

The main benefits of the proposed algorithm can be summarized as follows:

- *CACC differentiates the cause of packet loss and reacts accordingly.* Unlike the conventional algorithm, the proposed CACC algorithm determines whether packet loss is due to congestion or bad channel and tunes network parameters accordingly. Increased throughput give each vehicle can gain better tracking accuracy on nearby vehicles
- *CACC is simple and effective.* The CACC algorithm simply adjusts two parameters in each case without requiring any information from neighbors. Additionally, there is no need to exchange information with the application layer. Therefore, it can quickly respond to the channel situation.

The remainder of the paper is organized as follows. First, Section II provides the background and related work and describes the congestion control problem in detail for broadcast communication in VANETs. We propose our CACC algorithm in Section III. Section IV gives our performance evaluation results, which show the effectiveness of the proposed algorithm. Our conclusions follow in Section V.

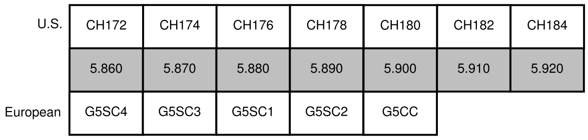

FIGURE 1. Spectrum allocation in VANETs.

II. BACKGROUND AND RELATED WORK

As shown in Fig. 1, the Federal Communications Commission (FCC) allocates 75 MHz of spectrum (seven 10 MHz channels) out of 5.9 GHz in the United States. Channel 178 is designated as the control channel (CCH) and limited to the roadside unit (RSU) communication. Among six other channels reserved for service channels (SCHs), the FCC assigned channel 172 "exclusively for V2V safety communication for accident avoidance." Meanwhile, the European CCH (G5CC) has a role for V2V applications corresponding to US Channel 172, which uses cooperative awareness messages (CAMs) [3].

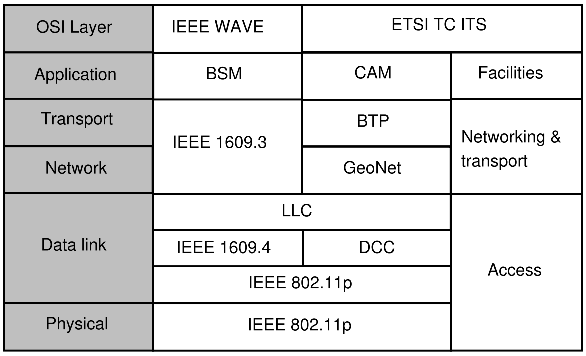

FIGURE 2. Comparison of VANET protocol stacks.

Fig. 2 compares ETSI ITS and IEEE WAVE. Both protocols use IEEE 802.11p for the physical and data link layers. IEEE 802.11p is designed to introduce minimum necessary changes to IEEE 802.11 PHY. It is based on the OFDM PHY defined for IEEE 802.11a but has a 10 MHz wide channel instead of 20 MHz, which works as an ad hoc mode without the basic service set for ITS communication.

In the case of IEEE WAVE, a basic safety message (BSM) is transmitted by a beacon instead of CAMs as in ETSI. The IEEE 1609 standards deal with the knowledge and complexities of operating dedicated short-range communications (DSRC) channels. IEEE 1690.3 covers WAVE connection setup and management, and IEEE 1609.4 enables multiple channels based on device capability. On the other hand, the facilities layer in ETSI ITS provides support for different applications.

TABLE 1. Data rate, coding rate, modulation, and SINR threshold for frame reception.

Data rate (Mb/s)	Coding rate	Modulation	SINR threshold (dB)
3	1/2	BPSK	5
6	1/2	QPSK	8
9	3/4	QPSK	11
12	1/2	16-QAM	15

Table 1 shows the possible data rates for IEEE 802.11p. Transmissions at a high data rate are more efficient in terms of network data rate, but they are more susceptible to packet error due to interference and noise, which requires high SINR. Lower data rates have better resistance against interference and noise [4].

In wireless communication, packet loss can occur due to either collision or channel error. In VANETs, the channel will become congested as the vehicle density increases because V2V safety applications periodically broadcast vehicle status information with at least the minimum beacon rate. In study of [5] showed that packet collisions in IEEE 802.11p significantly degrade the beaconing performance.

Because of the broadcasting nature of VANET safety applications, existing collision alleviation schemes cannot apply to VANETs. Although VANETs adopt carrier-sensing multiple access with collision avoidance (CSMA/CA), collision can still occur due to simultaneous transmission from a hidden node. Existing loss-based rate adaptation algorithms such as ARF [6], AARF [7], CARA [8], and RRAA [9] are not suitable for VANETs because vehicles broadcast messages without acknowledgements (ACKs). These rate adaptation algorithms use the number of successful transmission and loss statistics acquired by means of ACK or RTS/CTS (Request to Send/ Clear to Send) messages, which cannot be applied to broadcasting.

To resolve congestion in VANETs, ETSI has standardized an adaptive algorithm called linear message rate control algorithm (LIMERIC) and a reactive algorithm called distributed congestion control (DCC) that tunes its parameters for transmitting periodic safety messages. In DCC, each vehicle dynamically adapts its transmission parameters for transmit power, message rate, channel sensitivity, and beacon rate in response to the observed channel load based on channel busy percentage (CBP),[2] which is specified as the fraction of time that the channel is considered busy [10]. To calculate the CBP, N_p probes of the channel busy signal are uniformly sampled within a measurement interval of T_m. Then, an estimate of CBP is given as

$$\text{CBP} = (\text{Number of probes with busy channel})/N_p. \quad (1)$$

One simple solution for congestion is to decrease the beacon rate. The well-known algorithm for controlling the message rate is LIMERIC [11]. LIMERIC also uses the CBP to adapt the message rate to meet a specified CBP. In Kim *et al.* [12], it is noted that existing rate control schemes based on channel load render the rate assignment irrelevant to the given vehicle pattern, and it is proposed that the average beacon rate among neighbors should be used to resolve unfairness. Periodically Updated Load Sensitive Adaptive Rate control (PULSA) in [13] uses two-hop piggybacked information and an additive-increase multiplicative-decrease (AIMD) method for achieving better channel utilization and min-max fairness. Using a binary decision method, the rate is controlled by comparing the actual rate with the target value.

Another solution for congestion is to decrease the number of vehicles in the transmission range. For example, distributed fair power adjustment (D-FPAV) in [14] controls the transmit power according to the maximum beacon load threshold. Both predictions of application-layer traffic and the observed number of vehicles are used to calculate transmit power. D-FPAV achieves a certain level of fairness and prioritization, but the weakness of D-FPAV is that it introduces communication overhead and waste of bandwidth due to a fixed threshold for the maximum beacon. Statistical beaconing congestion control (SBCC) in [15] locally computes the power needed to comply with a given maximum beacon load by estimating the vehicle density and the beacon rate statistically using information from the beacons of surrounding vehicles.

A combination of transmit power and rate congestion control is performed by another type of algorithm. Congestion control in the SAE J2948/1 standard uses information about the number of vehicles in a 100 m range to control the message rate [2]. Additionally, the CBP is used to control transmit power. Therefore, to operate properly, it is important to know the number of vehicles and to understand the relationship between CBP, power, and collision. Environment- and context-aware combined power and rate (ECPR) congestion control in [16] is designed for meeting the target awareness and rate requirements given by the application context. ECPR controls the channel load by adjusting the rate and power by using path loss exponent estimation to improve cooperative awareness.

TABLE 2. Comparison of different algorithms.

Algorithm	Control parameter	Required information
DCC [10]	Power, data rate, channel sensitivity, message rate data rate	CBP
LIMERIC [11]	Message rate	CBP
PULSA [13]	Message rate	CBP, rate from neighbors
D-FPAV [14]	Power	Power from neighbors, the number of vehicles
SBCC [15]	Power	Power from neighbors, the number of vehicles
SAE J2948/1 [2]	Power, message rate	CBP, the number of vehicles
ECPR [16]	Power, message rate	CBP, power from neighbors

Table 2 summarizes the control parameters and required information for each algorithm. Because broadcasting makes it difficult to identify the exact channel situation and surroundings, many algorithms use the CBP to measure channel load and reduce channel usage. Additionally, some algorithms use information by sending other vehicles' current parameters in the message or estimating the number of vehicles. However, sending information in a message results in inaccurate predictions about the state of the channel when packet loss is frequent. Even the CBP cannot contain information about whether the current channel is good or bad and can only express how many signals can be detected. One critical issue that has not been considered in previous studies is that packet loss can result from either congestion or bad channel conditions. Many distributed congestion control algorithm always considers packet loss as an indication of congestion regardless of channel status. Consequently, they may even worsen the situation and degrade communication performance. Since the reaction to congestion should differ according to the cause of congestion, it is of critical importance to develop a distributed congestion control algorithm that can properly distinguish the cause and react accordingly.

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[2] CBP is also called CBT (channel busy time) or CBR (channel busy ratio).

III. PROPOSED ALGORITHM

In this section, we analyze the effect of fading on the throughput of the V2V network using the system model. Then, we propose a way to distinguish the cause of packet loss on the receiver side. Finally, we introduce the channel-aware congestion control (CACC) algorithm, which decreases not only packet collision but also packet loss due to weak signals. For the sake of description, some notations used in this model are listed in Table 3.

TABLE 3. Notations and descriptions.

Notations	Descriptions
m	Shape parameter for Nakagami-m model
μ	Scale parameter for Nakagami-m model
β	Path loss exponent
p	Transmit power
S	Sensitivity of the receiver
$r_{cs}(m)$	Average carrier sense range (in meters)
T_s	Sample period
N_s	The number of successfully decoded packets
N_c	The number of packets in error larger than cutoff value
N_w	The number of packets in error smaller than cutoff value
PCR	Packet collision rate
PDR	Packet delivery rate

A. SYSTEM MODEL AND EFFECT OF FADING

The wireless channel continuously changes with mobility, fading, the multipath propagation effect and so on. In this subsection, we analyze how fading affects the throughput of vehicular networks. We use the system model proposed in [15] to investigate the throughput of V2V to fading. We use the Nakagami-m model, which is the most commonly used model for vehicular communication. The parameters m and μ are called shape and scale parameters, respectively. $m = 1$ indicates severe fading conditions, $m = 3$ indicates medium fading conditions, and $m = 5$ indicates low fading conditions [14]. We use a one-slope path loss model $l = Ax^{\beta}$, where $A = (\frac{4\pi}{\lambda})^2$, λ is the wavelength of the carrier, and β is the path-loss exponent. Then, the average carrier sense range can be obtained as

$$r_{cs}\,(m) = \frac{\Gamma(m + \frac{1}{\beta})}{\Gamma(m)(SA\frac{m}{p})^{\beta}} \tag{2}$$

where p is transmit power, S is the sensitivity of the receiver. The average carrier sense range is the range in which the signal from the transmitter can be detected. Then, if all vehicles communicate with each other with the same power and data rate, the effect of fading on the average carrier sense range can be expressed as

$$\frac{r_{cs}(1)}{r_{cs}(5)} = \frac{\Gamma(1 + \frac{1}{\beta})\Gamma(5)}{\Gamma(5 + \frac{1}{\beta})\Gamma(1)}. \tag{3}$$

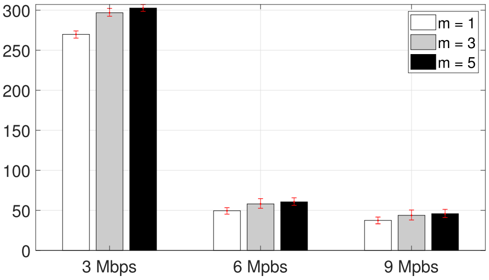


FIGURE 3. The average number of successfully decoded packets/s.

With a low path loss exponent, $\beta = 2$, the average carrier sense range with a severe fading channel is 90.86 % less than it is in a low fading condition. Similarly, in the case of higher path loss, $\beta = 2.5$, the average carrier sense range is 90.89 % less than it is in a low fading condition. Thus, a higher value of m results in a shorter transmission range, and 9.14 % of the packet cannot be sensed due to fading. To identify the effect of fading on V2V networks, we conduct a simulation based on the setting given in Section IV-A. We measure the average number of successfully decoded packets per second, with varying data rates and m, for 30 seconds. Fig. 3 shows that the average number of packets for $m = 1$ is 10.85 % of that for $m = 5$ in the case of a 3 Mbps data rate. The severe fading channel reduces the average carrier sense range, thereby reducing the number of successfully decoded packets for the same vehicle density. Since a lower data rate requires a low SINR, decreasing the data rate can increase the number of successfully decoded packets in the case of a severe fading channel. However, transmissions at a high data rate are more efficient in terms of reducing packet collisions. Therefore, proper selection of the data rate is important for increasing the reliability of V2V.

B. DIAGNOSIS OF PACKET ERROR

In this subsection, we propose a way to distinguish the cause of packet loss on the receiver side. There are several candidate metrics, such as received signal strength (RSS), bit error rate (BER), and 'symbol-level' error. Among these, we adopt RSS to properly distinguish the cause of packet loss. RSS is the aggregate signal plus interference measured in dBm.

The intuition behind using RSS is as follows: For packets suffering collision, RSS is typically higher than that of packets suffering signal attenuation for a given data rate. The experimental results in [17] report that 98 % of packet errors due to weak signals have an RSS of approximately 73 dBm or less, while only 10 % of packets suffering collisions have an RSS of 73 dBm or less. By using a cutoff value of 73 dBm, we can capture approximately 90 % of collision cases while incurring a false-positive rate of 2 %. Consequently, RSS is a simple yet effective metric for determining the cause of packet loss

However, this experiment was conducted with Wi-Fi. To show the effectiveness of RSS for identifying the cause of packet loss in V2V, we performed a simulation based on the setting given in Section IV-A. We conducted simulations for data rates of 3, 6 and 12 Mbps. The difference in RSS between the successfully decoded packet, packet loss due to low SINR, and packet loss due to collision cases are illustrated in Fig. 5. The RSS for collision is always greater to diagnose the cause of packet error between −96.26 dBm and the maximum RSS of channel error. Additionally, this range becomes larger at higher data rates. Therefore, choosing the cut-off value that decides whether packet error is due to collision is important when reducing the false-positive rate.

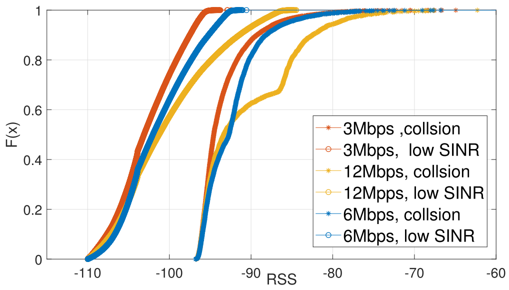
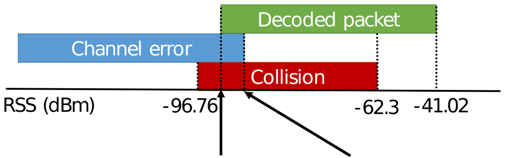


FIGURE 4. Cumulative distribution function of received signal strength.



Data rate	Minimum RSS of decoded packet	Maximum RSS of channel error
3 Mbps	-96.26	-92.43
6 Mbps	-93.24	-91.50
12 Mbps	-86.96	-84.48

FIGURE 5. Difference in RSS between successfully decoded packets, packet loss due to collision, and packet loss due to channel error.

Fig. 4 shows the cumulative distribution function (CDF) for the distribution of RSS values for collisions and weak signals. In the case of 3 Mpbs, 97.92 % of packets in error due to weak signal have an RSS of approximately −96 dBm or less, and only 9.2 % of packets suffering collision have an RSS of −96 dBm or less. By using a cutoff value of −96 dBm, it would be possible to capture approximately 90.8 % of collision cases while incurring a false-positive rate of 2.08.

On the other hand, in the case of 6 Mpbs, 86.67 % of packets in error due to weak signal have an RSS of approximately −96 dBm or less, and 9.1 % of packets suffering collision have an RSS of −96 dBm or less. By using a cutoff value of −96 dBm, it would be possible to capture approximately 90.89 % of collision cases while incurring a false-positive rate of 13.33.

Finally, in the case of 12 Mbps, approximately 76.01 % of packets in error due to weak signal have an RSS of approximately −96 dBm or less, and 10.38 % of packets suffering collisions have an RSS of −96 dBm or less. By using a cutoff value, it would be possible to capture approximately 89.62 % of collision cases while incurring a false-positive rate of 23.99.

From this RSS analysis, we establish −96.26 dBm as a cutoff value for determining the cause of packet error. −96.25 dBm is a minimum RSS of decoded packets in the case of 3 Mbps. The results show that the cause of packet errors are well distinguished at lower data rates than at higher data rates. Using RSS values with other metrics such as CBP and machine learning methods, the accuracy of the identified cause of packet failure will increase. However, the purpose of diagnosing packet error is to determine the channel circumstances, such as whether severe fading or severe collision occurs. Therefore, the proposed algorithm, which reduces both collisions and channel error, uses a determined cutoff value for identifying channel circumstances and reducing packet losses.

C. CHANNEL-AWARE CONGESTION CONTROL

In this section, we present the CACC algorithm, which makes use of transmit power control and data rate control to reduce packet error, which helps to achieve better tracking accuracy for nearby vehicles to ensure safety. The proposed CACC algorithm is a distributed algorithm that does not require global knowledge, such as node position. Each vehicle estimates channel circumstance, channel congestion and/or whether the channel is bad using RSS.

Algorithm 1 Pseudo Code of CACC Algorithm

```
for $T_s$ do
    if Pkt is successfully decoded then
        $N_s++$
    else
        READ RSS of packet-error signal
        if RSS $>$ cutoff then    ▷ Check if packet-error is due to collision
            $N_c++$
        else                      ▷ due to channel-error
            $N_w++$
        end if
    end if
end for
$PCR = N_c/(N_s + N_c)$
if $PCR > \mu$ then
    $TxPower = TxPower - \delta$
else
    $TxPower = TxPower + \delta$
end if
$PDR = N_s/(N_s + N_w)$
if $PCR > \mu$ then
    PhyRate =6 Mbps
else if $PCR < \mu$ and $PDR < \rho$ then
    PhyRate =3 Mbps
end if
```

Alg. 1 describes the pseudocode of the CACC algorithm. The first step is to distinguish the cause of packet loss for each packet error (Lines 1-12). We use the determined RSS cut-off value in Section III-B for the diagnosis of packet loss. During each sample period of T_s, CACC counts the number of successfully decoded packets N_s (Lines 1-3). If the packet is not decoded, CACC counts the number of packets in error, whose RSS value is larger than the cutoff value, denoted by N_c (Lines 6-7). Hence, N_c corresponds to the number of nondecoded packets with high RSS values and can be used as an estimated number of packet errors due to collision.

In a similar manner, CACC counts the number of non-decoded packets with RSS values smaller than the cutoff value, denoted by N_w, which is an estimate of the number of packet errors due to weak signals. After counting N_c and N_w in each sample period, CACC carries out transmit power control and data rate control (Lines 13-24). To make decisions regarding power control, we calculated the packet collision rate (PCR) as $PCR = N_c/(N_s + N_c)$ (Line 13). If the PCR is larger than the desired PCR μ, we increase the transmit power. Otherwise, we decrease the transmit power. Similarly, we calculate the packet delivery ratio as $PDR = N_s/(N_s+N_w)$ to control the data rate. Since we put the highest priority on reducing collisions, data rate control will be applied when the collision conditions are satisfied. This is because many more collisions can occur at low data rates than at higher rates. We use 3 Mpbs as the data rate for a more robust coding and modulation scheme if PCR is lower than μ and PDR is lower than ρ (Lines 22-24).

The CACC algorithm uses RSS of the received packets in error to calculate the number of packet errors due to collision and channel errors and the number of successfully decoded packets during T_s. In this case, the complexity increases linearly with the number of received packets during T_S. Given the number of neighbors in the carrier sensing range N and message rates R, the number of received packets during T_s is $N \times R \times T_s$. Therefore, its computational complexity is $O(T_s NR)$.

In other algorithms that use information from neighbors, the information is sent in packets. In this case, since the application layer information is used, the implementation complexity increases on real equipment. However, since the CACC algorithm uses only the information of the physical and the MAC layer generated in the packet reception process, it can be readily implemented in real equipment.

IV. PERFORMANCE EVALUATION

A. SIMULATION SETUP

To validate the proposed algorithm, we conduct a performance evaluation with a Veins 5.1a framework [18], an OMNeT++ network simulator [19] and SUMO, a road traffic simulator [20]. Traffic flows information from SUMO sent to the network simulator through the interface, and conversely, the directions from the OMNeT++ are sent to SUMO. [21]. Table 4 summarizes the parameters used for performance evaluation. As shown in Fig. 6, we use a road topology of a 2500 $m \times 2500$ m square block composed of 4 one-way lanes. Additionally, in our topology, buildings block radio propagation with an obstacle shadowing channel model for suburban and urban environments [22]. This channel model captures the state that large power signals are slightly affected by buildings while weak signals are blocked. As a path loss model, we use the Nakagami-m model, which is the most commonly used model for vehicular communication, as we discussed in. Besides, the capture effect is implemented in the simulation. For CCA, we use the energy detection (ED) mode, where the channel is considered busy when its energy level is above an ED threshold.

TABLE 4. Parameters used in simulation.

Parameter	Value
Channel	5.9 GHz Nakagami-m fading model Obstacle shadowing
Noise floor	−98 dbm
minimum power level	−110 dbm
Minimum transmit power	10 mW
Maximum transmit power	100 mW
Beacon header length	80 bits
Beacon data length	250 bits
Beacon interval	0.1 s
ED threshold	−85 dBm
Sample period (T_s)	1 s
Maximum Vehicle speed	35 km/s
Contention window size	15
Data rate	3, 6 Mb/s
Power step (δ)	0.5 dbm
Target level of PCR (μ)	0.1
Target level of PDR (ρ)	0.8

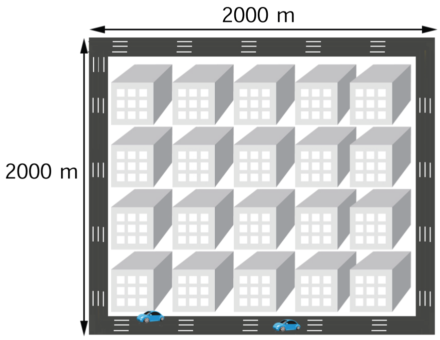


FIGURE 6. Road topology for performance evaluation.

The mobility model used in the simulations is a linear-mobility model where a node is made to move at a constant speed within a pre-determined mobility area. Maximum speed and initial acceleration is set to 40 m/s and 2.6 m/s^2, respectively. We generate vehicles on the road when the simulation starts and the vehicles travel around the road at a given speed until the simulation ends. Each vehicle continually broadcasts beacons with a size of 300 bytes. We consider safety-related applications with a beacon rate of 10 beacons/s. The initial data rate for 802.11p is set to 6 Mbps, and the values available for CACC are 3 and 6 Mbps. For the CACC algorithm, we set the target level of PCR (μ)

and PDR (ρ) to 0.1 and 0.8, respectively. The sample period T_s is set to 1 second to avoid unnecessarily frequent changes in the channel state.

We compare performance of the CACC algorithm with other algorithms in various types of scenarios. To consider the severe and moderate fading conditions, we set the Nakagami-m shape parameter to $m = 1$, $m = 3$, and $m = 5$. We set the path loss exponent β to 2.0 and 2.5. In addition, we experimented with 400 and 800 vehicles to compare performance in both a traffic-congested and uncongested situation. Therefore, the worst-case scenario is that there are 800 vehicles in the topology with $m = 1$ and $\beta = 2.5$.

We compared our performance with two well-known congestion control algorithms and 802.11p without any control algorithm, which we called Baseline. The first algorithm to compare is LIMERIC [11], which is a distributed algorithm for each vehicle control message rate based on the measured CBP. The other one is the congestion control protocol defined in SAE J2945/1 [2], which is a distributed algorithm in which each vehicle adjusts its message rate and transmit power based on the number of surrounding vehicles and the CBP. We used the parameters of the simulation in [23]. They were selected because they are both distributed algorithms that aim to reduce collisions using the CBP.

B. PERFORMANCE ANALYSIS

In this section, we present simulation results and compare the performance of the proposed CACC algorithm with LIMERIC, the congestion control protocol defined in SAE J2945/1 (SAE), and 802.11p without any control algorithm (Baseline). In the proposed algorithm, the experiment was carried out in two ways: using the data rate control (CACC) and not using the data rate control (CACC without DC). The reason for dividing the algorithm into two parts is to examine how packet error is affected by controlling the data rate and transmission power.

For comparison, we measured the following four evaluation metrics.

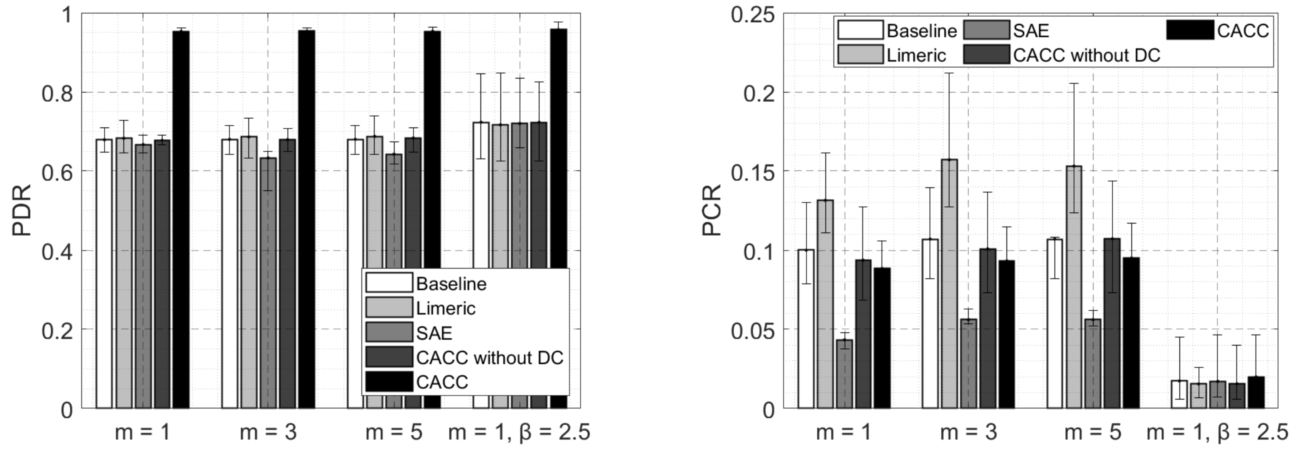
- **Packet delivery ratio**: The packet delivery ratio (PDR) is computed as the number of successfully decoded packets divided by the number of successfully decoded packets plus the number of packet errors due to a weak signal. PDR is mostly affected by the selection of the data rate. In bad channel conditions such as severe fading, decreasing the data rate can decrease the packet error due to the weak signal. This results in an increased PDR. However, decreasing the data rate can incur more collisions since transmission time increases. Therefore, proper selection of the data rate is important for increasing the number of decoded packets.
- **Packet Collision Ratio**: We calculated the packet collision ratio (PCR) as the number of collisions divided by the number of successfully decoded packets plus the number of collisions. The PCR can be increased by the transmission of hidden nodes at a higher vehicle density. Hence, decreasing the transmit power reduces the transmission range, which reduces PCR caused by hidden nodes. Additionally, decreasing the data rate can increase the PCR because the transmission time increases.
- **The number of decoded packets/s**: Both increased PDR and decreased PCR result in an increased number of successfully decoded packets per second. Thus, properly adjusting data rates and transmission power can lead to a higher number of decoded packets.
- **Channel Busy Percentage**: The channel can be declared as busy due to a higher energy level in the receiver. In general, high CBP is undesirable because a high number of collisions can occur with high CBP.

Therefore, the main goal of congestion control is to provide a high number of decoded packets/s for safety applications. The results are averaged over ten simulation runs. Each simulation time is set to 60 seconds and node placement is chosen randomly in each simulation. The performance results of the low-density case are shown in Fig. 7, which compares the following four cases.

1) $m = 1$ and $\beta = 2.0$: severe fading
2) $m = 3$ and $\beta = 2.0$: moderate fading
3) $m = 5$ and $\beta = 2.0$: light fading
4) $m = 1$ and $\beta = 2.5$: severe fading with higher path loss

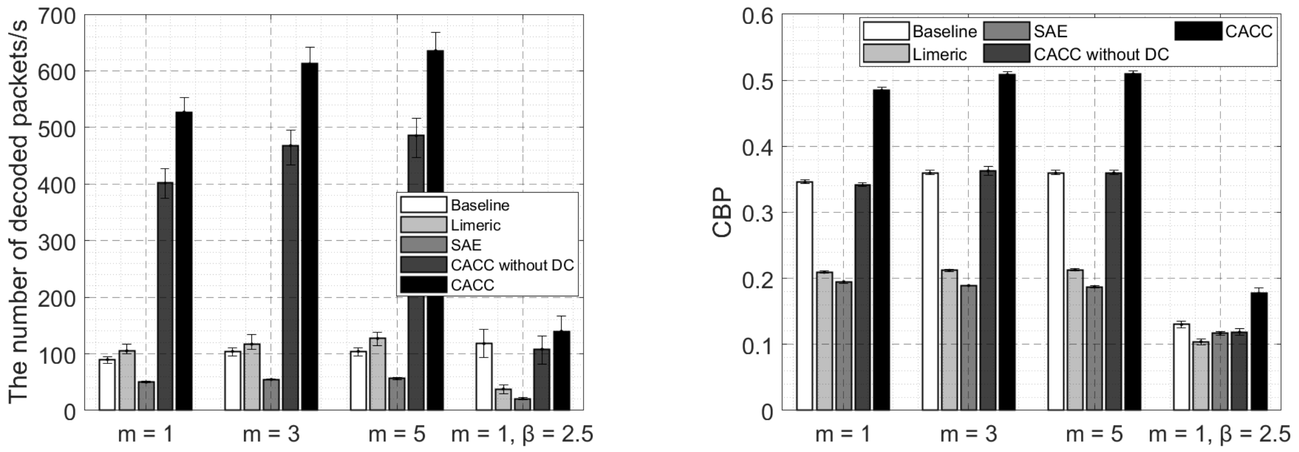
In the case of PDR, CACC with data rate control in all four cases shows a high PDR, as shown in Fig. 7b. This is because adjusting the power or the message rate does not reduce packet loss due to channel errors. On the other hand, in the case of PCR, the SAE controlling the transmission power and the message rate simultaneously shows the best performance, as shown in Fig. 7b. Our algorithm shows that PCR is approximately 0.1 because we set the desired PCR to 0.1. With low vehicle density, the proposed CACC algorithm shows little improvement over Baseline because collisions are infrequent and the improvement mainly comes from reducing the channel error. In Case 4, however, the reduced transmission range due to severe fading and higher path loss results in 8 fewer packet collisions. Thus, increased PDR and reduced PCR resulted in an increase in the number of successfully decoded packets, as shown in Fig. 7c. In all four cases, the results are better when data rate control is applied than they are without data rate control. Consequently, in Case 1, PDR increased 27.41 % compared to Baseline, 27.03 % compared to LIMERIC, and 28.62 % compared to SAE. The PER was 1.16 % lower than Baseline, 4.31 % lower than LIMERIC and 4.50 % higher than SAE. Finally, the number of successfully decoded packets increased 5.86 times compared to Baseline, 5.00 times compared to LIMERIC, and 10.53 times compared to SAE.

In the case of CBP, both SAE and LIMERIC use the CBP as an indicator to control the message rate. Since they regulate the message rate, the CBP is reduced compared to Baseline. However, our algorithm shows a higher CBP compared to other algorithms because our goal is not to reduce the CBP but to use channel resources efficiently. Additionally, as seen in Fig. 7d, despite having the same number of vehicles,



(a) Comparison of PDR

(b) Comparison of PCR



(c) Comparison of the average number of decoded packet

(d) Comparison of CBP

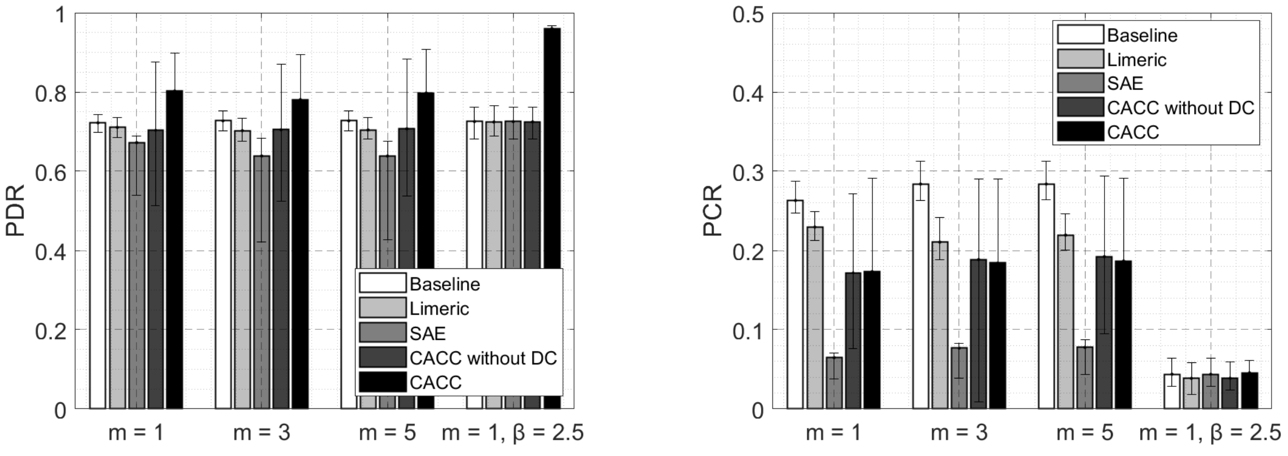
FIGURE 7. **Road topology with 400 vehicles.**

Case 4 shows a low CBP due to a lower transmission range as a result of high path loss. The CBP does not accurately reflect channel conditions. The CBP alone does not provide accurate information on how bad the channel is or how many vehicles there are.

The performance results of the high-density case are shown in Fig. 8 in a similar way as the low-density case. Due to the increased number of vehicles, all four cases show lower PDR and higher PCR than when the vehicle density is low. Compared to other mechanisms, the proposed CACC algorithm with a data rate control gives the best performance. In Case 1, where m is set to 1, PDR increased 8.02 % compared to Baseline, 9.18 % compared to LIMERIC, and 13.02 % compared to SAE as shown in Fig. 8a. From Fig. 8b, the PCR was 8.98 % lower than Baseline, 5.62 % lower than LIMERIC and 10.86 % higher than SAE. Therefore, from Fig. 8c, the number of successfully decoded packets increased 3.24 times compared to Baseline, 2.76 times compared to LIMERIC, and 6.47 times compared to SAE. In the case of CBP, our algorithm shows a higher CBP compared to other algorithms as shown in Fig. 8d. These results indicate that the proposed CACC algorithm fully utilizes network resources.

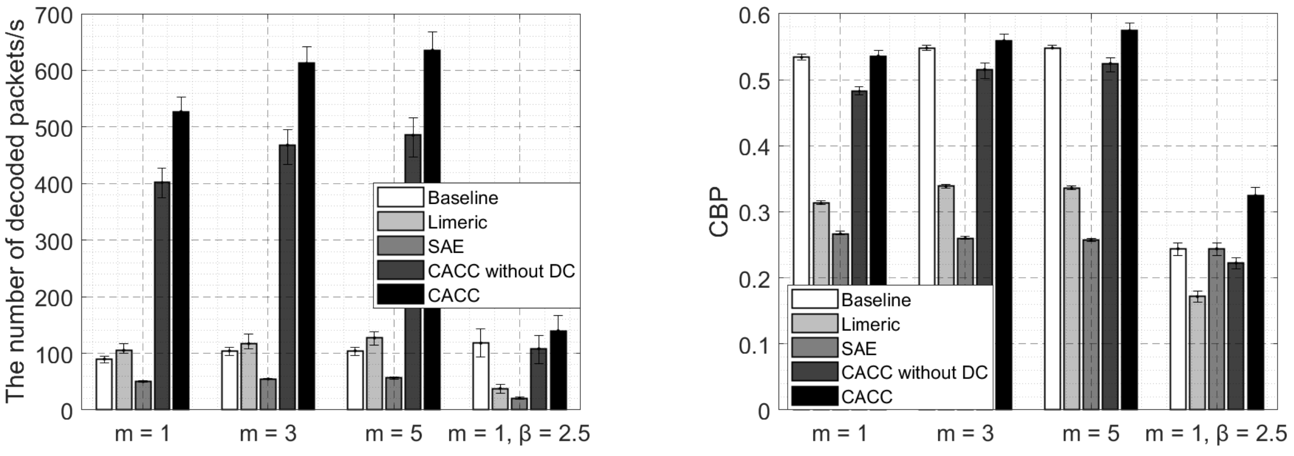
Fig. 9 compares the performance of CACC with LIMERIC and SAE for the vehicle density. The average number of generated packets of each vehicle per second is compared in Fig. 9a The initial message rate of CCAA is set to 10 Hz, but the SAE and LIMERIC control the message rate according to density. To reduce collision at a density of 0.025, the number of generated packets per second by SAE and LIMERIC are reduced to below 7 Hz on average. Also, the message rate of both SAE and LIMERIC is reduced below 3 Hz when vehicle density is high (0.1 vehicles/m). We can see that SAE and LIMERIC that handle channel congestion by lowering the message rate at high density have the disadvantage of showing an increased inter-packet delay (IPD) even without the collision and channel error.

As depicted in Fig. 9b, the average number of received packets of each vehicle per second is reduced compared



(a) Comparison of PDR

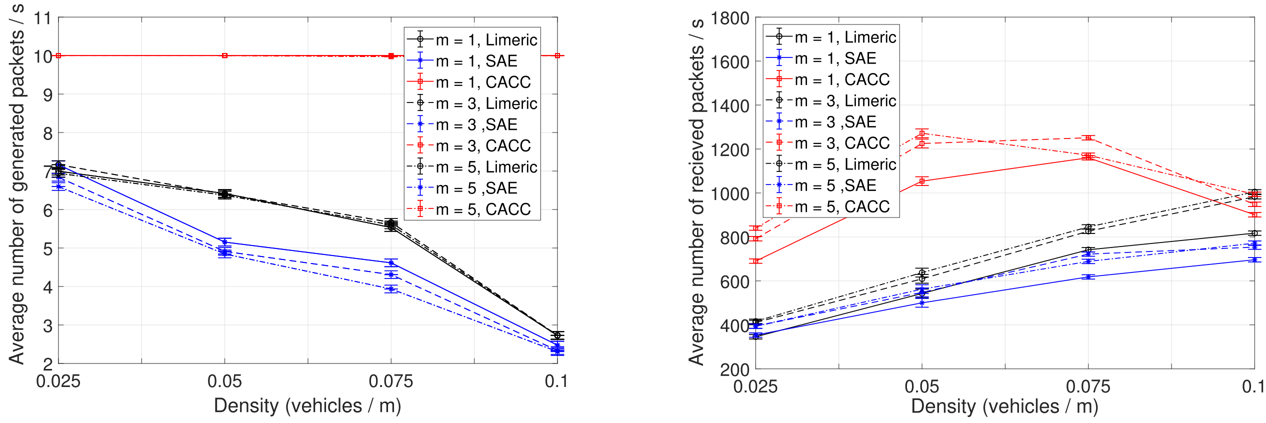
(b) Comparison of PCR



(c) Comparison of the average number of decoded packet

(d) Comparison of CBP

FIGURE 8. **Road topology with 800 vehicles.**



(a) Average number of generated packets

(b) Average number of received packets

FIGURE 9. **Performance results according to vehicle density.**

to CACC because of this lower message rate of LIMERIC and SAE. The relatively high density of 0.025, 0.05, and 0.075 vehicles/m show higher performance than the two algorithms. We can see that the average number of received packets of CACC is more than doubled compared to other algorithms. As a result of reducing the number of collisions and channel errors, CACC shows a higher average number of received packets than other algorithms. However, it is higher than SAE but shows similar performance to LIMERIC at a density of 0.1 vehicles/m. In the case of this LIMERIC, the message rate is set to 2.5 Hz to cope with the collision. On the other hand, CACC of the power was adjusted to 10 mW of the minimum transmit power while maintaining the generation of 10 packets/s. Hence, CACC can receive vehicle information between adjacent vehicles using a high message rate.

Overall, the performance evaluation results discussed here confirm that our proposed CACC algorithm is a simple but effective algorithm to reduce packet error due to collision and channel error. The main safety application of periodic V2V communication is cooperative awareness that road users are informed about each other's position, dynamics and attributes. Among use cases of cooperative awareness, emergency vehicle warning requires a 10 Hz message rate with 90-95 % reliability and 5-96 kbps data rate [1]. As shown in Fig. 7d, we can see that CACC uses a fixed 10 Hz message rate and satisfies the requirements compared to other algorithms. Even in a very crowded vehicle environment as shown in Fig. 8d, it improves reliability by increasing the number of packets that can be successfully decoded up to 6 times compared to existing algorithms by reducing channel collisions and errors with a fixed 10 Hz message rate. The proposed algorithm can greatly increase the performance of periodic safety applications in vehicular CPS.

V. CONCLUSION

Vehicular cyber-physical systems (CPS) employ real-time information exchange among vehicles by periodically broadcasting beacon signals containing vehicle status information. Since vehicle-to-vehicle safety applications heavily rely on timely delivery of status information, resolving packet loss is a critical issue. Since packet loss results from a bad channel as well as from congestion, it is of great importance to distinguish the cause of packet loss in congestion control.

We have proposed the channel-aware congestion control (CACC) algorithm, which can effectively resolve packet loss in vehicular CPS, unlike the conventional distributed congestion control algorithm, which always considers packet loss as an indication of congestion. CACC differentiates the cause of packet loss and reacts in a completely different manner to resolve each type of situation. If the current channel situation is congested, CACC increases the transmission power to reduce hidden node collisions. Additionally, CACC decreases the data rate to fight against a bad channel. Our simulation results have shown that CACC can significantly improve outcomes compared to the conventional distributed congestion control algorithm. We expect that the proposed algorithm can greatly increase the performance of periodic safety applications in vehicular CPS.

As our future work, we will study a technique to estimate channel state using packet loss more accurately in the broadcast environment. Besides, we will study algorithms that can be applied to event-driven V2V safety applications for more advanced vehicular applications.

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