AirComp-aided Safety-aware CAM Broadcast Rate Control in C-V2X Sidelink

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***Abstract*—Promising vehicle-to-everything (V2X) communication technologies can increase road safety by periodically broadcasting Cooperative Awareness Messages (sCAMs) that contain vehicles' status and attribute information, such as time, location, velocity, motion state, and vehicle type, to all nearby vehicles. However, out-of-date information and prediction deviations may cause potential risks and severe vehicle safety problems. In this paper, we propose an efficient safety-aware CAM broadcast rate control algorithm termed DESBRAC for vehicles to consider more safety metrics and determine the CAM broadcast rates cooperatively. Furthermore, we introduce Over-the-Air Computation (AirComp) to help vehicles aggregate information from their nearby vehicles instantly for metric estimation and cooperative CAM broadcast rate determination. Finally, the simulation results based on a simple and a realistic scenarios of vehicular networks show that our algorithm can achieve an improvement of about 31% in driving safety compared to the state-of-the-art algorithms.**

***Index Terms*—Vehicular networks, C-V2X sidelink, congestion avoidance, transmission rate control, over-the-air computation**

I. Introduction

In recent years, vehicle-to-everything (V2X) technology has evolved to facilitate more efficient, reliable, and safe Intelligent Tranportation Systems (sITSs). For V2X transmissions, the most promising standard is Cellular-V2X (C-V2X) defined in 3GPP 14/15/16.[1] C-V2X has two transmission modes, i.e., modes 3 and 4, to respectively support the in-coverage and out-coverage scenarios (i.e., the scenarios with and without base station (BS)) [2], [3]. With C-V2X, each vehicle can broadcast a Cooperative Awareness Message (CAM), which contains its status and attribute information, such as time, location, velocity, motion state, and vehicle type, to the others periodically [4]. In this way, every vehicle can collect others' information to estimate its potential risk and ensure driving safety. To make CAMs up-to-date, the standard [4] specifies that each vehicle should broadcast at least one CAM per second.

However, the design of broadcast mechanisms may encounter three major issues. First, how does a vehicle evaluate the freshness of CAMs? Old CAMs might make a vehicle difficult to be tracked by others and thus cause potential risks. Second, how do the vehicles choose an appropriate CAM broadcast rate to avoid safety risks caused by message congestion and delay? A higher CAM broadcast rate can reduce the distortion of distance prediction but may cause channel congestion. Moreover, channel congestion may deteriorate drastically as the number of vehicles in the same region increases. Third, CAM broadcast rate control in out-coverage scenarios is quite challenging since no BS exists for coordinating CAM broadcasts. Thereby, each vehicle has to compete for wireless resources, which may not be an efficient way for channel efficiency.

To overcome the above issues, in this paper, we innovate a novel system for out-coverage scenarios in C-V2X networks. For the first issue, many related works in the literature suggest employing Age of Information (AoI) [5] to quantify the freshness of information. In addition, Choudhury *et al.* showed that AoI should not be the only metric for risk estimation in time-critical V2X networks since the positions of vehicles with variable speeds are not easy to track [6]. To this end, our system will jointly consider more metrics to secure driving safety (detailed later). Subsequently, our system enables vehicles to adaptively control their CAM broadcast rates according to the estimated risk factors for the second issue. That is, the vehicles with low risk can yield the bandwidth for the others with high risk (i.e., the vehicles that require broadcast more) to avoid congestion. Last, for the third issue, we introduce Over-the-Air Computation (AirComp) [7] into our system. Then, vehicles can aggregate the information sent from the other vehicles in the multi-access channel (MAC) and get the computing result (e.g., the sum or average) within a time slot [8]. Compared to the ordinary way in C-V2X, AirComp can save wireless resources and take less time since vehicles no longer collect each message in a different time slot. Thus, AirComp can improve channel efficiency and lower messages' AoI.

To fully utilize the system, we then propose an efficient Decentralized Safety-aware CAM Broadcast Rate Control Algorithm (DESBRAC) for vehicles to calculate multiple safety metrics based on the information collected fastly via AirComp and determine the CAM broadcast rates cooperatively. With the algorithm, vehicles can efficiently balance the trade-off between information freshness and channel congestion. Finally, we conduct extensive simulations to show that our mechanism can outperform the existing mechanisms by about 31%.

The rest of this paper is organized as follows. Section II reviews the related works. Section III describes the system model. Then, Section IV introduces AirComp into our system. Section V formalizes the optimization problem. Section VI presents the proposed algorithm. Section VII shows the performance of the proposed algorithms with extensive simulation

[1]The other well-known standard is Dedicated Short Range Communication (DSRC) in IEEE 802.11p. However, C-V2X is expected to take over the position of DSRC in the near future after US Federal Communications Commission (FCC) reallocated the latter's bandwidth to other applications in 2020 [1]. Thus, we adopt C-V2X for our system in this paper.

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results. Finally, we conclude this paper in Section VIII.

II. Related Work

The broadcast rate control algorithm for safety messages, such as CAM and Basic Safety Message (BSM), has been extensively studied in vehicular networks to avoid channel congestion for many years. The European Telecommunications Standards Institute (ETSI) standardized a finite state machine based decentralized congestion control algorithm (DCC) to control channel loads [9]. Bansal *et al.* proposed the adaptive BSM message rate control algorithm, LIMERIC, in [10] to evenly distribute bandwidth among vehicles. In [11], Gani *et al.* introduced an algorithm to adjust both the rate and length of messages and organize the CAM transmission sequence. However, these previous works do not take AoI into account and may take a long time to converge, potentially increasing AoI dramatically and decreasing the safety of the vehicle.

Recently, AoI has attracted attention in vehicular networks. Baiocchi *et al.* examined the relationship between AoI, CAM broadcast rate, and the number of vehicles in a vehicular network in [12]. Choudhury *et al.* then proposed the Trackability-aware Age of Information (TAoI) metric in [6], which considers both AoI and self-risk in a V2V network, to improve the rate control algorithm. However, they do not use the edge-cutting technique, AirComp, to help acquire some crucial factors to determine the broadcast rate for safety quickly in C-V2X.

The promising technique, AirComp, has emerged to support fast information aggregation from different nodes in various scenarios. It has been widely used for federated learning in the network edge [13] and in the wireless network control system [14], [15]. Moreover, Li *et al.* adopted AirComp to reduce the Age of Aggregated Information (AoAI) and maintain the freshness of data aggregated in IoT networks [8]. Then, Zhu *et al.* mentioned the potential of using AirComp for distributed consensus control in vehicular networks in [16] but did not pursue further research on this topic. To our best knowledge, there has been limited exploration of the use of AirComp in determining CAM broadcast rate control for C-V2X sidelink, thereby providing the motivation for this paper.

III. System Model

In this section, we introduce the models used in this paper for V2X networks step by step. Section III-A illustrates the C-V2X scenario in this paper. Section III-B reviews the structure and points out the constraints of CAM. Section III-C describes the Tracking Error (TE) to help evaluate road safety. Section III-D defines the AoI to measure the information freshness.

A. C-V2X System Overview

We consider a C-V2X system that consists of a set of vehicles $\mathcal{V}$, each of which is equipped with a C-V2X-supported On-board Unit (OBU) in a road section without BS (i.e., out-of-coverage). Each vehicle $v \in \mathcal{V}$ moves with a certain speed $s_v \in [0, s_v^{max}]$ and communicates with its nearby vehicles with sidelink Particularly, different from traditional systems, we additionally introduce AirComp into our C-V2X system and reserve certain channels as MACs for AirComp to help fast aggregate more crucial safety factors. For ease of reading, we leave the discussion of AirComp later in Section IV-B.

B. Cooperative Awareness Message (CAM)

For safety applications, each vehicle broadcasts CAM to all nearby vehicles [4]. The CAM contains vehicle status and attributes information such as time, location, kinematic parameters (e.g., speed, position), and vehicle type which is defined by the specification [4]. For ease of presentation, we let m denote the size of a CAM packet.

Adaptive broadcast rates can achieve safer driving and more reasonable bandwidth utilization than uniform ones. Specifically, lowering high-risk vehicles' latency is a more efficient way for road safety than shortening all vehicles' latency in the system [6]. As a result, each vehicle should dynamically change the CAM broadcast rate based on the self-estimated potential risk. Let $r_v(t)$ denote the CAM broadcast rate of vehicle v at time t. The CAM broadcast rate is constrained by the channel capacity constraint and specification constraint [4].

For the first constraint, the rate of the CAM is limited by the channel capacity. That is, the rate sum cannot be infinitely large. If the rate sum approaches the channel capacity, the channel will become congested. We assume the total channel capacity of all vehicles is fixed to C, and each vehicle can measure the current channel busy ratio (CBR). The channel capacity constraint indicates that the total rate of the CAM packets transmitted in the channel cannot exceed a certain ratio of the channel capacity (e.g., 60%).[2] Let $CBR^* \in [0,1]$ denote the certain ratio and C denote the channel capacity, and then the channel capacity constraint can be formulated as follow:

$$\sum_{u \in \{v\} \cup \mathcal{V}_v} r_u(t) \leq \frac{CBR^* \times C}{m} = R_C^{max}, \ \forall v \in \mathcal{V}, \forall t \in T \tag{1}$$

where R_C^{max} is the maximum CAM broadcast rate limited by the channel capacity constraint.

For the second constraint, there are many types of CAM specifications for safety requirements [4]. Typically, they specify the maximum and the minimum number of CAMs required broadcasted in one second [18]. Then, the specification constraint can be formulated as follow:

$$r_{spec}^{min} \leq r_v(t) \leq r_{spec}^{max}, \quad \forall v \in \mathcal{V}, \forall t \in T \tag{2}$$

which r_{spec}^{min} and r_{spec}^{max} are the minimum and the maximum CAM broadcast rate, respectively, which are defined in the specification [18].

C. Tracking Error (TE) and Self Tracking Error (Self-TE)

In a vehicular network, each vehicle calculates the possible locations and Tracking Error (TE) of all nearby vehicles based on CAM [19]–[21]. Specifically, to track each nearby vehicle, each vehicle uses a linear extrapolation based on the speed information from the last received CAM to estimate the possible location of the (nearby) vehicle that sent the CAM. Thus, clearly, the position estimation error is the difference between the real position and the estimated location.

However, it is not easy for a vehicle to know the exact real-time positions of the other vehicles in practice [22]. To

[2]Generally, using 60% of channel capacity is practical and efficient in congestion control [17].

overcome the difficulty, following [6], our system also uses an alternative metric, Self Tracking Error (Self-TE), to estimate the potential risk, which is illustrated as follows.

Assume each vehicle v will save the last CAM it broadcasted. Then, it can use the last CAM to predict the possible location (i.e., the coordinate $(x'_{self,v}(t), y'_{self,v}(t))$) estimated by the other vehicles at time t with the following formulas:

$$x'_{self,v}(t) = x_v(t-a) + a \times s_v(t-a), \quad (3a)$$
$$y'_{self,v}(t) = y_v(t-a) + a \times s_v(t-a), \quad (3b)$$

which $a = t - (t-a)$ is the elapsed time since the last CAM was broadcasted at time $t-a$.[3] Then, the Self-TE for vehicle v at time t can be calculated by the following formula:

$$TE_{self,v}(t) = \sqrt{(x_v(t) - x'_{self,v}(t))^2 + (y_v(t) - y'_{self,v}(t))^2}, \quad (4)$$

where $(x_v(t), y_v(t))$ denotes the exact position of vehicle v. Note that each vehicle v can acquire its position precisely via Global Positioning System (GPS). Thus $TE_{self,v}(t)$ can be obtained by vehicle v easier than the TEs of the other vehicles.

D. Age of Information (AoI)

Since the latency of CAM is important in road safety, we import AoI [5] as a metric to evaluate the freshness of CAM. We define the AoI as the elapsed time from the time when the sender vehicle generates the CAM to the current time. Let $AoI_{uv}(t)$ denote the AoI of vehicle u's CAM cached by vehicle v at time t, and it can be calculated by $AoI_{uv}(t) = t - t_{uv}$, where t_u is the last timestamp at CAM sent by vehicle u and received by vehicle v. As each vehicle receives the CAM from all nearby vehicles, we define the AoI of the vehicle v as the average AoI of all nearby vehicles' CAMs at vehicle v at time t. Therefore, the AoI of the vehicle v can be calculated by

$$AoI_v(t) = \frac{1}{|\mathcal{V}_v|} \Sigma_{u \in \mathcal{V}_v} AoI_{uv}(t), \quad (5)$$

which $\mathcal{V}_v$ is the set of neighboring vehicles of vehicle v.

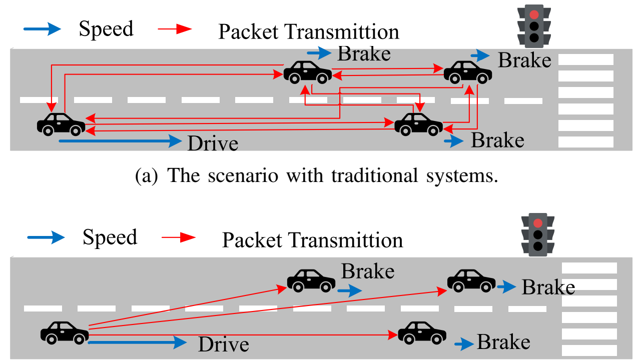
IV. Discussions of C-V2X and AirComp

This section discusses and points out the issues in traditional systems for C-V2X scenarios. Then, we introduce Over-the-Air Computation (AirComp) into our system to solve the problem.

A. Road safety in C-V2X Scenario

The traditional rate control algorithm may face some issues in specific C-V2X scenarios. Let us consider a C-V2X scenario of a road intersection with a traffic light as shown in Fig. 1(a). Vehicles decelerate when the traffic light changes to red while accelerating when it turns green again. Normally, every vehicle at the same intersection and direction would decelerate and accelerate together. Recall the Self-TE defined in Section III-C to measure road safety. Every vehicle has a high Self-TE when the traffic light changes because its speed has to change. Therefore, every vehicle at the intersection with a changing traffic light will be regarded as at higher risk and thus increase

[3]It is also considered as the AoI $AoI_{i,j}(t)$, which will be introduced later in Section III-D.



(a) The scenario with traditional systems.

(b) The scenario with the novel system in this paper.

Fig. 1. Comparisons of traditional systems and our system.

its CAM broadcast rate in traditional systems [6]. Moreover, since an intersection usually consists of at least four lanes with eight different directions, it may merge multiple traffic streams. That is, many vehicles may brake and accelerate at the intersection from multiple streams, leading to a large Self-TE and a high CAM broadcast rate. This means that vehicles may receive more CAMs at the intersection than on the road segment and thus could have a higher possibility of incurring severe channel congestion.

By observations, we can find that although every vehicle's speed changes after the traffic light changes, they may not be all in danger. Vehicles with similar speeds and similar acceleration are not dangerous to each other since their relative speed to each other is kept low. With a low relative speed, each vehicle would have a long Time To Collision (TTC) (i.e, safer) even if the acceleration and Self-TE may not be small. In other words, a vehicle with a much higher relative speed to others has a higher probability to crash other vehicles. Therefore, to mitigate channel congestion, giving each high-relative-speed vehicle a higher CAM broadcast rate is an excellent idea to make other vehicles notice this dangerous vehicle. As shown in Fig. 1(b), increasing only the CAM broadcast rates of high-relative-speed vehicles rather than increasing all the CAM broadcast rates of the vehicles changing their speeds in Fig. 1(a) could significantly avoid severe channel congestion. However, it is not easy for a vehicle to get enough information from many nearby vehicles to evaluate the average speed of nearby vehicles in a possible channel congestion situation. To this end, our system introduces AirComp to avoid exhausting wireless resources and solve this problem elegantly.

B. Over-the-Air Computation (AirComp)

AirComp is a promising wireless transmission technology and has attracted much attention [7]. AirComp exploits multi-source signal superposition to enable fast data collection and computation from concurrent wireless transmissions. With AirComp, every vehicle sends the preprocessed data via the same channel simultaneously, instead of collecting the data one by one via different channels. The channel gain will be the superposition of all signals and can be decoded into the sum of all transmitted data by each receiver vehicle. Moreover, with different pre-process and post-process, vehicles can get different results of computation processes besides summing all data such as average [23]. Therefore, vehicles with AirComp can mitigate channel congestion significantly and further facilitate real-time safety-aware information collection via vehicle-to-vehicle (V2V) communications.[4]

To this end, our system reserves two different MACs in each road section l for vehicles to aggregate and compute two different types of data via AirComp. Assume that the whole AirComp process will be completed within one time slot [8]. The AoI of such AirComp messages is equal to 1 based on Eq. 5 if no transmission failure happens. Thus, generally, it is much less than the AoI of typical CAMs and can be ignored. As a result, it suffices to consider the AoI of the CAM in the following discussion. To instantaneously track the current road status, in our system, each vehicle v sends its speed s_v and its Instant AoI (IAoI) $IAoI_v$ (defined later) respectively via the two reserved MACs in the road, where v is driving, to conduct the AirComp process. Subsequently, each vehicle receives the superposition of speed information of all nearby vehicles on the road section l and then computes their average speed as the average road speed s_l^{ave}. Similarly, each vehicle v receives the sum of IAoI of its nearby vehicles (denoted by $IAoI_v^{agg}$).

In the following, we will discuss s_l^{ave}, $IAoI_v$, and $IAoI_v^{agg}$ in depth in Section IV-C, Section V-A, and Section VI.

C. Road safety

In Section IV-A, we observed that most high-risk scenarios happen on the road, with vehicles having divergent speeds. Since the relative speed is the key parameter to estimate the road risk, we need to get the average road speed of the vehicles timely to calculate the relative speed. As a result, each vehicle in our system adopts AirComp to get the average road speed s_l^{ave} to calculate its relative speed to its nearby vehicles.

Specifically, our system innovates a relative speed metric called AirComp-based Relative Speed (ARS), which is defined as the difference between the vehicle v's speed s_v and the average road speed as follows:

$$ARS_v = |s_v - s_l^{ave}| \tag{6}$$

V. Instant AoI and Problem Formulation

A. Instant AoI (IAoI)

The previous sections have explained how the different factors affect the road safety of a vehicle. Determining the CAM broadcast rate based on the different factors jointly is important for higher safety. In this paper, we propose a new metric called Instant AoI (IAoI) $IAoI$. The IAoI consists of three factors to evaluate the status of our system to meet the high-safety requirement. The three factors are the Self Tracking Error $TE_{self,v(t)}$, Age of Information $AoI_v(t)$, and AirComp-based Relative Speed $ARS_v(t)$. They indicate different kinds of risks to road safety. The factor $TE_{self,v(t)}$ shows the self-position estimation error, the factor $AoI_v(t)$ indicates the freshness of the CAMs received by vehicle v, and the factor $ARS_v(t)$ gives the relative speed information derived via AirComp. They have been discussed in Section III-C, Section III-D, and Section IV-C, respectively.

Specifically, the IAoI for vehicles v at time t is defined as

$$\begin{aligned} IAoI_v(t) = c_{TE} \times TE_{self,v(t)} + c_{AoI} \times AoI_v(t) \\ + c_{ARS} \times ARS_v(t), \end{aligned} \tag{7}$$

where c_{TE}, c_{AoI}, c_{ARS} are the coefficients of the corresponding factors, respectively. The coefficients are the tunable knobs to balance the importance of the different factors.

Intuitively, vehicles have a lower $IAoI$ when they are not in danger. If a vehicle v has a potential risk at time t, the IAoI of vehicle v (i.e., $IAoI_v(t)$) will rise to indicate the risk. We use IAoI as a weight to help determine the CAM broadcast rate. This will be discussed in detail in Section VI.

B. Problem Formulation

Our problem aims to improve safety, information freshness, and channel efficiency with channel capacity and rate constraints. To achieve this goal, the objective function is to minimize the overall $IAoI$ of all vehicles in the system. The overall $IAoI$ can be represented as

$$\text{minimize} \quad \sum_{t \in T} \sum_{v \in \mathcal{V}} IAoI_v(t), \tag{8a}$$

$$\text{subject to} \quad \sum_{u \in \{v\} \cup \mathcal{V}_v} r_u(t) \leq R_C^{max}, \quad \forall v \in \mathcal{V}, \forall t \in T \tag{8b}$$

$$r_{spec}^{min} \leq r_v(t) \leq r_{spec}^{max}, \quad \forall v \in \mathcal{V}, \forall t \in T \tag{8c}$$

where $r_v(t)$ means the CAM broadcast rate of vehicle v at time t. The two constraints, Eq. 8b and Eq. 8c, have been introduced in Section III-B The former is the channel capacity constraint derived from Eq. 1, and the latter limits the minimum and the maximum CAM broadcast rate, similar to Eq. 2.

VI. Decentralized Safety-aware CAM Broadcast Rate Control Algorithm (DESBRAC)

To fit the C-V2X mode 4 environment, where BS is unavailable, this section presents a Decentralized Safety-aware CAM Broadcast Rate Control Algorithm termed DESBRAC. Each vehicle will use the algorithm to dynamically determine the proper CAM broadcast rate r_v^{opt} in a distributed manner. For ease of reading, the pseudocode is presented in Algorithm 1.

Recall that the CAM broadcast rate of the vehicle should be tuned according to the channel capacity and rate constraint (introduced in Section V-B). For the channel capacity constraint, the maximum CAM broadcast rate of the whole channel (i.e., R_C^{max}) can be calculated from Eq. 1:

$$R_C^{max} = \frac{CBR^* \times C}{m} \tag{9}$$

For the specification constraint, we bound the CAM broadcast rate of each vehicle v (i.e., $r_{spec}^{min} \leq r_v^{opt} \leq r_{spec}^{max}$) from the specification. Our system will choose the stricter one from the two CAM broadcast rate constraints.

For vehicles' road safety requirements, we have adopted a novel indicator, iaoi (see Eq. 7), to assist in determining the CAM broadcast rate of each vehicle. A higher iaoi of a vehicle represents a higher risk of the vehicle, encouraging the vehicle

[4]Devices that use AirComp have to synchronize with each other to ensure the signals are aligned properly. To this end, many studies investigated the synchronization techniques in the PHY layer [24]–[26]. Therefore, in this paper, we assume that the synchronization process can be done perfectly.

Algorithm 1 Decentralized Safety-aware CAM Broadcast Rate Control Algorithm

Input: At current vehicle v under consideration at time t, Location $(x,y)_v(t)$, Speed $s_v(t)$, Timestamp of last CAM t', Location in the last CAM $(x,y)_v^{CAM}$, Speed in last CAM s_v^{CAM}, Size of the set of neighboring vehicle of v $|\mathcal{V}_v|$, Channel busy ratio $CBR(t)$, Desire channel busy ratio CBR^*, Channel capacity constraint R_C^{max}, Specification constraints $r_{spec}^{max,min}$, coefficient of IAoI c_{ARS}, c_{AoI}, c_{TE}

Output: New broadcast rate of the current vehicle v r_v^{opt}

1: Aggregate s_l^{ave} via AirComp;
2: Calculate $IAoI_v(t)$ for vehicle v at time t by Eq. 7;
3: Aggregate $IAoI_v^{agg}$ via AirComp;
4: Calculate the maximum broadcast rate of the channel by Eq. 9;
5: **if** $|\mathcal{V}_v| = 0$ **then**
6: $\quad r_v^{opt} := r_{spec}^{min}$;
7: **else**
8: $\quad$ Evaluate the broadcast rate r_v^{opt} for vehicle v by Eq. 10;
9: **return** r_v^{opt};

to claim a higher CAM broadcast rate in our system. However, it is not easy for a vehicle to get the information in other vehicles' CAMs within a short time to derive the sum of the iaoi. Therefore, aircomp is exploited again to aggregate the iaoi of all vehicles (i.e., $IAoI_v^{agg}(t)$) sent from those vehicles simultaneously.

In this way, we can determine the CAM broadcast rate according to the sharing ratio of vehicle v's IAoI to the sum IAoI (i.e., $\frac{IAoI_v(t)}{IAoI_v^{agg}(t)}$) with the formula as follows:

$$r_v^{opt} = r^{min} + (R^{max} - (|\mathcal{V}_v|+1) \times r^{min}) \times \frac{IAoI_v(t)}{IAoI_v^{agg}(t)}. \quad (10)$$

The item r^{min} in Eq. 10 ensures that all vehicles meet the minimum CAM broadcast rate constraint, and r^{min} is equal to r_{spec}^{min} in the specification constraint. Then, the remaining channel capacity is shared by the vehicles according to the sharing ratio. Moreover, R^{max} is chosen from the minimum between R_C^{max} and $(|\mathcal{V}_v|+1) \times r_{spec}^{max}$ to avoid violating the channel capacity and rate constraints. Therefore,

$$r^{min} = r_{spec}^{min} \text{ and } R^{max} = \min\{R_C^{max}, (|\mathcal{V}_v|+1) \times r_{spec}^{max}\}.$$

Each vehicle executes our algorithm every time T_{eva}. The length of T_{eva} may be fixed or dynamic and provided by the system. A shorter T_{eva} will make it possible to change the CAM broadcast rate more timely. We execute the algorithm every time after vehicle v sent the CAM. As a result, we set T_{eva} to r_v^{opt} in our system.

Specifically, the algorithm is detailed as follows: In line 1, each vehicle v aggregate s_l^{ave}, which will be used to calculate $IAoI_v(t)$ in line 2. In line 2, each vehicle v calculates its iaoi (i.e., $IAoI_v(t)$) using Eq. 7. In line 3, each vehicle v aggregate $IAoI_v^{agg}$, which will be used to calculate r^{opt} in line 8, respectively. In line 4, each vehicle v calculates the maximum CAM broadcast rate using Eq. 9. In line 6, for those vehicles with no neighboring vehicle, we set their CAM broadcast rates to the minimum CAM broadcast rate r_{spec}^{min}.

Line 8 calculates r^{opt} by Eq. 10 to guarantee that r^{opt} will not exceed the capacity capacity and specification constraints while increasing the channel utilization.

TABLE I
SUMO TRAFFIC AND NETWORK SIMULATION CONFIGURATION

Type	Parameters	Value
SUMO setting	Number of vehicles	200-600
	SUMO step-length	1 ms
	Traffic scale of LuST scenario	5
	Car-Following Model	CACC
Network setting	CAM size	100 Bytes
	Number of subchannels	1
	Subchannel size	16 RBs
	Carrier frequency	5.9 GHz
	Channel bandwidth	10 MHz
	MCS	7 (QPSK 0.5)
	Transmission Power	20 dBm
Algorithm setting	r_{spec}^{max}	100 Hz
	r_{spec}^{min}	10 Hz
	Desired channel busy ratio CBR^*	0.6
	c_{ARS}	0.2
	c_{AoI}	1
	c_{TE}	10

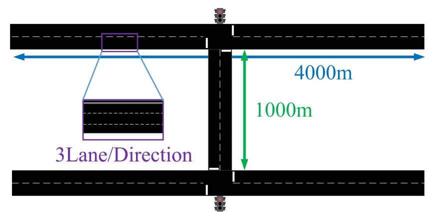


Fig. 2. Map of the simple scenario

Time complexity

The time complexity of Algorithm 1 for each vehicle is $O(1)$. Since the time complexity is low, we can apply the algorithm to any vehicle without concern about the running performance of the onboard computer.

VII. PERFORMANCE EVALUATION

In this section, we implement our algorithm into a C-V2X simulator and conduct extensive simulations to evaluate the performance compared to the state-of-the-art algorithms.

A. Simulation Settings

We compare our algorithm DESBRAC with two state-of-the-art methods to evaluate the performance of our algorithm. One is the baseline algorithm using a fixed CAM period of 10 Hz which is the fastest rate of adaptive DCC in the specification [9]. The other is the TAoI-based rate control algorithm proposed in [6]. The experiments are conducted in the simulated C-V2X networks based on OpenCV2X [27], which is an open-source vehicular simulator with 3GPP standard C-V2X sidelink. OpenCV2X integrates multiple simulators with different purposes, including SUMO [28] for vehicle mobility simulation, and Veins [29] for vehicular networks simulation. For ease of reading, the parameter settings are listed in Table I.

B. Simulation Scenarios

We conduct the simulations in a simple and a realistic scenarios of vehicular networks, respectively. The simple scenario contains two connected T-junctions with traffic lights, and each direction has three lines, as shown in Fig. 2. The realistic scenario extracts a 1000-second rush-hour period from the Luxembourg SUMO Traffic (LuST) Scenario [30] that covers an area of 156 km^2 and 932 km of roads in Luxembourg city.

C. Performance metrics

To evaluate the performance of DESBRAC, we consider the following metrics.

1) Collision Risk (CR): CR measures the number of times a vehicle gets into a dangerous situation. Specifically, CR counts the number of times the vehicle's safety metric (e.g., TTC and Deceleration to Avoid a Crash (DRAC)) violates the threshold.

a) Time To Collision (TTC): TTC is the minimum time-to-collision of two vehicles in a risk event, defined as follows:

$$TTC = \frac{\text{distance between the two vehicles}}{\text{speed difference of the two vehicles}} \tag{11}$$

The larger the TTC was, the less risky the event was.

b) Deceleration to Avoid a Crash (DRAC): DRAC is the maximum deceleration to avoid a crash of two vehicles in a risk event and is defined as follows:

$$DRAC = \frac{1}{2} \times \frac{(\text{speed difference of the two vehicles})^2}{\text{distance bewteen the two vehicles}} \tag{12}$$

Note that the smaller DRAC was, the less risky the event was.

2) Maximum Brake Rate (MBR): The MBR of vehicle v is the maximum brake (i.e., deceleration) that is recorded in the whole simulation. A large MBR often means a sudden brake that may degrade safety and comfort. We average the MBR of all vehicles in the same scenario to indicate the safety and comforts in the scenario.

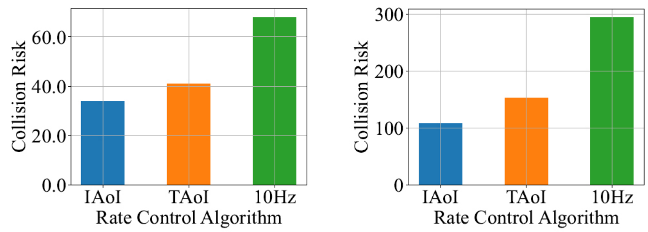
3) Packet Delivery Rate (PDR): The PDR of vehicle v is defined as the percent of the CAMs be received correctly by the vehicles within the broadcast range of v. That is,

$$PDR_v = \frac{CAM_v^{send}}{CAM_v^{recv}}. \tag{13}$$

D. Experimental Results

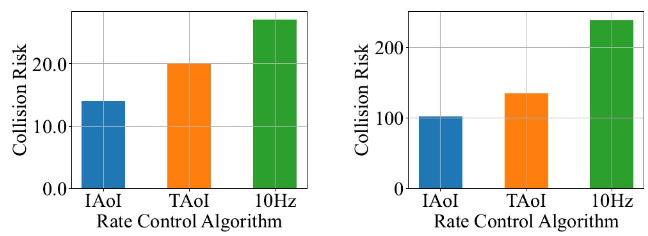
1) Safety analysis: Fig. 3 and Fig. 4 show the effect on the CR of different algorithms by measuring TTC and DRAC as the metrics in the both scenarios, respectively. DESBRAC has a 31% improvement on CR (i.e., a larger TTC and a smaller DRAC) compared to the TAoI-based algorithm and baseline algorithm in both scenarios. This indicates that DESBRAC can achieve better safety than the other algorithms. It is because vehicles with DESBRAC use AirComp to acquire a global view of information and choose an appropriate CAM broadcast rate more efficiently than the other algorithms.

Fig. 5 shows the effect on the average MBR of the different algorithms in both scenarios. Clearly, DESBRAC achieves a lower average MBR than other algorithms since DESBRAC can give more reaction time to vehicles than the others. Therefore, vehicles have more time to brake when a sudden situation happens, which leads to a lower MBR, higher safety, and better comfort. Moreover, DESBRAC can improve the average MBR more significantly than the others in the realistic scenario since the realistic scenario has more complex traffic patterns than the simple one.



(a) Simple scenario (b) Realistic scenario

Fig. 3. TTC of the different algorithms in different scenarios.



(a) Simple scenario (b) Realistic scenario

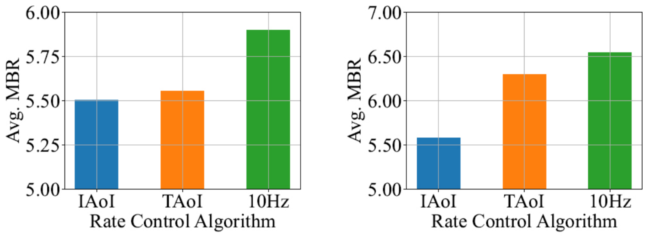
Fig. 4. DRAC of the different algorithms in different scenarios.

2) PDR and channel utilization analysis: Fig. 6 shows the effect on PDR of different algorithms in different transmission distance. The baseline algorithm has a higher PDR compared to DESBRAC and the TAoI-based algorithm, while DESBRAC has a slightly higher PDR than the TAoI-based algorithm. It is because the baseline algorithm does not attempt to utilize more channels to reduce the risk of vehicles. In contrast, DESBRAC can adaptively transmit more CAMs to significantly avoid the risk with an acceptable PDR since it can utilize a desired percent of channels in real-time.

3) Relationship between IAoI and safetey: Fig. 7 shows the relation between IAoI and safety to validate the effectiveness of IAoI. Here we choose DRAC as the safety metric. Each point in this scatter figure represents a vehicle in a simulation. The y-axis represents the maximum DRAC of the vehicle recorded in the simulation and shows the most dangerous event. The x-axis represents the maximum IAoI of the vehicle recorded in the simulation. These two metrics have a positive correlation in the figure. Since the greater maximum DRAC comes to a large dangerous situation, the figure implies that IAoI we proposed have well indicated the dangerous situation.

4) Broadcast rate convergence time analysis: Fig. 8 shows the broadcast period (i.e., the reciprocal of the CAM broadcast rate) within a certain time interval. It shows how long the algorithm takes to change the CAM broadcast rate to a stable value. Clearly, DESBRAC can achieve the appropriate rate immediately, but the TAoI-based algorithm takes almost five seconds on the convergence of the broadcast period. Thus, DESBRAC can give vehicles more time to react to dangerous situations and improve traffic safety significantly.

Fig. 9 shows the frequencies of different average CAM broadcast periods in the realistic scenario. DESBRAC has two peaks. The left one indicates DESBRAC sets a short broadcast period for vehicles to cope with the possibly dangerous situation. The right one implies DESBRAC uses a more extended broadcast period for the less risky vehicles. By doing so,



(a) Simple scenario (b) Realistic scenario

Fig. 5. Average MBR of the different algorithms in different scenarios.

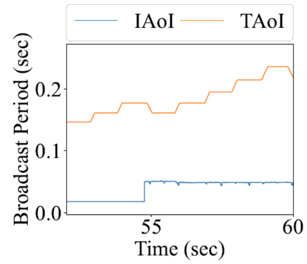


Fig. 8. Broadcast period in the realistic scenario.

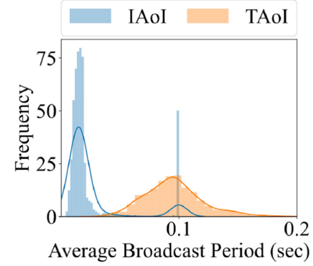


Fig. 9. Average Broadcast period in the realistic scenario.

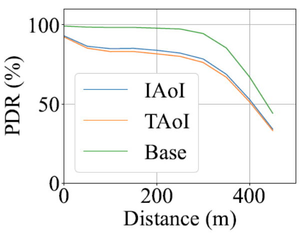


Fig. 6. PDR of the different algorithms

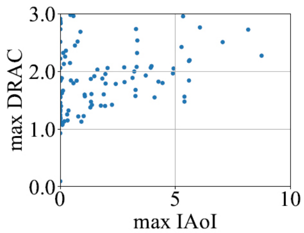


Fig. 7. Relationship between maximum DRAC and maximum IAoI.

vehicles can dynamically adjust their data rates to achieve an appropriate AoI without overwhelming the channels.

VIII. Conclusions

In this paper, we proposed a safety-aware CAM broadcast rate control algorithm that considers multiple metrics, including Self Tracking Error, Age of Information, and AirComp-based Relative Speed, to determine the CAM broadcast rate of each vehicle. To this end, our system model adopted a promising technique AirComp to help vehicles fast aggregate information from the nearby vehicles to get the input required by our algorithm for metric estimation and cooperative CAM broadcast rate determination. Finally, we conducted extensive simulations in both the simple road scenario and the realistic LuST Scenario to show that our rate control algorithm can reduce about 31% of Collision Risk compared with the state-of-the-art algorithms. Moreover, our rate control algorithm with AirComp can converge more efficiently than the existing TAoI-based rate control algorithm.

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