Simulation and Analysis of Vehicle-To-Vehicle (V2V) Communications

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***Abstract*—In this thesis, we mainly focus on the simulation and analysis of vehicle-to-vehicle (V2V) communication based on the DSRC (Dedicated Short Range Communication) system adopting IEEE 802.11 DCF MAC protocol (CSMA/CA). We obtain results that compare the packet delivery ratio and mean packet delay between heavy and low vehicle load scenarios under a fully-connected vehicle network case and a hidden terminal participation case. We also characterize the packet delivery ratio and mean packet delay of safety messages generated with deterministic inter-arrival time and exponential inter-arrival time, respectively. Our analytical model is shown to provide a good match with simulation results. We then study on improvement on DSRC performance, proposing an analytical model of Contention Intensity Control with Rate Control (CICRC). The simulation results we obtained show the packet delivery ratio under CICRC increases nearly 10% compared with that under CSMA (CW=16) in heavy vehicle load scenarios. Average successful packet reception time under CICRC is around 20*ms* lower than CSMA in heavy vehicle loads, which verifies that CICRC improves on CSMA for the DSRC performance especially in heavy vehicle load scenarios.**

***Index Terms*—Dedicated short-range communications (DSRC), medium-access control (MAC), performance analysis and simulations, MAC design, improvement on DSRC performance**

I. INTRODUCTION

Vehicle-To-Vehicle (V2V) communication are a cornerstone of connected vehicles (CV), which are emerging as an important component of the next generation intelligent transportation systems (ITS) [1]. The deployment of connected vehicles, combined with automated driving, is expected to significantly reduce traffic accidents and the resulting economic loss through integrating communications including V2V, Vehicle-To-Infrastructure (V2I), etc. and enabling an awareness of the surrounding traffic environment and events at all vehicles [2]. As an effort of deploying CV, technologies and standards have been actively developed. Dedicated short-range communications (DSRC) has been tested as an enabling technology for V2V and V2I communications [3]. The commercial DSRC systems have not been put into operation widely for V2V communication. Research and development activity increased dramatically among automobile enterprises recently.

DSRC is a high-efficiency wireless communication technology used in smart transportation system. It provides guideline for road safety message transmitted to all vehicles within their transmission range. The DSRC standard is licensed at 5.9 GHz with a 75-MHz spectrum reserved for Vehicular ad-hoc network (VANET) applications. The spectrum is divided into seven 10-MHz channels and a 5-MHz guard band. One of the channels, i.e., channel 78, is called the control channel (CCH) , which is dedicated for safety applications such as collision avoidance application. The other six channels, which are called service channels (SCHs) , will be used for non-safety or commercial applications to make this technology more cost effective. In the DSRC, vehicles should be equipped with sensors and a Global Positioning System (GPS) to collect information about their positions, speed, acceleration, and direction to be broadcasted to all vehicles within their range [4].

In V2V communications for CV applications, the most important component is the broadcast of safety messages. Such broadcast corresponds to the Basic Safety Message (BSM) in the SAE J2735 standard in the US or the Cooperative Awareness Message (CAM) in the ITS standard of European Telecommunications Standards Institute

The Section II and IV(A) are a collaboration between Liu Cao and Jie Hu. The Section I, III, IV(B and V are individually done by Liu Cao.

[5]. The safety messages are single-hop, periodic (i.e., time-driven as opposed to event-driven), and carry safety-related status information of vehicles such as their speed, acceleration, position, and direction. Through the broadcast of the safety messages, vehicles can be aware of each other's status, and traffic accidents can be reduced. As a result, the information conveyed in the safety message broadcast is the foundation to support all V2V safety applications [3]. Meanwhile, safety messages need to be exchanged at a high frequency, e.g., 10 messages per second, to be able to support safety applications in CV. Such a high frequency renders the safety message broadcast the major data traffic load on the DSRC control channel. Therefore, the safety message broadcast is significant in V2V communications in terms of both its importance and its data traffic volume. Accordingly, a protocol for V2V communications should incorporate elaborate designs to support reliable safety message broadcast.

Fig.1 shows the entire carrier sense multiple access (CSMA/CA) procedure applied in IEEE 802.11DCF access on which DSRC is based. Each vehicle prepared to send a packet must sense the channel idle for a period which is known as the distributed interframe space (DIFS). If the channel is sensed busy during this period, the access will be deferred and wait for a complete transmission from the other vehicle. Then a back-off process won't be initiated until the channel becomes idle again for a DIFS. The discrete back-off time is uniformly distributed in the range of the contention window. In the back-off process, a number is randomly selected as the back-off time counter which is then decremented by 1 and the packet starts to be transmitted when counter reaches zero. A collision occurs when the counters of at least two vehicles reach zero in the same slot. The time counter is stopped when a transmission is detected on the channel and will be reactivated after the channel is sensed idle again for a DIFS. Otherwise, if a vehicle senses the channel idle in the first DIFS period, it will occupy the channel and send the packet directly. DSRC safety messages are transmitted in broadcast mode, which means there is no ACK sent after the successful reception of a packet. Thus, the transmitter vehicle is unaware of any packet collision and there is no retransmission or augmentation of the contention window.

The primary goal of emerging DSRC applications are to improve road safety and transportation efficiency. One of the crucial challenges to achieve this goal is the packet loss caused by hidden terminals. Any vehicle within the sensing range of receivers but outside the transmission range of the transmitter vehicle is a hidden terminal.

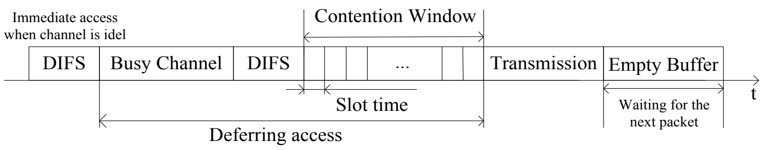


Fig.1: IEEE 802.11 DCF access

In this thesis, we concentrate on MAC layer communication, which mainly focuses on DSRC performance in normal load and heavy load situations by comparing simulations with analytic results under fully connected vehicle network case and hidden terminal participation case, respectively. We also characterize the packet delivery ratio (PDR) and mean delay of the safety messages generated with deterministic inter-arrival time and exponential inter-arrival time. PDR means the probability that a message from the tagged vehicle is successfully broadcasted to all other vehicles in range. Mean delay represents the entire period from the time a packet is generated to the time the packet is successfully delivered. Our objective is to develop a fixed-point approximation to compute the collision probability and the mean end-to-end packet delay experienced by a vehicle.

II. ANALYTICAL MODEL OF V2V COMMUNICATIONS

A. List of Notations for Analytical Model

To formulate our analytical model, the following definitions and notations are introduced first. A list of symbols used in this paper given in Table I.

The Section II and IV(A) are a collaboration between Liu Cao and Jie Hu. The Section I, III, IV(B and V are individually done by Liu Cao.

Tab I: List of main notations

Notation	Definition
R	Transmission/Sensing range (km)
N_{tr}	The average number of vehicles in transmission range of the tagged vehicle
N_{sr}	The average number of vehicles in carrier sensing range of the tagged vehicle
β	The vehicle density (vehicles/km)
ρ	The probability that packets are ready to transmit in the buffer
λ	Safety message rate (messages/sec)
p_b	The probability that the channel is sensed busy
$\{m_k\}$	The counter value of a broadcast vehicle
CW	Contention window
τ	The probability that a vehicle starts to transmit a packet in the back-off process
p_{fcn}	The collision probability for the fully connected vehicle network
T	The duration of transmitting a packet
T_H	The time to transmit the packet headers
δ	The propagation delay
n_c	The average collision number in one concurrent transmission
$E[PA]$	The mean packet length of payload
R_d	Data rate (bits/sec)
D_t	The total delivery delay for a packet
S	The service time of a packet
Q	The queuing delay
A	The access delay
T_{res}	The residual lifetime of an ongoing packet transmission
B	The back-off duration, including periods when the back-off counter is suspended
T_I	The packet inter-arrival time duration
N	The number of discarded packets
K	The number of discarded packets in one transmission.
σ	The duration of a time slot
I	The interruption duration per slot
M	The back-off counter value
N_{ht}	The average number of hidden terminals
E_1	The complement of the event of finding at least one hidden terminal in the transmitting state
E_2	The complement of the event that a packet is generated by the hidden terminal during the tagged vehicle's packet transmission
p_{htc}	The collision probability for the hidden terminal participation
C	The protocol parameter of contention intensity control
$c(k)$	The number of packets contending for channel access measured at the beginning of slot k
$S_{tate}(k)$	The state of slot k
$n_a(k[m])$	The number of packets arrived in slot $k[m]$ measured at the *m-th* slot during a transmission at slot k
$n_a(k)$	The number of packets arrived in slot k measured at the end of the slot k
$n_t(k)$	The number of packets with their back-off counter reducing to 0 at slot k
$b(k[m])$	The value of back-off counter at slot $k[m]$
$B^{\max}(k)$	Maximum back-off counter among all contending packets measured at the beginning of slot k
N_{ss}	The expected number of vehicles of which the packets initially collide
$P_{ss}^{n_{ss}}$	The probability that the vehicles of which the packets initially collide
n_{ss}	The number of vehicles of which the packets initially collide
n_s	The expected number of packets in a busy slot

$P_{C_k}(0)$	The probability that there is no packet contending for the channel access
P_c^l	The probability that l packets collide in one slot
P_I^s	The collision probability occur in slot k in an idle slot
P_B^s	The collision probability occur in slot k in a busy slot
P_c^{UB}	The upper-bound for collision probability
PDR^{LB}	The lower bound for packet delivery ratio
c_i	The expected number of contending packets in steady state
$P_{C_k}(j)$	The probability that there are j packets contending for the channel access
D_{total}^{bs}	The total mean delay of a packet in the busy slots
D_{total}^{is}	The total mean delay of a packet in the idle slots
D_{total}	The overall duration of contending for channel access and transmission of a packet under CIC
c_i^L	The expected number of contending packets in low vehicle load
c_i^H	The expected number of contending packets in heavy vehicle load
N_r	The number of vehicles (slots) from which each vehicle can receive packets
$r_{load}(t)$	The channel load at time t
r_{thre}	The threshold for channel load
γ	The convergence parameter
φ	The adaptive gain factor
$\lambda_{adjusted}$	The adjusted message rate (messages/sec)
ART	The average successful packet reception time from one vehicle

B. Assumptions

Radio communication networks are influenced by many factors. A typical highway topology and its corresponding mapping are described in Fig.2.

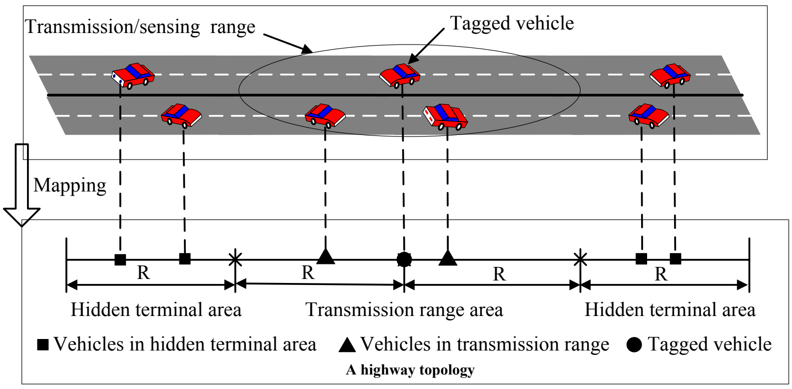


Fig.2: A typical highway topology

Here, we establish some assumptions to have a simplified but reasonable model to explain the real-world vehicle to vehicle communication.

a) As Fig.2 shows, the highway consists of several lanes with vehicles moving in both directions. The vehicles on the highway can be regarded as a collection of statistically identical wireless stations which are stationary during the communication interval in a one dimensional mobile ad hoc network.

b) All vehicles have the equal deterministic transmission range and sensing range R.

c) Each vehicle is assumed to generate packets according to exponential/uniform distribution with rate λ (in packets per second).

d) The collision probability experienced by vehicles is deterministic in the steady state.

e) The propagation delay in the studied transmission range is negligible.

For assumption a), the highway topology does not change significantly during one packet transmission time, and the distance between lanes on the highway is negligible compared with the length of the network.

For assumption b), we choose a vehicle (called the tagged vehicle) and place it in the origin. Apparently, the potential hidden terminal area of the tagged vehicle in broadcast communication is in the range of $\left[R,2R\right]$ and $\left[-2R,R\right]$. Let β denote a vehicle density in vehicles per kilometer on the highway. Let N_{tr} denote the average number of vehicles in transmission range of the tagged vehicle, and let N_{sr} denote the average number of vehicles in carrier sensing range of the tagged vehicle. Hence, we have

$$N_{tr}=N_{sr}=2\beta R. \tag{1}$$

Let N_{ht} denote the average number of vehicles in the potential hidden terminal area:

$$N_{ht}=2\beta R. \tag{2}$$

Assumption c) means if packets are generated with exponential distribution, the arrivals of such packets are Poisson arrivals. Meanwhile, packets with uniform distribution are generated in deterministic interarrivals.

Assumptions c)-e) are common in performance studies of the MAC protocol in mobile wireless and hoc networks, which helps make the analytic model tractable. Because there is no ACK sent after successful or unsuccessful reception of a data packet, the transmitter vehicle is unware of any packet transmission information. Thus, if a packet is collided, there is no subsequent retransmission, which indicates that packet is lost.

For assumption d), each vehicle can be modeled as a $G/G/1$ queue. In this thesis we assume the older packet waiting to be broadcasted in the buffer will be discarded if a new packet is generated and arrives to the buffer. In this case, a packet is also lost for the tagged vehicle because the older packet is discarded in this process.

C. Packet delivery ratio with fully connected vehicle network

In this section, we derive the collision probability in the fully connected network (without participation of hidden terminals). Each vehicle is fully connected and can sense whether the other vehicle is transmitting a packet.

To obtain the collision probability of a safety message, three scenarios will occur when a new packet is generated in a vehicle in the unsaturated network.

a) A packet arrives to an empty buffer and finds the channel idle for a DIFS period.

b) A packet arrives to an empty buffer and finds the channel busy.

c) A packet arrives to a nonempty buffer.

For the first case, the vehicle immediately sends the packet without performing a back-off process. A collision can occur only when another packet is generated at some other vehicles within the propagation delay. Since the propagation delay in the studied transmission range is negligible and the packet is generated with Poisson arrivals, the collision will not happen in the first case. As we describe before, each vehicle is modeled as a $G/G/1$ queue. We define ρ as the probability that there are packets in the buffer ready to transmit, which is expressed as

$$\rho=\lambda E\left[S\right] \tag{3}$$

where $E\left[S\right]$ is the expected service time of a packet. The service time of old packets drop from the buffer will be also included. According to $G/G/1$ queuing theory, the probability that a buffer is empty is given by $1-\rho$. Define p_b as the probability that the channel is sensed busy when a new packet arrives. Assume the event that buffer is empty and the event that channel is sensed idle are independent, the probability of finding an empty buffer and sensing the channel idle is $(1-\rho)(1-p_b)$.

For the second case, the joint probability of a packet arrival to an empty buffer and the channel being busy due to transmission by other vehicles is $(1-\rho)p_b$.

For the third case, the probability of a packet arrival to a nonempty buffer is ρ. For the last two cases, the packet must experience the back-off process before it is transmitted. Since DCF employs a discrete-time back-off scheme, if the back-off process is involved, a vehicle is only allowed to transmit the packet at the beginning of each slot time after an idle DIFS time duration. Therefore, if the tagged vehicle has not gone through the back-off process before transmitting the packet (with probability $(1-\rho)(1-p_b)$), the concurrent transmission will not occur. Otherwise, the packet transmission is synchronized to the beginning of a slot time, and concurrent transmission may occur if other vehicles' transmissions are also synchronized by the back-off process. Thus, collision only occurs between packets which experience the back-off process [6].

We construct a model to characterize back-off counter process in IEEE 802.11 broadcast network. The back-off counter process, a stochastic process $\{m_k\}$ which indicates the counter value of a broadcast vehicle, is a one-dimensional discrete-time Markov chain, the state transition diagram which describing back-off counter decrement is shown in Fig.3.

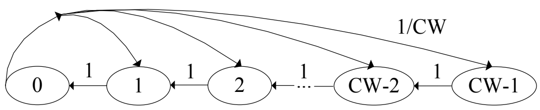


Fig.3: Markov chain model for IEEE 802.11 broadcast

The only non-null one-step transition probabilities being

$$\begin{cases} P(m_k \mid m_{k+1}) = 1 & k \in [0, CW-2] \\ P(m_k \mid 0) = 1/CW & k \in [0, CW-1] \end{cases} \tag{4}$$

where CW represents the contention window. We can then derive the following relations through chain regularities

$$\begin{cases} m_k = \dfrac{CW-k}{CW} m_0 \\ \sum\limits_{k=0}^{CW-1} m_k = 1 \end{cases} . \tag{5}$$

Let τ be the probability that a vehicle starts to transmit a packet in the back-off period. Because when the back-off counter value reaches zero, the transmission will occur [7], we can solve Equation (5) to get

$$\tau = m_0 = \frac{2}{CW+1} . \tag{6}$$

For any vehicle other than the tagged vehicle, the probability of transmitting a packet given that the last two cases is $\rho\tau$. A collision occurs when $N_{tr}-1$ vehicles in its transmission range area transmit in the same slot as the tagged vehicle given that the vehicle sees either of the last two cases [8]. Hence, the collision probability for the fully connected vehicle network case can be obtained by

$$p_{fcn} = \left(1-(1-\rho)(1-p_b)\right)\left(1-(1-\rho\tau)^{N_{tr}-1}\right). \tag{7}$$

Apparently, the PDR is

$$PDR = 1 - p_{fcn} . \tag{8}$$

Furthermore, we can derive the probability p_b that the channel is sensed busy when a new packet arrives,

$$p_b = (N_{tr}-1)\lambda T\left(1 - \frac{n_c - 1}{n_c} p_{fcn}\right) \tag{9}$$

where T is the deferred time, namely the duration of transmitting a packet. n_c is the average collision number in one concurrent transmission. When the channel is detected busy, the back-off time counters of the detecting vehicles will be suspended and deferred a period of time T which is expressed as

$$T=\frac{E[PA]}{R_d}+T_H+DIFS+\delta \tag{10}$$

where $E[PA]$ is the mean packet length of payload and R_d is the data rate. Hence, $E[PA]/R_d$ is the time to transmit a packet. T_H is the time to transmit the packet header including physical layer header and MAC layer header. δ is the propagation delay, in this paper, $\delta=0$.

Equation (9) is obtained based on the traffic load. Due to $N_{tr}-1$ vehicles other than the tagged vehicle transmitting λ packets per second, if there is no collision, all the packet transmissions should take $(N_{tr}-1)\lambda T$ per second. However, with collision probability p_{fcn}, $(N_{tr}-1)\lambda p_{fcn}$ packets will be involved in collision. If we consider the collision is always among two packets, the transmission time to send the collided packets would be $(N_{tr}-1)\lambda T p_{fcn}/2$.

D. Expression for the packet delivery delay

The total delay experienced by a packet of a tagged vehicle includes access delay and the whole time to transmit a packet. The access delay is defined as the time interval between the instant the packet reaches the head of the queue and the instant when the packet transmission starts. We define the total delivery delay for a packet is D_t, which is expressed as

$$D_t=Q+S=Q+A+T \tag{11}$$

where Q and A are random variables (r.v.'s) indicating the queuing and access delay. Because the packet waiting to be transmitted in the buffer will be discarded when a new packet is generated and arrives at the buffer, the queuing delay in this paper is 0. T is the duration of transmitting a packet. The service time of a packet in the buffer is the sum of access delay A and transmission delay T. According to the three scenarios illustrated above, access delay is classified as,

a) A new packet arrives to an empty buffer and finds the channel idle with probability $(1-\rho)(1-p_b)$. The access delay is zero because the tagged vehicle transmits the packet without back-off process.
b) A new packet arrives to an empty buffer and finds the channel busy with probability $(1-\rho)p_b$. The vehicle needs to wait for the ongoing packet transmission and then perform a packet process.
c) A new packet arrives to a nonempty buffer with probability ρ, the older packet staying in the buffer will be discarded. Then the new packet also needs to wait for the ongoing packet transmission and then performs a packet process. If the most recent packet experiences the process when several packets are discarded and is then transmitted, the delay of this packet includes those discarded packets' delay.

According to the illustration above, the access delay in the three cases can be expressed as respectively,

$$A=\begin{cases} 0 & w.p.\ (1-\rho)(1-p_b) \\ B+T_{res} & w.p.\ (1-\rho)p_b \\ NT_I+B+T_{res} & w.p.\ \dfrac{\rho^N(1-\rho)}{1-\rho^K}\ (1\le N\le K) \end{cases} \tag{12}$$

where T_{res} is the residual lifetime of an ongoing packet transmission; B is the back-off duration, including periods when the back-off counter is suspended; T_I is inter-arrival time duration. For deterministic inter-arrival time, $T_I=100ms$, and for exponential inter-arrival time, apparently, T_I is a random variable. N is the number of discarded packets. K is the number of discarded packets in one transmission.

When a packet is in the back-off process, every slot can be interrupted by successful transmissions or concurrent transmissions. During the interruption, the back-off counter is suspended. When the back-off counter is resumed, it starts from the beginning of the interrupted slot after deferring for a DIFS period. Thus, the back-off duration T is a random sum, which can be expressed as,

$$B=\sum_{n=1}^{M}\left(\sigma+I\right) \tag{13}$$

where σ is the duration of a back-off slot, I is the interruption duration per slot, and M is the back-off counter value, which is uniformly distributed in the range $\left[0,CW-1\right]$. If no other vehicle transmits in a given slot, an interruption does not occur, which indicates I of the tagged vehicle is equal to zero. A back-off slot of the tagged vehicle is interrupted when any of the other $N_{tr}-1$ vehicles transmit in that slot with probability $1-\left(1-\rho\tau\right)^{N_{tr}-1}$. Hence, I is obtained as,

$$I=\begin{cases}0 & w.p.\ \left(1-\rho\tau\right)^{N_{tr}-1}\\ T & w.p.\ 1-\left(1-\rho\tau\right)^{N_{tr}-1}\end{cases} \tag{14}$$

where $\left(1-\rho\tau\right)^{N_{tr}-1}$ is the probability that a slot is idle due to no transmission by other vehicles.

E. Mean and variance of delay

In this section, the mean and deviation of delay is derived. From Equation (11), since A and T are independent, we can write

$$E\left[S\right]=E\left[A\right]+E\left[T\right] \tag{15}$$

$$Var\left[S\right]=Var\left[A\right]+Var\left[T\right] \tag{16}$$

Where $E\left[X\right]$ and $Var\left[X\right]$ is the mean and variance of r.v. X.

Assume packet length are fixed for all vehicles, T is a constant.

$$E\left[T\right]=T \tag{17}$$

$$Var\left[T\right]=0. \tag{18}$$

From equation (12), the mean and variance of A can be expressed as,

$$E\left[A\right]=\left(\left(1-\rho\right)p_b+\rho\right)\left(E\left[B\right]+E\left[T_{res}\right]\right)+\frac{\left(1-\rho\right)}{\lambda\left(1-\rho^K\right)}\sum_{N=1}^{K}N\rho^N \tag{19}$$

$$\begin{aligned}Var\left[A\right]&=\left(1-\rho\right)\left(1-p_b\right)E\left[A\right]^2+\left(1-\rho\right)p_b\left(Var\left[B\right]+Var\left[T_{res}\right]+\left(E\left[A\right]-E\left[B\right]-E\left[T_{res}\right]\right)^2\right)\\&+\left(1-\rho\right)\sum_{N=1}^{K}\rho^N\left(N^2Var\left[T_I\right]+Var\left[B\right]+Var\left[T_{res}\right]+\left(E\left[A\right]-\frac{N}{\lambda}-E\left[B\right]-E\left[T_{res}\right]\right)^2\right)\end{aligned} \tag{20}$$

where for deterministic inter-arrival time, $Var\left[T_I\right]=0$, and for exponential inter-arrival time, $Var\left[T_I\right]=\frac{1}{\lambda^2}$. K is the maximum number of discarded packets in one transmission.

For exponential inter-arrival time, the interval between the starting time of an ongoing transmission and the arrival of a new packet at the tagged vehicle follows a memoryless exponential distribution with rate λ. Define this interval as $X\ \ 1-e^{-\lambda t}$. Hence, the distribution of T_{res} is represented as the remaining transmission time $Z=T-X$, which is conditioned on $X\le T$. The probability distribution function of Z can be expressed as $F_Z\left(z\right)=1-F_X\left(T-z\right)$. Conditioned on $X\le T$, we get

$$F_{Z|X\le T}\left(z\right)=1-F_{X|X\le T}\left(T-z\right)=\frac{e^{-\lambda\left(T-z\right)}-e^{-\lambda T}}{1-e^{-\lambda T}}. \tag{21}$$

Differentiating Equation (21), we obtain the probability density function as

$$f_{Z|X\le T}(z)=\frac{\lambda e^{-\lambda(T-z)}}{1-e^{-\lambda T}}. \tag{22}$$

Then, the mean and variance of T_{res} can be obtained

$$E[T_{res}]=E[Z|X\le T]=\int_0^T z f_{Z|X\le T}(z)dz=\frac{T}{1-e^{-\lambda T}}-\frac{1}{\lambda} \tag{23}$$

$$E\left[T_{res}^2\right]=E\left[Z^2|X\le T\right]=\int_0^T z^2 f_{Z|X\le T}(z)dz=\frac{\lambda T^2-2T}{\lambda\left(1-e^{-\lambda T}\right)}+\frac{2}{\lambda^2} \tag{24}$$

$$Var[T_{res}]=E\left[T_{res}^2\right]-E[T_{res}]^2=\frac{1}{\lambda^2}-\frac{T^2e^{-\lambda T}}{\left(1-e^{-\lambda T}\right)^2}. \tag{25}$$

For deterministic inter-arrival time, T_{res} follows uniform distribution. The mean and variance of T_{res} can be obtained as,

$$E[T_{res}]=\frac{T}{2} \tag{26}$$

$$Var[T_{res}]=\frac{T^2}{12}. \tag{27}$$

Next, the mean and variance of total back-off duration can be expressed according to well-known identities.

$$E[B]=(\sigma+E[I])E[M] \tag{28}$$

$$Var[B]=Var[I]E[M]+(\sigma+E[I])^2\,Var[M]. \tag{29}$$

As M is a r.v. that is uniformly distributed in the range $[0,CW-1]$, we can get

$$E[M]=\frac{CW-1}{2} \tag{30}$$

$$Var[M]=\frac{(CW-1)^2}{12}. \tag{31}$$

For interruption time I, the mean and variance are expressed as

$$E[I]=\left(1-(1-\rho\tau)^{N_{tr}-1}\right)T \tag{32}$$

$$Var[I]=\left(1-(1-\rho\tau)^{N_{tr}-1}\right)\left((1-\rho\tau)^{N_{tr}-1}\right)T^2. \tag{33}$$

According to Equation (15)-(33), we can derive the mean and variance of service time in term of p_b and ρ, Equation (3), (7), (9), (15) constitute a nonlinear system of equations that can be solved to compute ρ, p_b, p_{dc}, $E[S]$. Due to the queuing delay equal to 0, the mean delay is given by

$$E[D_t]=E[S]. \tag{34}$$

F. Packet delivery ratio with hidden terminal.

In this section, we will study the PDR in the hidden terminal case. Two necessary conditions must be satisfied to avoid collision between the packets from hidden terminals and from the vehicles in the transmission range. First, when tagged vehicle starts to transmit the packet, none of its hidden terminals are transmitting a packet or deferring for a DIFS period with an immediate packet transmission, which is denoted by E_1. Second, after the tagged vehicle starts its transmission conditioned on E_1, none of the hidden terminals starts transmitting until the tagged vehicle finishes its transmission. This event is denoted by E_2.

As there are N_{ht} hidden terminals transmitting λ (in packets per second), if there is no collision, it will take $N_{ht}\lambda T$ time each second for all packets' transmission. However, due to collisions among the hidden terminals, some packet transmissions will overlap. With the collision probability of p_{fcn} in the fully connected network, there are $N_{ht}\lambda p_{fcn}$ overlapping packets. If we only consider collisions among two packets from hidden terminals, the transmission time to send the collided packets would be $N_{ht}\lambda T p_{fcn}/2$. Note the event E_1 is the complement of the event of finding at least one hidden terminal in the transmitting state. We denote this complementary event by $\bar{E}_1$. Hence, the probability of event E_1 can be obtained:

$$P(E_1) = 1 - P(\bar{E}_1) = 1 - N_{ht}\lambda T\left(1 - p_{fcn}/2\right). \tag{35}$$

For the event E_2, we need to calculate the probability that a packet is generated by the hidden terminal after the tagged vehicle starts its transmission and collided with the transmission of tagged vehicle. Note that packets generated at the hidden terminal in the last time portion (a DIFS period) of the tagged vehicle's transmission will not collide with packets from tagged vehicle because packet transmissions will defer a DIFS period when they are generated at hidden terminal. Since packet arrival at each vehicle's buffer is based on the Poisson process, the combined packet arrival from all the hidden terminals is also a Poisson with rate λN_{ht} (in packets per second). Therefore, the event E_2 will meet the condition if no packet is generated at any of the hidden terminals during $T - 2DIFS$ period. Note the event E_2 is the complement of the event that a packet is generated by the hidden terminal during the tagged vehicle's packet transmission. We denote this complementary event by $\bar{E}_2$. Hence, the probability of event E_2 can be obtained:

$$P(E_2) = 1 - P(\bar{E}_2) = 1 - \left(1 - e^{-\lambda N_{ht}(T - 2DIFS)}\right) = e^{-\lambda N_{ht}(T - 2DIFS)} \quad . \tag{36}$$

Similarly, for deterministic inter-arrival time, the event E_2 will meet the condition if no packet is generated at any hidden terminal during $T - 2DIFS$ period conditioned on the inter-arrival time. Hence, the probability of event E_2 can be obtained.

$$P(E_2) = \left(1 - \lambda(T - 2DIFS)\right)^{N_{ht}}. \tag{37}$$

Since the collision for fully connected vehicle network and the collision due to hidden terminals are independent of each other, the collision probability for the hidden terminal participation case can be expressed as,

$$p_{htc} = 1 - \left(1 - p_{fcn}\right) \cdot P(E_1) \cdot P(E_2). \tag{38}$$

Based on the illustration above, the new PDR for the hidden terminal case can be expressed as,

$$PDR = 1 - p_{htc}. \tag{39}$$

III. IMPROVEMENT ON DSRC PERFORMANCE

The objective of this section is to develop a distributed scheme for safety message broadcast that improves the performance substantially compared to the CSMA protocol under fully connected vehicle network. We propose a CICRC (Contention Intensity Control with Rate Control) scheme to improve the performance of safety message broadcast (in this section, the packet inter-arrival time is deterministic). We will demonstrate that CICRC scheme leads to a very different system model and a different underlying cause of packet collision compared to CSMA. The term *contention intensity* refers to the number of safety messages that are either waiting for channel access or currently transmitting at a given instant. Rate Control is mainly used in high vehicle load, which is mainly aimed to avoid the saturated system. We will also discuss the results based on the CICRC and CSMA with Rate Control respectively in high vehicle density scenarios load later.

A. Contention Intensity Estimation

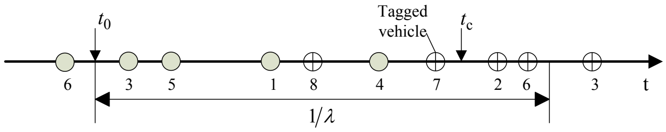


Fig.4 Contention intensity estimation

Fig.4 shows how a vehicle estimates the contention intensity when it has a packet ready to transmit. It can be applied for all the vehicles involved in this system. Suppose there are 8 vehicles within each other's transmission/sensing range. We take vehicle 7 as the tagged vehicle in this example. Vehicle 7 maintains a timeline and marks the instants at which each vehicle in its transmission range generates a safety message (hollow circles) based on the safety messages received in previous cycle. When a new safety message is received from a neighbor vehicle, the corresponding mark (solid circles) is changed to indicate that the message is no longer contending for channel access in the current cycle. Then, the packets that have been generated by neighbors and not yet received from the beginning of the current cycle t_0 to the current time instant t_c are contending for channel access. Counting the number of such packets gives the instantaneous contention intensity. The beginning of packet cycles should be aligned at all vehicles. For example, the beginning can be determined based on the GPS time.

B. CIC Model

The MAC layer design of Contention Intensity Control (CIC) is based on CSMA and inherits the slot based structure with carrier sensing, the back-off counter and the DIFS. The only and key modification in the MAC layer of CIC is regarding how the initial back-off counter of a packet is determined. In the CIC, the initial back-off counter is determined based on the contention intensity as opposed to a random selection in CSMA [9].

For each new packet, it initial back-off counter is set to C times the contention intensity (including itself), where the protocol parameter C is a positive integer. The above access strategy is illustrated in Fig.5. As Fig.5 (a) shows, a collision happens when two packets arrives at the same time slot before their back-off process. In this case, the collision must happen at the slot $k+nC$, where $n \in \{1,2,3...\}$.

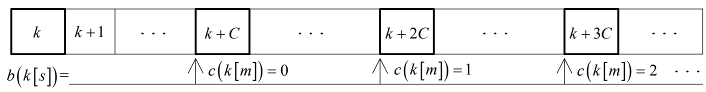


Fig.5 (a) Collision occurs at slot $k+nC$

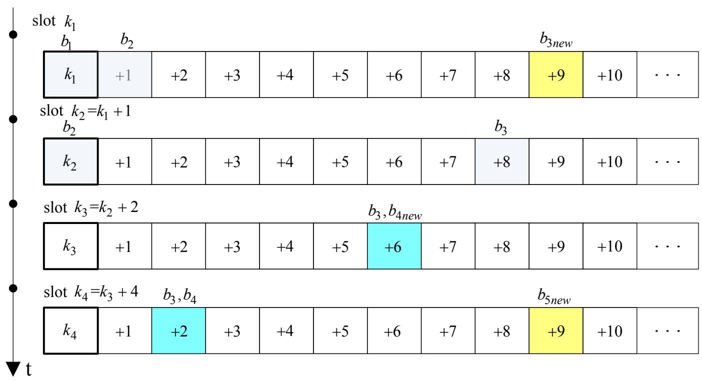


Fig.5 (b) Collision occurs when contention intensity reduces

In the second case shown as in Fig.5 (b), a packet collision can only happen when the contention intensity goes down. If the number of packets contending for channel access is constant or steadily increasing, a collision will not occur. In fig.5 (b), we assume C=3 , b_i represents the back-off counter of the ith contending packet and b_{inew} represents the initial back-off counter of the ith contending packet. At slot k_1, there are two packets (b_1 and b_2) contending for the channel access, so the initial back-off counter for new arriving packet b_{3new} is set to 9. At slot k_3, when the back-off counter of b_3 reduces to 6 and the contention intensity reduces to 2, the initial back-off counter for new arriving packet b_{4new} is set to 6, so two packets fall into the same time slot and the collison will occur. We will discuss two cases above with more details later.

Denote the number of packets contending for channel access measured at the beginning of slot k as $c(k)$. Let $S_{tate}(k)=1$ and $S_{tate}(k)=0$ represent the events that slot k is busy and idle. If slot k is busy, the back-off counter of packets contending for channel access will be frozen and new packets will arrive at slot $k[m]$ ($1 \le m \le T/\sigma$). If slot k is idle, new packets will arrive at slot $k[1]$. The initial back-off counter of a packet arriving at slot $k[m]$ depends on the instantaneous contention intensity $b(k[s])$ which is denoted as the entry point of this packet. Denote the number of packets that arrived in slot $k[m]$ measured at the *m-th* slot during a transmission at slot k as $n_a(k[m])$ and the number of packets that arrived in slot k measured at the end of the slot as $n_a(k)$. Denote the number of packets with their back-off counter reducing to 0 in slot k as $n_t(k)$. The system implementing the CIC is governed by the following rules:

$$c(k+1)=c(k)+\sum_{m\in S_k} n_a(k[m])-n_t(k) \tag{40}$$

$$b(k[s])=C\left(c(k)+\sum_{m=1,m\in S_k}^{s-1} n_a(k[m])S_{tate}(k)+n_a(k[s])\right) \tag{41}$$

$$S_{tate}(k+b(k[m]))=1 \ \ , if\ n_a(k[m])>0 \tag{42}$$

where C is CIC protocol parameter. If $S_{tate}(k)=1$, $s\ge 2$, if $S_{tate}(k)=0$, $s=1$. Equation (40) characterizes the change in the contention intensity after a slot. Equation (41) characterizes the proposed back-off counter selection rule based on the contention intensity. Equation (42) reflects the consequence of the back-off counter selection on the system status at a future time instant. In our analytical model, the event that more than one packet arrives in a time slot (16us in this paper) can be neglected as the probability of such an event is very small. Correspondingly, $n_a(k[m])$ is equal to either zero or one.

To study the PDR and mean delay of CIC, we first study another important parameter: Packet-to-Slot (PTS) ratio. It is introduced to represent the number of simultaneously contending packets over the number of slots that accommodate the back-off counters of these contending packets. In the case of CSMA, the PTS can be simply defined as the number of packets in the fixed range $[0, CW-1]$ divided by W, where W is the contention window. In the CIC, there is no contention window and both the number of packets and the range of their back-off counters vary over time. The PTS measured at the end of slot $k[m]$ is defined as follows:

$$PTS(k[s])=\frac{c(k)+\sum_{m=1,m\in S_k}^{s-1} n_a(k[m])S_{tate}(k)+n_a(k[s])}{\max\left\{B^{\max}(k),\ b(k[s])\right\}} \tag{43}$$

where $B^{\max}(k)$ represents maximum back-off counter which is among all contending packets measured at the beginning of slot k. The maximum back-off counter can be obtained by

$$B^{\max}(k+1)=\begin{cases}\max\left\{B^{\max}(k)-1,\,0\right\} & if \sum_{m\in S_k} n_a\left(k[m]\right)=0\\ \max\left\{\max_{m\in S_k}\left\{b\left(k[m]\right)\right\},B^{\max}(k)\right\}-1 & otherwise\end{cases}. \tag{44}$$

For the first case, we will study the expected number of vehicles which initially generates a packet at the same slots and its probability. Denote the number of vehicles of which the packets initially collide is n_{ss}. Denote the expected number of vehicles of which the packets initially collide is N_{ss} and its probability is $P_{ss}^{n_{ss}}$. Here, we assume each collision only occurs between two packets ($n_{ss}=2n,\ 1\le n\le\frac{N_{tr}}{2}$). Thus, the probability $P_{ss}^{n_{ss}}$ can be obtained by

$$P_{ss}^{n_{ss}}=\frac{\left(\frac{1}{\lambda\sigma}\right)!\binom{N_{tr}}{n_{ss}}\prod_{i=2n-1}\left(n_{ss}-i\right)}{\left(\frac{1}{\lambda\sigma}\right)^{N_{tr}}\left(\frac{1}{\lambda\sigma}-\left(N_{tr}-\frac{n_{ss}}{2}\right)\right)!}\ ,\quad \left(n_{ss}-i>0 \text{ and } n=1,2,3...\right) \tag{45}$$

where $\frac{1}{\lambda\sigma}$ means the number of slots from which all vehicle randomly select within $\frac{1}{\lambda\sigma}$. According to the probability $P_{ss}^{n_{ss}}$, we can get N_{ss}

$$N_{ss}=\sum_{n_{ss}=2n} n_{ss}P_{ss}^{n_{ss}}\ ,\ \left(1\le n\le\frac{N_{tr}}{2}\right). \tag{46}$$

Since there are N_{ss} vehicles of which the packets initially collide, we can get the $N_{tr}-\frac{N_{ss}}{2}$ different time slots taken by vehicles. Given $N_{tr}-\frac{N_{ss}}{2}$, λ, C, we study the expected value of $PTS\left(k[s]\right)$ in a steady state, denoted as PTS. Since the expected change of $c(k)$ in one slot is

$$E\left\{\Delta c(k)\right\}=\begin{cases}\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\sigma & if\ S_{tate}(k)=0\\ \lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)T-n_s & if\ S_{tate}(k)=1\end{cases} \tag{47}$$

where σ is the duration of a time slot. T is the duration of transmitting a packet, including the payload, the header and a DIFS. n_s is the expected number of packets in a busy slot, i.e., the expected $n_t(k)$ in the Equation (40). The probability of a slot being idle and busy are given respectively by

$$P\left(S_{tate}(k)=0\right)=P_{C_k}(0)+\left(1-P_{C_k}(0)\right)\left(1-PTS\right) \tag{48}$$

$$P\left(S_{tate}(k)=1\right)=PTS\cdot\left(1-P_{C_k}(0)\right) \tag{49}$$

where $P_{C_k}(0)$ represents the probability that $c(k)$ is equal to 0. In the steady state, the expected change of $c(k)$ should be equal to 0, so based on Equation (47), (48) and (49), it must hold that

$$\left(P_{C_k}(0)+\left(1-P_{C_k}(0)\right)\left(1-PTS\right)\right)\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\sigma+PTS\cdot\left(1-P_{C_k}(0)\right)\left(\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)T-n_s\right)=0 \tag{50}$$

which leads to

$$PTS = \frac{\lambda\left(N_{tr} - \frac{N_{ss}}{2}\right)\sigma}{\left(1-P_{C_k}(0)\right)\left(n_s - \lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)(T-\sigma)\right)}. \tag{51}$$

The expected number of packets in a busy slot n_s is greater than 1 due to the probability of packet collision. The probability that l packets collide in one slot P_c^l given by

$$n_s = 1 + \sum_l (l-1)P_c^l. \tag{52}$$

If we neglect the case where more than two packets collide, Equation (50) leads to

$$n_s = 1 + P_c. \tag{53}$$

We then study the PDR of CIC. For an arbitrary k, a collision occurring in a slot follows necessary conditions:

a) There is at least one contending packet, i.e., $c(k) > 0$.

b) The entry point at the current mini-slot $b(k[s])$ is not greater than maximum back-off counter $B^{\max}(k+1)$, i.e., $b(k[s]) \le B^{\max}(k+1)$.

c) There is a new packet arrival in slot k, i.e., $n_a(k) > 0$.

The probabilities that the above conditions are satisfied are given as follows

a) $1 - P_{C_k}(0)$

b) PTS when $b(k[s]) \le B^{\max}(k+1)$ and 0 when $b(k[s]) > B^{\max}(k+1)$

c) $1-(1-\lambda\sigma)^{N_{tr}-\frac{N_{ss}}{2}}$ when slot k is idle and $1-(1-\lambda T)^{N_{tr}-\frac{N_{ss}}{2}}$ when slot k is busy.

Thus, the collision probability occur in slot k is upper-bounded in an idle slot by

$$P_I^s = PTS\cdot\left(1-P_{C_k}(0)\right)\left(1-(1-\lambda\sigma)^{N_{tr}-\frac{N_{ss}}{2}}\right) \tag{54}$$

and is upper-bounded in a busy slot by

$$P_B^s = PTS\cdot\left(1-P_{C_k}(0)\right)\left(1-(1-\lambda T)^{N_{tr}-\frac{N_{ss}}{2}}\right). \tag{55}$$

Since each packet corresponds to $1/PTS$ equivalent exclusive slots on average, with 1 busy slot and $1/PTS-1$ idle slots. Therefore, the collision probability for a packet is upper-bounded by

$$P_c^{UB} = P_B^s + \left(\frac{1}{PTS}-1\right)P_I^s = PTS\cdot\left(a_T - a_\sigma\right) + a_\sigma \tag{56}$$

where $a_\sigma = \left(1-P_{C_k}(0)\right)\left(1-(1-\lambda\sigma)^{N_{tr}-\frac{N_{ss}}{2}}\right)$, $a_T = \left(1-P_{C_k}(0)\right)\left(1-(1-\lambda T)^{N_{tr}-\frac{N_{ss}}{2}}\right)$.

Using the Equation (51) and (53), the upper-bound of collision probability is given by

$$P_c^{UB} = \frac{\left(a_\sigma + \lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)(T-\sigma)-1\right) + \sqrt{\left(a_\sigma + \lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)(T-\sigma)-1\right)^2 + 4\left(a_\sigma\left(1-\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)(T-\sigma)\right) + \frac{\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\sigma\left(a_T-a_\sigma\right)}{1-P_{C_k}(0)}\right)}}{2}. \tag{57}$$

Thus, the lower bound of PDR can be obtained based on the first case and the second case:

$$PDR^{LB} = 1 - \left(1 - \frac{N_{ss}}{N_{tr}}\right) P_c^{UB} - \frac{N_{ss}}{N_{tr}}. \tag{58}$$

Then, we derive the mean delay for a packet in CIC, according to $b(k[m]) = C(c(k[m])+1)$, the expected entry point in steady state can be obtained by

$$b_s = C \sum_{j=0}^{N_{tr}-\frac{N_{ss}}{2}} P_{C_k}(j)(j+1) = C(c_i+1) \tag{59}$$

where c_i means the expected number of contending packets in steady state and $P_{C_k}(j) = P(c(k[m]) = j)$. When there are $c(k[m]) = j > 1$ existing packets, the average number of transmissions a new packet experience till the completion of its own transmission is $1 + j - \frac{1}{2}$ where 1 is its own transmission and $-\frac{1}{2}$ means the transmitting packet is regarded as being half-way transmitted on average upon the arrival of new packet. Thus, the total mean delay of a packet in the busy slot should be

$$D_{total}^{bs} = \left(1 + \sum_{j=1}^{N_{tr}-\frac{N_{ss}}{2}} P_{C_k}(j)\left(j - \frac{1}{2}\right)\right) T = \left(1 + c_i - \frac{1}{2}\left(1 - P_{C_k}(0)\right)\right) T. \tag{60}$$

Since the new packet enters from $C(c(k[m])+1)$ and there are $c(k[m])$ busy slots, the mean delay due to the number of idle slots is

$$D_{total}^{is} = \left(C(c_i+1) - c_i\right)\sigma. \tag{61}$$

The overall duration of contending for channel access and transmission of a packet is

$$D_{total} = D_{total}^{bs} + D_{total}^{is}. \tag{62}$$

As a packet arrives every $1/\lambda$ seconds, the probability that a vehicle has a contending packet is $\frac{D_{total}}{1/\lambda}$, so the expected number of contending packets should satisfy

$$c_i = \left(N_{tr} - \frac{N_{ss}}{2}\right) \cdot \frac{D_{total}}{1/\lambda} = \lambda \left(N_{tr} - \frac{N_{ss}}{2}\right) D_{total}. \tag{63}$$

Given the contending probability that one vehicle has, the probability that no packet is contending for the channel access over $N_{tr} - 1$ vehicles is given by

$$P_{C_k}(0) = \left(1 - \frac{D_{total}}{1/\lambda}\right)^{N_{tr}-\frac{N_{ss}}{2}} = \left(1 - \frac{c_i}{N_{tr} - \frac{N_{ss}}{2}}\right)^{N_{tr}-\frac{N_{ss}}{2}}. \tag{64}$$

From Equation (62), (63) and (64), c_i must hold

$$c_i\left(1 - \lambda\left(N_{tr} - \frac{N_{ss}}{2}\right)\left(T + \sigma(C-1)\right)\right) = \lambda\left(N_{tr} - \frac{N_{ss}}{2}\right)\left(T\left(\frac{1 + \left(1 - \frac{c_i}{N_{tr} - \frac{N_{ss}}{2}}\right)^{N_{tr}-\frac{N_{ss}}{2}}}{2}\right) + \sigma C\right). \tag{65}$$

According to Equation (65), $\left(1-\frac{c_i}{N_{tr}-\frac{N_{ss}}{2}}\right)^{N_{tr}-\frac{N_{ss}}{2}}$ can be approximated by 1 in low vehicle load, which leads to the expected number of contending packets,

$$c_i^L = \frac{\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\left(T+\sigma C\right)}{1-\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\left(T+\sigma\left(C-1\right)\right)}. \tag{66}$$

Meanwhile, $\left(1-\frac{c_i}{N_{tr}-\frac{N_{ss}}{2}}\right)^{N_{tr}-\frac{N_{ss}}{2}}$ can be approximated by 0 in heavy vehicle load, which leads to the expected number of contending packets,

$$c_i^H = \frac{\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\left(\frac{T}{2}+\sigma C\right)}{1-\lambda\left(N_{tr}-\frac{N_{ss}}{2}\right)\left(T+\sigma\left(C-1\right)\right)}. \tag{67}$$

C. RC Model

Rate control (RC) model, which aims to avoid the system saturated, is mainly applied in high vehicle load. We consider a model that is analogous to LIMERIC (Linear Message Rate Integrated Control) algorithm in the paper [4] for improving DSRC performance. Paper [10] emphasizes the convergence process of message rate when new vehicles participate in the network. Here, we care about the steady state message rate in the network. Assume that each vehicle can measure the fraction of network capacity/channel load that is in use at each moment. If there are N_r vehicles (slots) from which each vehicle can receive packets in the network ($N_r \le N_{tr}$), the channel load is measured as follows:

$$r_{load}\left(t\right)=\sum_{i=1}^{N_r}\lambda_i\left(t\right)\left(T-DIFS\right). \tag{68}$$

The fraction of the network load allocated in aggregate from all vehicles and this can be done without knowing or estimating neighborhood size. The way of estimating $r_{load}\left(t\right)$ is based on the IEEE 802.11 clear channel assessment (CCA) function [11]. Due to general variation in $r_{load}\left(t\right)$ with measurement location, in this thesis, we assume message rates between vehicles are always same at a given time, namely, $\lambda_1\left(t\right)=\lambda_2\left(t\right)=...=\lambda_{N_r}\left(t\right)$.

Our goal is to allocate fair rates to all participating vehicles while keeping the channel load below the specified threshold r_{thre}, to improve the DSRC performance like PDR and mean delay of packet delivery. With the added information available in $r_{load}\left(t\right)$, each vehicle can adjust its own rate linearly with respect to $r_{thre}-r_{load}\left(t\right)$. We consider the synchronous update case in discrete time step, which means all vehicles update their rates at the same time instants, and the effect of all rate adjustments appears in the measurement of the total channel rate at the next discrete time step. Each vehicle updates its message rate by

$$\lambda_i\left(t\right)=\left(1-\gamma\right)\lambda_i\left(t-1\right)+\frac{\varphi\left(r_{thre}-r_{load}\left(t-1\right)\right)}{T-DIFS} \tag{69}$$

where $0<\gamma<1$, $\varphi>0$. In (69), γ promotes the convergence to the steady-state rate between vehicles. φ is the adaptive gain factor which scale the linear message rate offset in the total rate error $r_{thre}-r_{load}\left(t\right)$.

According to (68) and (69),

$$\lambda(t) = H\lambda(t-1) + r_{thre}b \tag{70}$$

where

$$\vec{\lambda}(t) = \begin{bmatrix} \lambda_1(t) & \lambda_2(t) & \ldots & \lambda_{N_r}(t) \end{bmatrix}^T$$

$$H = \begin{bmatrix} 1-\gamma-\varphi & -\varphi & -\varphi & & -\varphi \\ -\varphi & 1-\gamma-\varphi & -\varphi & & -\varphi \\ -\varphi & -\varphi & 1-\gamma-\varphi & & -\varphi \\ & & & & \\ -\varphi & -\varphi & -\varphi & & 1-\gamma-\varphi \end{bmatrix} \tag{71}$$

$$b = \begin{bmatrix} \frac{\varphi}{T-DIFS} \\ \frac{\varphi}{T-DIFS} \\ \frac{\varphi}{T-DIFS} \\ \\ \frac{\varphi}{T-DIFS} \end{bmatrix}.$$

One eigenvalue of H is $z = 1-\gamma-N_r\varphi$, and its corresponding eigenvector is $\begin{bmatrix}1 & 1 & 1 & & 1\end{bmatrix}^T$.

Consider the dynamics of the load on the channel, which is controlled by the eigenvalue at $z = 1-\gamma-N_r\varphi$. Summing across all individual λ, we get

$$r_{load}(t) = (1-\gamma-N_r\varphi)r_{load}(t-1) + N_r\varphi r_{thre} \tag{72}$$

which leads to

$$r_{load}(t) = (1-\gamma-N_r\varphi)^t r_{load}(0) + \frac{N_r\varphi r_{thre}\left(1-(1-\gamma-N_r\varphi)^t\right)}{\gamma+N_r\varphi}. \tag{73}$$

The channel load r_{load} in the steady state requires $1-\gamma-N_r\varphi > -1$, which is given by

$$r_{load} = \frac{N_r\varphi r_{thre}}{\gamma+N_r\varphi}. \tag{74}$$

If channel load is below the specified threshold, vehicles just keep the original message rates. Otherwise, vehicles should adjust their message rate based on the r_{thre}. Thus, the adjusted message rate in the steady state should be

$$\lambda_{adjust} = \begin{cases} \lambda & r_{load} \le r_{thre} \\ \frac{\varphi r_{thre}}{(\gamma+N_r\varphi)(T-DIFS)} & r_{load} > r_{thre} \end{cases}. \tag{75}$$

In this thesis, we adopt the parameter assignment (γ=0.1, φ=1/150, r_{thre}=0.85). We use average successful packet reception time from one vehicle (ART) as a metric to compare CICRC model with CSMA. We will see whether CICRC model take advantage of CSMA based on ART which is given by

$$ART = \frac{1}{\lambda_{adjust} \cdot PDR} + D_t \,. \tag{76}$$

IV. RESULTS OF ANALYTICAL MODEL AND SIMULATION

In this section, we present the simulation setup used to validate our analytical model and present the validation results. The computation for analytic models and corresponding simulations are conducted in Matlab. All assumptions are the same in the simulation and analytic models. Each vehicle on the lanes is equipped with DSRC wireless capability. The control of DSRC is exclusively used for safety related broadcast communication. Table II shows the parameters used in this work, which could reflect typical DSRC network.

Tab II: DSRC communication parameters

Parameters	Values	Parameters	Values
Transmission/Sensing range, R	0.5 km	Propagation delay, δ	0 us
Packet length (payload), $E[PA]$	200, 400 $bytes$	PLCP header	4 us
PHY preamble	28 us	Contention window, CW	16
MAC header	50 $bytes$	Vehicle density, β	10-400 $vehicles/km$
Message rate, λ	2, 10 $packets/\sec$	DIFS	64 us
Slot time, σ	16 us	Data rate, R_d	6, 12, 24 $Mbps$

A. Results of simulations and analytical model in Section II

For fully connected vehicle network case, we use circle topology in the simulation, where we place vehicles on a circle to avoid any unwanted effects of vehicles located at the edge of the network, as Fig.6 shows. We set the length of circle road is $2R$. The vehicles are randomly placed on the circle and each vehicle is configured to broadcast safety message with same packet size and message rate.

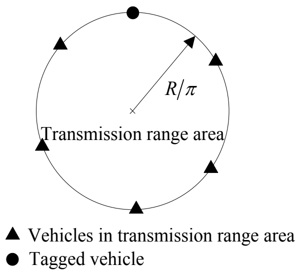
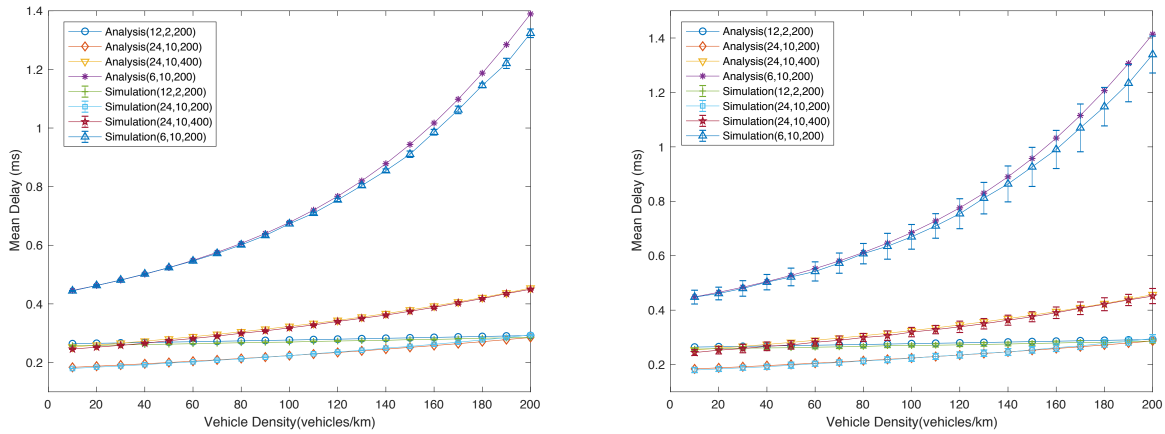


Fig.6: Circle topology

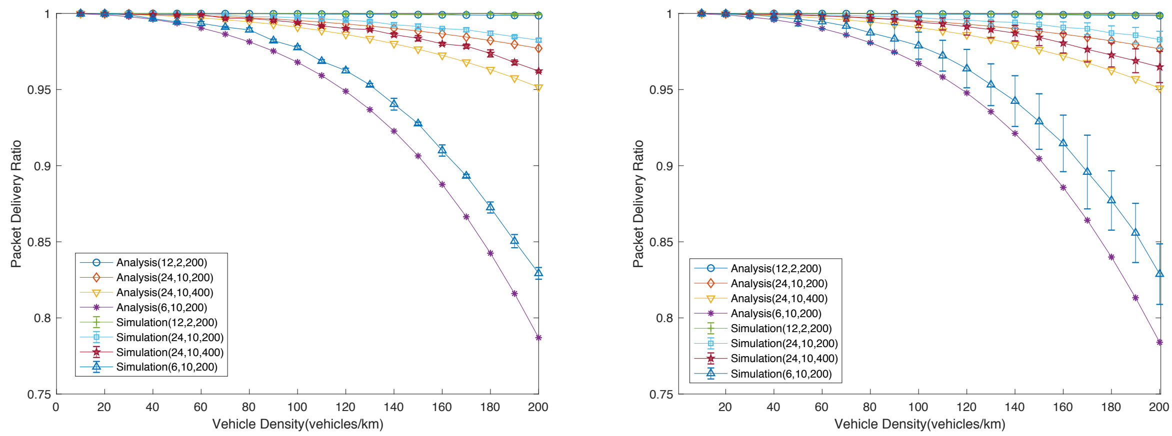
In Fig.7, we plot the mean delay as a function of vehicle density β, with different curves parameterized by date rate R_d (in megabits per second), mean packet length $E[PA]$ (in bytes) and message rate λ (in bytes per second). As we can see, the analytic model agrees well with the simulation results. In the plotted range, the average delay increases almost linearly with the vehicle density except the case of 6 Mbps/10 packets per second/ 200 bytes. The reason why the mean delay increasing dramatically in the case of 6 Mbps/10 packets per second/ 200 bytes can be caused by more interruptions in the back-off process in higher vehicle load and longer time of transmitting one packet.



(a) Exponential inter-arrival time (b) Deterministic inter-arrival time

Fig.7: Mean delay under fully connected vehicle network

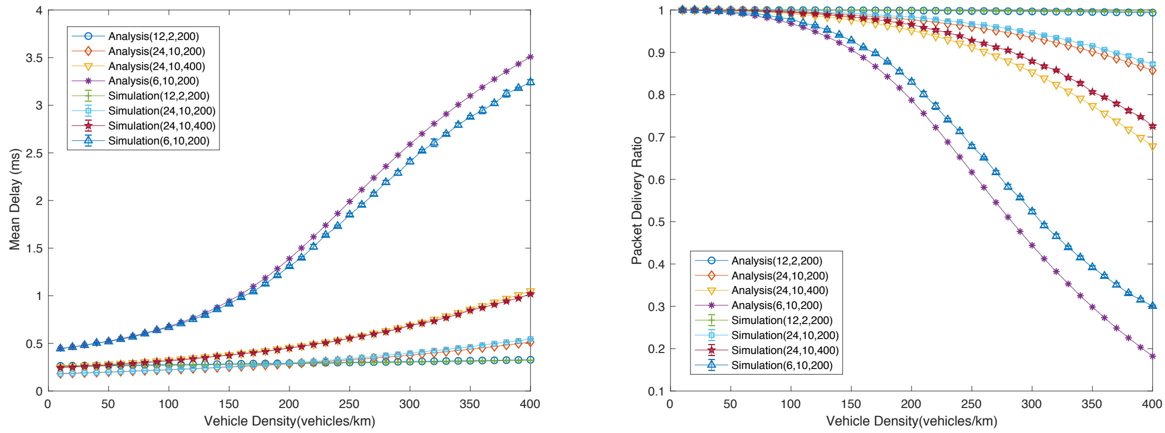
Then, we plot the PDR for fully connected vehicle network in Fig.8. The analytical results provide a reasonable match with the simulation results. For $\lambda=2$, we can see PDR is above 99% for each vehicle density load. For $\lambda=10$, PDR drops with the increasing vehicle density load. With longer time of transmitting a packet, the PDR drops more intensely. Especially, the PDR drops to around 80% in case of 6 Mbps/10 packets per second/ 200 bytes. Besides, we can see the error bar of PDR in deterministic inter-arrival time is larger than that in exponential inter-arrival time, which can be explained by the fact that packets are generated more randomly in exponential inter-arrival time, which provides better convergence than that in deterministic inter-arrival time. In other words, given a fixed simulation time, if packet collisions occur in some vehicles at the beginning, the collision probability between those vehicles in deterministic inter-arrival time will be always higher than that in exponential inter-arrival time.



(a) Exponential inter-arrival time (b) Deterministic inter-arrival time

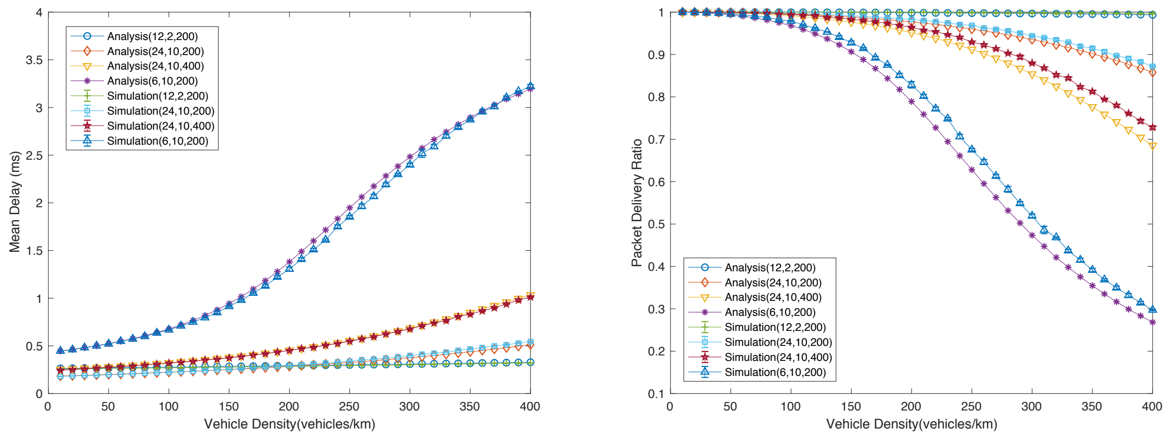
Fig.8: PDR under fully connected vehicle network

Fig.9 shows the mean delay and PDR with exponential inter-arrival time in heavy vehicle load for fully connected vehicle network case. We can see the difference between the analytical result and its corresponding simulation result become large in heavy vehicle density load, especially for the case of 6 Mbps/10 packets per second/ 200 bytes. We think it is mainly caused by the average collision number we proposed in the analytic model becoming inaccurate when more than two packets are involved in some collisions in heavy vehicle density load. We try to validate and improve the analytic model to make it more practical. Since the average collision number from simulation can be tracked, we plugged it into the analytic model. Fig.10 shows the corrected analytic curves provide a good match with the simulation results in heavy vehicle density load, which justifies our analytic model.



(a) Mean delay (b) PDR

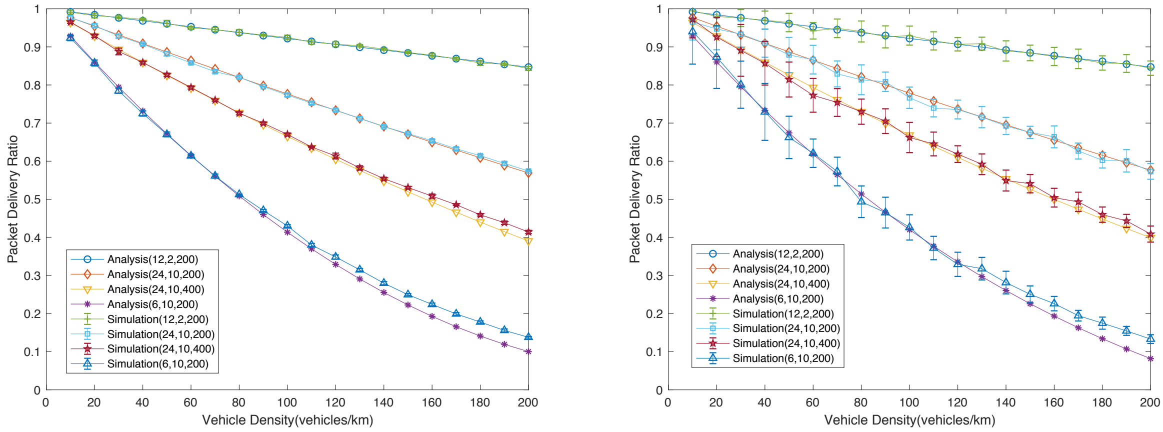
Fig.9: Simulation with uncorrected analytic model curves



(a) Mean delay (b) PDR

Fig.10: Simulation with corrected analytic model curves

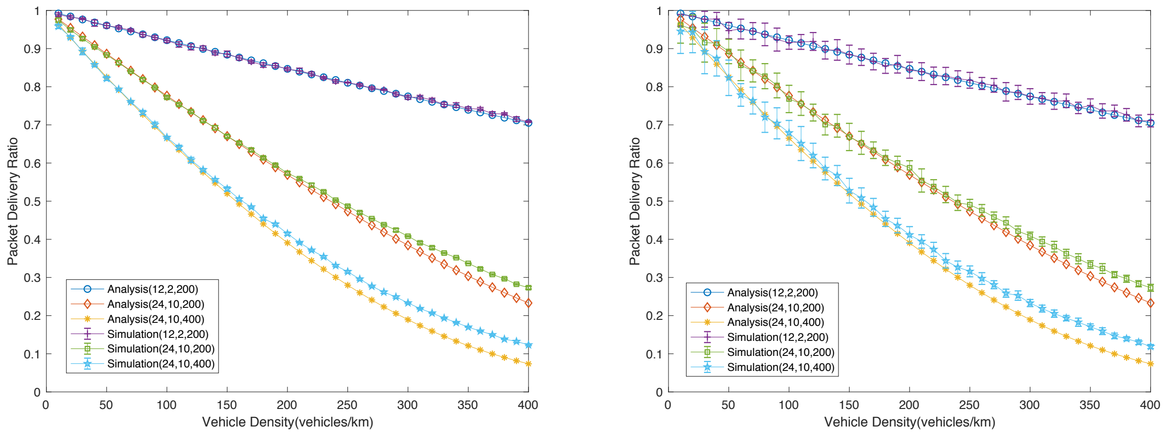
For the hidden terminal participation case, the packet delay distribution is the same as that for fully connected vehicle network case. This is because there is no retransmission and the presence of hidden terminals does not affect the back-off process of the tagged vehicle. Fig.11 shows the analytical results provide a good match with the simulation on PDR. We observe the PDR in hidden terminal participation case drops much quicker with increasing vehicle density load compared with the fully connected vehicle network case. Besides, the PDRs of $\lambda = 10$ case are much worse than those of the $\lambda = 2$ case. Comparing the PDR from the hidden terminal case with that from fully connected vehicle network case, we can get the conclusion that packet collision due to hidden terminals is the major source of collisions and can dramatically reduce PDR.



(a) Exponential inter-arrival time (b) Deterministic inter-arrival time

Fig.11: PDR with hidden terminal

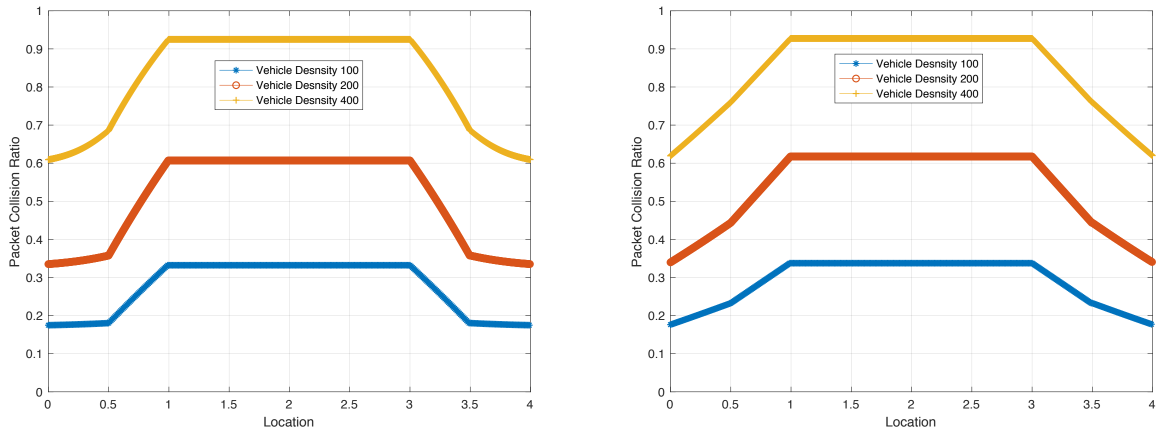
Next, we study the PDR and the mean delay in heavy vehicle density load under hidden terminal participation case. For the case of 6 Mbps/10 packets per second/200 bytes, the PDR has been below 10% with density 200 vehicles/km, which has been in heavy vehicle load. Therefore, Fig.12 only shows the PDR of another three cases in heavy vehicle load. In the Fig.12, the analytical results still match well with the simulation results.



(a) Exponential inter-arrival time (b) Deterministic inter-arrival time

Fig.12: PDR with hidden terminal in high vehicle load

In the hidden terminal participation case, PDR may change with location if road length is not infinity. We consider a case where the total length of lanes is 4km, where the transmission range is 0.5 km. We show how PDR changes with location under vehicle density 100, 200, 400. In the Fig.13, we can see PDR in the middle part is lower than that in the edge, because vehicles on the edge suffer less from the hidden terminals.



(a) Exponential inter-arrival time (b) Deterministic inter-arrival time

Fig.13: Collision probability with different location in 4km road

B. Results of simulations and analytical model in Section III

We observe the improvement on DSRC performance under fully connected vehicle case according to the proposed model. As Fig.14 shows, the analytic model matches well with the simulation results in the part of mean delay, which validates our model.

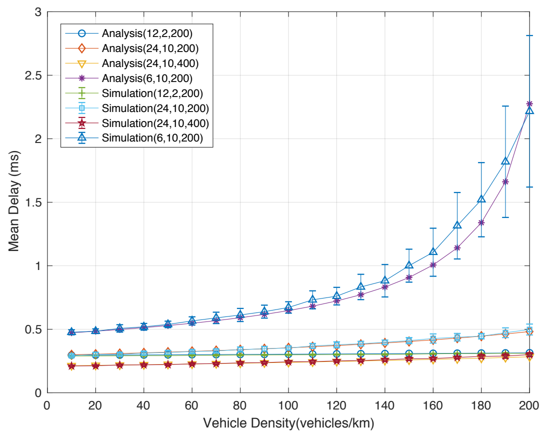


Fig.14: Mean delay under CIC

We next focus on the typical case (6 Mbps/10 packets per second/200 bytes) which best approximates the parameters in a real situation to compare CIC with CSMA. Fig.15 shows the mean delay under CSMA(CW=16), CSMA(CW=128) and CIC. The mean delay under CIC is always below the mean delay under CSMA(CW=128) while being very close to the mean delay under CSMA(CW=16) except in high vehicle load. For example, when vehicle load is equal to 200 vehicles/km, the mean delay under CIC is about 0.8ms longer than that under CSMA(CW=16), which can be explained by the contention intensity difference shown in Fig. 16. Fig.16 shows the contention intensity under CSMA (CW=16) and contention intensity of low vehicle load and heavy vehicle load under CIC. When vehicle load is equal to 200 vehicles/km, the contention intensity under CIC is two more than that under CSMA. Due to the duration of transmitting one packet being around 0.4ms, the mean delay difference between CIC and CSMA will be 0.8ms.

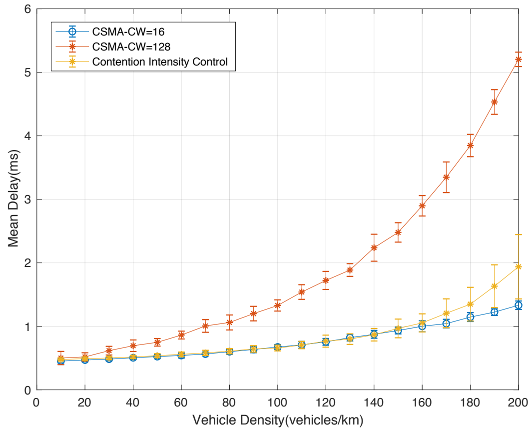


Fig.15: Mean delay under CSMA and CIC

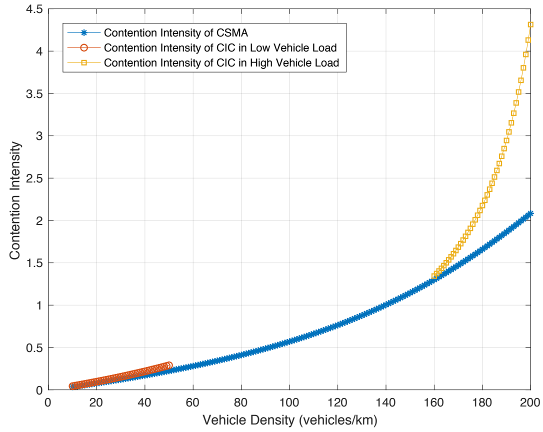


Fig.16: Contention intensity under CSMA(CW=16) and CIC

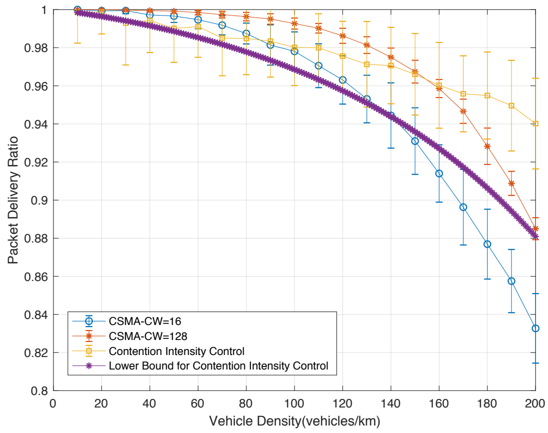


Fig.17: Simulation on PDR under CSMA and CIC

Fig.17 shows a simulation on PDR under CSMA and CIC, as we can see, the PDR under CIC increases nearly 10% compared with that under CSMA(CW=16) and 5% compared with that under CSMA(CW=128) in heavy vehicle load. Fig. 17 also intuitively provides the lower bound of PDR under CIC. It can be seen that the analytical lower bound is valid although not very tight when the vehicle load is heavy. Nevertheless, even the lower bound lies above the simulation on PDR of CSMA (CW=16) in heavy vehicle load.

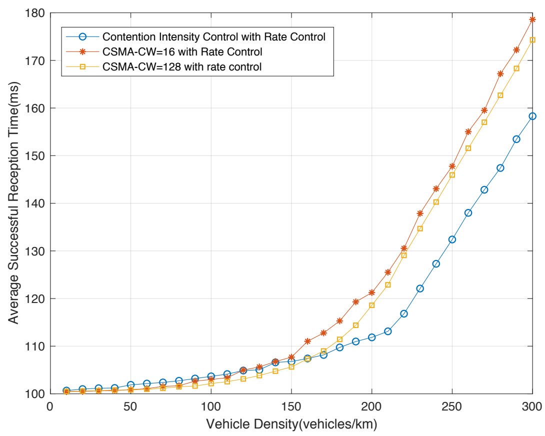


Fig.18: ART under CSMA and CICRC

Fig.18 provides the average successful packet reception time under CSMA and CICRC. ART under CICRC is around 20ms lower than CSMA in heavy vehicle load, which verify that CICRC takes advantage of CSMA on the DSRC performance especially in heavy vehicle load. Here, the average inter packet reception time includes average inter-packet generation time and mean delay. Besides, it is reasonable that the message rate decreases when the vehicle load becomes heavy because maximum message rate (10 packets/sec) is not always necessary in the heavy vehicle load scenario: Vehicles are much likely to experience a traffic jam or move slowly, a vehicle actually don't need to disseminate its BSMs (updating its location, speed and etc.) with such high frequency because the variation in these parameters change little in heavy vehicle load scenario. Thus, contention intensity control with rate control makes sense in mitigating channel congestion and improving DSRC performance.

V. CONCLUSION

In this thesis, we first focus on the simulation and analysis of Vehicle-to-Vehicle (V2V) communication which adopts the DSRC protocol. We compared the PDR and mean packet delay between heavy and low vehicle load scenarios under fully-connected vehicle network case and a hidden terminal participation case. We also presented the PDR and mean packet delay of safety messages generated with deterministic inter-arrival time and exponential inter-arrival time, respectively. Our analytic model provides a good match with simulation results. Then we studied an improvement on DSRC performance. We proposed an analytical model of Contention Intensity Control with Rate Control (CICRC). We also verified the model by showing our simulation provides good match with analytical results. Finally, comparing CSMA with proposed CICRC by some metrics, we can verify that CICRC improves DSRC performance compared to CSMA.

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