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Provisioning QoS controlled media access in vehicular to infrastructure communications

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The emerging IEEE 802.11p standard adopts the enhanced distributed channel access (EDCA) mechanism as its Media Access Control (MAC) scheme to support quality-of-service (QoS) in the rapidly changing vehicular environment. While the IEEE 802.11 protocol family represents the dominant solutions for wireless local area networks, its QoS performance in terms of throughput and delay, in the highly mobile vehicular networks, is still unclear. To explore an in-depth understanding on this issue, in this paper, we develop a comprehensive analytical model that takes into account both the QoS features of EDCA and the vehicle mobility (velocity and moving directions). Based on the model, we analyze the throughput performance and mean transmission delay of differentiated service traffic, and seek solutions to optimally adjust the parameters of EDCA towards the controllable QoS provision to vehicles. Analytical and simulation results are given to demonstrate the accuracy of the proposed model for varying EDCA parameters and vehicle velocity and density.

1. Introduction

Our life nowadays is more absorbed in various kinds of multimedia services than ever, like watching videos on Youtube, talking face to face with friends on Skype and browsing daily news on Facebook. In the near future, it is envisioned that the must-have option for vehicles would no longer be the sunroof or leather seat – it will be the ultra high-speed Internet connectivity that provides the drivers and passengers the same splendid multimedia experience as they have at home. Catering to this ever-increasing demand, vehicular networks have recently been proposed as a promising solution to provision the high-rate yet cheap Internet access to the in-motion vehicles. In this new paradigm of networking, vehicles are equipped with the on-board-unit (OBU) to perform wireless communications among each other, called vehicle-to-vehicle (V2V) communication, or to the road-side infrastructure (namely road-side unit (RSU)) along the road or a pedestrian passageway, called vehicle-to-infrastructure (V2I) communication. As a result, a variety of novel applications are enabled to drivers and on-board passengers with the persistently enhanced safety and entertainments, such as the traffic alert and media streaming, which revolutionize the in-vehicle experience.

To promote communications in the rapidly changing vehicular environment, the IEEE 802.11 standard body is currently working on a new amendment, IEEE 802.11p, called Wireless Access in Vehicular Environment (WAVE). This new flavor of wireless access is based on the 802.11a radio technology on the dedicated short range communication (DSRC) frequency band (5.85–5.925 GHz), and adopts the 802.11e enhanced distributed channel access (EDCA) as the MAC aiming at providing copious multimedia service to on-road vehicles. Meanwhile, the academic community also reveals intense interest in the

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performance of IEEE 802.11 for vehicular communications. In [1], Ott et al. report the first real-world measurements, namely driving-thru Internet, between a moving car with an external antenna and a road-side WLAN access point (AP). They demonstrate that using off-the-shelf IEEE 802.11b hardware, a vehicle can maintain a connection to a road-side AP for 500 m and transfer 9 MB of data at 80 km/h using either Transmission Control Protocol (TCP) or User Datagram Protocol (UDP). Inspired by this result, they further propose a TCP-based session protocol in [2] to provide end-to-end connections that allows the download of large data volumes across intermittent Wi–Fi connectivity. CarTel [3] evaluates the V2I communication with city-wide trials in Boston and reports the upload bandwidth to vehicles using the unplanned open residential access. It observes that the plethora 802.11b APs spreading in cities can provide intermittent and short-lived connectivity yet high performance while available. Encouraged by the measurement results, numerous works are devoted to provisioning guaranteed QoS for multimedia service in the paradigm of vehicular communications. In [4], Yu et al. devise a call admission control scheme to enforce selective channel access and guaranteed QoS to the drive-thru vehicles. Ou et al. [5] propose a packet scheduling algorithm to provide high-quality video on demand service to passengers on board.

In this work, we investigate on provisioning QoS ensured multimedia applications to in-motion vehicles. Particularly, we focus on the MAC layer for V2I communications where multiple fast moving vehicles with different on-top applications and QoS requirements compete for the transmissions to the road-side infrastructure.[1] To this end, we establish a mathematical model to evaluate the performance of EDCA, the fundamental MAC scheme of 802.11p, in terms of the mean throughput and transmission delay for different service traffic. Our model considers the node mobility, represented by the velocity, in the modeling of MAC and unveils the impacts of mobilities on the resultant QoS performance provisioned to vehicles. Based on the analytical model, we reinforce the QoS provision by adjusting the QoS parameters in EDCA in tune with the mobility of vehicles.

1.1. Related works

Several studies devise the QoS mechanisms [6] to provide guaranteed service to on-board passengers. [5] proposes a downlink scheduler to deliver high-quality video on demand services over V2I networks. The proposed scheduler is deployed at the RSU to coordinate the transmission of packets according to their importance to the video quality, playback deadline and the real-time information of vehicles such as the velocity, link quality and sojourn time in the RSU. [7] also devises a scheduling algorithm to coordinate the distribution of data files in the vehicular network. In [7], a collection of data files are stored at distributed locations and delivered to passing vehicles. According to the popularity of files, the proposed algorithm schedules the location of files through the selective upload and download of RSUs to maximize the delivery ratio of files to vehicles. [4] proposes a call admission control scheme to guarantee the QoS of vehicles with intermittent connectivity. Based on the sojourn time of vehicles in the RSU and their requirements on the throughput, [4] admits the connection of vehicles which can complete their download within the drive through. In contrast to aforementioned previous works that focus on devising new media access schemes for QoS provisioning, in this work, we take a more holistic perspective on the problem by evaluating and optimizing the performance of EDCA in the presence of highly mobile vehicles. [8] develops a theoretical study on the end-to-end delay of the disrupted V2I communications. Based on the effective bandwidth theory, the maximum distance between adjacent RSUs is derived so that the worst case packet delivery delay is controlled under a certain limit.

There are other works focusing on the MAC performance of V2I communications, however, from different aspects. [9] proposes a scheduling algorithm incorporating with EDCA to provision controlled QoS to the driving through vehicles. Based on the current queue length and packet error rate of vehicles, [9] adaptively controls TXOP of vehicles iteratively to maximize the integrated throughput of nodes. In contrast to [9], our work focuses on evaluating the impacts of mobility on EDCA and seeking the best setting of EDCA parameters with guaranteed QoS in prepense of high mobility. Existing works on the analytical model of EDCA [10–12], however, mainly focus on the performance of EDCA in the static WLAN scenario. Without taking the mobility into consideration, these results can not be deployed directly in the vehicular communications.

1.2. Organization of the work

The remainder of the paper is organized as follows. In Section 2, we provide an overview of EDCA and discuss its related issues when implemented in vehicular networks. Section 3 develops the analytical model to evaluates the QoS performance of EDCA in V2I communications and Section 4 validates the accuracy of the model using simulations. Section 5 concludes the paper with discussion on future work.

2. Overview of 802.11p and EDCA

The upcoming IEEE 802.11p standard is a set of specifications to permit communications in the rapidly changing vehicular environment. It cooperates with the IEEE 1609 standard family [13] which would be dealing with secure, reliable and fast vehicular communications with a QoS feature.

The IEEE 802.11p MAC adopts the same core mechanism of the EDCA specified in 802.11e. EDCA is an extension of IEEE 802.11 DCF mechanism with the enhancement to support QoS. It stores the application packets into separate queues and maps each queue to a specific access category (AC) according to the characteristics of traffic such as voice,

[1] We focus on the V2I communications as most media contents are normally in the remote sites of Internet and can only be retrieved through road-side gateways.

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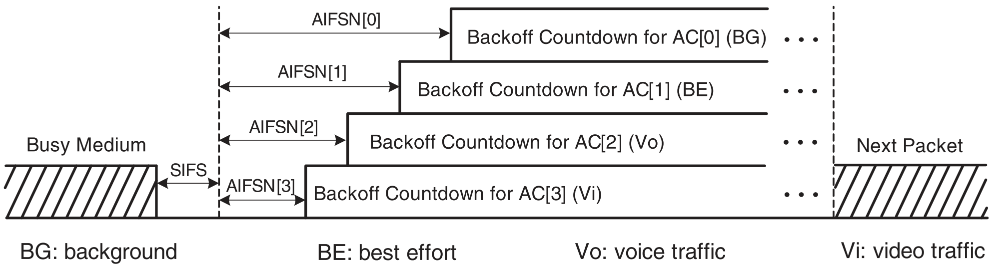

Fig. 1. Example of packet transmission using EDCA.

video, best effort and background traffic. Each AC contends for the transmission independently under the rule of DCF, but employs different channel access parameters as: arbitrary inter-frame spaces (AIFS), contention window (CW) sizes and transmission opportunity (TXOP) limits.

As shown in Fig. 1, each AC[i] is permitted to contend for the medium access after an AC-specific period of arbitration inter-frame space (AIFS)

$$\mathrm{AIFS}[i] = \mathrm{SIFS} + \mathrm{AIFSN}[i] \times \delta \tag{1}$$

where SIFS is the length of the short inter-frame space. AIFSN[i] is the AIFS number of AC[i]. δ is the duration of one backoff unit.

After waiting for AIFS[i] since the channel is released idle, each AC[i] starts a backoff procedure before the transmission of packets. In this case, a uniformly distributed random integer, namely backoff time, is selected from the range $[1, W_i]$ where W_i is called the contention window (CW). The backoff time is decremented at the slot boundary if the previous time slot is idle; otherwise, the backoff is frozen and resumes until the channel is idle for another period of AIFS[i]. When the backoff time deducts to zero, the packet in the AC[i] is transmitted in the ensuing slot. The size of CW, W_i, depends on the history of transmissions. At the first transmission attempt, W_i is set to a predefined value $CW_{\min,i}$, namely *minimum contention window*. Upon each unsuccessful transmission s, W_i is updated as $W = 2^s CW_{\min,i}$ until W_i reaches a maximum value $CW_{\max,i}$.

Upon gaining access to the medium, each AC[i] could transmit multiple packets in sequence separated by SIFS as long as the total transmissions do not exceed TXOP[i]. A TXOP limit value of zero indicates that only one frame is exchanged between vehicles[2] to RSU per access.

Therefore, the QoS of ACs is provisioned by rendering different priorities of transmissions. The higher priority ACs are assigned with smaller AIFSNs, and correspondingly, shorter waiting time to start the backoff and channel contention, while lower priority ACs are still waiting in their AIFS. Meanwhile, the higher priority ACs would select the backoff times from a relatively smaller CW range, resulting in the higher probability to acquire the channel when the channel is released idle. TXOP also differentiates the QoS. With a larger TXOP, more packets are exchanged between the vehicle nodes and RSU upon each transmission, and therefore to boost the throughput.

[2] We use the terms vehicle, node and vehicle node interchangeably in the paper.

While the 802.11 MAC is proven to be efficient with the world-wide deployments, originally designed for the static indoor environment, its performance in the outdoor vehicular environment is still arguable. When implementing EDCA for QoS provision in the highly mobile vehicular communication, the following issues need to be addressed.

- *Performance anomaly*: With nodes at different locations to the RSU, their channel conditions and data transmission rates diverse as shown in Fig. 2. With nodes presenting multiple transmission rates, DCF is shown to suffer from the performance anomaly, *i.e.*, the system throughput is throttled to the minimum transmission rate among different connections [14]. As there always exist vehicles far away from the RSU and presenting low transmission rates, how to address the performance anomaly is crucial for the system performance.
- *Throughput variation*: When vehicles approach to RSUs and then leave, their throughput varies significantly over time due to the changing SNR at different locations. Such throughput variations are harmful to multimedia applications in different amplitudes. Interactive applications, e.g., VoIP, online gaming, typically require flat and static throughput with minimum variations to maintain the interactivity. Media streaming, e.g., IPTV, can tolerate the throughput variations in some extent with the use of playout buffer [15]; nevertheless, they demand much more capacity than the interactive applications to achieve superior video quality. With vehicle nodes subscribing to different multimedia services, they demand diverse QoS supports. As such, how to tune the QoS parameters of EDCA, i.e., AIFS, CW, and TXOP, for different service traffic to efficiently provision the desired QoS in the highly mobile environment is crucial.

In the following section, we will establish an analytical model to evaluate the QoS performance of EDCA in high-speed vehicular environments.

3. Analytical model

3.1. System model

We consider the V2I communication, as shown in Fig. 2, where vehicles connect to intermittent and serial RSUs along the road. We focus on the MAC layer under the assumption of perfect channel conditions (no transmission

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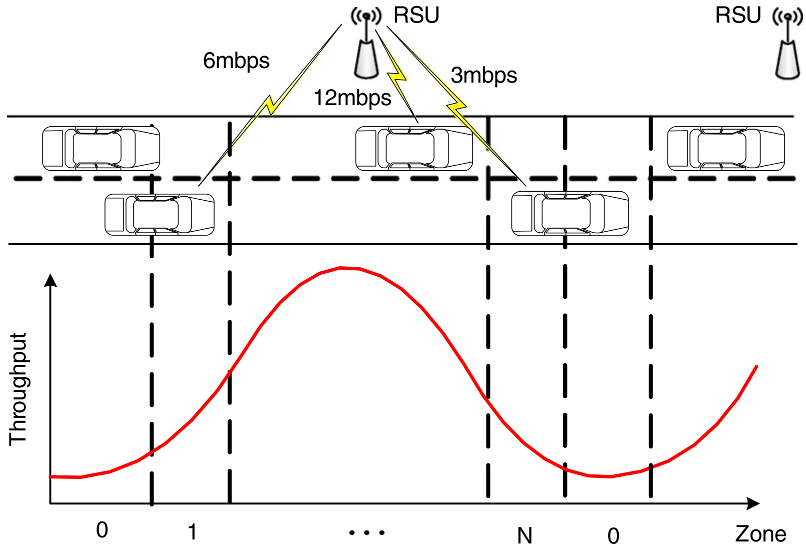

Fig. 2. Vehicle to infrastructure road-side unit communication.

errors and hidden terminals) with line-of-sight communications. In this case, the channel SNR and data modulation rates of vehicles are mainly determined by their distance to the RSU [1,16,17].

We consider a road with consecutive RSUs. Without loss of generality, we focus on a single road session including the communication coverage of one RSU and the adjacent region outside the coverage of the RSU and ahead of it. According to the location to RSU, the road session is divided into multiple spatial zones denoted by $\mathbb{Z} = \{0, 1, 2, \ldots, N\}$ as shown in Fig. 2, where zone 0 represents the region outside the communication range of RSU, and zones $\{1, 2, \ldots, N\}$ represent the areas within the RSU coverage. Despite that vehicles are disconnected to any RSUs in zone 0, we assume that they still acquire a dedicated throughput with bounded delay denoted by κ using other communication means, e.g., cellular networks or V2V communications. In each zone z within the RSU coverage, $z \in \{1, 2, \ldots, N\}$, vehicles have distinct payload transmission rates, denoted by r_z, according to their distance to the RSU. Let d_z denote the length of the partition zone z, and v the mean velocity of vehicles along the road session.

Within the coverage of RSU, packet transmissions are coordinated by EDCA as described in Section 2. We consider the *saturated case* such that each vehicle always has packets to transmit. According to their on-top applications and the QoS requirements, vehicles are categorized into three classes with increasing priorities as, class 0 (AC[0]) for best effort (BE) traffic, class 1 (AC[1]) for media streaming (MS) such as IPTV, and class 2 (AC[2]) for interactive applications (IA) such as VoIP. Let $\mathbb{V}$ denote the set of vehicle nodes in the road segment. Let c_k denote the portion of class k nodes in $\mathbb{V}$, where $k \in \{0,1,2\}$, and L_k the mean payload length of the application running on class k nodes. We assume that each vehicle node belongs to one class only and transmits all its packets through the same AC. In the general case where each vehicle could have numerous on-top applications and multiple ACs transmitting simultaneously, our model can be extended by regarding each node as multiple sub-nodes where each sub-node runs one application. To address the performance anomaly, we set the minimum contention window $CW_{\min,k}$ of AC[k], dependent on the zones such that nodes in different zones transmit with differentiated probabilities. Let $W_{k,z}$ denote the $CW_{\min,k}$ of nodes in zone z, and m the maximum number of backoff stage of ACs.

3.2. Markov model of moving vehicles

We evaluate the QoS performance of vehicles in terms of the mean transmission throughput and delay. To this end, we examine a randomly tagged vehicle of class i (transmitting through AC[i]), where $i \in \{0,1,2\}$, and represent its status by a three-dimensional Markov chain $\{Z_i(t), S_i(t), B_i(t)\}$ at each time slot t. $Z_i(t)$ denotes the spatial zone that the node is currently in. $S_i(t)$ denotes the current backoff stage of the tagged node using DCF. $B_i(t)$ denotes the backoff time of the tagged node at the current time slot. The time slot t is a discrete and integer scale value, where slot times t and $t+1$ correspond to the beginning of two consecutive backoffs of the tagged node.

The principle of the three-dimensional Markov chain is sketched in Fig. 3. The mobility of vehicles is modeled by the transitions among spatial zones and represented by a Markov chain in which each state corresponds to one spatial zone. We assume that the sojourn time of nodes in each zone $z \in \mathbb{Z}$ is geometrically distributed with mean $t_z = d_z/v$. As such, within a small duration, e.g., Δ, vehicles either move to the next zone (or state) with the transition probability Δ/t_z, or remain in the current zone with the rest probability $1 - \Delta/t_z$.

Fig. 4 plots a snapshot of the state space when the tagged node is in zone z, where $W_{i,\max} = max\{W_{i,z} | z \in \mathbb{Z}\}$ is the maximum $W_{i,z}$ of AC[i] among zones. As shown in Fig. 4, from slot time t to the next slot, the tagged node would either stay in the original zone z or move to the next

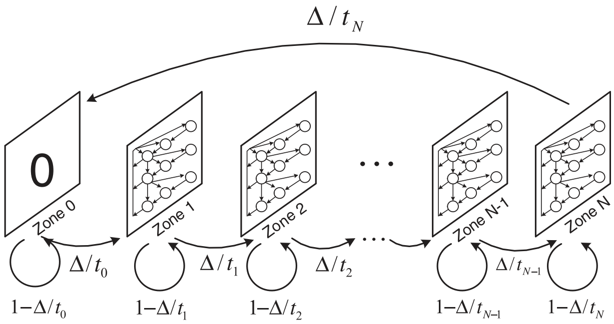

Fig. 3. Model of a tagged node with three-dimensional Markov chain.

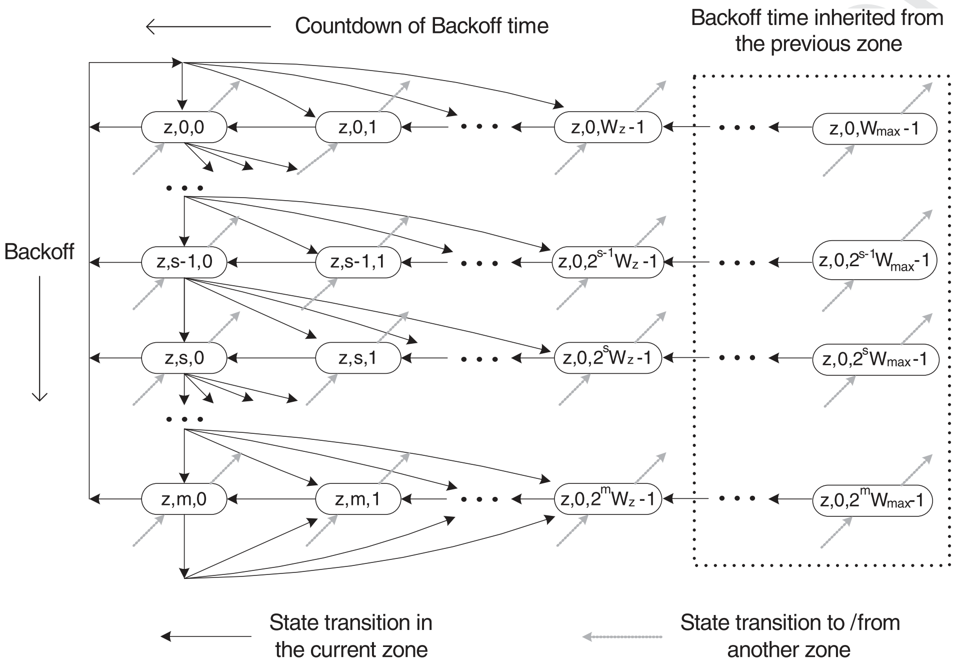

Fig. 4. State space of Markov chain in zone z.

zone. When moving to the next zone, the backoff time of the tagged node inherits the value in the previous time slot, while the CW range is updated with a new minimum contention window. The non-null transitions of the Markov chain from time slot t to $t+1$ are

(i) Arriving to the RSU from zone 0,

$$P_i(1,0,b|\mathbb{0}) = \frac{E[T_{i,\text{slot}}]}{t_0 W_{i,1}}, \quad b \in [0, W_{i,1}-1], \tag{2}$$

where $\mathbb{0}$ represents zone 0, and $E[T_{i,\text{slot}}]$ is the mean duration of a slot time for AC[i]. In this transition, $E[T_{i,\text{slot}}]/t_0$ is the probability that the tagged move from zone 0 to zone 1 in the new time slot, and $1/W_{i,1}$ is the probability that a new backoff time is selected from the CW range $[1, W_{i,1}]$. Here, when leaving one RSU to the next one, we assume that vehicles reset their backoff stage values to 0.

(ii) Inside the RSU coverage without and with zone transitions, respectively,

$$P_i(z,s,b|z,s,b+1) = 1 - \frac{E[T_{i,\text{slot}}]}{t_z}, \quad z \in [1,N], \; s \in [0,m], \; b \in [1, 2^s W_{i,\max}), \tag{3a1}$$

$$P_i(z,s,b|z-1,s,b+1) = \frac{E[T_{i,\text{slot}}]}{t_{z-1}}, \quad z \in [2,N], \; s \in [0,m], \; b \in [1, 2^s W_{i,\max}), \tag{3a2}$$

$$P_i(z,0,b|z,s,0) = \frac{1-p_{i,\text{col}}}{W_{i,z}} \left(1 - \frac{E[Tx_{\text{suc},i,z}]}{t_z}\right), \quad z \in [1,N], \; s \in [0,m], \; b \in [1, W_{i,z}], \tag{3b1}$$

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$$P_i(z,0,b|z-1,s,0) = \frac{1-p_{i,\mathrm{col}}}{W_{i,z}} \times \frac{E[Tx_{\mathrm{suc},i,z-1}]}{t_{z-1}}, \quad z \in [2,N],\ s \in [0,m],\ b \in [1,W_{i,z}], \tag{3b2}$$

$$P_i(z,s,b|z,s-1,0) = \frac{p_{i,\mathrm{col}}}{2^s W_{i,z}}\left(1-\frac{E[Tx_{\mathrm{col},i,z}]}{t_z}\right), \quad z \in [1,N],\ s \in [1,m],\ b \in [1,2^s W_{i,z}], \tag{3c1}$$

$$P_i(z,s,b|z-1,s-1,0) = \frac{p_{i,\mathrm{col}}}{2^s W_{i,z}} \times \frac{E[Tx_{\mathrm{col},i,z-1}]}{t_{z-1}}, \quad z \in [2,N],\ s \in [1,m],\ b \in [1,2^s W_{i,z}], \tag{3c2}$$

$$P_i(z,m,b|z,m,0) = \frac{p_{i,\mathrm{col}}}{2^m W_{i,z}}\left(1-\frac{E[Tx_{\mathrm{col},i,z}]}{t_z}\right), \quad z \in [1,N],\ b \in [1,2^m W_{i,z}], \tag{3d1}$$

$$P_i(z,m,b|z-1,m,0) = \frac{p_{i,\mathrm{col}}}{2^m W_{i,z}} \times \frac{E[Tx_{\mathrm{col},i,z-1}]}{t_{z-1}}, \quad z \in [2,N],\ b \in [1,2^m W_{i,z}], \tag{3d2}$$

where $p_{i,\mathrm{col}}$ is the collision probability when the tagged node of AC[i] transmits. $E[Tx_{\mathrm{suc},i,z}]$ and $E[Tx_{\mathrm{col},i,z}]$ denote the mean time of one successful and collided transmission of the tagged node in zone z, respectively.

From (3a)–(3d), the state transitions in (3) correspond to the decrement of the backoff time after a backoff slot, a successful transmission, a failed transmission, and any transmission attempt in the last backoff stage, without and with zone transitions, respectively.

(*iii*) Departing from the RSU in the backoff procedure or after transmission attempt, respectively,

$$P_i(\mathbb{0}|N,s,b) = \frac{E[T_{i,\mathrm{slot}}]}{t_N}, \quad s \in [0,m],\ b \in [1,2^s W_{\max}-1], \tag{4a}$$

$$P_i(\mathbb{0}|N,s,0) = \frac{(1-p_{i,\mathrm{col}})E[Tx_{\mathrm{suc},i,N}] + p_{i,\mathrm{col}}E[Tx_{\mathrm{col},i,N}]}{t_N}, \quad s \in [0,m]. \tag{4b}$$

where (4a) and (4b) represents the probability that the tagged node moves into zone 0 after the backoff and transmissions, respectively.

Let $\pi_i(z,s,b) = \lim_{t\to\infty}\Pr\{Z_i(t)=z,\ S_i(t)=s,\ B_i(t)=b\}$ be the steady state probability of the Markov chain and $\boldsymbol{\pi}_i = \{\pi_i(z,s,b)\}$ denote the corresponding matrix. Given the state transition probability matrix $\mathbf{P}_i$ with each non-null element shown in (2)–(4), $\pi_i(z,s,b)$ could be derived from the following balance equations

$$\begin{cases} \boldsymbol{\pi}_i \mathbf{P}_i = \boldsymbol{\pi}_i, \\ \sum_{z=0}^{N}\sum_{s=0}^{m_i}\sum_{b=0}^{2^s W_{\max}-1} \pi_i(z,s,b) = 1. \end{cases} \tag{5}$$

3.3. Parameters associated with Markov state transitions

Let X denote the mean node population in the road segment, excluding the tagged node. As indicated in 27 of [15], the network size X is solely dependent on the mean node velocity v as

$$X = k_{\mathrm{jam}}\left(1-\frac{v}{v_{\mathrm{f}}}\right)\sum_{z\in\mathbb{Z}} d_z - 1, \tag{6}$$

where k_{jam} is the vehicle jam density at which traffic flow comes to a halt. v_{f} is the free-flow speed corresponding to the speed when the vehicle is driving alone on the road (usually taken as the road's speed limit).

Let $X_{k,z}$ denote the mean number of class k nodes in zone z, where $k \in \{0,1,2\}$, with the tagged node excluded,

$$X_{k,z} = \frac{c_k X d_z}{\sum_{z'\in\mathbb{Z}} d_{z'}}, \tag{7}$$

where $d_z/\sum_{z'\in\mathbb{Z}} d_{z'}$ is the limiting probability that a node is in zone z.

3.3.1. Transmission probability of nodes

A node could transmit only when it has its backoff time deducted to 0. Therefore, the conditional transmission probability $\tau_{k|z}$ of a class k node, given that it is in zone z, is

$$\tau_{k|z} = \frac{\sum_{s\in[0,m]}\pi_k(z,s,0)}{d_z/\sum_{z'\in\mathbb{Z}} d_{z'}}, \quad z \in \mathbb{Z}. \tag{8}$$

3.3.2. Mean duration of one time slot $E[T_{i,\mathrm{slot}}]$

As shown in Fig. 1, after the channel is released idle, different ACs need to wait for different AIFS periods before starting the backoffs. In this context, the tagged node can not decrement its backoff time if the channel becomes busy while the tagged node (with AC[i]) is still waiting for AIFS[i]. Henceforth, we call it a self-loop of AC[i] in this case as the backoff time remains unchanged.

Let $p_{i,\mathrm{self}}$ denote the probability that AC[i] engages a self-loop at any time. The mean time slot $E[T_{i,\mathrm{slot}}]$ may be composed of multiple self-loops until the backoff time decreases by one. Let $E[T_{i,\mathrm{self}}]$ denote the mean time of the self-loop of AC[i]. Mathematically, we have

$$E[T_{i,\mathrm{slot}}] = \frac{p_{i,\mathrm{self}}}{1-p_{i,\mathrm{self}}}E[T_{i,\mathrm{self}}] + \delta + \sum_{k=0}^{i}\mathscr{C}(k)\left(p_{\mathrm{suc}}E[T_{k,\mathrm{suc}}] + (1-p_{\mathrm{suc}})E[T_{k,\mathrm{col}}]\right) \tag{9}$$

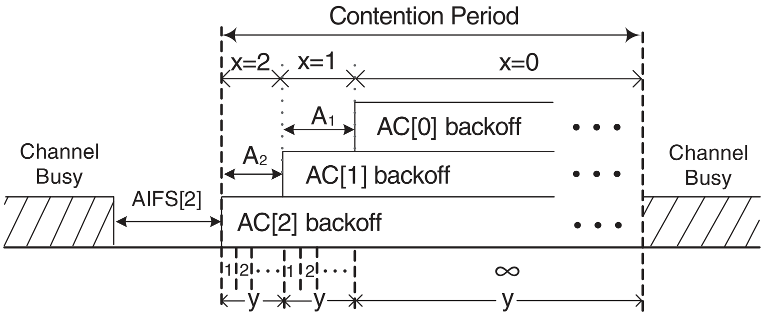

Fig. 5. Example of a channel contention period.

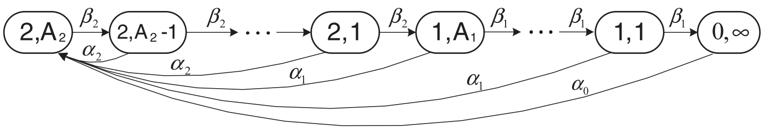

Fig. 6. Markov chain model of the composition of contention nodes.

where $\frac{p_{i,\mathrm{self}}}{1-p_{i,\mathrm{self}}}E[T_{i,\mathrm{self}}]$ collectively represents the waiting time of the tagged node in the self-loop. $\frac{1}{1-p_{i,\mathrm{self}}}$ is the mean number of self-loops encountered as the self-loops happens following a geometric distribution with parameter $(1-p_{i,\mathrm{self}})$. $E[T_{i,\mathrm{suc}}]$ and $E[T_{i,\mathrm{col}}]$ are the mean time of the in-progress transmission with the transmission to be successful and collided, respectively, when AC[i] finishes waiting for AIFS[i] and has started the backoff. $\mathscr{C}(x)$ denotes the limiting probability that only ACs with the equal or higher priority (*i.e.*, equal or smaller AIFS) than AC[x] start the backoff. p_{suc} is the probability that the in-progress transmission during the backoff frozen is successful.

To evaluate the self-loop probability $p_{i,\mathrm{self}}$ and the waiting time in the loop, we focus on a channel contention period [10,18], as shown in Fig. 5, which starts when the channel is released for a period of AIFS[2] and terminates when the channel becomes busy again. We model this period using a two-dimensional Markov chain.[3] Let (x,y) denote the state of the contention period. At a transient time, x represents that AC[k], where $k \geqslant x$ and $x \in \{0,1,2\}$, has finished waiting for AIFS[k] and is contending for transmissions with the decrements of backoff time. y, where $y \in [1,A_x]$, A_x = AIFS[$x-1$] − AIFS[x] if $x \in \{1,2\}$ and $A_x = \infty$ otherwise, represents that AC[$x-1$] still has to wait for y backoff slots to start the backoffs. The state space of the two-dimensional Markov chain is shown in Fig. 6 where the state $(0,\infty)$ represents that all the ACs start the backoffs and are contending for the channel access.

In Fig. 6, when the channel keeps idle for one backoff slot in the state (x,y) of the contention period, y deducts by one. Let β_x denote the probability of this transition. When y deducts to zero, AC[$x-1$] starts the contention and decrements the backoff time; meanwhile, y changes to A_{x-1}. Nevertheless, when the channel becomes busy during this period, the state returns to $(2,A_2)$, representing a recursion to the next contention period. Let α_x denote the transition probability from state (x,y) to state $(2,A_2)$. We have,

$$\alpha_x = 1 - \prod_{j=x}^{2}\prod_{z=1}^{N}(1-\tau_{k|z})^{X_{j,z}}, \tag{10}$$

and

$$\beta_x = 1 - \alpha_x. \tag{11}$$

With above transitions, we can obtain the steady state probability of the Markov chain, denoted by $\zeta(x,y)$,

$$\zeta(x,y) = \begin{cases} \gamma^{-1}\beta_2^{A_2-y}, & x=2,\ y\in[1,A_2] \\ \gamma^{-1}\beta_2^{A_2}\beta_1^{A_1-y}, & x=1,\ y\in[1,A_1] \\ \gamma^{-1}\beta_2^{A_2}\beta_1^{A_1}\beta_0\alpha_0^{-1}, & x=0, \end{cases} \tag{12}$$

where $\gamma = \sum_{y=1}^{A_2}\beta_2^{A_2-y} + \sum_{y=1}^{A_1}\beta_2^{A_2}\beta_1^{A_1-y} + \beta_2^{A_2}\beta_1^{A_1}\beta_0\alpha_0^{-1}$.

The probability $\mathscr{C}(x)$ is thus $\mathscr{C}(x) = \sum_{y=1}^{A_x}\zeta(x,y)$ for x = 1,2 and $\mathscr{C}(0) = \zeta(0,\infty)$. The self-loop probability of the tagged node is

$$p_{i,\mathrm{self}} = \begin{cases} 0, & i=2, \\ \sum_{x=i+1}^{2}\mathscr{C}(x)\alpha_x, & i<2, \end{cases} \tag{13}$$

i.e., the probability that the channel becomes busy when only ACs with priority higher than AC[i] start the backoff. The mean sojourn time of the tagged node in the loop at each slot is

$$E[T_{i,\mathrm{self}}] = \begin{cases} \mathrm{AIFSN}[2]\times\delta, & i=2, \\ \mathrm{AIFSN}[2]\times\delta + \sum_{x=i+1}^{2}\sum_{y=1}^{A_x}(y\delta\zeta(x,y) \\ \quad +E[T_{x,\mathrm{trans}}])\alpha_x, & i<2, \end{cases} \tag{14}$$

[3] The two-dimensional Markov chain is independent of the previously established Markov chain to characterize the composition of backoff ACs in the contention period.

where $E[T_{x,\text{trans}}]$ is the mean time of the in-progress transmission for AC[x] and above, mathematically, $E[T_{x,\text{trans}}] = p_{\text{suc}}E[T_{x,\text{suc}}] + (1 - p_{\text{suc}})E[T_{x,\text{col}}]$. The expressions of $E[T_{x,\text{suc}}]$ and $E[T_{x,\text{col}}]$ will be shown later.

3.3.3. Collision probability

The conditional collision probability of the tagged node, assuming that it is transmitting, is

$$p_{i,\text{col}} = \sum_{k=0}^{i} \Pr\{\text{Channel becomes busy}|\text{AC}[k] \text{ starts backoff}\}$$

$$\Pr\{\text{AC}[k] \text{ starts backoff}\} = \sum_{k=0}^{i} \frac{\mathscr{C}(k)\alpha_k}{\sum_{k'=0}^{i}\mathscr{C}(k')}, \tag{15}$$

where $\mathscr{C}(k)/\sum_{k'=0}^{i}\mathscr{C}(k')$ is the probability that AC[k] starts the backoff given that the tagged node is transmitting, and α_k is the probability that channel becomes busy given AC[k] starts the backoff while AC[$k-1$] is still waiting for AIFS[$k-1$].

3.3.4. Mean time of the in-progress transmission

The mean time of the successful in-progress transmission of AC[i] and above, $E[T_{i,\text{suc}}]$, in (9) can be represented as

$$E[T_{i,\text{suc}}] = \sum_{i\leqslant k\leqslant 2}\sum_{z\in\mathbb{Z}} p_{\text{suc},k,z}T_{\text{suc},k,z}. \tag{16}$$

where $p_{\text{suc},k,z}$ is the conditional probability that the in-progress transmission is done by a node of class k in zone z, given that the transmission is successful. Mathematically,

$$p_{\text{suc},k,z} = \frac{1}{p_{\text{suc}}} X_{k,z}\tau_{k|z}(1-\tau_{k|z})^{X_{k,z}-1} \prod_{\substack{i\leqslant k'\leqslant 2, z'\in\mathbb{Z}\\ k'\neq k, z'\neq z}} (1-\tau_{k'|z'})^{X_{k',z'}}. \tag{17}$$

$T_{\text{suc},k,z}$ in (16) is the successful transmission time when the in-progress transmitting node is in zone z. Mathematically,

$$T_{\text{suc},k,z} = (\text{TXOP}[k]+1) \times \left(\frac{\text{H}}{r_z} + \frac{L_k}{r_z} + \text{SIFS} + \frac{\text{ACK}}{r_1} + \text{SIFS}\right), \tag{18}$$

where H is the packet header, ACK the length of acknowledgement frame, $\text{AIFSN}_{\text{min}}$ the minimum AIFSN among ACs, i.e, AIFSN[2] in this context.

The transmission collision time T_{col} in (9) is determined by the longest transmission in the collision. Let $p_{\text{col},k,z}$ denote the probability that the longest transmission is from nodes of class k in zone z or the mirror zone $z_{\text{mir}} = N + 1 - z$ along the AP. We jointly consider zones z and z_{mir} as vehicles have equal payload rates in the two zones, and therefore, same transmission time.[4] Similar to [19], $p_{\text{col},k,z}$ could be computed as

$$p_{\text{col},k,z} = \begin{cases} \frac{1}{1-p_{\text{suc}}}(p_{\text{hcol},k,z} + p_{\text{dcol},k,z}) & \text{if } z \leqslant \lfloor (N-1)/2 \rfloor, \\ \frac{1}{1-p_{\text{suc}}} p_{\text{hcol},k,z} & \text{if } z = \lceil N/2 \rceil. \end{cases} \tag{19}$$

where $p_{\text{hcol},k,z}$ is called the homogeneous collision probability representing the probability that only nodes of class k in zones z or z_{mir} transmit, for $z \leqslant \lceil \frac{N}{2} \rceil$. $p_{\text{dcol},k,z}$ is called diverse collision probability representing the probability that the collision is from at least one node of class k in zones z or z_{mir}, where $z \leqslant \lfloor \frac{N}{2} \rfloor$, and one or more nodes in other zones with smaller transmission time.

$p_{\text{hcol},k,z}$ is composed of three components: (1) the collisions are of nodes in zone z only; (2) the collision are of nodes in zone z_{mir} only; and (3) the collision is of mixed nodes in both zones z and z_{mir}, which is given by

$$\begin{aligned} p_{\text{hcol},k,z} = {} & [(1-(1-\tau_{k|z})^{X_{k,z}} - X_{k,z}\tau_{k|z}(1-\tau_{k|z})^{X_{k,z}-1})(1 \\ & - \tau_{k|z_{\text{mir}}})^{X_{k,z_{\text{mir}}}} + (1-(1-\tau_{k|z_{\text{mir}}})^{X_{k,z_{\text{mir}}}} \\ & - X_{k,z_{\text{mir}}}\tau_{k|z_{\text{mir}}}(1-\tau_{k|z_{\text{mir}}})^{X_{k,z_{\text{mir}}}-1})(1-\tau_{k|z})^{X_{k,z}} \\ & + (1-(1-\tau_{k|z})^{X_{k,z}})(1-(1-\tau_{k|z_{\text{mir}}})^{X_{k,z_{\text{mir}}}})] \\ & \times \prod_{\substack{i\leqslant k'\leqslant 2, z'\in\mathbb{Z}\\ k\neq k', z'\neq z, z'\neq z_{\text{mir}}}} (1-\tau_{k'|z'})^{X_{k',z'}}. \end{aligned} \tag{20}$$

Let $\mathbb{V}_{k,z}$ denote the set of nodes which have longer transmission time than the class k nodes in zone z, and $\widehat{\mathbb{V}}_{k,z}$ the complement set of $\mathbb{V}_{k,z}$ excluding the class k nodes which are in zones z and z_{mir}. The expression of $p_{\text{dcol},z}$ is given by

$$\begin{aligned} p_{\text{dcol},k,z} = {} & \left[1-(1-\tau_{k|z})^{X_{k,z}}(1-\tau_{k|z_{\text{mir}}})^{X_{k,z_{\text{mir}}}}\right] \prod_{s\in\mathbb{V}_{k,z}} (1 \\ & - \tau_s)\left(1 - \prod_{s\in\widehat{\mathbb{V}}_{k,z}}(1-\tau_s)\right). \end{aligned} \tag{21}$$

where τ_s represents the transmission probability of node s.

The mean collision time of the in-progress transmission of AC[i] and above, $E[T_{i,\text{col}}]$, is then

$$E[T_{i,\text{col}}] = \sum_{k=i}^{2}\sum_{z=1}^{\lceil \frac{N}{2} \rceil} T_{\text{col},k,z}p_{\text{col},k,z}, \tag{22}$$

where $p_{\text{col},k,z}$ is obtained in (19). $T_{\text{col},k,z}$ is the packet collision time of class k nodes in zone z, and

$$T_{\text{col},k,z} = \frac{\text{H}}{r_z} + \frac{L_k}{r_z} + \text{SIFS} + \text{anACKTimeout}, \tag{23}$$

where anACKTimeout is a predefined system parameter.

By substituting (16) and (22) to (9), we can obtain $E[T_{\text{slot}}]$. p_{suc} is dummy in the computation of $E[T_{i,\text{slot}}]$ and $E[T_{x,\text{trans}}]$.

3.3.5. Mean transmission time $E[Tx_{suc,i,z}]$ and $E[Tx_{col,i,z}]$ of the tagged node

The successful transmission time $Tx_{\text{suc},i,z}$ of the tagged node in zone z is deterministic as given in (18), so

$$E[Tx_{\text{suc},i,z}] = T_{\text{suc},i,z}. \tag{24}$$

The collision time $Tx_{\text{col},i,z}$ of the tagged node is a random variable equal to the longest transmission time involved in the collision. Given that one collision node is the tagged

[4] In case N is odd and $N + 1 - z = z$, z_{mir} is null with both its population $X_{z_{\text{mir}}}$ and transmission opportunity $\tau_{k|z_{\text{mir}}}$ to be 0 for any $k \in \{0,1,2\}$.

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node of class i in zone z, and AC[k] has finished waiting for AIFS, the probability that the longest transmission is by the tagged node is

$$p_{\text{tag},i,z,k} = \prod_{s\in\mathbb{V}_{i,z},AC[s]\geqslant k}(1-\tau_s)\left[1-\prod_{s\in\widehat{\mathbb{V}}_{k,z},AC[s]\geqslant k}(1-\tau_s)\right] \tag{25}$$

i.e., only nodes of shorter transmission time collide with the tagged nodes.

The probability that the longest transmission is from class k nodes in zone z, given that AC[k] has finished waiting for AIFS, is

$$p_{\text{tag},k,z,k'} = \frac{1}{p_{\text{col}}}\left[1-(1-\tau_{k|z})^{X_{k,z}}(1-\tau_{k|z_{\text{mir}}})^{X_{k,z_{\text{mir}}}}\right] \times \prod_{s\in\mathbb{V}_{i,z},AC[s]\geqslant k}(1-\tau_s), \quad \text{for } T_{\text{col},k,z}\geqslant T_{\text{col},i,z}. \tag{26}$$

The mean collision time $E[Tx_{\text{col},i,z}]$ of the tagged node in zone z is hence

$$E[Tx_{\text{col},i,z}] = \sum_{k=0}^{i}\mathscr{C}(k)\left(T_{\text{col},i,z}p_{\text{tag},i,z,k} + \sum_{\substack{k\leqslant k'\leqslant 2, z\in\mathbb{Z},\\ T_{\text{col},k',z}\geqslant T_{\text{col},i,z}}} T_{\text{col},k',z}\,p_{\text{tag},k',z,k}\right), \tag{27}$$

conditioned on the probability that AC[k] has finished waiting for AIFS. $T_{\text{col},k,z}$ is shown in (23).

3.4. Performance analysis

3.4.1. Throughput analysis

We evaluate the normalized throughput of a class k node in each zone z, denoted by $s_{k,z}$. It is calculated as the ratio of the payload length in a successful transmission to the expected interval between two consecutive transmissions, as

$$s_{k,z} = \frac{\tau_{k,z}(1-p_{i,\text{col}})L_k}{(1-\tau_{k,z})E[T_{i,\text{slot}}]+\tau_{k,z}((1-p_{i,\text{col}})E[Tx_{\text{suc},i,z}]+p_{i,\text{col}}E[Tx_{\text{col},i,z}])}. \tag{28}$$

By substituting (8), (15), (9), (24) and (27) into (28), the normalized nodal throughput $s_{k,z}$ can be readily obtained. With vehicle nodes traversing through different zones, their nodal throughput varies according to (28). For different applications requiring different throughput guarantee, the QoS parameters of EDCA should be adapted accordingly, which will be discussed in the next section.

3.4.2. Mean transmission delay

We investigate the mean transmission delay of a given AC (i.e., the average time between the first transmission attempt of a packet until it is successfully transmitted). We still focus on the tagged node of class i. Let $D_{i,z,s}$ denote the mean transmission delay of the tagged node since it attempts to transmit a packet at zone z with backoff stage s until the packet is successfully transmitted. Mathematically,

$$D_{i,z,s} = (1-p_{i,\text{col}})E[Tx_{\text{suc},i,z}] + p_{i,\text{col}}D^{\text{col}}_{i,z,s}, \tag{29}$$

where $D^{\text{col}}_{i,z,s}$ represents the mean transmission delay of the tagged node from when its transmission in zone z with backoff stage s collides until the packet is successfully transmitted. We have

$$D^{\text{col}}_{i,z,s} \approx E[Tx_{\text{col},i,z}] + \left(1-\frac{E[Tx_{\text{col},i,z}]}{t_z}\right)(E[B_{z,s+1}]E[T_{i,\text{slot}}]+D_{i,z,s+1}) + \frac{E[Tx_{\text{col},i,z}]}{t_z}(E[B_{z+1,s+1}]E[T_{i,\text{slot}}]+D_{i,z+1,s+1}), \quad \text{if } s<m, \tag{30}$$

and

$$D_{i,z,s} = D_{i,z,s+1} \text{ if } s=m \tag{31}$$

where $E[B_{z,s}] = 2^{s-1}W_{i,z}$ is the mean value of the selected backoff time by the tagged node in zone z at backoff stage s. For ease of computation, (30) is an approximation by assuming that nodes do not switch zone during the backoff. As the probability that nodes switch zone during the backoff is pretty low comparing the scale of backoff slot and zone transition time, the approximation is reasonably accurate. The assumption will also be validated later using simulations.

Recall that nodes in zone 0 have a bounded transmission delay κ using other communication means. Substituting it into (30) and (31), we have

$$D^{\text{col}}_{i,N,m} \approx E[Tx_{\text{col},i,z}] + \left(1-\frac{E[Tx_{\text{col},i,z}]}{t_z}\right)(E[B_{z,s+1}]E[T_{i,\text{slot}}] + D_{i,N,m}) + \frac{E[Tx_{\text{col},i,z}]}{t_z}\kappa \tag{32}$$

and by substituting (32) into (29), we could derive $D_{i,N,m}$. By substituting (30) and (31) into (29), $D_{i,z,s}$ for different z and s can be represented by $D_{i,N,m}$ and obtained accordingly. Once $D_{i,z,s}$ for all z and s is known, we can obtain the mean transmission delay of a class k in the RSU coverage as

$$\mathscr{D}_k = \sum_{z=1}^{N}\frac{d_z}{\sum_{n\in\mathbb{Z}}d_n}\sum_{s=0}^{m}\left(\sum_{b=0}^{2^sW_{\max,k}-1}\pi(z,s,b)\right)D_{k,z,s}. \tag{33}$$

4. Simulation evaluation

In this section, we compare our analytical results with the simulation ones obtained by means of a session level C++ simulator. For simplicity, we simulate a single-session road in which the RSU is deployed in the middle of the road and vehicles passing through contend for channel access using EDCA. The whole road session is divided into 8 partition zones with zone-specific parameters shown in Table

Table 1
Parameters of zones.

Zone number	0	1	2	3	4	5	6	7
Length (m)	50	50	60	80	120	80	60	50
Payload rate (mbps)	0	3	6	12	27	12	6	3
$CW_{\min,0}$	∞	128	64	32	16	32	64	128

1. Once reaching the end of the road session, vehicles reenter the road from zone 0 as a new arrival. The packet transmission delay in zone 0 is fixed to $\kappa = 100$ ms. In each test, unless otherwise specified, the vehicles are moving at a constant velocity of 80 km/h along the same direction with the traffic jam density k_{jam} set to be 300 vehs/km and free-way speed v set to be 200 km/h. As such, there are by default 99 vehicles on the road including one tagged node. Similar as Section 3, we consider three service categories AC[0], AC[1] and AC[2] with increasing priorities. Each vehicle node is associated with one service category and transmits fixed-size UDP packets to the RSU. By default, the parameters of the three service categories are as follows: portion of users in each category $c_0 = 0.6$, $c_1 = 0.3$, $c_2 = 0.1$; AIFSN[0] = 9, AIFSN[1] = 4, AIFSN[2] = 2; payload length $L_0 = 1400$ Bytes, $L_1 = 1000$ Bytes, $L_2 = 200$ Bytes; and TXOP is 0 for all ACs.

In what follows, we investigate QoS performance of EDCA in presence of high node mobility and heterogeneous service traffic. As described in Section 2, the high node mobility would result in performance anomaly and severe throughput variations which are both very harmful to the QoS provision. In this work, we mainly focus on the impacts of throughput variations on QoS and seek its cure as the performance anomaly has been thoroughly investigated in our previous work [15] on the throughput evaluation of drive-thru Internet. We apply the conclusion in [15] to address the performance anomaly by setting differentiated contention windows in the zones, with $CW_{min,0}$ shown in Table 1, and setting the maximum backoff stage m to 1 for all zones. With differentiated priorities, the contention window of other ACs are set as $CW_{min,2}:CW_{min,1}:CW_{min,0} = 4:2:1$. In what follows, we vary the EDCA parameters, node velocities and population in simulations to evaluate their differentiation effects on the QoS. Each simulation result is averaged from 30 simulation replications, and each simulation replication lasts for 1 simulation minute. The results are reported with 95% confidence interval.

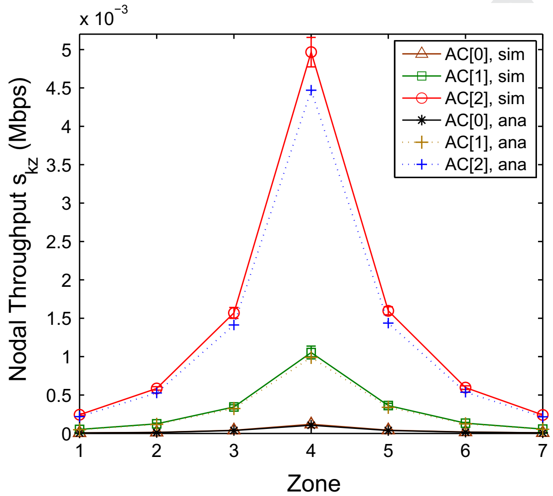

Fig. 7. Nodal throughput for different ACs with default setting of the simulator.

Fig. 7 shows the nodal throughput of different service categories in the coverage of RSU with the default simulation setting. It can be seen that the curve is bell-shaped due to the symmetry of zones along the RSU, and our analysis matches the simulation well. With the lowest transmission priority, AC[0] has the smallest nodal throughput in the zones. Although the throughput of AC[2], representing the real-time interactive applications, could be well guaranteed, the greedy use of the channel by the high priority traffics make the lower priority traffic starve. Therefore, a call admission control mechanism to selectively admit the different service traffics is desirable to balance the quality between different categories.

Fig. 8 shows the nodal throughput of different ACs when AIFSN[0] changes. To simplify the plot, we only show the throughput of AC[0] and AC[2]. It can be seen that reducing AIFSN[0] makes the throughput of AC[2] decrease and that of AC[0] increase. This is because that with reduced AIFSN[0], AC[0] becomes more aggressive to

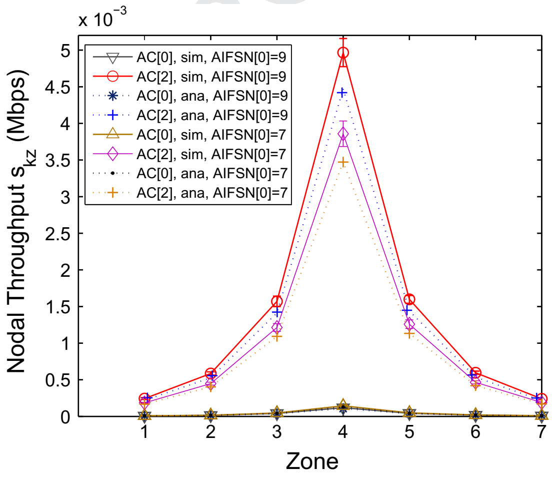

Fig. 8. Nodal throughput of AC[0] and AC[1] with different AIFSN[0].

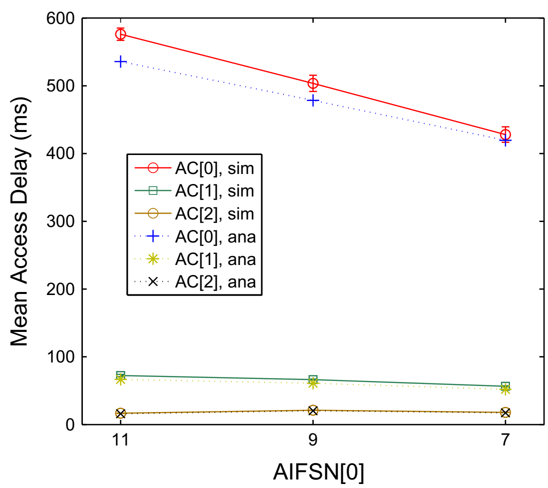

Fig. 9. Delay of different ACs with different AIFSN[0].

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compete for the channel which reduces the throughput of AC[2]. However, with all the nodes of AC[0] reduce their waiting time equally, the boost of throughput for AC[0] is not obvious. Fig. 9 shows the transmission delay of different ACs with different AIFSN[0]. It can be seen that reducing AIFSN[0] would result in reduced transmission delay of AC[0] while its impacts to AC[1] and AC[2] are not obvious. In summary, for different ACs, AIFSNs have different impacts. For high priority nodes, adjusting AIFSNs severely affects the throughput, and for low priority nodes adjusting AIFSNs should affect the transmission delay more.

Fig. 10 shows the mean transmission delay of different ACs with increasing node velocity. As we can see, when the node velocity increases, the mean transmission delay of different ACs only increases slightly. In other words, the mean transmission delay of different ACs is not sensitive to the velocity.

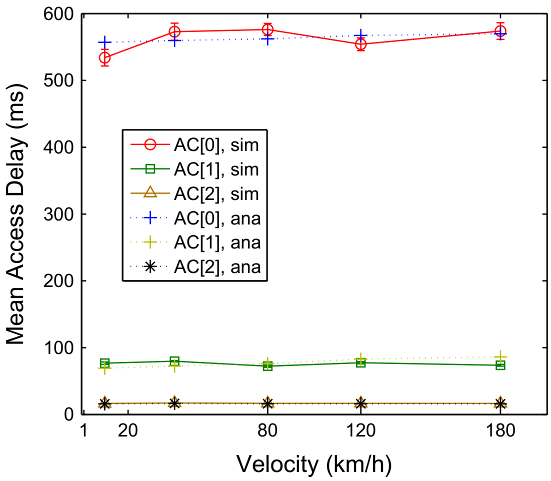

Fig. 10. Mean transmission delay of different ACs with increasing velocity and default setting of the simulator.

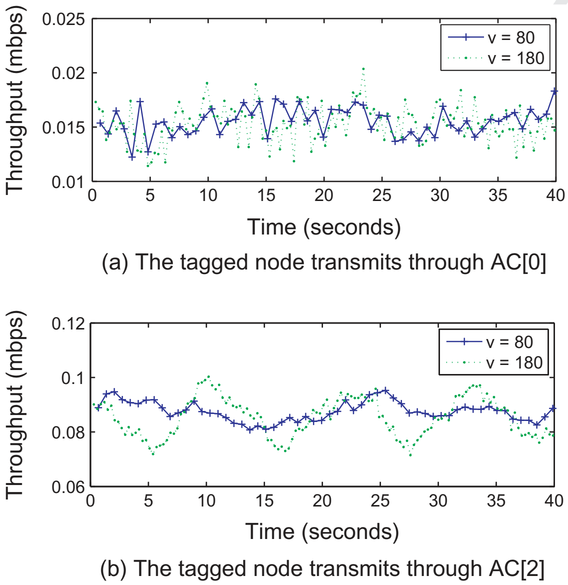

Fig. 11. Throughput of the tagged node over time with default TXOP (0 for all ACs).

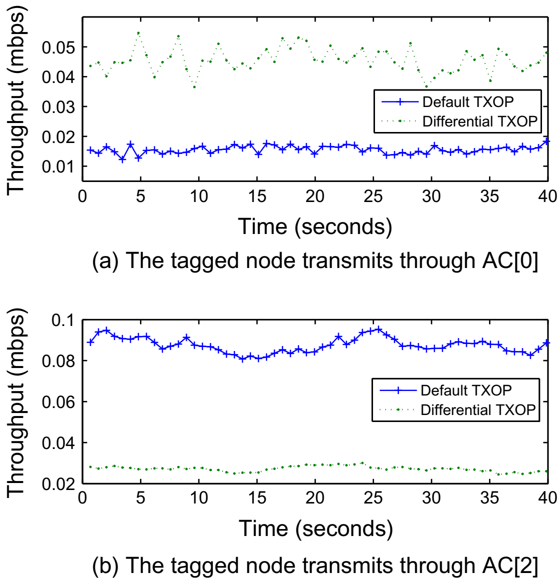

Fig. 12. Throughput of the tagged node over time with TXOP to be 4, 1 and 0 for AC[0], AC[1] and AC[2], respectively

Fig. 11 shows the throughput of the tagged node over time when the velocity increases from 80 km/h to 180 km/h and TXOP is 0 for all ACs. It can be seen that, as the node moves with varying data rates to RSU, the throughput fluctuates extraordinarily over time. Increasing the velocity exacerbates the throughput variations. Compared with AC[0], AC[2] acquires relatively smooth throughput. This attributes to the high priority of transmission. Fig. 12 shows the throughput of the tagged node over time when the TXOP limits of ACs are different. With the enlarging TXOP, we can see that AC[0] acquires enhanced throughput while the throughput of AC[2] reduces. Moreover, as shown in Fig. 12a, increasing TXOP would further intensify the throughput variation. In summary, it is effective to tune TXOP of ACs to balance the throughput achieved by ACs.

5. Conclusion

EDCA provisions service differentiation by configuring different traffic classes with different contention window sizes, AIFSN and TXOP values. However, without responding to the node mobility, the implementation of EDCA in the vehicular communications is quite arguable. In this paper, we have conducted a comprehensive analysis of EDCA in the highly mobile vehicular environment. We have identified the impacts of node mobility and EDCA parameters on the QoS performance and shown that with high node mobility, the communication of vehicles suffers from severe variations. As our analysis characterizes the effects of EDCA parameters and node mobility on the resultant

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QoS performance, it could be used to optimally devise EDCA and guide the real-world implementation.

For the future work, we intend to perform real-world measurements to evaluate the performance of EDCA in the V2I communications. By comparing the measurements with the analytical results, we will conduct a more practical and in-depth evaluate of EDCA. In addition, we will study the performance of EDCA in the multi-channel communication which is specified in 802.11p.

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