Performance Analysis of DSRC Priority Mechanism for Road Safety Applications in Vehicular Networks

Jianhua He, Zuoyin Tang, Tim O'Farrell and Thomas M. Chen

***Abstract*—Dedicated short range communications (DSRC) has been regarded as one of the most promising technologies to provide a robust medium and affordable enough to be built into every vehicle. It is designed to support both road safety and commercial applications. Road safety applications will require reliable and timely wireless communications. However, as the medium access control (MAC) layer of DSRC is based on the IEEE 802.11 distributed coordination function (DCF), it is well known that the random channel access based MAC can not provide guaranteed quality of services (QoS). It is very important to understand the quantitative performance of DSRC, in order to make better decisions on its adoption, control, adaptation and improvement. In this paper we propose an analytic model to evaluate the DSRC based inter-vehicle communication. We investigate the impacts of the channel access parameters associated with the different services including AIFS and contention window. Based on the proposed model, we analyze the successful message delivery ratio and channel service delay for broadcast messages. The proposed analytical model can provide a convenient tool to evaluate the inter-vehicle safety applications and analyze the suitability of DSRC for road safety applications.**

***Index Terms*—IEEE 802.11, DSRC, Vehicle Networks, Road Safety Application**

I. Introduction

Road traffic safety has been a subject of worldwide concern. Recently the UK Department for Transport reported that there were more than 240,000 casualties of all severities in 2007, in which 2,946 people were killed and more than 27,000 were seriously injured. The road accidents resulted in tremendous economic and productivity loss. During the last decade extensive studies have been conducted on road safety systems to actively prevent accidents or passively minimize the consequences of accidents. With the advances in wireless communications and mobile networking, collaborative safety applications (CSA) enabled by vehicular communications is widely regarded as a key to future road safety. Through vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications, complex traffic situation information may be acquired to support collaborative safe driving. For example, V2V communications can be used to determine and warn drivers of hazardous conditions such as other vehicles braking for emergency stops, merging traffic, vehicles in a driver's blind spot, or an imminent collision.

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Vehicle communications can be realized by long range radio networks such as cellular networks and local wireless communications. However, cellular networks can not fulfill the stringent delay requirements of real-time safety applications (e.g., 50 ms). Local communications with an 802.11-like radio can easily support both broadcast and unicast applications [1]. It is much more cost-effective for large scale networks and desirable for safety applications as the useful safety information is usually limited to the area around a vehicle. CSA with local communications has high potential to reduce the crashes and accidents. Among the local communication technologies, DSRC has been regarded as one of the most promising technology to provide a robust medium and affordable enough to be built into every vehicle and installed along every major road [2] [3] [4]. The US FCC has allocated 75 MHz of spectrum in the 5.9 GHz band for DSRC [5]. The DSRC standards are currently developed underway through organizations such as the IEEE [6]. IEEE is developing a wireless access in vehicular environment (WAVE) for DSRC to provide seamless, interoperable services to transportation with V2R and V2V communications [6].

The DSRC is designed to provide both road safety (e.g. collaborative collision warning and collaborative collision avoidance) and commercial services (e.g. navigation, map and Internet access). The road safety and commercial services are usually operated in different channels. For the road safety applications, it is expected that reliable and real-time wireless communications will be required. However, as DSRC's physical layer is based on IEEE 802.11a and its MAC layer is based on the IEEE 802.11 enhanced distributed coordination access (EDCA) [7], it is well known that random channel access based IEEE 802.11 MAC can not provide QoS guarantee for channel access delay and message success ratio. To make it worse, DSRC will be operated under a wide range of vehicle network scenarios including possibly saturated and congested channels. It is very important to understand quantitatively the performance of DSRC, in order to make better decisions on the adoption, control, adaptation and improvement of the technology. Although there are many simulation based studies of the DSRC technology, the simulations are very time consuming and not easy to generate the results. In this paper, we quantitatively study the DSRC technology for the road safety applications. There are two main contributions in this paper. First, we propose an analytical model for the priority mechanisms in the DSRC for the broadcast based road safety applications. The model is simple and shown to be accurate. We take into account the main factors that may affect the performance, such as the channel access contention window size and arbitration inter-frame space (AIFS). Second, with the analytical model, we investigate the DSRC communication performances in terms of channel access delay and message delivery ratio in details.

We briefly overview the DSRC channel access and management mechanisms in Section II. The analytical model is proposed in Section III. Performances of channel access delay and message delivery ratio are derived in Section IV. Section V presents the numerical results.

II. Overview of DSRC Technology

In this section, we will give a brief overview of the MAC layer mechanisms developed under the IEEE WAVE system for DSRC. The overall WAVE architecture includes IEEE Std1609.1 to 1609.4 (for resource management, security architecture, networking service and multi-channel operation, respectively) and IEEE P802.11p (MAC and PHY standard). IEEE 802.11p uses essentially the same PHY defined for 802.11a but operates in a 10 MHz wide channel instead of 20 MHz. Next we will introduce the draft IEEE 802.11p channel access scheme and the multi-channel operation.

A. IEEE 802.11p Channel Access

In the IEEE 802.11p MAC, the channel access scheme over a single channel is a slightly modified version of the DCF defined in the IEEE 802.11 standard with enhanced QoS support [13]. The IEEE 802.11 MAC provides a shared access to the wireless channel and supports two medium access protocols: DCF and optional point coordination function (PCF) [1]. DCF is used as a basis for PCF.

DCF employs a carrier sense multiple access with collision avoidance (CSMA/CA) as the access method [1]. A truncated binary exponential backoff (TBEB) scheme is used in the access method. Before initiating a transmission, each station with pending data packets is required to sense the medium. If the medium is busy, the station defers its transmission and initiates a backoff timer. The backoff timer is randomly selected between 0 and contention window (CW). The initial CW value for new packets is set to CW_{min}. Once the station detects that the medium has been free for a duration of DCF, it begins to decrement the backoff counter as long as the channel is idle. Upon the expiration of the backoff timer, the station begins to transmit if the medium is still free. If the data packet is unicast (i.e. for a single receiver), an optional mechanism is to transmit a short ready-to-send (RTS) to the destination before the transmission of the data packet. If RTS is transmitted, a clear-to-send (CTS) message will be expected from the destination. An acknowledgment is expected for every unicast data packet. If an acknowledgment (or CTS) is not received within a timeout period, the transmitted packet is inferred to be lost due to either packet collision or corruption. Then the above backoff procedure is repeated to retransmit the packet. The size of the CW is doubled for every retransmission until it reaches the CW_{max} value. If number of retransmissions for a packet reaches the maximal allowed retries, the packet is discarded. It is noted that for a broadcast data packet, the data packet will be transmitted without RTS handshaking. Neither acknowledgment nor retransmission is required.

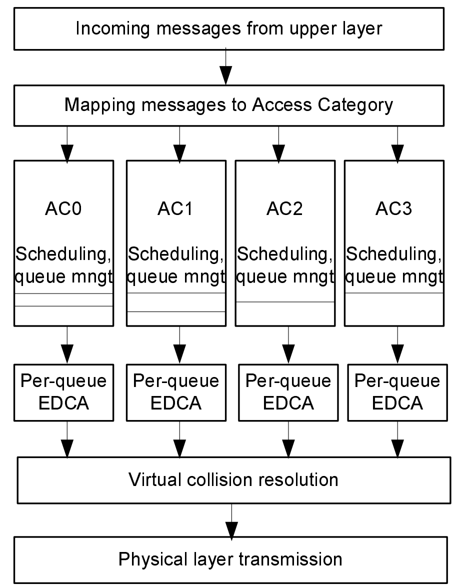

Fig. 1. A simple illustration of IEEE 802.11e EDCA scheme.

The legacy IEEE 802.11 MAC lacks of QoS support for real-time applications. The need for a better access mechanism to support service differentiation and QoS has led to the standardization of IEEE 802.11e [7]. The 802.11e standard introduces the hybrid coordination function (HCF) that concurrently uses a contention-based mechanism EDCA, and a polling-based mechanism, HCF controlled channel access (HCCA) [7]. The EDCA mechanism provides differentiated, distributed access to the channel using eight different user priorities (UPs), which are mapped to four access categories (ACs) [7]. For each AC, an EDCA process will be started to contend for transmission opportunities (TXOPs) using a set of distinct EDCA parameters, including AIFS instead of DIFS in DCF and a pair of CW_{min} and CW_{max}. AIFS[AC] is determined by AIFS[AC] = SIFS + AIFSN[AC], where AIFSN[AC] is an integer indicating the number of slots that a station belong to AC should defer before either invoking a backoff or starting a transmission after a SIFS duration. AC values of 0, 1, 2, and 3 represent best effort, background, video, and voice AC, respectively. If there are more than one ACs in a station and the backoff timers associated with the ACs expire simultaneously, a virtual resolution function will be used to assign the transmission opportunity to the higher priority message, while the lower priority message will be retried (or discarded if the maximal retries reached) as if the transmission attempt fails. An illustration of the EDCA scheme is shown in Fig. 1.

B. DSRC Multi-channel Operation

DSRC operates in the 5.9 GHz licensed band and is divided into seven channels, one of which is the control channel (CCH) to be used for exchanging only road safety messages, and the others are service channels (SCH). The IEEE 802.1609 standard for a WAVE system defines functional extensions to IEEE 802.11 to enable multi-channel coordination. The CCH is used for exchange of management frames and short messages; the SCHs are used for application specific information exchanges. IP data frames can only be transmitted over SCHs. User priority per channel will use the IEEE 802.11e EDCA mechanism. Each AC over a channel has an independent channel access function. The differentiation in priority between AC for channel access parameters is implemented using the appropriate EDCA parameter set values. The default values for the EDCA parameter set may differ from IEEE Std 802.11. The EDCA parameter set used on the CCH has been optimized for the transmission of WAVE short messages. The EDCA parameter set shown in Table 1 are used for all WAVE devices when operating on the CCH. The values of CW_{min} and CW_{max} are specified in the IEEE P802.11p standard. The EDCA parameter set on the CCH shown in Table I is usually pre-configured in the IEEE 1609.4 standard.

TABLE I
ACCESS CATEGORY PARAMETERS

AC	Example	CW_0	CW_m	AIFSN (slots)
AC0	Background	aCW_{min}	aCW_{max}	9
AC1	Best effort	aCW_{min}	aCW_{max}	6
AC2	Video	$aCW_{min}/2$	$aCW_{max}/2$	2
AC3	Voice	$aCW_{min}/2$	$aCW_{max}/2$	2

As there can be one or more devices not capable of simultaneously monitoring the CCH and exchanging data on SCHs (so-called single-channel WAVE devices), the channels need to be coordinated by a synchronization procedure. CCH and SCH intervals are uniquely defined with respect to an absolute external time reference. A synchronization interval is the sum of the CCH interval and SCH interval. An illustration of the synchronization interval is shown in Fig. 2. All WAVE devices need to monitor the CCH during the CCH interval. At the beginning of each scheduled channel interval, a guard interval is used to account for variations in channel interval time and timing inaccuracies. Upon startup, a device monitors the CCH until an announcement of service that utilizes an SCH, or the device chooses to utilize the SCH based on WAVE announcement frames it transmits.

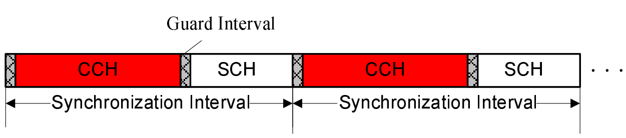

Fig. 2. Synchronization interval.

III. SYSTEM ASSUMPTION AND ANALYTICAL MODEL

A. Model Assumption

DSRC is designed to operate under a wide range of scenarios, for example, freeway and urban intersections. Various vehicle safety applications can be enabled through the DSRC based wireless communications. For both freeway and urban intersections scenarios, the real-time and reliable delivery of messages based on DSRC will be critical for the safety applications. For the DSRC based freeway safety applications, the safety applications and the DSRC techniques will operate in a distributed way, as there are normally no or much fewer controllers in the freeway scenarios. On the other hand, in the intersection scenarios, roadside unit (RDU) DSRC devices may be installed at the traffic light post. The RDUs can be connected to the fixed network and act as the controllers of safety applications and the DSRC based wireless communications for the vehicles in wireless communications zones centered at the RDUs. Due to the distributed system operations as well as the hidden terminal communications problem, theoretic analysis of DSRC based safety application performances in the freeway scenarios is very difficult, if not impossible. In this paper we will focus on the scenario of an urban intersection as shown in Fig. 3. Investigation of the DSRC in the freeway scenarios will be our future work.

In the investigated intersection scenarios, we assume the transmission range and the carrier sense range of the RDU to be L_t and L_c, respectively. For simplicity, we will focus on the safety applications over the CCH and the SCH interval is simply set to zero. For the safety applications over the CCH, two general applications are considered, namely emerging applications and routine applications. Emerging applications will generate critical safety messages (such as notification of collision events), which have the highest priority and require reliable and timely transmission. Such messages are called emerging messages in the rest of the paper. On the other hand, the routine applications are assumed to generate some periodic messages (such as position broadcast). The messages are called routine messages and they are important for collaborative safety but occasional loss of the message may not result in disastrous consequences.

In the carrier sensing range of the RDU we assume N_e devices will generate emerging messages, and N_r devices will generate routine messages. And each device will simply generate only one type of messages. The devices generating emerging messages are called emerging devices and those generating routine messages will be called routine devices. All the devices are assumed to be capable of sensing the transmissions from all the other devices. The EDCA parameter set of $\{CW_{min}, AFIS\}$ associated with the N_e messages are configured with $\{W_e, DIFS\}$. For the routine messages, CW_{min} is configured to W_r and $AIFS$ is configured to $DIFS$ plus d backoff slots, with $d > 0$. The emerging messages will have absolute priority over the routine messages with $W_r = 2W_e$ and $d > 0$. We assume that there is no hidden terminal problem. Each application will generate saturated traffic, which means messages are always available for transmission. Each message has the same length of L_d and the transmission rate is R_t. It can be simple to calculate the required time to transmit a message, which is denoted by T_d in the unit of backoff slots, with $T_d = \frac{L_d}{\delta R_t}$, where δ is the duration of a backoff slot. Hidden terminal problem and unsaturated traffic will be investigated in our future work.

Furthermore, we assumed both emerging and routine messages will be broadcasted over the CCH. This assumption is reasonable due to the highly dynamic change of the connec-

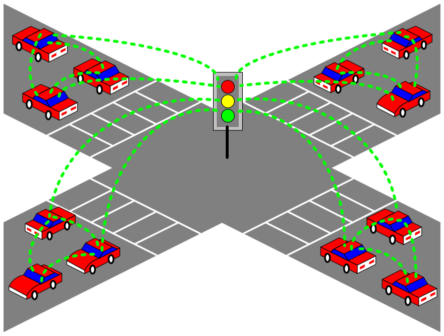

Fig. 3. Scenario of an urban intersection.

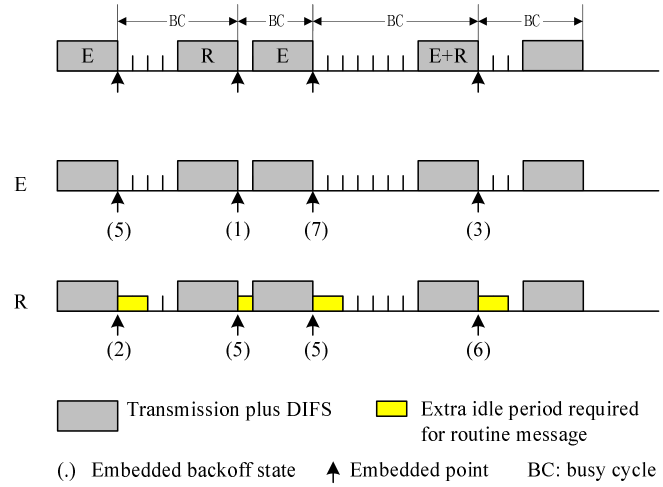

Fig. 4. A simple illustration of embedded state.

tions and the topology. It will be very difficult to be aware of the neighbors' addresses. In addition, the safety related information usually needs to be transmitted to the vehicles in the vicinity of a sender and the interested receivers may be unknown at the time of message transmission. In such way, the vehicles that may be involved in the impending safety related event can take corresponding reactions upon receiving the messages. For the delivery of the broadcast messages, we assume a perfect wireless channel, over which the messages will be correctly received by the vehicles in the vicinity of a sender unless message collision occurs.

B. Embedded Markov Chain

In this section, we will present an embedded Markov chain to model the EDCA mechanism for the safety messages over the CCH. In the literature, Markov chains have been widely used to model the TBEB defined in the DCF of IEEE 802.11. As the safety messages are assumed to be broadcast messages, we do not need to consider the exponential backoff procedure. But it is still challenging to model the impacts of the different AIFS set for the emerging and routine messages. In this paper we will use a two-dimensional embedded Markov chain to model the impacts of differentiated AIFS. Define a transmission point as the beginning of a transmission event over the channel. An embedded point is defined as the instant that the duration of DIFS elapsed with the channel sensed idle after the end of the transmission event. The time between two consecutive embedded points is called a busy cycle. An embedded state of a device in the embedded Markov chain can be represented by the backoff counter j of the device at the embedded points, denoted by $b(j)$, $j \in [0, W_q - 1]$, where q may be e for emerging applications or r for routine applications. The backoff counter at the embedded points is called embedded backoff counter (EBC). For a specific device, the embedded state $b(t)$ will be modeled as a discrete-time embedded Markov chain, where the time t represents the beginning of the embedded point.

An illustration of the embedded state is presented in Fig. 4 where an emerging device (represented by E) and a routine device (represented by R) are contending for the channel. Device E is assumed to have an AIFS equal to DIFS, while device R is assumed to have AIFS equal to DIFS plus 2 extra backoff slots. The evolution of the embedded states for the emerging device and routine device are independent. The instant of time in which device R may start decrementing its backoff counter is 2 backoff slots apart from the corresponding instant for device E.

C. Transmission Probability

As emerging and routine devices will have different distributions of embedded states, we use superscripts e and r to distinguish the variables associated with embedded and routine devices. Let $b_e(j)$ and $b_r(j)$ denote the stationary distributions of embedded states (j) for a tagged station with emerging and routing applications, respectively. From the stationary distributions, we denote by $B_e(j)$ and $B_r(j)$ the cumulative probability that the EBC of tagged emerging and routing devices is not larger than j, respectively. We have

$$B_e(j) = \sum_{j=0}^{W_e-1} b_e(j), \quad j \in [0, W_e - 1] \tag{1}$$

$$B_r(j) = \sum_{j=0}^{W_r-1} b_r(j), \quad j \in [0, W_r - 1] \tag{2}$$

Denote by $\tau_e(j)$ and $\tau_r(j)$ the probability that the tagged emerging and routing devices transmit in a general busy cycle with EBC of j, respectively. Given that, in a busy cycle, a tagged device is in backoff state $j \geq 0$, the probability that the tagged device will transmit in this busy cycle is given by the probability that no other device transmits in the busy cycle. If $j > d$, this event occurs if all the other emerging devices have a backoff counter greater or equal to j, and all the other routine devices have a backoff counter greater or equal to $j-d$. Therefore we can get

$$\tau_e(j) = [1 - B_e(j-1)]^{N_e-1}[1 - B_r(j-1-d)]^{N_r} \tag{3}$$

for $j \in [d+1, W_e - 1]$. If $j \leq d$, as the routine devices will not transmit in this busy cycle at all, this event occurs if all the other emerging devices have a backoff counter greater or equal to j. Then we get

$$\tau_e(j) = [1 - B_e(j-1)]^{N_e-1} \tag{4}$$

for $j \in [0, d]$.

Similarly for the routine devices, we take into account that backoff process starts after d idle time-slots apart from instant of emerging devices starting backoff process. Therefore, $\tau_r(j)$ is the probability that all the other routine devices have backoff counter greater or equal to j and all emerging devices have backoff counter greater or equal to $j + d$. Therefore we can get $\tau_r(j)$ by:

$$\tau_r(j) = [1 - B_r(j-1)]^{N_r - 1}[1 - B_e(j - 1 + d)]^{N_e} \quad (5)$$

for $j \in [0, W_r - 1]$.

Let τ_e and τ_r denote the unconditional probability that the tagged emerging and routine device transmit in a busy cycle, respectively. We can calculate τ_e and τ_r by:

$$\tau_e = \sum_{j=0}^{W_e - 1} b_e(j)\tau_e(j) \quad (6)$$

$$\tau_r = \sum_{j=0}^{W_r - 1} b_r(j)\tau_r(j) \quad (7)$$

Let us define with $P_e(j)$ $(P_r(j))$ the probability that, at steady state, the tagged emerging (routine) device extracts a backoff value j after it transmits in a general busy cycle. This probability distributions can be easily obtained:

$$P_e(j) = \frac{1}{W_e}, \quad j \in [0, W_e - 1] \quad (8)$$

$$P_r(j) = \frac{1}{W_r}, \quad j \in [0, W_r - 1] \quad (9)$$

For the embedded Markov chain, there is a possibility that any embedded Markov state transits to itself or other states. Therefore we can use state balance equations to directly and efficiently calculate the steady-state distributions of the embedded Markov states without constructing the state transition diagraph. Next we will derive the state balancing equations. Consider a tagged device found, at a general busy cycle, in backoff state $j > 0$. This can occur either because, during the previous busy slot, the device has transmitted and a backoff value j has extracted with probability $\tau_e P_e(j)$ for emerging device and with probability $\tau_r P_r(j)$ for routine device, or because the tagged device at the previous embedded point was in state $j + l$, and exactly $l + I$ idle slot-times have elapsed. Thus, at steady state, the following probability flow balancing equations hold for emerging device ($j \in [1, W_e - 1]$):

$$b_e(j) = \tau_e P_e(j) + \sum_{l=0}^{W_e - 1 - j} b_e(j + l)[\tau_e(l) - \tau_e(l + 1)] \quad (10)$$

and $b_e(0) = \tau_e P_e(0)$. Similarly we can have the flow balancing equations for routine device ($j \in [1, W_r - 1]$)

$$\begin{aligned} b_r(j) = {} & \tau_r P_r(j) + b_r(j)[1 - (1 - B_e(d))_e^N] \\ & + \sum_{l=0}^{W_r - 1 - j} b_r(j + l)[\tau_r(l) - \tau_r(l + 1)] \end{aligned} \quad (11)$$

and $b_r(0) = \tau_r P_r(0) + b_r(0)[1 - (1 - B_e(d))_e^N]$.

Let p_e (p_r) denote the probability that the tagged emerging (routine) device transmits in a general busy cycle and the message collides. It is easy to calculate p_e and p_r as:

$$p_e = \sum_{j=0}^{W_e - 1} b_e(j)[\tau_e(j) - \tau_e(j + 1)] \quad (12)$$

$$p_r = \sum_{j=0}^{W_r - 1} b_r(j)[\tau_r(j) - \tau_r(j + 1)] \quad (13)$$

From the above equations, if we consider a common system for the embedded state distributions together with normalization conditions, we obtain a system of $2(W_e + W_r + 2)$ nonlinear equations in the same number of unknown parameters, which can be numerically solved. The successful message deliver rate and delay performances are then readily computed as shown in the next section. It is noted that the above model can easily extended to more than 2 priority classes and unicast applications.

IV. PERFORMANCE METRICS

For the broadcast safety applications, we are interested in the performance metrics of normalized throughput, average channel access delay and successful message delivery ratio. In this section, we will derive the expressions for the above performance metrics based on the expressions derived in the previous section.

Let N_{idle} denote the average number of idle slots between the end of an embedded point and the beginning of the subsequent transmission point. Denote ψ_j the probability that at least one emerging device transmits in a general busy cycle with EBC j. ψ_j can be computed for $j = [0, W_e - 2]$ by

$$Pr[\psi = j] = [1 - B(j-1)]\tau_e(j) - [1 - B_e(j)]\tau_e(j + 1) \quad (14)$$

Then we can compute N_{idle} by:

$$N_{idle} = \sum_{j=0}^{W_e - 2} j\psi_j. \quad (15)$$

Define normalized throughput (denoted by S) as the average data payload (in slot) successfully transmitted in a general busy cycle. Absolute network throughput can be easily obtained as the normalized throughput multiplied by the PHY data rate R_t. We can compute S by (17):

$$S = \frac{(N_e P_{suc,e} + N_r P_{suc,r})T_d}{N_{idle} + T_d} \quad (16)$$

Let S_e and S_r denote the normalized throughput for a single emerging device and routine device, which is the average data payload (in slot) successfully transmitted by an emerging device and a routing device in a general busy cycle, respectively. We can compute S_e and S_r by:

$$S_e = \frac{P_{suc,e}T_d}{N_{idle} + T_d} \quad (17)$$

$$S_e = \frac{P_{suc,r}T_d}{N_{idle} + T_d}. \quad (18)$$

The average access delay performance, i.e. the average time D_e (D_r) elapsing between the instant of time an emerging (routine) message is put in the head-of-line position of the transmission buffer, and the instant of time the message is transmitted, can be computed by:

$$D_e = \frac{N_{idle} + T_d}{\tau_e}, \quad (19)$$

$$D_r = \frac{N_{idle} + T_d}{\tau_r}. \quad (20)$$

Let $p_{s,e}$ ($p_{s,r}$) denote the average message success ratio that a transmitted emerging message (routine message) does collide with other messages. We can calculate $p_{s,e}$ and $p_{s,r}$ by:

$$p_{s,e} = \frac{1 - p_e}{\tau_e}, \quad (21)$$

$$p_{s,r} = \frac{1 - p_r}{\tau_r}. \quad (22)$$

V. NUMERICAL RESULTS

A. System Configuration

In this section, we will present numerical results for the safety applications over the DSRC control channel. As the analytical model is very general, we have obtained results for a wide range of parameter configurations. However, due to limited space only a small part of the results will be presented. We consider an urban road intersection with two roads as shown in Fig. 3, where are N_e emerging devices (including the RDU) and N_r routine devices inside the transmission range of the RDU installed at the traffic light post. We simply assume that each vehicle will have either a single emerging device or a single routine device. The carrier sensing range is set to be twice of the transmission range, so each device will sense a busy channel if any other device transmit a message over the channel. Suppose that each road has N_l lanes in each direction. The transmission data rate is 1 Mbps. Each backoff slot is 16 us. In the rest of this section, we will investigate the impacts of the transmission range and the EDCA channel access parameters on the performance of DSRC safety applications.

B. Impact of Transmission Range

In this subsection, we investigate the impacts of the transmission range on the performance of normalized throughput, message success ratio and average delay. Typical results are presented in Fig. 5 to Fig. 10.

Fig. 5 to Fig. 7 show the results with a parameter setting of relatively light traffic load over the CCH. The message length L_d is set to 50 bytes. Each road has 1 lane in each direction, i.e. $N_l = 1$. The number of emerging devices N_e is fixed to 5. The vehicles with routine applications inside the communication ranges of the RDU is assumed to be uniformly distributed along the roads with a density of V_d vehicles per meter. We set the vehicle density V_d with routine applications to 0.025. Then the number of routine devices N_r can be computed by $N_r = \lceil 8 N_l V_d R_t \rceil$. The minimal contention window W_e is set to 2^7 for emerging messages and W_r is set to 2^8 for routine messages. The AIFS for emerging messages is set to 2, while for routine messages it is set to 2, 4, 6 and 9 (denoted by "AIFS2" in the figures), to investigate the effects of AIFS differentiation.

It can be observed that under light traffic load, the emerging applications can achieve a good performances with differentiated AIFS. For example, the average message success ratio is higher than 0.8 and the average channel access delay is less then 10 ms. Such performances should be acceptable for the emerging safety applications. The performances of routine applications is also acceptable and not affected largely by the AIFS setting. It is also observed that in the case of the same AIFS for the emerging and routine applications, the service differentiation is not so effective. For example, the average message success ratio of the emerging applications and the routine applications is very close with AIFS=2 for both applications.

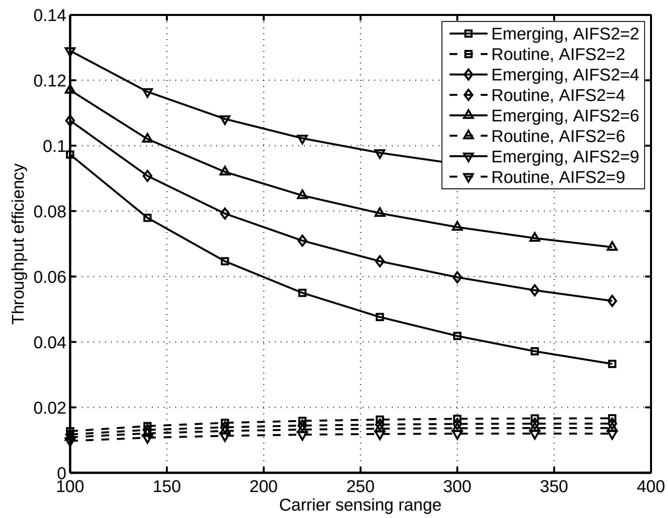

Fig. 5. Normalized throughput of emerging and routine applications versus carrier sensing range. $N_e = 5$, $L_d = 50$ bytes, $R_t = 1$ Mbps, V_d=0.025, $W_e = 2^7$.

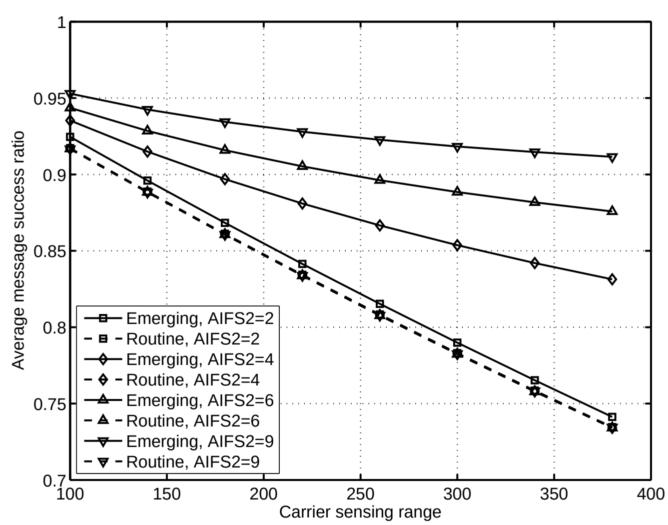

Fig. 6. message success ratio of emerging and routine applications versus carrier sensing range. $N_e = 5$, $L_d = 50$ bytes, $R_t = 1$ Mbps, V_d=0.025, $W_e = 2^7$.

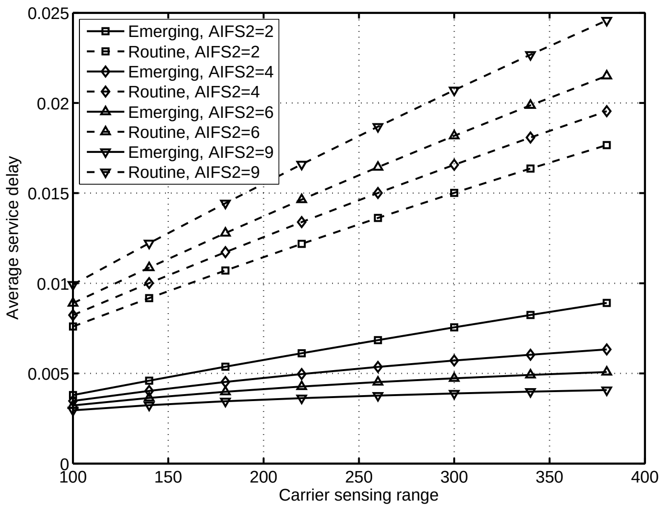

Fig. 7. Average channel access delay of emerging and routine messages versus carrier sensing range. $N_e = 5$, $L_d = 50$ bytes, $R_t = 1$ Mbps, V_d=0.025, $W_e = 2^7$.

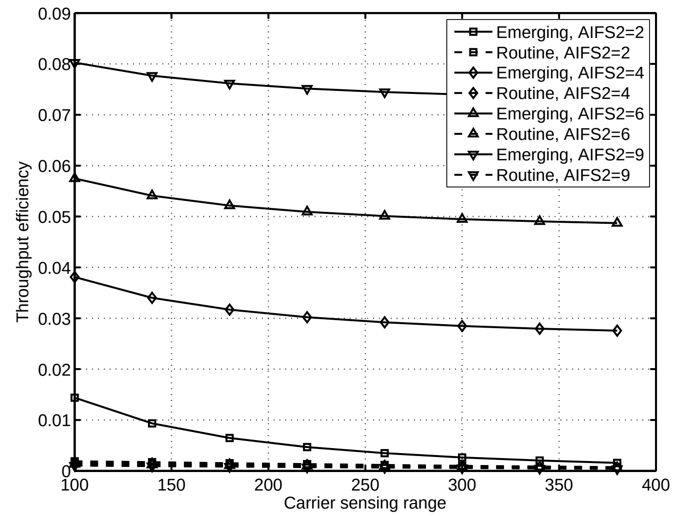

Fig. 8. Normalized throughput of emerging and routine applications versus carrier sensing range. $N_e = 5$, $L_d = 150$ bytes, $R_t = 1$ Mbps, V_d=0.1, $W_e = 2^7$.

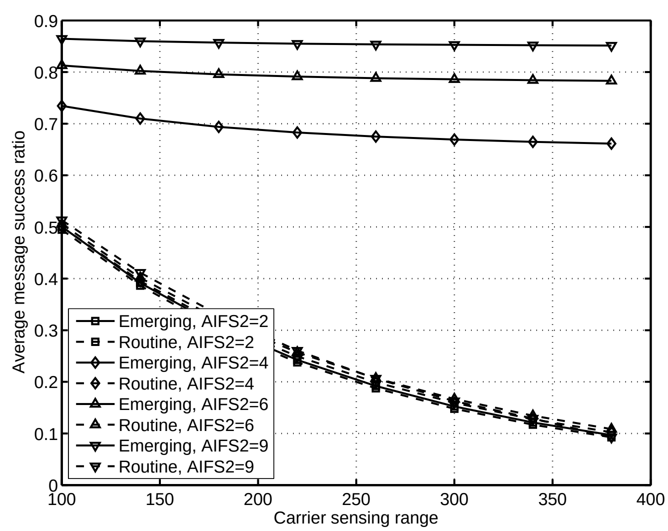

Fig. 9. Successful message delivery rate of emerging and routine applications versus carrier sensing range. $N_e = 5$, $L_d = 150$ bytes, $R_t = 1$ Mbps, V_d=0.1, $W_e = 2^7$.

Next we have a look of Fig. 8 to Fig. 10, which show the results with a parameter setting of relatively heavy traffic load over the CCH. The message length L_d is 150 bytes. Each road has 2 lanes for each direction. The vehicle density V_d for routine applications is 0.1 vehicle per meter. Under heavy traffic load, it can be observed that the impact of AIFS differentiation is much more prominent. The throughput efficiency of the routine applications is now close to zero and message success ratio is low up to 0.1. Without AIFS differentiation, the performances of the emerging applications suffer big degradation. For example, the message success ratio is almost as bad as that of the routine applications. Even with AIFS differentiation, the emerging application performances are also significantly affected. The average channel access delay is now up to 30 ms, which will have negative impacts on the safety applications. The emerging application performance can be even worse with heavier traffic load. Therefore efficient traffic load control will be required to deliver reliable and timely DSRC communications.

It is obvious that for both light and heavy traffic loads, increasing the AIFS value for routine applications can achieve stronger differentiation between the performances of the emergency and routine applications. However, in practice it may be improper to set too large AIFS value for routine applications. One concern is that although routine applications have lower priority compared to the emergency applications, they do have certain requirements on the message delivery latency and throughput. Too large AIFS value for routine applications may result in unnecessarily large delivery latency, especially under relatively light traffic load conditions, and may completely starve the routine applications under heavy traffic load conditions.

C. Impact of Contention Window

In this subsection, we investigate the impact of the back-off contention window. As the maximal contention window CW_{max} does not have impact on the broadcast messages, we will focus on the CW_{min}. As set in the previous subsection, CW_{min} for routine messages is set to be twice of that for emerging messages. Other system parameters are set as follows. The number of emerging devices N_e is 5. Message length L_d is 100 bytes. Transmission range is 110 m and carrier sensing range is 220 m. Vehicle density for the routine applications is 0.1 vehicle per meter. Fig. 11 and Fig. 12 shows the results of normalized throughput and message success ratio versus $log_2(W_e)$ for emerging applications, respectively. It can be observed with small contention window, the performances of both emerging and routine applications are very low. With larger contention window, the message success ratio for both application is improved largely. But the normalized throughput of the emerging applications is reduced. Therefore a tradeoff needs to be made on normalized throughput and message success ratio by properly configuring the CW_{min}.

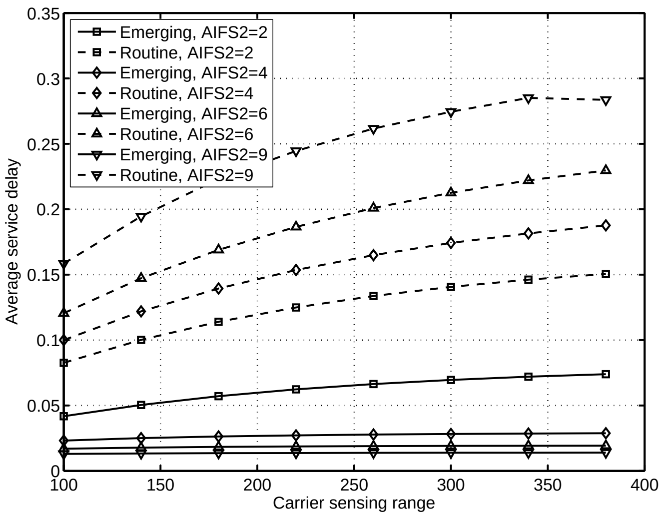

Fig. 10. Average channel access delay of emerging and routine messages versus carrier sensing range. $N_e = 5$, $L_d = 150$ bytes, $R_t = 1$ Mbps, V_d=0.1, $W_e = 2^7$.

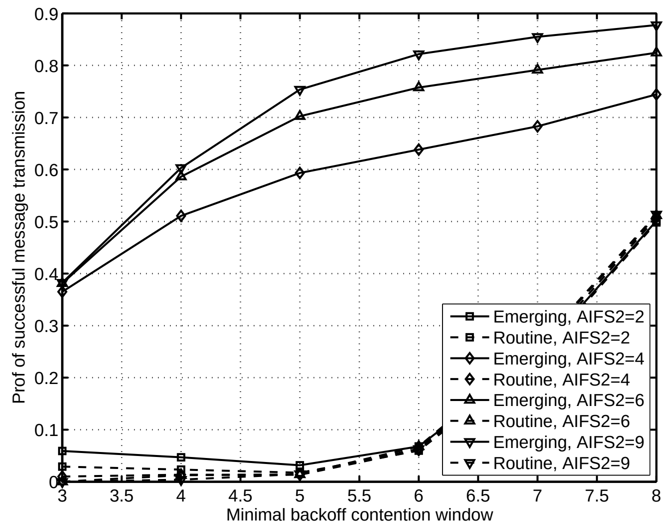

Fig. 12. Successful message delivery rate of emerging and routine applications versus $log_2(W_e)$ for emerging applications. $N_e = 5$, $L_d = 100$ bytes, $R_t = 1$ Mbps, V_d=0.1, $R_t = 110$ m.

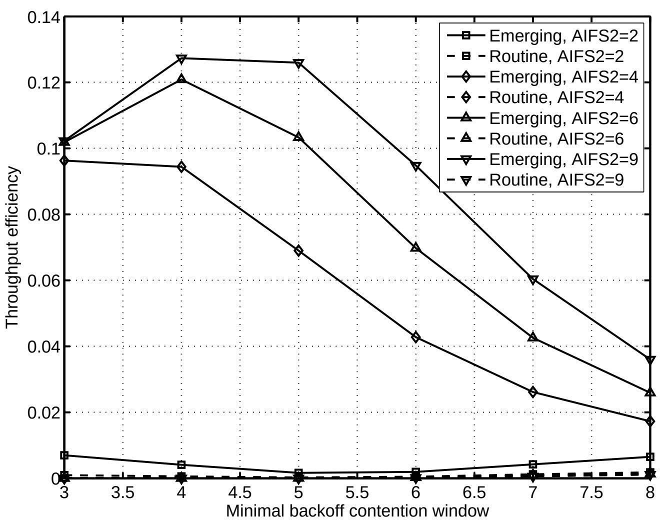

Fig. 11. Normalized throughput of emerging and routine applications versus $log_2(W_e)$ for emerging applications. $N_e = 5$, $L_d = 100$ bytes, $R_t = 1$ Mbps, V_d=0.1, $R_t = 110$ m.

VI. Related Work

There are two main streams of works related to the work presented in this paper. The first is on the DSRC communications performance for vehicle networks and safety applications. The second is on the analytical modeling of the 802.11 and 802.11e channel access schemes.

With regards to DSRC, studies were conducted mainly based simulation to evaluate or to improve its performance [8]- [12]. Limitations of 802.11a in DSRC environment are identified in [8]. Broadcast reception and channel access delay with the IEEE 802.11e EDCA priority channel access mechanisms were quantified by simulation in [9]. It was shown that for safety-critical applications, the proper design of repetition or multi-hop retransmission strategies should be used for robustness and network reliability of vehicular networks. A concept of communication density was introduced in [13], attempted to serve as a metric for channel load in vehicular communications. To adjust transmit power for V2V broadcast safety communication in vehicular ad hoc networks, a feedback-based power control algorithm is designed in [14]. The algorithm is designed to select a transmit power no greater than necessary for a targeted range. Mittag et al presented a detailed survey on congestion control and transmit power control for vehicular ad hoc networks. They also proposed a low overhead transmit power control scheme [15]. Ma and Chen presented an analytical model for the broadcast performance of the DSRC in a highway scenario [16]. Both delay and packet delivery ratio are derived. However, it is noted that only backoff contention window based priority scheme was studied. As shown in our numerical results, backoff contention window based priority scheme is much less effectively than the AIFS based priority scheme. Therefore the investigation in [16] is not sufficient for a deep and correct understanding of the DSRC communications performances.

With the rapid deployment of the IEEE 802.11 WLAN in the 1990s, the contention based DCF MAC access function has been studied extensively by analytical means. Among those analytical studies three major performance models have been proposed in parallel in order to analyze the saturation throughput performance [17] [18] [19] [20]. Driven by the need of QoS support for real-time applications over WLAN, the basic DCF MAC access function was enhanced in the IEEE 802.11e standard [7] [21]. In recent years, the performance of EDCA has also been explored by means of analytical evaluations. The EDCA analytical studies are mainly based on the modifications of DCF analysis mentioned above. Most of the analytical models proposed for EDCA modify or extend Bianchi's Markov chain model [18] to accommodate the differentiation of contention window and/or AIFS. [22] [23] analyze the impacts of only contention on service differentiation, while [24] [25] [26] analyze the differentiation effects of both contention window and AIFS. [24] enlarges the original bidimensional Markov chain to tri-dimensional. [25] provides a new analytical approach to model the AIFS-based priority mechanism. In our paper the proposed analytical model is based on the one presented in [25] with proper modifications to make our proposed model more scalable and accurate. To our best knowledge, our proposed model is the first one reported for the AIFS and contention window based DSRC priority schemes.

VII. CONCLUSION

DSRC is regarded one of the most promising technology for vehicle communications. It is expected that the road safety applications will require reliable and timely wireless communications. However, the MAC layer of DSRC is based on the IEEE 802.11 DCF, which can not provide guaranteed QoS. In this paper we propose a simple and accurate analytic model to evaluate the DSRC priority mechanism based inter-vehicle communication, with focus on a road intersection scenario. We investigated the impacts of the transmission range and the channel access parameters for multiple priority services (i.e. AIFS and contention window size). We studied the throughput efficiency, message success ratio and channel access delay for both emerging and routine messages. It is observed that differentiation of channel access parameters especially AIFS can help achieve a satisfactory communication performance for the emerging applications under light to medium traffic load. However, under the heavy traffic load scenario, the differentiation is still working but the communication performance for the emerging applications suffer large degradation. It will be necessary to control the channel traffic load to provide a reliable and timely communications for the emerging applications.

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