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Modelling, analysis and performance improvement of an SRU's access request queue in multi-channel V2I communications

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ABSTRACT

This paper presents a concise yet comprehensive description of a multi-channel Vehicle-to-Infrastructure (V2I) communication system. Existing mathematical models for such a system overlook some of its essential behavioural characteristics such as the reneging, force-termination and ultimately blocking of service requests. A multi-server queueing model with First-In–First-Out (FIFO) service policy is proposed for the purpose of accurately capturing the dynamics of the above-mentioned communication system and evaluating its performance. Approximations were exploited as a mean to enhance this model's mathematical tractability. Simulations are conducted in the context of a realistic scenario with the objective of validating the proposed approximate model, verifying its accuracy and characterizing the system's performance in terms of several new metrics. The reported results indicate a cataclysmic access request blocking probability ranging from 66% to 85%. An Access Request Deadline-Aware (ARDA) service policy is then proposed to reduce the blocking probability and improve the system's response time. Indeed ARDA achieved an improvement over FIFO of almost 70% in terms of the overall blocking probability and 22% to 66% in terms of the system's response time.

1. Introduction

1.1. Overview

MODERN intelligent transportation systems resort to information and communication technologies as a mean to revamp transportation systems and enhance their quality and effectiveness. Vehicular Networking aims at transforming vehicles into smart mobile entities that are able to wirelessly communicate with each other as well as to communicate with

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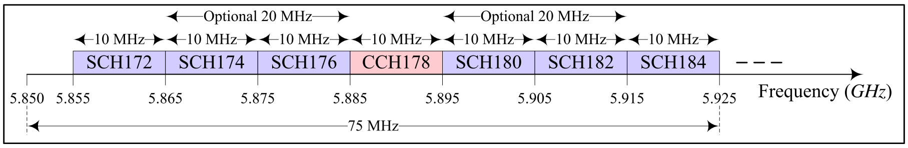


Fig. 1. 75 MHz spectrum channel subdivision and frequency allocation.

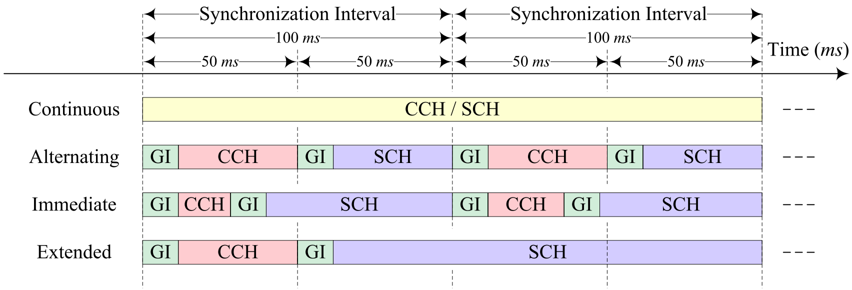


Fig. 2. IEEE 1609.4 multi-channel access mechanisms.

Stationary Roadside Units (SRUs) (*e.g.* access points, routers, etc., deployed along roadsides). The combination of intelligent transportation systems and vehicular networking presents a variety of new services such as: (a) improvement of passenger and road safety [1], (b) traffic management [2], (c) monitoring and road surveillance [3], (d) hot-spot guidance [4], (e) on-the-fly broadband Internet access [5], (f) remote region connectivity [6], (g) information sharing and dissemination [7], (h) peer-to-peer services [8], and so forth.

For the purpose of supporting all of these new services, the US FCC has allocated 75 MHz of the Dedicated Short Range Communication (DSRC) Spectrum over the licenced 5.9 GHz band for vehicular networks [9]. As shown in Fig. 1, this spectrum is subdivided into one Control CHannel (CCH) and a number of $m = 6$ Service CHannels (SCHs). In addition, the IEEE has developed two novel protocol standards aiming at providing Wireless Access in Vehicular Environments, namely: (a) the IEEE 802.11*p* [10] and (b) the IEEE 1609 [11]. While the IEEE 802.11*p* operates over a single channel, multi-channel access is governed by the IEEE 1609.4 protocol. As illustrated in Fig. 2, this latter protocol presents four multi-channel access mechanisms, namely:

1. *Continuous access*: Radio devices remain continuously tuned to a single of either one of the channels (*i.e.* CCH or SCH). No channel coordination is required in this case.
2. *Alternating access*: Devices periodically alternate between two time intervals, namely: (a) a CCH interval (CCI) and (b) an SCH interval (SCI). Both intervals are of equal length of 50 (ms); hence composing a nominal synchronization interval of 100 (ms). The start of each CCI and SCI, a Guard Interval (GI) of 5 (ms) is used during which devices remain silent. Access synchronization is typically realized using satellite Coordinated Universal Time (CUT) signals. Alternatively, in the absence of any positioning device or in cases of interim signal losses, in-range radio devices resort to a distributed synchronization mechanism which is driven by timing signals they receive from each other.
3. *Immediate access:* Devices immediately switch from CCH to SCH without having to wait for the beginning of the SCI.
4. *Extended access:* Devices relentlessly communicate over either one of the SCHs without reverting back to the CCH.

Note that it is explicitly stated in the IEEE 1609.4 standard specifications [11] that the above-mentioned intermediate and extended access schemes can be combined to form a single access scheme that allows for the exchange of relatively large amounts of non-safety data (*e.g.* media streaming and other infotainment-related data) over an SCH.

1.2. Motivation

On-the-fly broadband Internet provisioning to vehicles navigating over roads and highways (particularly for drivers and passengers commuting onboard these vehicles) has received significant attention over the past years. SRUs are deployed along the sides of roads and highways for this purpose. Fig. 3 shows an SRU, called G, which has a communication range that covers a finite-length segment of the road along which it is deployed. A vehicle residing within the range of G and requiring access to the Internet will directly communicate with G through Vehicle-to-Infrastructure (V2I) communication. Note that a vehicle navigating within a dark area (*i.e.* outside the range of any SRU) may resort to a combination of V2I and Vehicle-to-Vehicle (V2V) communications to establish multihop connectivity with the nearest possible SRU, [12].

This paper revolves around direct multi-channel V2I communication taking place between a vehicle and an SRU G as illustrated in Fig. 3. In this context, we note that multiple vehicles may be simultaneously residing within G's range and more than one vehicle may request to communicate with that SRU at a time. This together with the IEEE 1609.4 protocol's multi-channel access regulations give birth to a joint multiple-access and channel assignment problem whose resolution

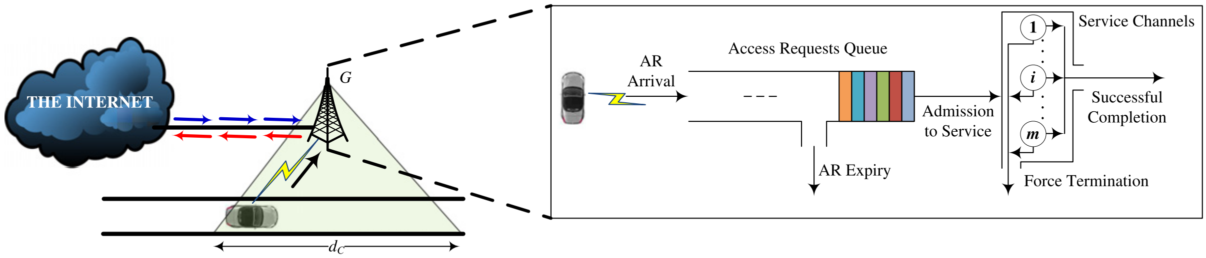


Fig. 3. Multi-channel V2I communication scenario.

is, indeed, challenging. Also, it is worthwhile mentioning that in order to allow for concurrent multi-channel operations to take place the SRU has to be equipped with multiple radios each of which is tuned to one of the available channels. Such a configuration gives rise to adjacent channel interference; a particular Physical Layer (PHY) challenge underlining the complexity behind the standardization of the IEEE 1609, which until this date, remains unfinalized. Currently, PHY-level complexities are outside the scope of this paper whose main focus is the mathematical modelling as well as performance analysis and improvement of multi-channel access at higher layers. To this end, it appears that existing work in the literature (*e.g.* [13–16]) exhibit a trend that consists of abstracting the existence of an observer looking at the packet queue of an arbitrary vehicle and examining the throughput performance of that queue. However, the response time (*i.e.* the period that elapses between the time a vehicle enters an SRU's range and the time that vehicle gets assigned a service channel), the service time (*i.e.* the amount of time during which a vehicle occupies a channel to upload/download content from the Internet), the blocking probability, the probability of force-termination and the probability of service completion are important Quality-of-Service (QoS) metrics that, thus far, have not been adequately considered. For example, the analytical queueing model used by the authors of [17] to quantify these metrics was developed on top of restrictive assumptions specific to the context of the particular multi-channel V2V communication scenario considered therein.

1.3. Novel contributions

An analytical $M/G_S/m + G_R$ queueing model is developed herein with the objective of addressing the above-listed shortcomings of the existing work. In particular, we aim at: (a) jointly characterizing the multiple-access and channel assignment mechanisms in the context of multi-channel V2I communication scenario and (b) evaluating the performance of this type of communication in terms of the vehicle's service time, the system's response time as well as the probability of blocking. As reported hereafter, the considered V2I communication system exhibits a remarkable blocking probability. In addition, the system's response time is relatively high. To this end, an Access Request Deadline-Aware (ARDA) scheme is proposed for the purpose of improving the system's quality-of-service performance (*i.e.* reduce the blocking probability as well as the response time). Given the considerable complexity of the mathematical analysis underlying queueing systems with deadline-aware service policies (*i.e.* [18]), extensive simulations are conducted with the objective of gauging the merits of ARDA. To the best of the authors' knowledge, no previously published work revolved around the development and performance analysis of deadline-aware service policies in the context of the V2I communication scenario illustrated in Fig. 3. Hence, the reported simulation results herein constitute a first step towards improving the performance of the considered V2I communication system.

1.4. Paper's organization

The remaining part of this paper is organized as follows. Related work is briefly surveyed in Section 2. A description of the V2I communication scenario is presented in Section 3. Section 4 summarizes the adopted vehicular mobility model. The proposed analytical queueing model is developed in Section 5. Numerical analysis and simulations are presented in Section 6. An Access Request Deadline-Aware (ARDA) scheduling scheme is proposed and discussed in Section 7. Finally, concluding remarks are presented in Section 8.

2. Related work

Recently the authors of [19] have extensively presented the problematics of multi-channel access in vehicular environments. They have enumerated a number of technical approaches that may lead to the resolution of each one of the identified problems.

The work of [17] revolved around a scenario of multi-channel communications in vehicular environments with spectral resource scarcity. In this context, the authors resorted to cognitive radio technologies and studied the feasibility of dynamic spectrum access schemes that tapped into other licenced spectrum bands (*e.g.* TV bands) in an attempt to secure vacant channels suitable for establishing communication between two or more vehicular network nodes. Two preemptive-priority multi-server queueing models were formulated to represent only a snapshot of the system where a static subset of the licenced channels happened to be unoccupied. These two models account for the fact that licenced channels have to be immediately vacated once being requested by their licensees. However, they are built on top of the assumption that the number of inter-communicating nodes was fixed. That assumption was proven in [20] to be restrictive especially in the context of V2I communication scenarios where the number of vehicles residing within the coverage range of an SRU becomes random. Furthermore, a vehicle entering the range of an SRU may depart without obtaining service at all. Such a vehicle is said to be blocked. This may be the case whenever the average service time of vehicles is large compared to the average of their residence time. The occurrence of such events has been overlooked in [17].

The authors of [13] highlighted the severe impact of the WAVE channel switching on the communication's reliability and provided design guidelines for improving the performance of the WAVE's multi-channel broadcast mechanism. These guidelines, although are technically valid, they came out as the result of a mathematical study based on top of several simplifying assumptions such as: (a) the non-existence of hidden terminal nodes and (b) the idealism of the wireless medium.

In the context of a scenario similar to the one illustrated in Fig. 3, the authors of [16] developed a MAC protocol that allows for high-bandwidth V2I communications to take place over multiple SCHs in concurrence with ongoing emergency V2V communications over the CCH. The typical IEEE 802.11 radios can only tune to a single channel at a time. Consequently, it is likely that, upon the release of an emergency message over the CCH, some vehicles, particularly those within an SRU's coverage range, be tuned to an SCH in order to take advantage of some non-safety-related services. Triggering these vehicles' awareness of the emerging safety alert is therefore the major challenge.

3. V2I communication scenario description

As illustrated in Fig. 3, the SRU G is equipped with a First-In–First-Out (FIFO) Access Request Queue (ARQ). An arriving vehicle wishing to communicate with G will transmit to it over the CCH an Access Request (AR). An AR is characterized by its:

1. *Nominal Service Time* (NST): the total amount of time the AR's generating vehicle requires to successfully complete service (*e.g.* complete the upload/download of a certain file).
2. *Deadline*: the total amount of time during which the AR remains valid. An AR's deadline is equivalent to its generating vehicle's residence time within the SRU's range.
3. *Effective Service Time* (EST): the total amount of time during which an AR receives service before its generating vehicle departs from the SRU's range.

After transmitting their ARs to the SRU's ARQ, vehicles remain tuned to the CCH while waiting for the SRU to grant them access to one of the SCHs. Upon the vacancy of any one of the m SCHs, the SRU announces the availability of that SCH to the vehicle whose AR is occupying the buffer's front position. In turn, to start receiving service, that vehicle switches to the available SCH and remains locked there until it either moves out of the SRU's range or it successfully completes service. This kind of access is made feasible by merging the IEEE 1609.4 protocol's immediate and extended access mechanisms as mentioned in Section 1.1.

Now, a closer look at the ARQ reveals the following AR dynamics. On one hand, whenever the ARQ is empty, an incoming AR, say r, that finds any one of the m channels to be readily vacant, grabs that channel and starts receiving its service. Otherwise, r queues within the ARQ until a channel becomes available. On the other hand, if, upon the arrival of r, the ARQ was not empty, r is inserted at the rear end of the ARQ. Observe that, while queueing in the ARQ, there exists a possibility that r's initiator leaves G's range. Consequently, r has to be immediately discarded. This is analogous to associating to r a deadline which is equivalent to its initiator's residence time within the G's range. Upon expiry, r is said to *renege* from the ARQ. Moreover, while being served, r's service gets *force-terminated* whenever r's initiator moves out of G's range.

The service of an AR consists of providing its originating initiator with access to a particular one of the m channels. Only one service initiator may access a channel at a time. Given that the channels are orthogonal and that the SRU is the sole channel access arbitrator, multiple initiators may, using the IEEE 1609.4 protocol, communicate with the SRU over different channels in a collision-free environment.

Finally, the above described communication scheme is, in essence, suitable for vehicles that are solely interested in non-safety data exchanges that do not require them to be regularly tuned to the CCH. Appropriate use cases of such a scheme have been identified in [19] where the authors argue that vehicles leveraging the IEEE 1609.4 extended scheme will remain tuned over the SCHs and hence cannot participate in critical cooperative cruise operations. This also applies to the above-described scheme especially whenever a vehicle is allocated an SCH by the SRU and hence switches to that SCH to start service. Nonetheless, as opposed to [19], observe that, herein, a vehicle remains tuned to the CCH during all the time it waits until its AR gets served. Throughout this proportion of time, the vehicle can surely get involved in critical safety-related message exchanges occurring over the CCH.

4. Vehicular traffic model

In Fig. 3, the SRU's communication range covers a road segment of length d_C (*meters*), which is assumed to experience Free-flow traffic conditions. Under such conditions, according to [20], the per-vehicle speeds in ($\frac{meters}{second}$) are identical and

Table 1
Vehicular traffic model parameters.

Parameter	Description
V_{min}	Minimum vehicle speed.
V_{max}	Maximum vehicle speed.
$\overline{V}$	Mean vehicle speed.
σ_V	Standard deviation of vehicle speeds.
$f_V(v)$	Density function of vehicle speeds.
d_C	Length of the considered road segment.
$R_j = \frac{d_C}{v_j}$	Residence time of a vehicle j with speed v_j within the SRU's range.
R_{min}	Minimum vehicle residence time.
R_{max}	Maximum vehicle residence time.
$f_R(t)$	Density function of the vehicle residence time.
μ_v	The vehicle arrival rate.
$f_I(t)$	Density function of the vehicle inter-arrival time.
ρ_v	Vehicular density over the considered road segment.

independent random variables distributed according to a truncated Normal distribution. In addition, each vehicle maintains a constant speed during its navigation along the segment of length d_C. Furthermore, the vehicle inter-arrival time intervals constitute a sequence of identical, independent and exponentially distributed random variables. The reader is referred to [20] for more details regarding the mathematical derivations of this model's characteristic parameters, which are summarized together with their significance in Table 1.

The vehicular traffic model presented in [20] overlooks a few required microscopic details, namely: (a) the arriving vehicle's type and (b) the number of onboard passengers. The remaining part of this subsection aims at filling this gap.

Let T be a discrete random variable (r.v.) representing the type of the arriving vehicle. In this paper, our interest lies in discerning between regular automobiles and buses. $T = 0$ if the vehicle is an automobile and $T = 1$ if the vehicle is a bus. The probability mass function (p.m.f.) of T is given by:

$$f_T(\tau) = Pr[T = \tau] = \begin{cases} p_0, & \tau = 0 \\ 1 - p_0, & \tau = 1 \end{cases} \tag{1}$$

where the value of p_0 follows from statistical measures described in [21]. Now, denote by N_p the number of passengers onboard an arriving vehicle. N_p depends on the type of the arriving vehicle. Let $f_{N_p|T}(n)$ denote the p.m.f. of N_p conditioned on the arriving vehicle's type. It follows that:

$$Pr\left[N_p = n \middle| T = \tau\right] = \begin{cases} \dfrac{1}{A_{max} - A_{min} + 1}, & \tau = 0, n \in [A_{min}; A_{max}] \\ \dfrac{1}{B_{max} - B_{min} + 1}, & \tau = 1, n \in [B_{min}; B_{max}] \\ 0, & \text{Otherwise} \end{cases} \tag{2}$$

where A_{min} and A_{max} are the respective lower and upper bounds on the number of passengers that may be transported by a regular automobile while B_{min} and B_{max} are the respective lower and upper bounds on the number of passengers that may be transported by a bus. Accordingly, the unconditional p.m.f. of N_p is given by:

$$\begin{aligned} f_{N_p}(n) &= \sum_{\tau=0}^{1} Pr\left[N_p = n \middle| T = \tau\right] \cdot f_T(\tau) \\ &= \frac{p_0}{A_{max} - A_{min} + 1} + \frac{1 - p_0}{B_{max} - B_{min} + 1} \end{aligned} \tag{3}$$

where $n \in [A_{min}; B_{max}]$. Note that the values of p_0, A_{min}, A_{max}, B_{min} and B_{max} considered throughout the simulation study presented later in Section 6 together with the choice of the uniform distribution for N_p are borrowed from [21] as they follow from realistic statistical measures described therein.

5. Multi-channel V2I communication analysis

This section presents a multi-server queueing model that aims at capturing the dynamics of the generic multi-channel V2I communication system described in Section 3, characterizing the behaviour of the ARQ and evaluating its performance in terms of several metrics such as: (a) the average system's response time, (b) the AR service time, (c) the probability of AR reneging, (d) the probability of AR service force termination and (e) the overall probability of AR blocking. Deriving mathematical expressions for these metrics necessitates the characterization of the AR arrival process, service and expiry time distributions. This is done next.

Vehicles enter the communication range of (*i.e.* arrive at) G at random times. Each vehicle is assumed to upload, upon its arrival, a single AR to G's ARQ. The AR inter-arrival time is, therefore, equivalent to the vehicle inter-arrival time. Thus, AR arrivals follow a Poisson process with parameter $\lambda_{AR} = \mu_v$.

Assume that a vehicle j arrives at time t_j and uploads to G's ARQ an AR r_j. r_j has deadline which is equivalent to R_j being the residence time of vehicle j within G's range. The vehicular traffic model in Section 4 dictated that R_j has a general distribution, which is given by:

$$G_R(t) = \int_{R_{\min}}^{t} f_R(t)dt, \quad t \in [R_{\min}; R_{\max}]. \tag{4}$$

Now, denote by N_j the Nominal Service Time (NST) of an AR r_j. N_j is defined as the total amount of time required for r_j to successfully complete service. Note that the service required by an AR originating from one vehicle is independent of that required by ARs originating from other vehicles. Also, knowledge of the time interval during which an AR has been receiving service does not provide any information regarding the residual duration until r_j successfully completes its service. Under such conditions, N_j is best modelled using an exponential distribution with parameter μ_N. The Effective Service Time (EST) S_j of r_j is defined as the amount of time during which r_j holds one of the m channels until its service either completes successfully or gets force-terminated.

Consider the general case where, eventually, at a certain point in time t_s ($R_{\min} \le t_s \le R_j$), r_j gets assigned a channel i ($1 \le i \le m$) and starts service. $t_s - t_j$ represents the waiting time of r_j in the ARQ before it started service and is equivalent to the elapsed residence time of vehicle j within the SRU's range. The residual residence time of vehicle j within the SRU's range, denoted by R_j^s, depends directly on the value of t_s. It is only during R_j^s that r_j will receive service. If $N_j \le R_j^s$ then r_j will successfully complete service. Alternatively, r_j's service will be force-terminated. Hence, we have:

$$S_j = \min\left(N_j, R_j^s\right), \quad \forall t_s \in \left[R_{\min}; R_j\right]. \tag{5}$$

Eq. (5) is general and applies to all ARs. Thus, in the sequel, the subscript j will be removed and an SR's EST will be denoted by S. S has a general probability distribution whose density function is denoted by $g_S(\cdot)$. Deriving a closed form expression for $g_S(\cdot)$ is difficult and evaluating it numerically is computationally complex. Fortunately, a highly accurate approximation for S is feasible. The approximation details are presented next.

Extensive discrete-event simulations were conducted using the simulator developed in Section 6. These simulations served the purpose of collecting AR EST traces and investigating the possibility of approximating $g_S(\cdot)$ and hence allow for the mathematical tractability of the queueing model proposed hereafter. The conducted simulations covered several scenarios distinguished by their respective sets of input vehicular and data traffic parameters. However, due to space limitations, only a subset of the simulation results are reported together with appropriate guidelines on how to exploit these results for approximating $g_S(\cdot)$. The simulator's input parameter values corresponding to the simulated scenarios are: (a) $m = 6$, (b) $\mu_N = 0.1\ (s^{-1})$, (c) $\rho_v \in [0.0022; 0.0109]$ (Veh/m), (d) $d_C = 1000$ (m), (e) $V_{\min} = 10$ (m/s) and (f) $V_{\max} = 50$ (m/s). Note that, for each of the simulated scenarios, the simulator was executed for a period of time that is long enough to collect 10^8 AR EST samples.

The squared coefficient of variation c_S^2 pertaining to the collected EST data sets corresponding to each one of the simulated scenarios was determined. $c_S^2 = \frac{\sigma_S^2}{\overline{S}^2}$ where σ_S^2 and $\overline{S}$ are the respective EST's variance and average. The value of c_S^2 corresponding to a given EST data set indicates which density function (*e.g.* Exponential, Gamma-mixture, Log-Normal, Phase-type, etc.) best approximates the p.d.f. of that set [22]. A close observation of the determined values of c_S^2 reveals the fact that $c_S^2 \approx 1$. This, in turn, suggests that $g_S(\cdot)$ may be very well approximated by an Exponential density function (refer to [23]) given by:

$$\widetilde{g}_S^{Exp}(t) = \alpha \cdot e^{-\alpha t}, \quad \text{for } t \ge 0 \text{ and } \alpha = 2\overline{S}. \tag{6}$$

The Mean Square Error (MSE) quantifies the difference between $g_S(t)$ and $\widetilde{g}_S^{Exp}(t)$. It is expressed as:

$$\overline{\varepsilon}_{Exp}^2 = \int_0^{\infty} [g_S(t) - \widetilde{g}_S^{Exp}(t)]^2 dt. \tag{7}$$

Fig. 4 shows the different MSE values obtained for vehicular traffic densities that span the entire range of ρ_v. Fig. 4 is a tangible proof of the high accuracy of the established approximation. This is especially true since the maximum MSE is of the order of 10^{-7}.

Denote by $\widetilde{G}_S^{Exp}(\cdot)$ the approximated AR EST c.d.f. It is given by:

$$\widetilde{G}_S^{Exp}(t) = \int_0^t \widetilde{g}_S^{Exp}(x)dx = 1 - e^{-\alpha t}, \quad t \ge 0. \tag{8}$$

All of the above has, thus far, prepared the ground for establishing an approximate multi-server queueing model with customer impatience that represents the V2I communication system described in Section 3. In Queueing Theory, the notation $M/G_S/m + G_R$ refers to such a queueing model where $G_S(\cdot)$ and $G_R(\cdot)$ differentiate between the general probability

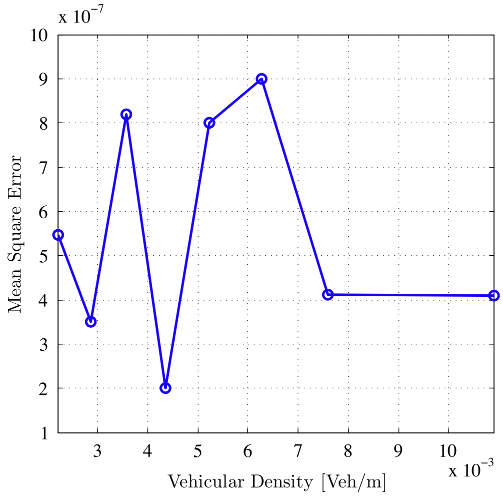


Fig. 4. AR EST p.d.f. approximations and their corresponding MSEs.

distributions of the SR's effective service time and deadline, respectively. The analytical tractability of this model is enhanced whenever the customer service time can be characterized by an Exponential distribution, [23]. Fortunately, the suggested approximation of $G_S(\cdot)$ by an Exponential distribution, namely $\widetilde{G}_S^{Exp}(\cdot)$, allows for accurately approximating the above-proposed $M/G_S/m + G_R$ queueing model by an $M/\widetilde{G}_S^{Exp}/m + G_R$ model. The seminal work of [23] encloses a comprehensive study on the characteristics of this queueing system whose fundamental results, typically those that are relevant to the study presented in this paper, are summarized below.

Input parameters:

In the context of modelling the multi-channel V2I communication system described in Section 3, the $M/\widetilde{G}_S^{Exp}/m + G_R$ queueing model has four input parameters, namely: (a) λ_{AR} being the AR arrival rate, (b) $\mu_{AR} = \alpha$ being the AR service rate, (c) m being the total number of servers (*i.e.* channels) and (d) $G_R(\cdot)$ being the AR expiry time distribution as given in Eq. (4).

Building blocks:

In order to preserve the ease of the notation, clear and neat presentation of the mathematical analysis, the following integrals are defined:

$$\Psi(t) = \int_0^t \overline{G_R}(x)dx \quad (9)$$

$$\delta = \int_0^\infty e^{(\lambda_{AR}\Psi(t) - m\mu_{AR}t)}dt \quad (10)$$

$$\eta = \int_0^\infty \Psi(t) \cdot e^{(\lambda_{AR}\Psi(t) - m\mu_{AR}t)}dt \quad (11)$$

$$\zeta = \int_0^\infty e^{-t}\left(1 + t\frac{\mu_{AR}}{\lambda_{AR}}\right)^{m-1} dt. \quad (12)$$

Relevant performance metrics:

Several performance metrics pertaining to the $M/\widetilde{G}_S^{Exp}/m + G_R$ may be expressed in terms of the above established building blocks, [23]. Of these metrics, the most relevant for the study presented herein are:

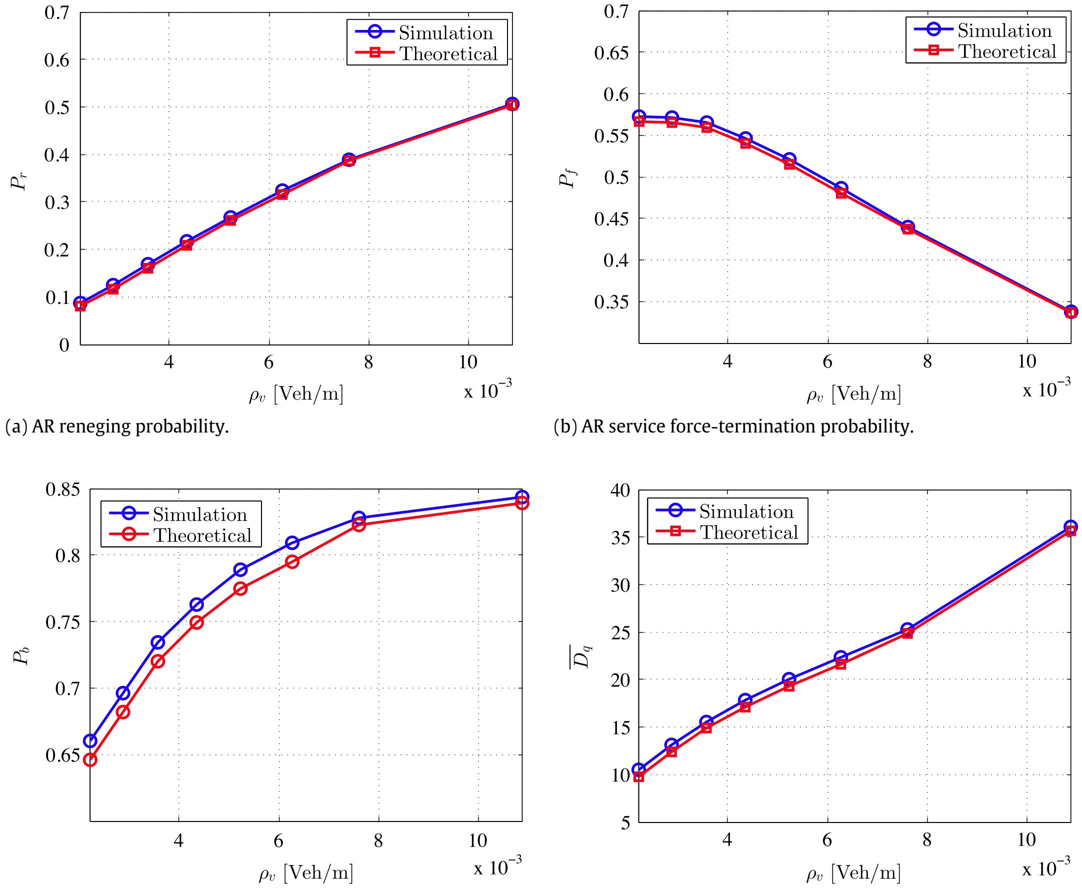
1. The probability of AR reneging:

$$P_r = \frac{1 + \delta(\lambda_{AR} - m\mu_{AR})}{\zeta + \lambda_{AR}\delta}. \quad (13)$$

2. The system's response time (*i.e.* the average AR queueing delay):

$$\overline{D_q} = \frac{\lambda_{AR}\eta}{\zeta + \lambda_{AR}\delta}. \quad (14)$$

In addition to the above metrics, the probability of AR service force-termination is given by:



(a) AR reneging probability.

(b) AR service force-termination probability.

(c) AR blocking probability.

(d) System's response time measured in seconds.

Fig. 5. V2I communication system model verification and performance evaluation.

$$P_f = \int_0^{R_{\max}} \mu_{AR} e^{-(\mu_N+\mu_{AR})t} dt$$
$$= \frac{\mu_{AR}}{\mu_N + \mu_{AR}} \left(1 - e^{-(\mu_N+\mu_{AR})R_{\max}}\right). \quad (15)$$

Finally, the AR blocking probability is given by:

$$P_b = P_r + P_f. \quad (16)$$

6. Numerical analysis and simulations

This section is dedicated for the verification of the validity and accuracy of the model laid out in Section 5 as well as for evaluating the multi-channel V2I communication system's performance in the context of the scenario shown in Fig. 3. The adopted performance metrics are: (a) $\overline{D_q}$ being the system's response time, (b) P_r being the AR reneging probability, (c) P_f being the AR service force-termination probability and (d) P_b being the AR blocking probability.

6.1. Simulator's input parameters

A custom-built JAVA-based discrete-event simulator was developed. The adopted performance metrics were evaluated for a total of 10^8 ARs and averaged out over multiple runs of the simulator to ensure that a 95% confidence interval is realized. The simulator's input parameter values are: (a) $m = 6$, (b) $\mu_N = 0.1$ (s^{-1}), (c) $\rho_v \in [0.0022; 0.0109]$ (Veh/m), (d) $d_C = 1000$ (m), (e) $V_{\min} = 10$ (m/s), (f) $V_{\max} = 50$ (m/s) and (g) $p_0 = \frac{2}{3}$.

6.2. V2I communication system's performance evaluation

Fig. 5 is decomposed into four separate graphs plotting the theoretical curves representing P_r, P_f, P_b and $\overline{D_q}$ versus ρ_v concurrently with their respective simulated counterparts. The four graphs, all together, constitute tangible evidence of the validity and accuracy of the proposed model. This is especially true since the theoretical curve representing each of the above-listed performance metrics almost coincides with its corresponding simulated counterpart. Fig. 5(a) plots P_r versus ρ_v. The figure indicates that P_r increases as a function of ρ_v. As a matter of fact, the increase in ρ_v is directly mapped into an increase in the vehicle arrival rate μ_v. Recall from Section 5 that each vehicle generates a single AR. Hence, the AR arrival rate $\lambda_{AR} = \mu_v$. Under such circumstances, an increase in ρ_v reflects an increase in λ_{AR}. This, in turn, leads to an increase in the average ARQ length. The system's response time being directly proportional to the ARQ's length will, therefore, also increase as illustrated in Fig. 5(d). As a result, ARs queueing at the ARQ become more likely to expire before being admitted into service and hence will renege. This explains the quasi-linear growth of P_r as a function of ρ_v. Notice that P_r can be as high as 50%. As a matter of fact, the system's performance evaluated herein pertains to scenarios of Free-flow (*i.e.* light-to-medium density) vehicular traffic. It is natural for P_r to bypass the 50% as ρ_v further increases. From a users point of view, not receiving service (*i.e.* the inability to grab a channel) is interpreted as a deteriorated Quality-of-Service (QoS). Fig. 5(b) plots P_f versus ρ_v. The figure indicates that P_f decreases as a function of ρ_v. In addition to the increase in μ_v, an increase in ρ_v also implies a decrease in the average vehicle speeds. This fact has been well elaborated in [20]. Accordingly, the average vehicle residence time (*i.e.* the AR expiry deadline), $\overline{R}$, increases. However, as indicated by Fig. 5(a), the increase in $\overline{R}$ is not enough to guarantee an admission into service for the ARs, now, arriving at a higher rate. Yet, as a result of this increase, those SRs that are admitted into service will benefit from higher chances to successfully complete service. This explains the decrease in P_f as a function of ρ_v.

Observe that P_r and P_f seem to act as two opposing forces where an increase in the former is faced by a decrease in the latter. Nonetheless, P_f decreases at much slower rate than that at which P_r increases. This explains the increase in the AR blocking probability P_b as illustrated in Fig. 5(c).

7. AR deadline-aware scheduling scheme

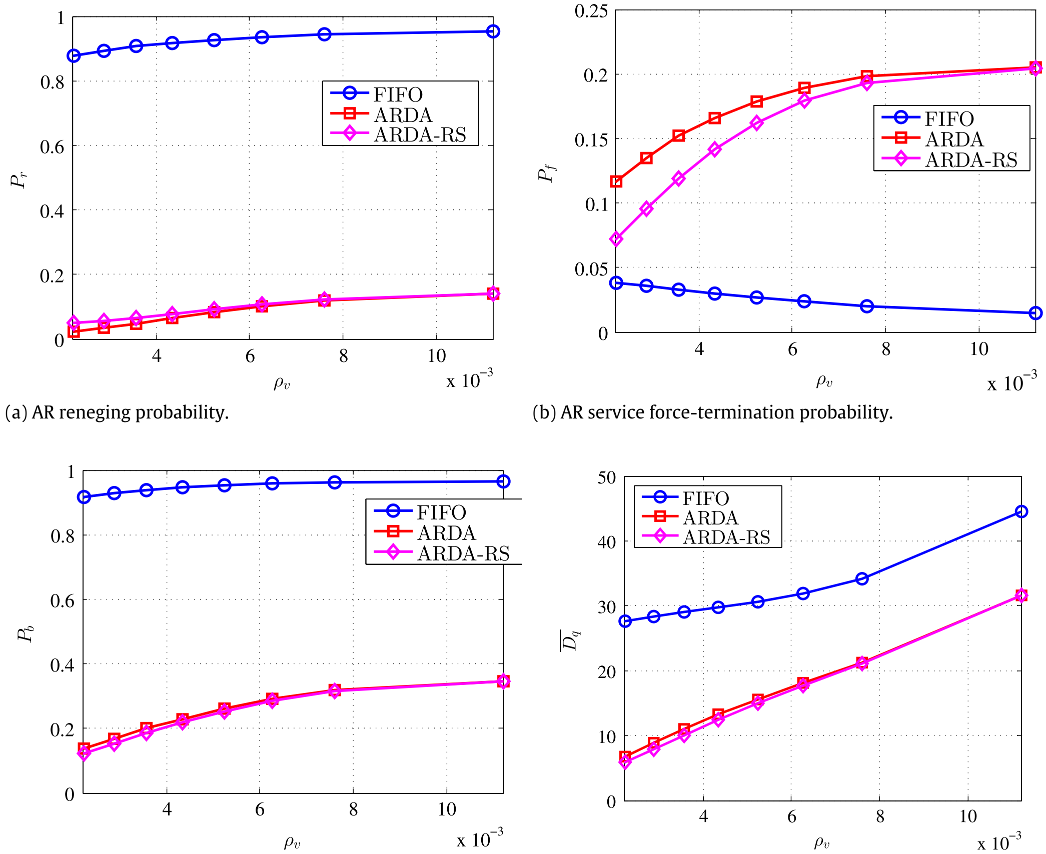
The results reported in Fig. 5 reveal a remarkable inefficiency of considered V2I communication system. Indeed, the generic multi-channel V2I communication system as described in Section 3 suffers from a serious problem, namely, the extravagant AR blocking probability ranging between 65% and 85% and hence appears to have marginal utility. Nonetheless, a close analysis of the reasons behind the elevated blocking probability uncovers an original tweak that, once embedded in a scheduling scheme such as the Access Request Deadline-Aware (ARDA) scheme proposed below, will impressively improve the performance of the system.

7.1. ARDA scheme description

Recall that the blocking probability P_b is the sum of the reneging and force-termination probabilities, respectively P_r and P_f. As explained earlier, P_r is the bottleneck. In fact, in the context of the V2I communication scenario illustrated in Fig. 3, each vehicle resides within the SRU's coverage range for a finite time period. Vehicle residence times differ from one another. Fast vehicles have smaller residence times than slow vehicles. Consequently, the ARs generated by fast vehicles will expire before those generated by slow vehicles. As such, the respective residence times of vehicles within the SRU's coverage range can be interpreted as deadlines associated with these vehicles' ARs. Taking these deadlines into consideration will allow for maximizing the system's throughput while improving the system's QoS performance (*i.e.* reduce the system's response time and AR blocking probability). Thus, AR deadlines can be interpreted as periods of time during which ARs can tolerate being queued in anticipation for service opportunities.

In addition, these deadlines can be exploited as service differentiators. That is, they indicate which of the incoming ARs is to be served first. In this regard, the SRU's ARQ will operate under the well-known Earliest Deadline First (EDF) scheduling algorithm (as opposed to the earlier FIFO scheduling) where the incoming ARs are queued at the ARQ in increasing order of their deadlines. In other words, ARs with the shorter deadlines are placed ahead of the ARs with the larger deadlines and the priority of an AR relatively increases as that AR's deadline further approaches towards its expiry. In this context, the AR with the shortest deadline will be prioritized over all other ARs stored in the queue and, hence, will be served first. An arbitrary incoming AR queueing at the ARQ will keep on advancing until it reaches the Head-of-Line (HoL) position of the EDF queue. Once it reaches the ARQ's HoL position, the AR waits there until one of the m SCHs becomes idle. Meanwhile, if this AR expires (*i.e.* its originating vehicle departs from the SRU's coverage range), then it reneges from the queue. Upon availability of an SCH, the AR occupying the queue's HoL position is admitted into service. If an AR expires while being serviced, that AR's service is immediately force-terminated.

The above-described ARDA scheme is expected to significantly improve the system's performance. This is especially true since serving the incoming ARs according to their shortest deadline will enable a larger proportion of these ARs to start receiving service before they expire. Accordingly, both P_r and $\overline{D_q}$ will decrease.



(a) AR reneging probability.

(b) AR service force-termination probability.

(c) AR blocking probability.

(d) System's response time measured in seconds.

Fig. 6. V2I communication system performance evaluation under ARDA.

7.2. Performance analysis of the ARDA scheme

ARDA has been implemented in the simulator developed in Section 6 and used to simulate the generic V2I communication system. The adopted performance metrics were evaluated for a total of 10^8 ARs and averaged out over multiple runs of the simulator to ensure that a 95% confidence interval is realized. The simulator's input parameter values are the same as those used in Section 6.

Fig. 6(a) plots P_r versus ρ_v. The results reported in this figure indicate an uncanny decrease in P_r under ARDA. Indeed, the ARDA service scheduling discipline was able reduce P_r to almost zero at low vehicular densities with a relatively slow increase whenever the ρ_v increases. This, however, has caused the force-termination probability P_f to increase as reported in Fig. 6(b). Nonetheless, the increase in P_f is remarkably overshadowed by the decrease in P_r in such a way that the blocking probability P_b is still significantly reduced under ARDA as compared with FIFO. In fact the improvement in the blocking probability is almost 70% as illustrated in Fig. 6(c).

Finally, Fig. 6(d) plots $\overline{D_q}$ versus ρ_v. The figure shows an improvement in the response time for the ARDA-based ARQ. In fact, servicing ARs with shorter deadlines causes the admission rate of ARs into service to increase. As such the ARQ length decreases and so does the average response time.

7.3. Further discussions

A trade-off exists between achieving high channel utilization as opposed to fair service access across vehicle speeds. Observe a larger view of the system. Vehicles navigating along a highway may traverse several SRU zones and attempt to access the Internet in each zone. Under ARDA, slower vehicles may be denied access in the presence of faster vehicles. This is because the deadlines of ARs originating from faster vehicles are shorter than deadlines of ARs originating from slower vehicles. As such, slower vehicles may suffer from a starvation problem. A preliminary attempt to resolve this problem consists of accounting for the service time when computing an AR's deadline. In this case, the following example illustrates how ARs could be sorted in the ARQ. Consider two vehicles 1 and 2 with respective residence times R_1 and R_2. Let r_1 and r_2 be two ARs generated respectively by these two vehicles with required service times $N_{p,1}$ and $N_{p,2}$. Without loss of generality, assume that $R_1 < N_{p,1}$, $R_2 > N_{p,2}$ and $R_2 > R_1$. Under such conditions, vehicle 1 is unable to complete service within its residence time within the SRU's range while vehicle 2 will. Consequently, r_2 is placed ahead of r_1 in the ARQ. Note here that, even though vehicle 2 is slower than vehicle 1, it was serviced first since it is able to successfully complete service if it was granted access to an SCH in a timely manner while vehicle 1, in all cases, will lead to a force termination. Now, it might be the case that, ultimately r_1, ends up reneging from the ARQ if several vehicles similar to vehicle 2 happen to be in range. Nonetheless, the increase in the reneging probability is expected to be overshadowed by the decrease in the force-termination probability. The cumulative result of this ARDA variant called ARDA-RS is expected to be a decrease in the overall blocking probability. Indeed, simulation results confirm this fact as shown in Fig. 6.

8. Conclusion

This paper revolves around multi-channel V2I communications. Following a comprehensive description of how this type of communications takes place, a realistic $M/G_S/m + G_R$ queueing model was proposed to characterize the behaviour of an SRU's ARQ. The proposed model accounts for several fundamental factors that have been overlooked by existing work in the literature. For the purpose of mathematical tractability, the AR effective service time distribution was accurately approximated by an exponential distribution. Consequently, an approximate $M/\widetilde{G}_S^{Exp}/m + G_R$ queueing model has been established. Extensive simulations and numerical analysis were conducted to validate the approximate model, highlight its accuracy and evaluate its performance. Results show that the reneging of ARs has a significant impact on the systems performance and, most importantly, on the end-users' QoS satisfaction. An in-depth investigation of the reasons behind these results lead to identifying the FIFO AR service discipline as being the bottleneck. Fortunately, an Access Request Deadline-Aware service scheduling scheme presents itself as a mean to reduce the reneging probability by almost 70% and the system's response time by 22%–66%. The mathematical analysis of ARDA is left for future work.

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