DSA-based V2I Communication Under The Microscope

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***Abstract*—This paper presents a consice yet comprehensive description of a DSA-based Vehicle-to-Infrastructure (V2I) communication system operating under spectral scarcity conditions. Existing mathematical models for such a system overlook some but essential ones of its behavioural characteristics. Thus, these models' reported performance results seem to be unrealistically overoptimistic. In this paper, a simulation study is conducted in the context of a real-life scenario. As opposed to the existing studies, the study herein aims at providing more insights into the dynamics of this type of communication systems and assessing its performance in terms of several new metrics.**

***Index Terms*—Performance Evaluation, Dynamic Spectrum Access, Vehicular Networks, Cognitive Radio, V2I, SRU.**

I. Introduction

An essential factor circumscribing the evolution of wireless communication technology is spectrum scarcity which is due to the inefficient spectrum allocation and utilization rather than the unavailability of usable natural frequencies. Indeed, a close observation of the U.S. frequency charts reveals the existence of a significant number of underutilized spectrum fragments referred to as spectrum *holes*. However, the recently emerging Radio Cognition Technology (RCT) together with its associated Dynamic Spectrum Access (DSA) strategies enable unlicensed accessors known as secondary users (SUs) to opportunistically capture and efficiently exploit the spatiotemporally available licensed spectrum holes as long as this does not impact the performance of the incumbent licensees referred to as primary users (PUs). This has the objective of satisfying the growing hunger for quality all-time-anywhere wireless broadband connectivity.

Vehicular networks involve two types of Dedicated Short Range Communication (DSRC) services, namely: *a*) vehicle-to-vehicle (V2V) and *b*) vehicle-to-infrastructure (V2I). These two types of communication enable diverse applications (*e.g.* traffic safety and management, on-the-fly Internet access and infotainment, etc). Also, vehicular networks contribute to increasing the broadband coverage as they are poised to become the most widely distributed and largest ad-hoc networks. However, vehicular networking applications are bandwidth intensive and their dedicated 75 MHz band will soon become insufficient. Further spectrum allocation for these applications will add more stress to the already crowded spectrum. Under such circumstances, RCT comes to the rescue as it enables spectrum sharing and coordination between vehicular networks and other legacy wireless networks allowing thus for the co-existence of these networks all together. Nonetheless, the feasibility of DSA in vehicular environments remains questionable and is further investigated in this paper.

Figure 1 shows a Stationary Roadside Unit (SRU), S, that is deployed along a road segment. S has a communication range that covers part of that segment of length d (*meters*). Through minimal networking infrastructure, S is connected to the Internet. Vehicles enter the communication range of (*i.e.* arrive at) S at random times

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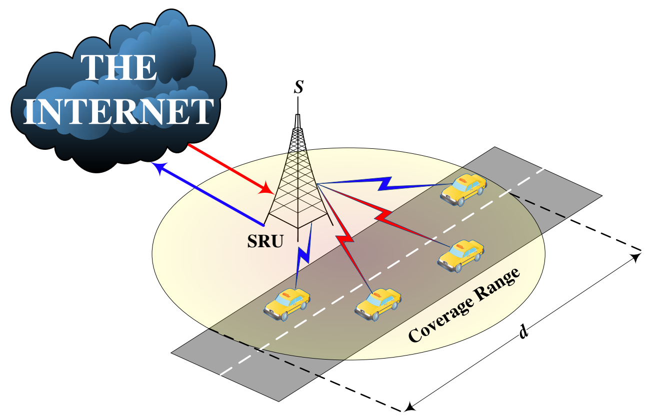


Fig. 1. DSA-based V2I communication scenario.

and may communicate with this SRU only if spectrum is available. Multiple vehicles may be simultaneously present within S's range and request to communicate with this SRU. This renders the Vehicular Dynamic Spectrum Access (VDSA) a multiple access problem which has been investigated in [1]. Therein, the UHF TV spectrum was assumed to be shared among TV broadcasters being the PUs and a vehicular network whose communicating nodes (*i.e.* vehicles and SRUs) were considered as the SUs. That spectrum was subdivided into a number of channels regarded as servers. Then, only a spatiotemporal snapshot of the system was studied where a subset of these servers happened to be unoccupied by PUs and the number of inter-communicating SUs was fixed. That study abstracted the existence of a virtual queue and regarded each individual access request originating from an arbitrary communication set of SUs as a single customer incoming to this queue. The authors have formulated two preemptive-priority multi-server queueing models for the purpose of determining the system's response time as well as the average probability of server unavailability.

As far as V2I communication is concerned, the reported performance results in [1] are overly optimistic due to the fact that both models discussed therein unrealistically assumed that all of the SUs present at the time the snapshot was taken will successfully complete their service. In reality, vehicles, being mobile, they reside within the coverage range of S for a limited period of time and then depart. Thus, any request associated with a vehicle that went out of range has to be discarded. Moreover, the two models in [1] assume single request generation per arriving vehicle. However, an arriving vehicle may generate a randomly-sized bulk of requests. This is especially true since several passengers may be travelling on board of an arbitrary vehicle and each one of these passengers may independently require access. The $M/M/m$ and $M/G/m$ models of [1] fail to capture these particular aspects.

This paper aims at providing realistic insights into the dynamics of the above described DSA-based V2I communication system. Then, throughout an Extensive Simulation Study (ESS), the system's performance will be evaluated in terms of new essential metrics. In addition, a direct comparison between the results of [1]

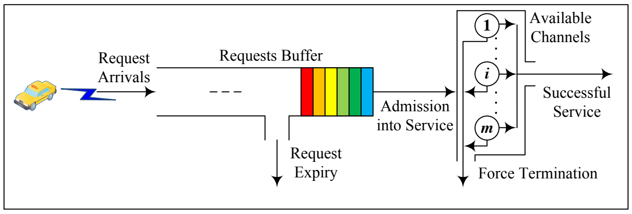


Fig. 2. DSA-Based V2I communication scenario.

and those of ESS will be established. For this purpose, a refined version of the metrics defined in [1] is used herein.

II. DSA-based V2I Communication Scenario

This section focuses on investigating the feasibility of the DSA-based V2I communications in an environment where communicating SU sets (*i.e.* the SRU S and an arbitrary vehicle within its range) may opportunistically exploit vacant holes in the licensed spectrum associated with a network of PU sets.

It is widely established in the literature that the static channel usage by TV broadcasters renders the UHF TV spectrum suitable for VDSA. This spectrum presents a total of $m = 30$ 6 MHz orthogonal channels usable for VDSA. At the cost of reduced data rates, these channels may be further subdivided into 1 MHz sub-channels resulting in a total of 180 sub-channels. These m channels are licensed for registered PUs. However, an SU set whose communication attempt is blocked due to scarce spectral resources may resort to RCT in order to tune to and utilize any vacant channel of the PU spectrum as long as this does not interfere with or impact the communication performance of other PU sets. This requires SUs to be highly transparent and immediately vacate their respective channels once these latter are requested by PUs.

A. Scenario Description:

As illustrated in Figure 2, the SRU S is equipped with a First-In-First-Out (FIFO) Request Buffer (RB). An arriving vehicle wishing to communicate with S will transmit to it a Access Request (AR). On one hand, whenever the RB 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 RB until a channel becomes available. On the other hand, if, upon the arrival of r, the RB was not empty, r is inserted at the rear end of the RB. Observe that, while queueing in the RB, there exists a possibility that r's initiator leaves S's range. Consequently, r has to be immediately discarded. This is analogous to associating to r a deadline which is equivalent to it's initiator's residence time within the S's range. Upon expiry, r is said to *renege* from the RB.

Moreover, while being served, r's service gets *force-terminated* whenever either one of the below events occurs:

- **E1:** a PU set requests the channel servicing r.
- **E2:** r's initiator moves out of the SRU's range.

Upon the occurrence of E1, the channel is immediately vacated and granted to the newly incoming PU communication request. Meanwhile, being still in range, r's initiator may retransmit a new AR in an attempt to exploit another communication opportunity. The newly incoming AR will be inserted at the rear end of the RB. However, the mean vehicle residence time within S's range is relatively smaller than the service time of a communicating PU set. Hence, the probability that r's initiator is re-granted access to a channel before moving out of range is negligible. Therefore, it becomes reasonable to assume that force-terminated ARs are lost which is also, obviously, the case whenever E2 occurs.

Finally, 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 channels are orthogonal and that the SRU is the sole channel access arbitrator, multiple initiators may, using the IEEE 802.22 protocol, communicate with the SRU over different channels in a collision-free environment.

B. Novel Contributions:

As opposed to existing work in the literature, the first point that marks off the study presented herein is the revelation of new system behavioural dynamics. One such behaviour is the reneging of ARs from the RB upon their expiry. To characterize this behaviour, a new metric, P_r, is introduced herein. P_r is the *reneging probability* which is defined as the probability of prematurely discarding an AR from the RB upon the departure of its initiator from S's range. Another behaviour is the AR service force-termination. The queueing models defined in [1] overlooked the possibility of force-termination upon the occurrence of event E2. Herein, the *force-termination probability* denoted by P_f is refined so as to cover the occurrences of both events E1 and E2. Both of a reneging AR or a force terminated one are counted as being blocked ARs. To this end, P_b being the *blocking probability* is introduced and defined as being the sum of the reneging and force-termination probabilities.

Second, the assumption of singly AR generation per vehicle is restrictive. In reality, ARs exhibit bursty arrivals at the RB. This is especially true since, in addition to the driver, more than one passenger may be commuting onboard of an arriving vehicle. It is possible that multiple of these passengers demand access to S. Hence, each passenger will generate an AR using his/her hand-held mobile wireless device (*e.g.* laptop, smart phone or pad, etc). These ARs are collectively buffered at the vehicle's OnBoard Unit (OBU). Upon arrival at S, the arriving vehicle's OBU uploads the bulk of ARs it holds to S's RB. The size of the incoming bulk (*i.e.* the number of ARs contained in that bulk) is a random variable (r.v.) depending on the number of passengers onboard of the arriving vehicle. For example, the number of passengers onboard a regular sedan ranges, on average, between 1 and 6 while the average number of passengers onboard a local bus ranges between 40 and 70. This is a rather microscopic parameter that is typically considered in vehicular traffic engineering studies (*e.g.* [2]). Further details in this regard are left for section III-A.

Third, it is observed that, thus far, the literature lacks accurate mathematical studies that adequately account for the above-highlighted DSA-based V2I communication system's dynamics. In this regard, section III of this paper is dedicated to providing brief insights into the development of a generic and accurate queueing model which is suitable for the representation of the system illustrated in Figure 2. The complete derivation of such a model is beyond the scope of this paper. Instead, an Extensive Simulation Study (ESS) is conducted for the purpose of evaluating the system's performance. ESS's reported simulation results, however, indicate that the current system under study suffers from a remarkably elevated blocking probability. The resolution of this problem is then further discussed.

III. On the Modelling of PU and SU Activities

The preliminary modelling guidelines presented in this section constitute a first step towards the appropriate mathematical description of the PU and SU activities in the context of the above-described DSA-based V2I communication system. They prepare the ground for the development of an accurate queueing model that best characterizes these activities and hence captures the realistic behavioural dynamics of this system.

The typical *M*/*G*/m queueing model is, obviously, not a suitable model. This is particularly true since this model accounts neither for the expiry of ARs nor for the possible force termination of their service. A preemptive variant of this model accounts for the possible force-termination of an AR's service as a result of a PU set requesting the channel servicing that AR. However, such a variant does not take into consideration the expiry of ARs as well as the force-termination of their service due to their initiators' leaving the SRU's range. As such, the preemptive *M*/*G*/m queueing model is also not suitable.

Notice that the AR expiry and service force-termination aspects, as described earlier, both indicate the premature departure of ARs from the system as illustrated in Figure 2. In other words, these aspects expose the rather natural impatience of ARs as these ARs depart from the system before engaging into service and, let alone, before completing service. To capture this particular behaviour of ARs, one has to resort to what is known in the literature as *queueing models with reneging/customer impatience*. Existing such models in the literature differ by their respective customer deadline distribution as well as by the type of reneging, that is:

- **Reneging until the beginning of service:** customers only renege from the queue upon expiry. Once admitted into service, a customer's deadline is cancelled and that customer will occupy the server until service completion, [5].
- **Reneging until the end of service:** customers renege from both the queue and servers. A customer's deadline is never cancelled. Irrespective whether a customer has been admitted to service or not, that customer will renege upon expiry, [6].

In light of the above, an accurate queueing model that conforms with the system description laid out in section II is the *M*/G_S/m+G_R model with customer reneging until the end of service where $G_S(\cdot)$ and $G_R(\cdot)$ are the respective distributions for the AR service times and deadlines. Observe that, in such a model, the reneging until the end of service will account for the occurrence of both events E1 and E2 as described in section II. However, this model suffers from two major drawbacks, namely: *i*) it is complex and *ii*) it does not account for the bursty AR arrivals as pointed out in section II-A.

One way to reduce the complexity of the above proposed *M*/G_S/m+G_R queueing model while maintaining its accuracy is to decouple the PU and SU user activities. In other words, resort to the statistical properties of the PU traffic and, accordingly, determine the average number of free channels usable for VDSA. Further details are provided in the below subsection.

A. Primary User Activity:

PU activity over an arbitrary channel i ($1 \leq i \leq m$) exhibits a sequence of alternating ON/OFF periods. These periods are random but highly correlated to the offered PU traffic load. In the sequel, the PU traffic is assumed to be stationary and ergodic. Hence, according to [4], the alternation of channel i between the ON and OFF states follows a Markov renewal process where the PU AR arrivals follow a Poisson process with parameter λ_p and the PU AR service times constitute a sequence of independent and identically distributed (i.i.d) exponential random variables (r.v.s.) with mean $\frac{1}{\mu_p}$. Let $\rho_p = \frac{\lambda_p}{\mu_p}$ denote the PU traffic load. Figure 3 depicts channel i's state transition rate diagram. With a rate equal to λ_p channel i will transition from the OFF state to the ON state. The transition in the opposite direction will occur with a rate that

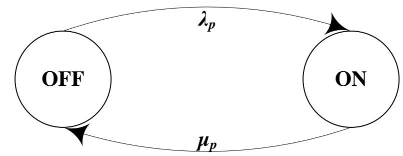


Fig. 3. State transition rate diagram of channel i's PU activity.

is equal to μ_p. Let $\pi_{OFF} = \frac{\rho_p}{1+\rho_p}$ and $\pi_{ON} = \frac{1}{1+\rho_p}$ denote the respective long-term probabilities of finding channel i in the OFF and ON states. The channels, being identical, are assumed to be subject to the same statistical PU load of ρ_p. Let N_{ON} be a random variable (r.v.) that represents the total number of ON channels. N_{ON} is binomially distributed with a probability mass function (p.m.f.):

$$f_{N_{ON}}(k) = \binom{m}{l} \pi_{ON}^{l} \cdot \pi_{OFF}^{m-l} \text{ , for } 0 \leq l \leq m \quad (1)$$

Thus, the long-term average number of OFF channels is:

$$c = m - E[N_{ON}] = m - \sum_{k=0}^{m} k f_{N_{ON}}(k) = \lfloor m(1-\pi_{ON}) \rfloor \quad (2)$$

Of the overall number of m channels, only the above-determined c will, on average, be available for DSA-based V2I communication. Thus, the earlier proposed *M*/G_S/m+G_R model reduces to *M*/G_S/c+G_R. In the remainder of this subsection the *M*/G_S/m+G_R and *M*/G_S/c+G_R models are respectively referred to as M1 and M2 with both models being with customer reneging until the end of service.

At first glance, it appears that the only difference between M1 and M2 is the reduction of the number of servers from m to c. As such, one may be easily mislead to believe that, in terms of complexity of their mathematical analysis, both of these two models are equivalent. However, the major difference between them lies is the fact that, throughout M2, there is no longer the need to worry about the force-termination of an AR's service by incoming PU communication requests. This by itself remarkably simplifies the mathematical analysis. Yet, it preserves the accuracy of M2. This is especially true since, as explained below, M2 will maintain all of M1's characteristics in terms of capturing the essential system's behavioural dynamics described in section II. However, it is much easier to analyze.

In M2, the c channels are solely dedicated to serve the ARs placed by SU sets. The PUs, themselves, will be communicating over the other $m - c$ channels. At this level, notice that c is a function of the PU traffic load, ρ_p, where an increase in ρ_p causes a decrease in c. This, indeed, preserves the higher priority that PUs have over SUs in the sense that, whenever the PU traffic intensity is high, PUs occupy a larger number of channels. Consequently, SUs, being obliged to remain highly transparent, will have less channels to communicate over. With this in mind, an incoming SU-generated AR becomes less likely to find a readily vacant channel and will have to queue at the RB. It follows that, under the circumstances of heavy PU traffic, ARs queueing at the RB are expected to suffer from a longer average queueing delay (*i.e.* average response time as referred to in [1]). Eventually, the respective initiators of these ARs will, with a high probability, leave the SRU's range before they get the chance to be served. On this hand, the decay in the SUs' performance will reflect itself in the remarkable increase of the reneging probability. On another hand, a close observation of the system reveals that it does not take long before those ARs which were admitted into service get force-terminated. This is particularly the case since these ARs were lucky enough to grab a channel, however, at a point where their initiators were close to going out of range. As a result the force termination probability will also increase.

Now, the focus is turned to addressing the second limitation of M1, namely, the bursty arrival of SU-generated ARs to the RB. For this purpose, a brief overview of the adopted vehicular traffic model is necessary. It is laid out in the next subsection followed by preliminaries on modelling the SUs' activity.

B. Vehicular Traffic Model:

This paper borrows the Simple Free-flow Traffic Model (SFTM) developed in [3]. Particularly, in Figure 1, the road segment of length d is assumed to experience Free-Flow traffic conditions. The characteristic parameters of SFTM are summarized as follows: *a*) S_{min}, S_{max}, $\overline{S}$ and σ_S designate the minimum, maximum, average, standard deviation and probability density function (p.d.f.) of car velocities, *b*) $D_j^R = \frac{d}{s_j}$ denotes the residence time of a car j having a velocity s_j within the range of the SRU where D_{min}, D_{max} and $G_D(t)$ represent the minimum, maximum and cumulative distribution function (c.d.f.) of car residence times, *c*) λ_c represents the car arrival rate, *d*) $F_I(t)$ denotes the c.d.f. of the car inter-arrival time and *e*) Δ_c denotes the car density over the considered road segment. The reader is referred to [3] for complete details regarding the mathematical derivations of these parameters.

SFTM is a macroscopic vehicular traffic model. Even though this model constitutes a building block for the analysis whose guidelines are presented herein, it overlooks a few required microscopic details, namely: *a*) the type of the arriving vehicle and *b*) the number of passengers commuting onboard that vehicle. The remainder of this subsection aims at filling this gap.

Let T be a discrete r.v. representing the type of the arriving vehicle. As various as the vehicle types are (*i.e.* automobile, taxi, local and express buses, para-transit, etc), in this paper, interest lies in discerning between regular automobiles and buses. Hence, only the set composed of the combination of these two types of vehicles navigating over the road segment in Figure 1 is considered thereafter. As such, T takes on two values as follows:

$$T = \begin{cases} 0 & \text{, vehicle is an automobile} \\ 1 & \text{, vehicle is a bus} \end{cases} \tag{3}$$

The probability mass function (p.m.f.) of T is given by:

$$f_T(\tau) = Pr[T = \tau] = \begin{cases} p_0 & , \tau = 0 \\ 1 - p_0 & , \tau = 1 \end{cases} \tag{4}$$

where the value of p_0 follows from statistical measures described in [2]. Now, denote by N_p the number of passengers onboard an arriving vehicle. As discussed in section II, 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:

$$\begin{aligned} f_{N_p|T}(n) &= Pr\left[N_p = n \middle| T = \tau\right] \\ &= \begin{cases} \frac{1}{A_{max} - A_{min} + 1} & , \tau = 0 \text{ , } n \in [A_{min}; A_{max}] \\ \frac{1}{B_{max} - B_{min} + 1} & , \tau = 1 \text{ , } n \in [B_{min}; B_{max}] \\ 0 & \text{, Otherwise} \end{cases} \end{aligned} \tag{5}$$

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:

$$\begin{aligned} f_{N_p}(n) &= \sum_{\tau=0}^{1} f_{N_p|T}(n) \cdot f_T(\tau) \\ &= \frac{p_0}{A_{max} - A_{min} + 1} + \frac{1 - p_0}{B_{max} - B_{min} + 1} \end{aligned} \tag{6}$$

where $n \in [A_{min}; B_{max}]$.

In light of the above-established vehicular mobility model, the next section provides guidelines pertaining to the modelling of the bursty AR arrivals to the RB.

C. SU-Generated AR Arrivals:

The arrival process of SU-generated ARs is governed by the arrivals of vehicles as well as by the number of passengers commuting onboard the arriving vehicles. Recall that the vehicle arrival rate is λ_c $\left(\frac{\textit{vehicles}}{\textit{second}}\right)$ and that the number of passengers commuting onboard an arriving vehicle is N_p whose p.m.f. is $f_{N_p}(n)$ given in equation (6). For simplicity, let $f_n = f_{N_p}(n)$ $(A_{min} \leq n \leq B_{max})$. Now, imagine drawing a state-transition-rate diagram for the RB. Denote by N_Q the RB's length (*i.e.* the number of ARs queueing at the RB) and take it as being the state variable. Assume being at an arbitrary state k (*i.e.* $N_q = k$). Then with a rate equal to $\lambda_c f_{N_p}(n)$ a transition occurs from state k to state $k + n$ where this transition is the result of the arrival of a vehicle transporting $N_p = n$ passengers each of which will generate an additional AR. Observe that there are $B_{max} - A_{min} + 1$ upper states to which the RB may transition to from state k. The net rate for leaving state k is:

$$\lambda_c f_{A_{min}} + \lambda_c f_{A_{min}+1} + ... + \lambda_c f_{B_{max}} = \lambda_c \sum_{n=A_{min}}^{B_{max}} f_n = \lambda_c \tag{7}$$

Observe that, similar to the arrival process in model M1, the AR arrivals considered at this point also follow a Poisson process with parameter λ_c, however, with the difference that, here, an "arrival" corresponds to the arrival of a bulk of ARs of random size, n. As such, the arrival process is now a Poisson process with bulk AR arrivals. To represent this, a superscript $[n]$ is appended to the paper *M* representing the arrival process of the model. Hence, together with the refinements made in section III-A, the model M2 is further refined to account for the bursty arrivals of ARs and hence becomes an $M^{[n]}/G_S/c$+G_R.

A final note on characterizing the AR arrival process stems from the observation that vehicle arrivals follow a Poisson process only under free-flow vehicular traffic conditions, [3]. Under heavy-flow traffic conditions, the vehicle arrival process is no longer Poisson. A few existing work in the literature (*e.g.* [7]) model the inter-arrival times of vehicles under heavy-flow traffic conditions as being distributed according to a mixture of the gaussian and the exponential distributions. It has been well justified in [3] that such a model is inaccurate. Thus far, the literature lacks an accurate mathematical model for heavy-flow vehicular traffic. In light of this, to preserve generality, it can be considered that vehicle arrivals follow a general process. Yet, each vehicle arrival is, as explained earlier, equivalent to the arrival of a bulk of ARs having a random size n. Consequently an appropriate queueing model, in this case, would be $G_A^{[n]}/G_S/c$+G_R where $G_A(\cdot)$ represents the general distribution characterizing the ARs' arrival process.

D. SU-Generated AR Service Time:

Recall that SU-generated ARs are those ARs generated by the different passengers commuting over arriving vehicles at the

TABLE I
SIMULATION INPUT PARAMETERS

Parameter	Value
c	10
μ_S	0.02
Δ_c	$[0.000202; 0.003576]$
p_0	$\frac{2}{3}$
d	1000
$[S_{min}; S_{max}]$	$[10; 50]$
$[A_{min}; A_{max}]$	$[1; 4]$
$[B_{min}; B_{max}]$	$[1; 70]$

SRU. Note that passengers generate their ARs independently and, depending on the mobile application that a passenger is using, the length of each AR as well as the time for processing these ARs are independent from one to the other. In addition, the period of time required to successfully process one AR does not provide any information on the length of time required to process any other AR that is uploaded to the RB. In this regard, the exponential distribution, due to its memoryless property, seems to be an appropriate distribution to model the AR service time. Throughout this study, it will be assumed that the AR service time is exponentially distributed with parameter μ_S. Nonetheless, a general distribution $G_S(\cdot)$ for the service time would preserve generality but would lead to more complex analysis. For more certainty, one may choose to collect realistic data. Then, based on thorough numerical analysis of the collected data, a proper distribution may be selected. This, however, is currently outside the scope of this present paper. Ultimately, the system under study in this paper is the $M^{[n]}$/*M*/*c*+G_R.

After the above laid out briefing on the modelling of the DSA-based V2I communication system illustrated in Figure 2, in the next section, extensive simulations are conducted to study the performance of this system.

IV. SIMULATION STUDY AND RESULTS

In this section, the DSA-based V2I communication performance will be evaluated in the context of the scenario illustrated in Figure 1. The adopted performance metrics are: *a*) $\overline{Q_D}$ being the mean waiting time in the RB *b*) P_r being the reneging probability and *c*) P_f being the force-termination probability. The obtained results herein (*i.e.* labeled ESS) are directly compared to those of [1] (*i.e.* labeled as $M/M/m$) as illustrated in Figure 4. Note that the simulation study laid out thereafter does not include the verification of any of the above-discussed queueing models. This is especially true since, in section III, the objective was to rather provide preliminary insights on the mathematical modelling of the system and not to, actually, develop and test a full-fledged model.

A. Simulator and Input Parameters:

A custom-built JAVA-based discrete event simulator was developed. The adopted performance metrics were evaluated for a total of 10^6 ARs and averaged out over multiple runs of the simulator to ensure that a 95% confidence interval is realized. Simulations were conducted using the parameter values listed in Table I.

B. Simulation Results:

Figure 4(a) concurrently plots P_r versus Δ_c for both ESS and the preemptive $M/M/m$ queueing model of [1]. Recall that, P_r is the reneging probability of ARs from the RB after their corresponding initiators leave the SRU's range (*i.e.* as consequence of the occurrence of event E2 in section II). Obviously, the typical preemptive $M/M/m$ model does not account for this particular aspect of the system. Particularly, the dynamics of that model indicate that, once ARs join the RB, these ARs will remain there until their admission into service. In other words, there, ARs will renege from the RB with zero probability. In contrast, following the realistic system's description in section II, ESS reveals that 80% and above of the incoming ARs to the RB will renege from the RB as a result of the occurrence of E2. Note that, the range of Δ_c considered in this study covers Free-flow vehicular traffic (*i.e.* as per the guidelines in [3], a low-to-moderate arrival rate of vehicles). Truely, a further increase in Δ_c leads to a higher level of AR offered load and hence P_r will further increase.

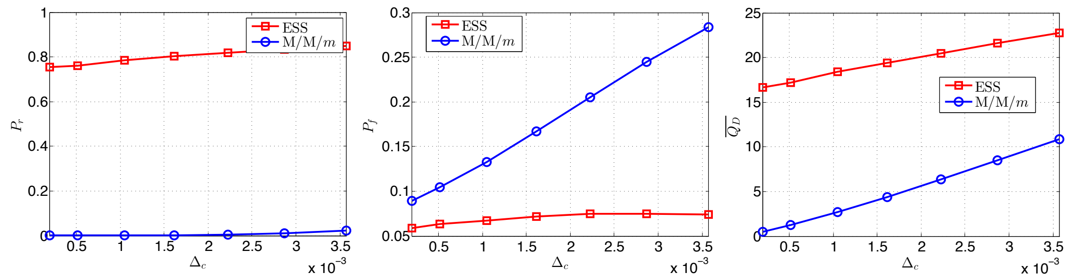
Figure 4(b) concurrently plots P_f versus Δ_c for both ESS and the preemptive $M/M/m$ queueing model of [1]. Reminisce about the fact that P_f is the force-termination probability of an AR's service. The reported curves in Figure 4(b) indicate, that P_f for ESS is much lower than it is for the preemptive $M/M/m$ queueing model. This finding can be explained as follows. Recall that for the preemptive $M/M/m$ queueing model, all ARs queueing at the RB will eventually go into service. Under such circumstances, it becomes more probable that a PU-set initiating communication over an arbitrary one of the available channels will find an ongoing SU-set communication over that channel and hence will force terminate it. In contrast, for ESS, recall from Figure 4(a) that a very large proportion of the ARs queueing at the RB will renege before being admitted into service. In other words a low number of SU-generated ARs is going to reach the service level. As such, an incoming PU-generated AR is more likely to find its requested channel vacant and hence use it without having to force-terminate an ongoing SU communication. This directly translates into a decrease of P_f.

Figure 4(b) concurrently plots $\overline{Q_D}$ versus Δ_c for both ESS and the preemptive $M/M/m$ queueing model of [1]. Observe that $\overline{Q_D}$ for ESS is much higher than its counterpart for the preemptive $M/M/m$ queueing model. It is well known in Queueing Theory that the average queueing delay for a queueing system where customers do not renege is higher than its reneging-enabled counterpart. The reason behind this is the fact that reneging customers will cause the average queue length to decrease. Hence, by Little's Theorem, [9], the average queueing delay will also decrease. One may be easily mislead to expect that this principle applies to the system studied herein. However, truly, it does not. Indeed, under the typical $M/M/m$ queueing model, ARs arrive singly at a time which is not the case for ESS since here each vehicle arrival is mapped into the arrival of a random-sized-bulk of ARs. As such, the average queue length of the system studied herein is much larger than its $M/M/m$ queueing model correspondent. As a result the queueing delay herein is much higher.

C. Further Discussions:

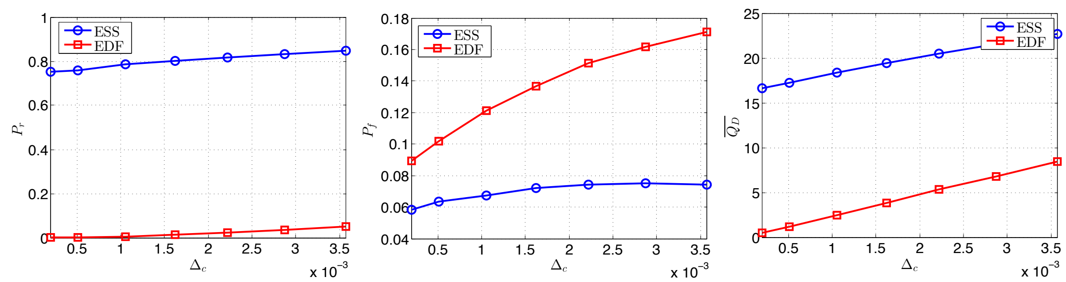
The results reported in Figure 4 reveal a remarkable inefficiency of VDSA. Indeed, more than 80% of the incoming ARs to the RB end up being blocked. Obviously, the DSA-based V2I communication system as described in section II suffers from a serious problem, namely, the extravagant AR blocking probability and hence appears to have marginal utility. Nonetheless, a close analysis of the reasons behind the elevated blocking probability uncover an original tweak that impressively improves the performance of the system as discussed below.

The blocking probability P_b is the sum of the reneging and force-termination probabilities P_r and P_f. From Figure 4, P_r is the Achille's heal. In fact, the AR initiators' residence time within the range of the SRU can be interpreted as a deadline whose expiry will cause these AR to renege from the RB. As opposed to the



(a) Reneging Probability (b) Force-Termination Probability (c) Mean Queueing Delay

Fig. 4. Performance evaluation of the DSA-based V2I communication system.



(a) Reneging Probability (b) Force-Termination Probability (c) Mean Queueing Delay

Fig. 5. RB with FIFO versus EDF AR service diciplines.

FIFO AR service discipline, the Earliest Deadline First (EDF) (*e.g.* [8]) AR service discipline is expected to significantly improve the performance of the system. This is especially true since serving the incoming ARs according to their earliest deadline will enable a larger proportion of these ARs to start receiving service before their initiators move out of the SRU's range and hence will reduce P_r. Simulations are conducted using the same input parameters as in subsection IV-A. However, now, the RB follows an EDF AR service discipline. The obtained results are reported in Figure 5 where they are concurrently compared with those of the original system under ESS.

Figure 5(a) concurrently plots P_r versus Δ_c for both EDF and ESS. The results reported in this figure indicate an uncanny decrease in P_r under EDF. Indeed, the EDF AR service discipline was able to reduce P_r to almost zero at low vehicular densities with a marginal increase whenever the Δ_c increases. This, however, has caused the force-termination probability P_f to increase as reported in Figure 5(b). This is expected since servicing an AR whose deadline is short increases the probability that the initiator of this AR leaves the SRU's range while being served. As such the AR's service time has to be force-terminated. 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 EDF as compared with ESS. As a matter of fact the improvement in the blocking probability is almost 70%.

Finally, Figure 5(c) concurrently plots $\overline{Q_D}$ versus Δ_c for both EDF and ESS. The figure shows an improvement in the response time for the EDF-based RB. In fact, servicing ARs with shorter deadlines causes the admission rate of ARs into service to increase. As such the RB length will decrease and, by Little's Theorem, the average response time will decrease as well.

V. Conclusion

This paper investigated a DSA-based V2I communication system operating under scarce spectral resources conditions. Following a comprehensive description of how this type of communication takes place in the context of a limited spectral resources scenario, a brief realistic modelling overview was provided with guidelines on how to account for fundamental factors that have been overlooked in existing work. Then, extensive simulations were conducted in order to examine the system's performance. Results show that the AR reneging and force-termination probabilities have a cataclysmic impact on the system's performance as well as on an end-user's Quality-of-Service (QoS) satisfaction. A comparison with the results of a study proposed in an existing work where these probabilities are not taken into account shows a dramatic performance deviation of more than 80%. Fortunately, the EDF service discipline incurred a significant improvement in the performance of the system as it almost nullified the reneging probability.

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