A Probabilistic and Traffic-Aware Bundle Release Scheme for Vehicular Intermittently Connected Networks

Maurice J. Khabbaz, Wissam F. Fawaz, and Chadi M. Assi

***Abstract*—Delay-optimal data delivery in Vehicular Intermittently Connected Networks (VICNs) is challenging since vehicular traffic is affected by numerous recurring and completely random events. Some of these events cause breakdowns and jams while others subserve traffic stability. Researchers observed that mobile vehicles might be wisely exploited to connect two isolated, Stationary Roadside Units (SRUs). In this context, the design of effective delay-minimal data relaying strategies is receiving significant attention. However, many existing such schemes either do not adequately model vehicular traffic behaviours or adapt typical Internet packet-like forwarding protocols to VICNs. In contrast, this manuscript presents a concise, yet comprehensive study of vehicular traffic states based on which a "comme-il-faut" vehicular traffic model is established. This model captures the fundamental traffic characteristics and enables the selection of appropriate distributions for vehicular flow and speeds that parallel the realistic measurements made by traffic theorists. These distributions constitute the basis of a novel Probabilistic Bundle Release Scheme with Bulk Bundle Release (PBRS-BBR) that is proposed with the objective to minimize the average bundle delivery delay. An analytical queueing model is formulated to assess the performance of PBRS-BBR under medium-to-light vehicular traffic. Extensive simulations are conducted to prove the models validity and accuracy.**

***Index Terms*—Modelling, performance evaluation, DTN, vehicular, ICNs.**

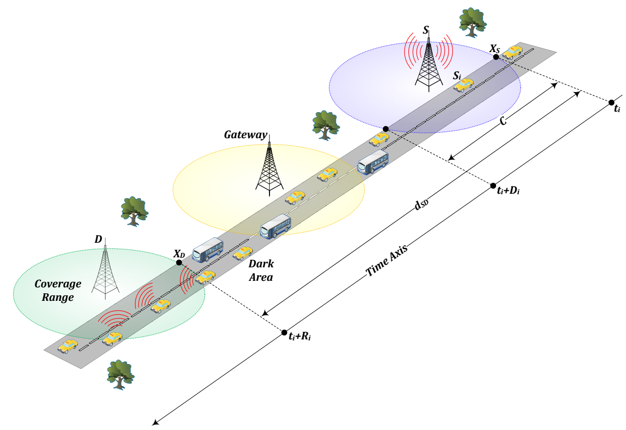

Fig. 1. Vehicular intermittently connected network scenario.

I. Introduction

THE conception of Vehicular Ad-hoc NETworks (VANETs) consists of transforming vehicles into intelligent mobile entities that are able to wirelessly communicate with each other as well as with stationary roadside units (SRUs). Thus, a highly dynamic self-organized network that supports a large variety of safety, convenience and leisure applications can be formed. Pragmatically, throughout the past couple of years, researchers, network operators and engineers as well as the large vehicular industry and some governmental authorities have shown a remarkable interest in this emerging networking conception, [1]–[4], [7]–[11]. In fact, the majority of the leading vehicle manufacturers are producing communication-enabled vehicles equipped with small yet powerful wireless devices, global positioning system (GPS) units, navigation systems loaded with digital maps and a large number of real-time monitoring sensors. The U.S. Federal Communications Commission (FCC) has dedicated the 5.9 GHz band for short/medium-range communication services supporting Intelligent Transportation Systems in order to expedite inter-vehicle and vehicle-to-roadside communication [3], [4]. Nevertheless, due to the highly random nature of vehicular mobility and the relatively high vehicle speeds, the topology of a vehicular network becomes highly dynamic and prone to recurrent link intermittence. In this context, timely and reliable data delivery becomes a gruelling task, the realization of which intersects with several underlying concepts and challenges that have to be handled with care before a full-fledged VANET can be deployed. The networking research community has thus far witnessed numerous publications on inter-vehicle and SRU-to-vehicle communications. However, the SRU-to-SRU delay-minimal data delivery problem has not yet been adequately addressed and will be further investigated herein. Consider the scenario illustrated in Figure 1 which depicts a large uninterrupted[1]

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[1]No grade intersections, traffic lights, STOP signs, direct access to adjoint lands, bifurcations, etc.

highway along which several SRUs are deployed. Due to the elevated communication infrastructure setup costs, only a very small number of these SRUs, known as *gateways*, are connected to the Internet or a backbone network. The rest are completely isolated[2]. Connectivity is to be established between two isolated SRUs, a source S and a destination D. Wireless nodes mounted over mobile vehicles serve as opportunistic *store-carry-forward* devices that transport bundles[3] from S to D. Vehicles have random speeds and enter the coverage range of S at random time instants. No inter-vehicle communications may occur. Under such conditions, an intermittence-free end-to-end S-D path does not exist. A network of this type belongs to a subclass of VANETs that is conveniently referred to as *Two-Hop Vehicular Intermittently Connected Networks* (VICNs).

In [7], the authors investigated the delay-minimal bundle delivery problem in the same context of Figure 1. Besides its underlying complexity, their solution framework seems to be an attempt to adapt a typical Internet packet-like forwarding mechanism to the VICN under study. Throughout their study, the authors assumed complete network information availability. In contrast, the work in [8] captured the essence of DTNs where the authors proposed a Probabilistic Bundle Release Scheme (PBRS) that revolves around minimal network information knowledge. The core of this scheme consists of releasing a single bundle to a subset of arriving vehicles that contribute the most to the minimization of the bundle transit delay. The performance of PBRS was compared to that of a Greedy Bundle Release Scheme (GBRS) where bundles are greedily (rather than opportunistically) released to every arriving vehicle. The authors' assumption of a uniformly distributed vehicular speeds however restrained the validity of their work only to cases where the highway facility is strictly experiencing very light traffic[4]. Under such conditions, vehicle arrivals become considerably spaced out in time causing bundles to accumulate relatively large queueing delays.

In this manuscript, a concise yet comprehensive study of vehicular traffic behaviour is presented first. Based on this study, a traffic model is established where appropriate distributions for vehicular flow and speeds are selected. Furthermore, a Bulk[5] Bundle Release (BBR) variation of PBRS, namely PBRS-BBR, is proposed to reduce the bundle queueing delay. As a result the overall bundle delivery delay[6] is improved. Founded on the results of the proposed vehicular traffic model, a mathematical framework is setup to analyze the network performance achieved under PBRS-BBR in terms of queueing, transit and end-to-end delay metrics. The performance of its greedy counterpart (GBRS-BBR) serves as a benchmark. As opposed to [7], this present study preserves the fundamental characteristics of Disruption-Tolerant Networking.

The rest of this manuscript is organized as follows. Section II, summarizes the topmost related work and explains in more details our major contributions. In section III a comprehensive study of vehicular traffic behaviour is laid out followed by a discussion of the proposed traffic model. Section IV describes PBRS-BBR's framework and introduces its associated release probability. In that same section a queueing model is formulated to theoretically analyze the performance of an SRU under PBRS-BBR and GBRS-BBR. In section V, extensive simulations are conducted to highlight the accuracy and validity of the proposed models and evaluate the performance of the schemes under study. Finally, section VI presents the final concluding remarks.

II. Related Work

A. Selective Literature Survey:

Vehicular Networks outline a challenging terrestrial application of the emerging Disruption-Tolerant Networking paradigm. The research community reported in the open literature on some real experiments conducted in this field. For example, in [5], DieselNet, a VICN where only buses were exploited as bundle transporters, was deployed over a wide urban area. The work of [6] presents POR, a Packet-Oriented Routing protocol for Vehicular Intermittently Connected Sensor Networks. POR performs neighbour selection based on the probability of transfer success. The authors of [7] studied a complex joint scheduling/delay-minimization problem in the context of the VICN scenario illustrated in Figure 1. All of the previously described work revolves around one central problem: appropriate forwarding. However, all their proposed solutions do not capture the fundamental properties of VICNs as they rely on the complete network information availability (*e.g.* encounter instants, data traffic volumes, exact vehicle speeds, etc). In contrast, the work in [8] presented two forwarding strategies namely, the Probabilistic Bundle Release Scheme (PBRS) and a Greedy Bundle Release Scheme (GBRS). Both schemes rely on minimal network information knowledge. On one hand, under PBRS, a source releases a single bundle to a subset of arriving vehicles that contribute the most to the minimization of the bundle transit delay. On the other hand, under GBRS, a source greedily releases bundles to every arriving vehicle. Under conditions of light-to-medium traffic flows, PBRS outperformed GBRS as it remarkably minimized the average bundle transit delay. However, due to the fact that vehicle inter-arrival times were relatively large, the release of a single bundle per opportunity was proven to inhibit subsidiary queueing delays.

In addition, similar to [8], several recently published studies in the field are established based on the essential architectural features of VICNs. However, these studies do not account for the random behaviour and characteristics of vehicular traffic. For example, in [10], the authors investigate a multi-hop packet delivery problem in VICNs. The authors assumed that vehicles navigate at only two speed levels namely a low and a high speed. A vehicle will navigate at a certain speed level for an exponentially distributed period of time before

[2]Isolated SRUs are located outside their mutual coverage ranges and therefore cannot directly communicate. In the rest of this manuscript, an isolated SRU is simply referred to by SRU. Otherwise, the term gateway is used.

[3]Data and control signals are combined in a single atomic entity, called bundle, that is transmitted across an ICN, [1].

[4]It is understood from traffic theory that, only in cases of very light traffic, drivers may freely navigate at arbitrary speeds. Hence the long-term distribution of vehicle speeds tends to be uniform.

[5]A group of bundles released to an in-range vehicle is referred to as a *bulk of bundles* or simply a *bulk*.

[6]The bundle delivery delay also called end-to-end delay is the sum of the queueing and the transit delay.

it abruptly starts cruising at the second level. Obviously, that model is unrealistic as vehicle speeds smoothly vary according to a certain distribution over a certain range whose lower and upper bounds are constrained by both the vehicular traffic flow and density. The authors of [9] considered both single and two-hop infrastructure-based vehicular network scenarios and investigated the trade-offs between key system parameters, such as inter-SRU distance and nodal communication ranges. They also analyzed the collective impact of these parameters on both the access probability and connectivity probability under different communication channel models. However, the authors did not consider the variations of vehicle speeds as a function of density especially that those latter (*i.e.* density and speeds) are known to have a direct impact on connectivity and channel characteristics (*e.g.* fading). In [11], the authors formulated a queueing model to study the performance of mobile routers in VICNs. They consider a scenario where some traffic sources tend to selfishly confiscate resources (*i.e.* buffer and bandwidth) and thus severely impact the performance of the network. The authors studied this competitive situation by means of a non-cooperative gaming model where they assumed that vehicles navigate at the same constant vehicle speed.

Finally, the seminal work of [12] revolved around the connectivity dynamics of VANETs where the authors investigated the probability of full network connectivity. They adequately used a generic density-dependent velocity profile to capture the shockwave propagation at traffic signals. The obtained results constitute a strong knowledge-base for carrying out connectivity optimization planning and systems engineering.

B. Novel Contributions:

In the context of the VICN Scenario of Figure 1, the establishment of an enhanced (*i.e. delay-minimal*) connectivity between two isolated SRUs is the primary objective of this manuscript. Relative to previous work referenced above, a set of original contributions are described herein.

It is observed, on one hand, that the random behaviour of vehicular traffic has a direct impact on the performance of SRU-to-SRU data communication stratagems. This is especially true since as the vehicular traffic density increases over a highway segment vehicle speeds become normally much lower than the allowed speed limit over that segment. It follows that reduced speeds will lead to longer transit periods from the source to the destination SRU. On the other hand, during a non-congested period, drivers may freely navigate at high speeds and possibly attain the maximum allowable speed limit. Hence, transit periods are significantly reduced.

Enlightened by rudimentary principles borrowed from vehicular traffic theory, the first contribution appears in the layout of a concise yet comprehensive study of traffic behaviour. This is augmented with the foundation of an accurate vehicular traffic model that allows for the adoption of appropriate flow and speed distributions in order to parallel the experimental measurements and observations on traffic behaviour as made by traffic theorists over the years.

Furthermore, notice that the advancements in wireless technology have allowed for data transmission rates in the order of tens of Mbps resulting in a negligible bundle transmission time when compared to the vehicle *dwell time*[7]. Consequently, the opportunistic release of only a single bundle (as PBRS does, [8]) yields a waste of precious amounts of residual vehicle dwell times during which the source remains idle while buffered bundles rapidly accumulate queueing delays. Alternatively, releasing as many bundles as possible during the entire vehicle dwell time seems to be a promising and much more efficient approach. Therefore, the second contribution consists of proposing a variation of PBRS and GBRS with Bulk Bundle Release (BBR). The size of a bulk is a random variable that highly depends on the number of buffered bundles at the source and the bundle admission capabilities of arriving vehicles. PBRS-BBR inherits from its non-BBR ancestor the efficiency of releasing bulks to vehicles that contribute the most to the minimization of the mean bundle transit delay. GBRS-BBR, however, unwisely releases bulks to every arriving vehicle. The general potency of the BBR mechanism in boosting the performance of VICN bundle release strategies, the delay performance of PBRS-BBR and GBRS-BBR as well as their realistic aspect are underlined using a detailed analytical study that exploits the probability distributions of traffic flow and vehicle speeds drawn from the established vehicular traffic model.

III. VEHICULAR TRAFFIC ANALYSIS

When modelling vehicular traffic over uninterrupted one-dimensional road-path segments (*e.g.* [*SD*] in Figure 1), one may reasonably visualize commuters and vehicles as a coupled system where vehicle operation comes as a direct response to the occurrence of numerous haphazard real-time circumstances including, but are not limited to: weather, road condition and infrastructure, vehicular technology, commuters' characteristics and habits, day time, population density, increased circulation demands, economic prosperity and so forth. As a result, in addition to being mechanical by nature, vehicular traffic is also a stochastic process driven by human decisions and involving an elevated degree of variability. Indeed, the vehicular traffic behaviour varies both spatially and temporally. In practice, the determination of a particular roadway segment's traffic conditions is typically linked to some spatiotemporal traffic features[8] that are identified through real-time observations and measurements taken over several years. Such observations and statistical data collections are not generic but rather highly dependent on the observed facility. Until this date, traffic researchers are still unable to capture and accurately model the primary causes of abrupt changes in vehicular traffic behaviour.

The microscopic traffic observation and the trace of traffic variations as a function of all the above mentioned factors is outside the scope of our research. Instead, in this manuscript, we focus our attention on the macroscopic traffic parameters, namely: *i*) average vehicle speed $\overline{S_v}$ in $\left(\frac{meters}{second}\right)$, *ii*) average vehicular flow μ_v in $\left(\frac{vehicles}{second}\right)$ and *iii*) average vehicular

[7] The amount of time a vehicle spends in the range of the source

[8] Empirical traffic features that are qualitatively identical for different highway segments in different countries.

density $\overline{\Delta_v}$ in $\left(\frac{vehicles}{meter}\right)$. Part of Figure 2 sketches the flow-density relationship based on which two traffic states can be identified:

- *Free-flow state*: Whenever both μ_v and $\overline{\Delta_v}$ are low, [*SD*] is said to be experiencing a stable flow where vehicles independently navigate at completely random speeds and may arbitrarily attain the maximum allowable speed limit.
- *Heavy-flow state*: As $\overline{\Delta_v}$ further increases, a critical point will be reached at (Δ_c, μ_c) where the formation of vehicle platoons within [*SD*] begins. At this point and beyond, [*SD*] experiences flow instability. Thus, vehicles can no longer navigate independently and are naturally subject to substantial speed reduction.

The next subsection is dedicated for the microscopic description of the vehicular traffic behaviour in these two states.

A. Behavioural Description of Vehicular Traffic:

Consider a one-dimensional uninterrupted highway segment [*SD*] of length d_{SD} (*meters*) as shown in Figure 1. Vehicles enter this segment at point X_S. A vehicle i arriving at time t_i with a random speed S_i will navigate for a time period $R_i = \frac{d_{SD}}{S_i}$ over [*SD*] before it exits the segment at point X_D at instant $e_i = t_i + R_i$. Let $\overline{N_v}$ and $\overline{R_v}$ denote the mean number of vehicles within [*SD*] and the mean navigation time of vehicles over that segment respectively. It follows from *Little's Law* that $\overline{N_v} = \mu_v \times \overline{R_v}$. The proper manipulation of this equation leads to the *Fundamental Flow-Speed-Density Relationship* (in [15], [20])

$$\mu_v = \overline{\Delta_v} \times \overline{S_v} \tag{1}$$

Where it has been established that $\overline{R_v} = \frac{d_{SD}}{\overline{S_v}}$, with $\overline{S_v}$ being the mean vehicle speed and $\overline{\Delta_v} = \frac{\overline{N_v}}{d_{SD}}$ denotes the mean vehicular density over [*SD*]. Furthermore, traffic theorists observed that there exists a connection between the traffic density and vehicle speed: "*The more there are vehicles on the road, the slower their velocities will be.*", [15], [17]. Based on this observation, they expressed $\overline{S_v}$ as a function of $\overline{\Delta_v}$:

$$\overline{S_v}\left(\overline{\Delta_v}\right) = S_{max}\left(1 - \frac{\overline{\Delta_v}}{\Delta_{max}}\right) \;, 0 \leq \overline{\Delta_v} \leq \Delta_{max} \tag{2}$$

Combining (1) and (2), μ_v may be expressed as:

$$\begin{aligned}\mu_v\left(\overline{\Delta_v}\right) &= \overline{\Delta_v} \times S_{max}\left(1 - \frac{\overline{\Delta_v}}{\Delta_{max}}\right)\\ &= -\frac{S_{max}}{\Delta_{max}}\overline{\Delta_v}^2 + S_{max}\overline{\Delta_v} \;, 0 \leq \overline{\Delta_v} \leq \Delta_{max}\end{aligned} \tag{3}$$

Notice in Figure 2 (bottom-left) the Flow as expressed in (3) is a parabolic function of the density. As the density starts to increase, the flow also increases. It continues to increase until it attains a maximum of $\mu_c = \frac{S_{max}\Delta_{max}}{4}$ at $\Delta_c = \frac{\Delta_{max}}{2}$ where [*SD*] is said to be in a critical state. Beyond this point, as the density further increases, [*SD*] moves the stable Free-flow state (state *F*) to an unstable Heavy-flow state (state *H*) where the flow starts to decrease. The Speed-Density relationship in (2) is shown in Figure 2 (top-left). Finally, the Speed-Flow relationship is shown in Figure 2 (top-right). The horizontal line $S_c = \frac{S_{max}}{2}$ splits the graph in two regions. The upper region of the graph summarizes the variations of the average speed in state *F* while the lower region describes the speed variations in state *H*. To sum up, observe from Figure 2 that for appropriate description of the traffic state, it is necessary to couple the flow rate value with that of the average speed. Consequently, when doing this, one can localize idiosyncratic points on any of the three characteristic curves in Figure2.

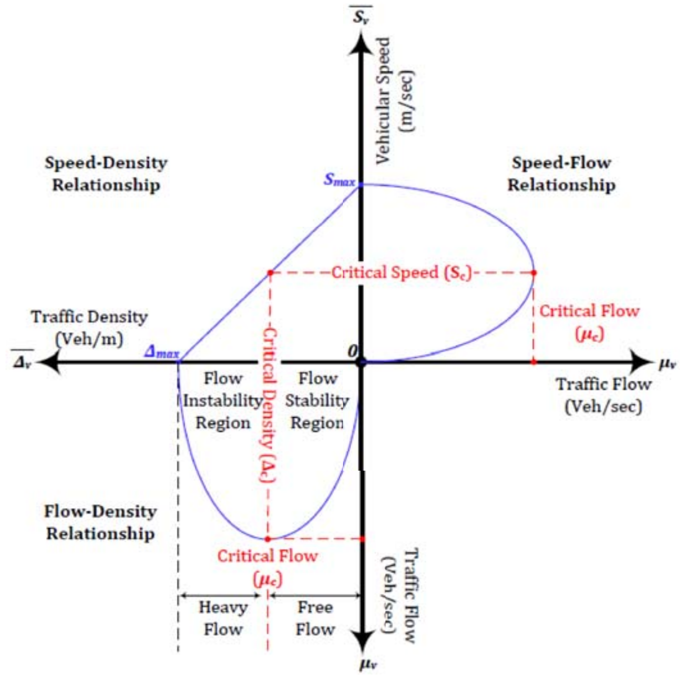


Fig. 2. Fundamental traffic diagram.

Now, from a data networking point of view, according to [9], inter-vehicular connectivity is enhanced under heavy-flow vehicular traffic conditions; hence incentivizing the utilization of typical Mobile Ad-Hoc Networking (MANET) communication protocols. In contrast, under the free-flow conditions, the network becomes sparse and subject to highly repetitive link disruptions that contribute to the failure of existing MANET communication protocols. Consequently, the benefits of inter-vehicular communication become quite marginal. Nonetheless, as illustrated in Figure 1, two-hop data communication between two SRUs is still feasible through the exploitation of the transport infrastructure and presents several advantages as discussed in [1], [5], [7]. This manuscript investigates the possibility of achieving delay-minimal bundle delivery in this context. This being highly affected by the vehicular traffic behaviour, it is therefore essential to develop a model that mimics the realistic free-flow vehicular traffic behaviour as observed by observed by traffic theorists and engineers. The next subsection explains how the curves of Figure 2 can be used to establish such a model and hence select realistic probability distributions for the vehicular flow and speeds.

B. Distributions of Vehicular Flow and Speed Under Free-flow Traffic Conditions:

As it was described earlier, the average flow represents the rate at which vehicles enter (leave) a highway segment (*e.g.* [*SD*]). Particularly, as illustrated in Figure 1, an arbitrary vehicle i enters [*SD*] as soon it enters the communication range of the source S at a random time instant t_i. This is subsequently referred to as the i^{th} *vehicle arrival*. Vehicle $i+1$ then arrives at $t_{i+1} > t_i$. Let $I_{i+1} = t_{i+1} - t_i$ denote the $(i+1)^{th}$ vehicle inter-arrival time. In traffic theory, the *time headway* is defined as the time interval between successive vehicles crossing the same reference point on a road segment, [15]–[17]. In the present study, it is assumed that the reference point is the entry point to [*SD*] (*i.e.* point X_S). Thus, the time headway becomes equivalent to I_{i+1}. Selecting a distribution for I_{i+1} is a delicate task that has to be handled carefully. Traffic theorists have observed that free-flow traffic occurs during non-rush hours (*i.e.* late night and early morning hours from 7:00 P.M to 8:00 A.M as well as mid-day hours from 10:00 A.M to 4:00 P.M). In [18], large sets of realistic traces have been collected during these hours on the $I-80$ freeway in CA, USA. These traces showed that the vehicle inter-arrival time during non-rush hours is exponentially distributed. Further analysis in [18] shows that, during these hours and particularly whenever the vehicular flow is below 1000 vehicles per hour, vehicles appear to be isolated and hence, the vehicle arrivals to an arbitrary geographical reference point become i.i.d. This have been also confirmed in [19]. Following these guidelines, vehicle inter-arrival times I_j $(j > 0)$ are assumed to be i.i.d exponential random variables with a p.d.f. given by:

$$f_I(t) = \frac{1}{\mu_v} e^{-\frac{t}{\mu_v}} \ , t \geq 0 \tag{4}$$

Moreover, vehicular traffic theorists have widely agreed that the vehicle speeds follow a Gaussian distribution [15]–[17], [20]. Let S_v be a normally distributed random variable that denotes the vehicle speed with a p.d.f. that is given by:

$$f_{S_v}(s) = \frac{1}{\sigma_{S_v}\sqrt{2\pi}} e^{-\frac{(s-\overline{S_v})^2}{2\sigma^2_{S_v}}} \tag{5}$$

Observe that S_v cannot be negative nor can it bypass the maximum allowable speed limit S_{max}. Based on this observation, two speed limits V_{min} and V_{max} are defined to be the respective minimum and maximum navigation speeds over [*SD*] under a particular traffic state and experiencing a specific flow rate. Hence, subsequently, the following truncated version of $f_{S_v}(s)$ is adopted:

$$\begin{aligned} f^t_{S_v}(s) &= \frac{f_{S_v(s)}}{\displaystyle\int_{V_{min}}^{V_{max}} f_{S_v}(s)ds} \\ &= \frac{2 f_{S_v}(s)}{\text{erf}\left(\frac{V_{max}-\overline{S_v}}{\sigma_{S_v}\sqrt{2}}\right) - \text{erf}\left(\frac{V_{min}-\overline{S_v}}{\sigma_{S_v}\sqrt{2}}\right)} = \zeta \cdot f_{S_v}(s) \end{aligned} \tag{6}$$

where $s \in [V_{min}; V_{max}]$. Hence, the c.d.f. of S_v is:

$$F_{S_v}(x) = \frac{\zeta}{2}\left[1 + \text{erf}\left(\frac{x-\overline{S_v}}{\sigma_{S_v}\sqrt{2}}\right)\right] \ , x \in [V_{min}; V_{max}] \tag{7}$$

Knowing the state of the system and the value of μ_v, $\overline{S_v}$ is determined as in subsection III-B. The values of σ_{S_v}, V_{min} and V_{max} are determined next. It is established that 99.7% of the entire area under the Normal curve of speeds lie within $\pm 3\sigma_{S_v}$ from the mean $\overline{S_v}$. Hence, $\sigma_{S_v} = m\overline{S_v}$ whereas $V_{min} = \overline{S_v} - k\sigma_{S_v}$ and $V_{max} = \overline{S_v} + k\sigma_{S_v}$ ($m = 0.3$ and $k = 3$, [20]). However, m and k are strongly dependent on the observed facility and are determined based on experimental measurements.

IV. Probabilistic Bundle Relaying Scheme with Bulk Bundle Release

In the two-hop VICN scenario depicted in Figure 1, communication is to be established between the source SRU S and destination SRU D. S has a coverage range that spans a distance C of the highway. S and D are separated by a distance $d_{SD} \gg C$. In the absence of all sorts of networking infrastructures and backbone network connectivities, vehicles navigating at distinct speeds enter the range of S at random time instants and are opportunistically exploited to transport bulks of bundles to D. Under PBRS-BBR, S releases bulks only to the relatively fast vehicles in order to ensure a minimal transit delay to D. At the heart of PBRS-BBR is the bundle release probability $P_{br,i}$, a novel decision parameter expressed as a function of the mean vehicle flow rate μ_v, the speed S_i of a vehicle i present in the range of S and the source-destination distance d_{SD}. This parameter gives S insight into the level of contribution of an arriving vehicle to the minimization of the overall average bundle transit delay. In this section, a mathematical model is formulated to represent the source S operating under PBRS-BBR.

A. *Mathematical Formulation and Basic Notations:*

The source S becomes aware of the speed S_i of an arbitrary vehicle i only at the arrival instant t_i of the vehicle. Hence, with a probability $P_{br,i}$, S immediately starts releasing a bulk of bundles to vehicle i. With a probability $1 - P_{br,i}$, S retains the bulk for a better subsequent release opportunity. If the bulk is released to the i^{th} vehicle, it will be successfully delivered at the instant $d_i = t_i + \frac{dSD}{S_i}$. Otherwise, if it is released to the $(i+1)^{th}$ vehicle, it will be successfully delivered at the instant $d_{i+1} = t_{i+1} + \frac{dSD}{S_{i+1}}$. Recall that $I_{i+1} = t_{i+1} - t_i$ represents the $(i+1)^{th}$ vehicle inter-arrival time. It follows that a better subsequent release opportunity occurs whenever $d_{i+1} < d_i \Rightarrow I_{i+1} + \frac{d_{SD}}{S_{i+1}} < \frac{d_{SD}}{S_i}$ where I_{i+1} and S_{i+1} are the only unknowns. Before deriving a closed-form expression for the bundle release probability $P_{br,i}$, the following fundamental assumptions are made:

- A1: Vehicle inter-arrival times have a p.d.f. $f_I(t)$.
- A2: Vehicle speeds have a p.d.f $f^t_{S_v}(s)$.
- A3: A vehicle's speed remains constant during its entire navigation period on the road.

Assumptions (A1) and (A2) have been extensively justified throughout section III-D. As for assumption (A3), on one hand, it has been clearly highlighted in [15] through [17] that, whenever vehicular traffic is light, commuters tend to drive at relatively high constant speeds. On the other hand, whenever the vehicular traffic is heavy, the emphasis is to focus on the segment of the road that falls within the coverage range of the source SRU *S*. This segment is short where vehicle speeds are most likely to remain constant. Furthermore, *S*'s vehicle selection is based on the speeds of only those vehicles present within its coverage range. *S* becomes completely unaware of any speed variations of a chosen vehicle once that vehicle exits its range (a chosen vehicle may vary its speed after it exits the range of *S* especially under heavy flow where vehicles undergo repetitive periods of acceleration/deceleration). In addition, the majority of the existing related work in the open literature (*e.g.* [5], [9]–[11] adopt (A3) since it promotes the tractability of the mathematical analysis. All of the above observations justify the utilization of assumption (A3) throughout the rest of our study.

B. Conditional Bundle Release Probability:

The probability of retaining a bulk given that $s \leq S_i < s + ds$ can be expressed as:

$$Pr\left[d_{i+1} < d_i \middle| s \leq S_i < s+ds\right] = Pr\left[I_{i+1} + \frac{d_{SD}}{S_{i+1}} < \frac{d_{SD}}{S_i} \middle| s \leq S_i < s+ds\right] \quad (8)$$

Let *R* be the event of a bulk release. Thus, the conditional bundle release probability $P_{br,i}(s)$ is:

$$\begin{aligned} P_{br,i}(s) &= Pr\left[R \middle| s \leq S_i < s+ds\right] \\ &= 1 - Pr\left[\Omega < \frac{d_{SD}}{S_i} \middle| s \leq S_i < s+ds\right] \end{aligned} \quad (9)$$

Where $T_i = \frac{d_{SD}}{S_{i+1}}$ and $\Omega = I_{i+1} + T_i$ are two defined random variables with respective p.d.f $f_T(t)$ and $f_\Omega(t)$. The p.d.f of I_{i+1} is $f_I(t)$ is given in (4). Using assumption (A2), it is shown that:

$$f_T(t) = \frac{\zeta \cdot d_{SD}}{t^2 \sigma_{S_v}\sqrt{2\pi}} e^{-\left(\frac{\frac{d_{SD}}{t} - \overline{S_v}}{\sigma_{S_v}\sqrt{2}}\right)^2}, \ t \in \left[\frac{d_{SD}}{V_{max}}; \frac{d_{SD}}{V_{min}}\right] \quad (10)$$

Since $I_{i+1} \in [0; +\infty]$ and $T \in \left[\frac{d_{SD}}{V_{max}}; \frac{d_{SD}}{V_{min}}\right]$ then $\Omega \in \left[\frac{d_{SD}}{V_{max}}; +\infty\right]$. Let $f_\Omega(t)$ denote the p.d.f of Ω. It is given by the convolution of the two density function $f_I(t)$ and $f_T(t)$. Nonetheless, the remarkable complexity of the resulting convolution integral results in having no closed-form expression for $f_\Omega(t)$. Therefore, we propose (and justify) to approximate this distribution by an m-harmonic Fourier series whose parameters are determined using the *Least Squares Fitting* criterion. This approximation has the advantages of: *i*) being highly accurate for all investigated traffic conditions and *ii*) presenting relatively simple closed-form expressions for both $f_\Omega(t)$ and $P_{br,i}$. The approximated version of $f_\Omega(t)$ is:

$$\widetilde{f_\Omega^m}(t) = \begin{cases} \sum_{j=0}^{m} [\varphi_j \cos(j\omega t) + \psi_j \sin(j\omega t)] & , \frac{d_{SD}}{V_{max}} \leq t \leq \frac{d_{SD}}{V_{min}} \\ 0 & , \text{Otherwise} \end{cases} \quad (11)$$

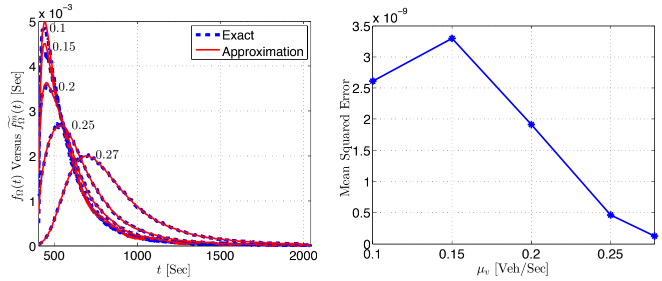


Fig. 3. Exact versus approximated p.d.f of Ω for different flow rates under stable traffic conditions.

where φ_j and ψ_j are the magnitude components ($\forall j = 1, 2, ..., m$) and ω is the angular frequency. φ_j, ψ_j and ω were chosen to minimize the Mean Square Error (MSE) given by:

$$\overline{\varepsilon^2} = \int_0^{+\infty} [f_\Omega(t) - \widetilde{f_\Omega^m}(t)]^2 dt \quad (12)$$

The above least-squares nonlinear curve fitting problem is solved using the *Gauss-Newton Numerical Algorithm*, [14]. Thorough numerical analysis showed that a value of $m > 8$ in equation (11) caused $\overline{\varepsilon^2}$ to decrease marginally. Consequently, throughout this manuscript, 8-harmonic Fourier functions are used to approximate $f_\Omega(t)$ for different values of the flow rate in each of the two previously identified traffic states. Figure 3 (upper) plots $f_\Omega(t)$ versus the $\widetilde{f_\Omega^8}(t)$ counterparts for the different flow rate values. The numbers close to each of the curves indicate the flow rate value corresponding to that curve. Figure 3 (lower) plots the mean squared error corresponding to each of the density function pairs. The largest observed error value is of the order of 10^{-9} proving the validity and accuracy of the approximations.

Let $\widetilde{F_\Omega^m}(\tau)$ denote the m-component c.d.f. of Ω. It is expressed as:

$$\begin{aligned} \widetilde{F_\Omega^m}(\tau) = &\sum_{j=0}^{m} \frac{\varphi_j}{j\omega}\left[\sin(j\omega\tau) - \sin\left(j\omega\frac{d_{SD}}{V_{max}}\right)\right] \\ &- \sum_{j=0}^{m} \frac{\psi_j}{j\omega}\left[\cos(j\omega\tau) - \cos\left(j\omega\frac{d_{SD}}{V_{max}}\right)\right] \end{aligned} \quad (13)$$

Define $\delta = \frac{1}{\widetilde{F_\Omega^m}\left(\frac{d_{SD}}{V_{min}}\right)}$. At this point, equation (9) can be rewritten as:

$$P_{br,i}(s) = 1 - \delta \widetilde{F_\Omega^m}\left(\frac{d_{SD}}{s}\right) \quad (14)$$

The probability of *R*, the event of a bulk release can be expressed as:

$$P_{br} = \int_{V_{min}}^{V_{max}} \left[P_{br,i}(s) \cdot f_{S_v}^t(s)\right] ds \quad (15)$$

Let $g_{P_{br}}(s) = P_{br,i}(s) \cdot f_{S_v}^t(s)$. This function becomes highly complex after the substitution of $P_{br,i}$ by its expression in (14). Therefore, the same approximation technique as in section IV-B is used to find a valid approximation for (15). $g_{P_{br}}(s)$ can justifiably be approximated by an m-component mixture of Normal distributions as:

$$\widetilde{g_{P_{br}}^m}(s) = \sum_{j=1}^{m} \frac{1}{\sigma_j\sqrt{2\pi}} \exp\left[-\frac{(s-\mu_j)^2}{2\sigma_j^2}\right] \quad (16)$$

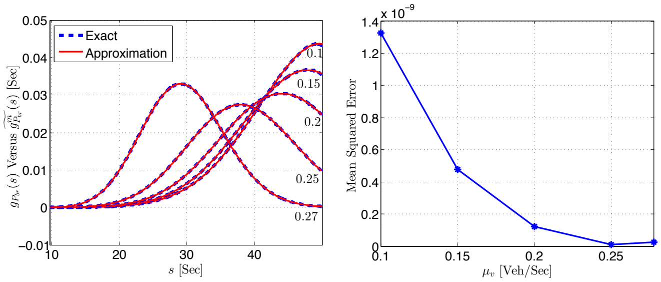


Fig. 4. Exact versus approximated $g_{P_{br}}(s)$ functions for different flow rates under stable traffic conditions.

From Figure 4 (upper) it is concluded that $\widetilde{g^2_{P_{br}}}$ (*i.e.* $m = 2$) is highly accurate. The numbers close to each of the curves indicate the flow rate value corresponding to that curve. Figure 4 (lower) shows that the highest MSE is of the order 10^{-9}. Using (16), equation (15) is re-written as:

$$P_{br} = \frac{1}{2}\sum_{j=1}^{m}\left[\mathrm{erf}\left(\frac{V_{max}-\mu_j}{\sigma_j\sqrt{2}}\right) - \mathrm{erf}\left(\frac{V_{min}-\mu_j}{\sigma_j\sqrt{2}}\right)\right] \tag{17}$$

Having derived the probability of bundle release, the focus is now turned towards modelling and analyzing the behaviour of *S* under PBRS-BBR. This is done in the next section.

V. Bundle End-to-End Delay Analysis Under PBRS-BBR

Following the above description of the networking scenario and the mechanism of PBRS-BBR, throughout the delivery process, an incoming bundle *M* at *S* is subject to two types of delay, namely: *a)* $Q_D(M)$ being the queueing delay at *S* and *b)* $T_D(M)$ being the transit delay or, in other words, the travel time of the vehicle carrying *M* from *S* to *D*. As a result, the overall end-to-end delivery delay of *M* can be expressed as $E_D(M) = Q_D(M) + T_D(M)$. Let $\overline{Q_D}$, $\overline{T_D}$ and $\overline{E_D}$ denote respectively the average bundle queueing, transit and end-to-end delays. In order to determine $\overline{E_D}$, both $\overline{Q_D}$ and $\overline{T_D}$ have to be evaluated first. The remaining of this section is dedicated for the mathematical derivation of these two delay factors. Note that throughout the below delay analysis it is assumed that *S* is equipped with an infinite buffer. Bundle arrivals to *S* follow a Poisson process with parameter $\lambda\left(\frac{bundles}{second}\right)$. All bundles have a fixed size of b (*bytes*). *S* transmission rate is denoted by T_R (*bps*). Consequently, the transmission time of a single bundle is $\tau = \frac{8b}{T_R}$ (*seconds*).

A. Derivation of $\overline{Q_D}$:

In order to derive $\overline{Q_D}$, a queueing model is developed to describe the behaviour of *S* under PBRS-BBR. The resolution of this model leads to the computation of the average number of bundles in *S*'s buffer and therefore $\overline{Q_D}$ is computed using *Little's Theorem*.

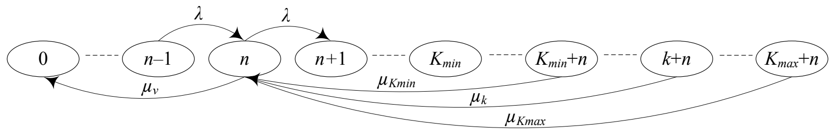
Using standard notation, let the number of bundles in *S*'s buffer observed at an arbitrary instant be represented by a random variable N that takes on discrete values $n = 0, 1, 2, \ldots$. N is also adopted as the state variable of the queueing process that describes the behaviour of *S*'s buffer contents. Let $P_n = Pr[N = n]$ denote the long-term probability that N takes on a particular value n. Without loss of generality, assume that at a random observation instant, *S*'s buffer is found to be in state n. At this level, an incoming bundle to *S* causes an upward state transition (*i.e.* from state $N = n$ to state $N = n + 1$) to which corresponds a transition rate that is equivalent to the bundle arrival rate λ. In contrast, the arrival of a vehicle to *S* causes downward state transitions that are more complex as compared to their upward counterparts. This complexity stems from the dependence of that vehicle's *bundle admissibility* on the vehicle's dwell time; that being if the arriving vehicle was selected as a bundle carrier from *S* to *D*.

Definition: The bundle admissibility K_i of a vehicle *i* represents the total number of bundles that vehicle can successfully receive from *S* during its corresponding dwell time.

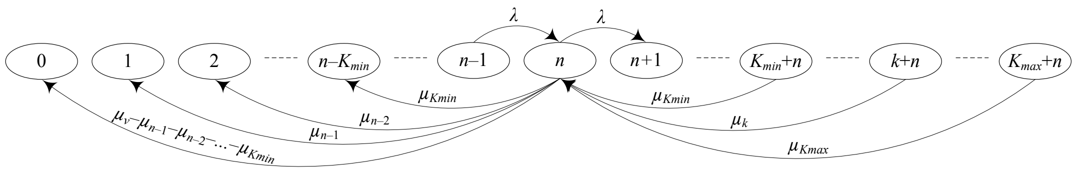
Upon the arrival of a vehicle *i*, *S* determines its speed S_i and computes $P_{br,i}(S_i)$ based on which it decides whether or not to select this vehicle to carry bundles to *D*. If vehicle *i* is selected, then *S* computes its dwell time $\frac{C}{S_i}$ and hence determines its *bundle admissibility* as $\frac{C}{S_i\tau}$. In this paper, it is considered that each bundle is an atomic entity that cannot be fragmented. Therefore, K_i can only take on positive discrete values. However, the quantity $\frac{C}{S_i\tau}$ is obviously not discrete. Hence, K_i is justifiably assigned the value $\lfloor\frac{C}{S_i\tau}\rfloor$. Notice that, since S_i is bounded by V_{min} and V_{max}, therefore K_i will also be bounded by $K_{min} = \lfloor\frac{C}{V_{max}\tau}\rfloor$ and $K_{max} = \lfloor\frac{C}{V_{min}\tau}\rfloor$. In the sequel it will be considered that $K_i = k$ such that $K_{min} \leq k \leq K_{max}$. At this point, it is important to highlight the existence of a well determined range of vehicle speeds $(V^k_{low}; V^k_{up}]$ in such a way that, if S_i falls within that range, then $K_i = k$. In fact, $V^k_{low} = \frac{C}{(k+1)\tau}$ and $V^k_{up} = \frac{C}{k\tau}$. Let π_k denote the joint probability that vehicle *i* is selected for bundle release and has a bundle admissibility of $K_i = k$. It is given by:

$$\pi_k = \int_{\frac{C}{(k+1)\tau}}^{\frac{C}{k\tau}} P_{br,i}(s)\cdot f^t_{S_v}(s)ds \text{ , for } k \in [K_{min}; K_{max}] \tag{18}$$

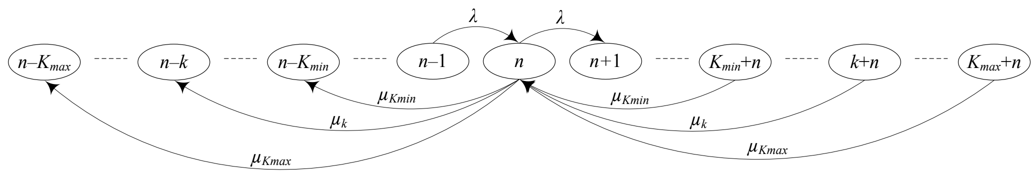
Now, in light of the above, since k is directly dependent on s, therefore downward transitions to many different states are possible from a given state n. Indeed, the fact that $K_{min} \leq k \leq K_{max}$ leads to having $K_{max} - K_{min} + 1$ potential downward transitions originating at state n. Furthermore, there exists $K_{max} - K_{min} + 1$ downward transitions originating from upper states of the queueing process (as will be shown further below) and sinking into state n. Note that the rate associated with a downward transition as a result of the arrival of a vehicle *i* whose bundle admissibility is $K_i = k$ can be expressed as $\mu_k = \mu_v\pi_k$ where $\sum_{k=K_{min}}^{K_{max}}\mu_k = \mu_v$. At this stage, the ground has been prepared to illustrate the flows into and out of state n and hence derive the appropriate balance equations. Four cases can be distinguished, namely: *a)* $0 < n \leq K_{min}$, *b)* $K_{min} < n \leq K_{max}$, *c)* $n > K_{max}$ and finally *d)* $n = 0$. On one hand, it is obvious from Figures 5(a) through 5(c) that cases (*a*) through (*c*) lead to establishing the



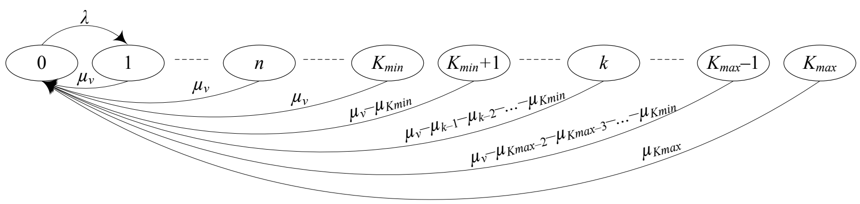
(a) Case 1: $0 < n \leq K_{min}$.



(b) Case 2: $K_{min} < n \leq K_{max}$.



(c) Case 3: $n > K_{max}$.



(d) Case 4: $n = 0$.

Fig. 5. State transition rate diagrams showing the transitions into and out of state n ($n = 0, 1, 2, \ldots$).

same balance equation:

$$(\lambda + \mu)P_n = \lambda P_{n-1} + \sum_{k=K_{min}}^{K_{max}} \mu_k P_{n+k} \text{ , for } n > 0 \quad (19)$$

On the other hand, the balance equation pertaining to case (d) is given by:

$$\lambda P_0 = \mu \sum_{n=1}^{K_{min}} P_n + \sum_{n=K_{min}+1}^{K_{max}} \sum_{k=n}^{K_{max}} \mu_k P_n \quad (20)$$

Let $P(z) = \sum_{n=0}^{\infty} z^n P_n$ denote the p.g.f of N. Using equation (19) and following a similar approach to the one described in [13], $P(z)$ can be expressed as in (21). Let $\alpha(z) = z^{K_{max}+1}$ and $\beta(z) = -\left(1 + \mu\lambda^{-1}\right) z^{K_{max}} + \lambda^{-1} \sum_{k=K_{min}}^{K_{max}} \mu_k z^{K_{max}-k}$. Following a similar argument to the one presented in [13], it is found that, whenever *S* is operating under stability conditions, then $\left|\beta(z)\right| > \left|\alpha(z)\right|$. Furthermore, using *Rouché's Theorem*, it is found that $D(z) = \alpha(z) + \beta(z)$ and $\alpha(z)$ have the same number of zeros in the range $\left|z\right| < 1 + \epsilon$. As such, since $\alpha(z)$ has $K_{max} + 1$ zeros in $\left|z\right| < 1 + \epsilon$, then $D(z)$ also has $K_{max} + 1$ zeros in this range. Observe from (21) that, of these $K_{max} + 1$ zeros, exactly one of them occurs at $\left|z\right| = 1$, $K_{max} - 1$ of them are such that $\left|z\right| < 1$ and only one denoted by z^* is such that $\left|z^*\right| > 1$. At this point, $P(z)$ being the z-transform of a probability distribution, it must analytic in the range $\left|z\right| \leq 1$ indicates that the $K_{max} - 1$ zeros of $D(z)$ whose respective magnitudes are less than or equal to 1 are also the zeros of $N(z)$ and hence will cancel each other. As a result, after appropriate manipulation of $P(z)$, its inversion leads to having:

$$P_n = \left(1 - \frac{1}{z^*}\right)\left(\frac{1}{z^*}\right)^n \text{ , } n \geq 0$$

Accordingly, the average number of bundles in *S*'s buffer is $\overline{N} = \sum_{n=0}^{\infty} n P_n$. Finally, the average bundle queueing delay is computed from *Little's Theorem* as:

$$\overline{Q_D} = \lambda^{-1}\overline{N} \quad (22)$$

B. Derivation of $\overline{T_D}$:

PBRS-BBR is a scheme developed to allow the release of a bulk of bundles *B*, to a selected vehicle. Truly, $T_D(B)$, the transit delay of *B*, is equivalent to the ratio of the travel distance to the speed of the selected vehicle. At the bundle level, $T_D(M)$, the transit delay of a particular bundle $M \in B$ is equivalent to $T_D(B)$. Nonetheless, one must carefully observe that the average bundle transit delay is not equivalent to the average bulk transit delay. This follows from the fact that the number of bundles constituting each of the released bulks potentially differs from one bulk to the other. Hence, *length biasing* plays a major role in this regard and has to be

$$P(z)=\frac{N(z)}{D(z)}=\frac{\lambda^{-1}\sum_{k=K_{min}}^{K_{max}}\sum_{n=0}^{k}\left(z^{n}P_{n}\right)\mu_{k}z^{K_{max}-k}-\left(1+\mu\lambda^{-1}\right)z^{K_{max}}P_{0}}{z^{K_{max}+1}-\left(1+\mu\lambda^{-1}\right)z^{K_{max}}+\lambda^{-1}\sum_{k=K_{min}}^{K_{max}}\mu_{k}z^{K_{max}-k}} \tag{21}$$

accounted for adequately. The following example serves the purpose of a better explanation.

Let $f_{S_c}(s)$ denote the p.d.f. of the speed of a vehicle whose numerical index is i_n and which is carrying a randomly targeted bundle n. Resorting to the typical ergodicity arguments, $f_{S_c}(s)$ can be expressed as:

$$f_{S_c}(s)ds=\lim_{m\rightarrow\infty}\frac{\sum_{n=1}^{m}U_{i_n}(s,s+ds)}{m} \tag{23}$$

where $U_{i_n}(s,s+ds)$ is an indicator function which is equal to 1 if the speed of vehicle i_n falls within the range $(s,s+ds)$ and 0 otherwise. At this level, in order to account for the above-mentioned length biasing, the number of bundles carried by vehicle i_n is introduced into the expression of $f_{S_c}(s)$ and (23) refined to become:

$$f_{S_c}(s)ds=\lim_{m\rightarrow\infty}\frac{\sum_{r=1}^{i_m}x_rY_r(s,s+ds)}{m} \tag{24}$$

where $Y_r(s,s+ds)$ being indicator function which is equal to 1 if the speed of vehicle whose numerical index is r falls within the range $(s,s+ds)$ and is equal to 0 otherwise, and x_r is the number of bundles carried by vehicle r. Note that $x_r=0$ either if, at the time of its arrival, vehicle r navigating at speed S_r was selected to carry bundles to *D* but *S*'s buffer was empty, or if vehicle r was not selected to carry bundles to *D*. Since $i_m \xrightarrow[m\rightarrow\infty]{} \infty$, (24) can be re-written as:

$$f_{S_c}(s)ds=\lim_{m\rightarrow\infty}\frac{\sum_{r=1}^{i_m}x_rY_r(s,s+ds)}{m}=\frac{\overline{X}(s)\cdot f_{S_v}^{t}(s)ds}{\overline{X}} \tag{25}$$

where $f_{S_v}^{t}(s)$ is given in (6), $\overline{X}(s)$ is the expected size of a bulk of bundles that is carried by a vehicle navigating at speed s (*i.e.* the length biasing factor) and $\overline{X}$ is the expected size of a bulk of bundles that is carried by an arbitrarily selected vehicle. Given that vehicle arrivals follow a Poisson process and that a bulk of bundles is released to a vehicle r navigating at speed s with probability $P_{br,r}(s)$, therefore:

$$\overline{X}(s)=\left[\sum_{n=1}^{K_r}nP_n+\sum_{n=K_r+1}^{\infty}K_rP_n\right]P_{br,r}(s) \tag{26}$$

where K_r is the bundle admissibility of vehicle r and P_n is the steady-state probability of *S*'s buffer being in state n. As such:

$$\overline{X}=\int_{V_{min}}^{V_{max}}\overline{X}(s)\cdot f_{S_v}^{t}(s)ds \tag{27}$$

This concludes the derivation of $f_{S_c}(s)$ which can now be utilized to compute the average bundle transit delay as:

$$\overline{T_D}=\int_{V_{min}}^{V_{max}}\frac{d_{SD}}{s}f_{S_c}(s)ds \tag{28}$$

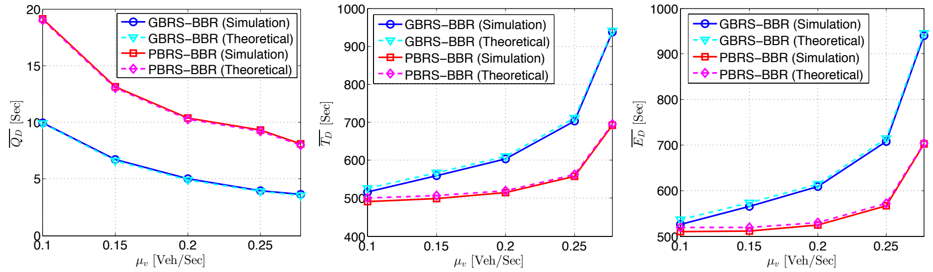
Remark: A Greedy Bundle Release Scheme with Bulk Bundle Release (GBRS-BBR) will be used as a benchmark. Under GBRS-BBR, a bulk of bundles is released to every arriving vehicle. The same above analysis applies to GBRS-BBR with $P_{br,i}=P_{br}=1$.

VI. Simulation and Numerical Analysis

An in-house Java-based discrete event simulator was developed to examine the performance of PBRS-BBR and GBRS-BBR in terms of the average bundle queueing delay, $\overline{Q_D}$, the average bundle transit delay, $\overline{T_D}$ and the average bundle end-to-end delay, $\overline{E_D}$. Each of the two schemes is simulated under Free-flow vehicular traffic conditions. The delay metrics were evaluated for a total of 10^7 bundles and averaged out over multiple simulator runs to ensure the realization of a 95% confidence interval. The following input parameter values were assumed: *i*) the vehicle flow rate $\mu_v \in [0.1;0.27]\left(\frac{Vehicles}{second}\right)$, *ii*) the bundle arrival rate $\lambda=1\left(\frac{Bundles}{second}\right)$, *iii*) the source-destination distance $d_{SD}=20000$ (*meters*), *iv*) the maximum allowable speed$S_{max}=50\left(\frac{meters}{second}\right)$, the transmission rate of the source *v*) $T_R=1$ (*Mbps*) and *vi*) the coverage range of the source $C=200$ (*meters*).

Figures 6(a) through 6(c) concurrently plot the resulting theoretical curves of $\overline{E_D}$, $\overline{T_D}$ and $\overline{E_D}$ along with their simulated counterparts as a function of μ_v. These figures constitute tangible proofs of the validity of the earlier-presented mathematical analysis as well as the accuracy of the developed simulator. This is particularly true given that the theoretical curves in all of the three plots almost perfectly overlap with their simulated counterparts. The rest of this section contrasts the performance of the PBRS-BBR with that achieved by GBRS-BBR.

Figure 6(a) shows that GBRS-BBR outperforms PBRS-BBR in terms of $\overline{Q_D}$. In fact, a source SRU *S* employing GBRS-BBR releases bulks to every arriving vehicle. Hence, during a single vehicle inter-arrival period, this will not allow the accumulation of too many newly incoming bundles. Under PBRS-BBR, the source often witnesses several vehicle arrivals before releasing a bulk to the most suitable one. Accordingly, this has the effect of: *i*) increasing the queueing delays experienced by existing bundles and *ii*) forcefully exposing the newly incoming bundles to extended queueing periods. Notice, however, that $\overline{Q_D}$ is a decreasing function of μ_v. As μ_v increases the vehicle inter-arrival time decays but the probability of fast vehicle arrivals increases. Hence, both PBRS-BBR and GBRS-BBR are able to release bundles faster.



(a) Mean Queueing Delay. (b) Mean Transit Delay. (c) Mean End-To-End Delay.

Fig. 6. Performance evaluation of PBRS-BBR and GBRS-BBR under free-flow vehicular traffic conditions.

On a transit delay level, PBRS-BBR outperforms GBRS-BBR as shown in Figure 6(b). By design, PBRS-BBR selects the relatively fast vehicles so as to achieve the minimum possible transit delays while GBRS-BBR does not differentiate between fast and slow vehicles and releases a bulk to every arriving vehicle. Observe that, as μ_v increases the vehicular density also increases thus causing a decay in the average speed. As a result, the bundle transit delay is an increasing function of μ_v.

Now observe that the queueing delay improvement of GBRS-BBR over its probabilistic counterpart ranges from a few seconds to almost ten seconds while the transit delay improvement of PBRS-BBR over GBRS-BBR ranges from a couple of tens to more than two hundred seconds. It follows that queueing delays are completely overshadowed by transit delays. Hence, on the overall end-to-end delay level, PBRS-BBR clearly outperforms GBRS-BBR. This fact is reflected in Figure 6(c).

Finally, it is important to mention the fact that vehicle speeds and hence their residence periods within the source SRU's coverage range are totally uncontrollable by the SRU. This actually imposes a limitation on the capability of the SRU in clearing out bundles. As a matter of fact, an SRU cannot release bundles to a vehicle more than that vehicle's bundle admissibility. Now, the arrival of bundles to the SRU is also outside of the control of the SRU itself and clearly depends on the intensity of user service demands. Hence, note that, if the offered load to the SRU increases beyond what the SRU can release to vehicles given its data transmission rate, then the SRU will experience a serious case of buffer instability. This is especially true since the bundle queueing delay will exhibit a rapid irregular increase. Consequently, PBRS-BBR, irrespective of its ability to decrease transit delays, will not be able to overcome this phenomenon. It may seem that GBRS-BBR, under such conditions, will prevail. However, in reality it will not because, then, the delay it achieves, although finite, is quite significant to the point that this scheme becomes inefficient. In fact, at this point, two-hop VICNs present marginal utility in data communication from one SRU to another unless offline data is being transferred with high delay tolerance. Recall that, the analysis presented herein assumes the utilization of the IEEE 802.11 protocol with 200 meters transmission range and 1 Mbps transmission rate. Nevertheless, the advances in wireless communications technology come to the rescue as the recently developed IEEE $802.11p$ (refer to [4]) standard for vehicular environment offers very high transmission rates of up to 27 Mbps. It, as well, enlarges the SRU's coverage range to almost 1 Km. This remarkably stabilizes the source SRU's queue even in situations where the offered data traffic load is very high. Equipping the SRU with IEEE $802.11p$ comes at no additional cost but has the above described benefits. Under such conditions, PBRS-BBR will still outperform GBRS-BBR.

VII. Conclusion

This manuscript addresses the enhancement of connectivity between two isolated stationary roadside units (SRUs) in the context of a two-hop Vehicular Intermittently Connected Network (VICN) scenario. In VICNs, vehicular traffic highly affects the performance of bundle forwarding schemes. A comprehensive study of the random traffic dynamics constituted the core of a realistic traffic model based on which a Probabilistic Bundle Relaying Scheme with Bulk Bundle Release (PBRS-BBR) and a Greedy Bundle Relaying Scheme with Bulk Bundle Release (GBRS-BBR) are proposed with the objective of minimizing the mean bundle delivery delay. A queueing model was formulated to characterize a source SRU employing PBRS-BBR and its greedy counterpart and evaluate the average bundle queueing delay. In addition, mathematical analysis were presented with the objective of evaluating the average bundle transit delay and hence the average bundle end-to-end delay. A simulation study was conducted to prove the validity and accuracy of the proposed mathematical model and analysis. The performance of GBRS-BBR served as a benchmark. The reported results show that PBRS-BBR outperforms GBRS-BBR in terms of the mean end-to-end delivery delay. Nevertheless, there exists a bundle arrival rate threshold beyond which the achieved delays under PBRS-BBR will start to irregularly increase. However, under such heavy data traffic offered loads GBRS-BBR will also exhibit delays that, although finite, are very significant. At this point, TH-VICNs will exhibit marginal benefits for delay-minimal bundle deliveries and more sophisticated schemes have to be considered. These however, are outside the scope of our present study and are left for future work.

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