Modeling and Analysis of Bulk Bundle Release Schemes in Two-Hop Vehicular DTNs

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Abstract—**The use of vehicular infrastructure to establish connectivity between isolated stationary Information Relay Stations is an appealing application of Terrestrial Delay-Tolerant Networking. A source opportunistically releases data bundles to vehicles that randomly enter its range. In turn, those vehicles store the received bundles, carry and deliver them to their intended destination. It follows that a contemporaneous source-destination end-to-end path does not exist. Consequently, bundles experience longer queueing periods at the source. Under such circumstances, the end-to-end bundle delivery delays become several orders of magnitude higher than those experienced in traditional wireless networks. In this context, bundle delivery delay minimization emerges as a challenging problem that has not been adequately addressed in the open literature. This paper proposes a simple Probabilistic Bundle Relay Strategy with Bulk Bundle Release (PBRS-BBR) that aims at minimizing the average end-to-end bundle delivery delay while capturing the essence of vehicular delay-tolerant networking in that it revolves around minimal network information knowledge. A queueing model is formulated to represent stationary sources operating under PBRS-BBR. This model is mathematically analyzed and validated through extensive simulations that gauge its merit.**

I. Introduction

Nowadays, wireless networks are witnessing several deployments in various extreme environments where they suffer from different levels of link disruptions depending on the severity of the operating conditions. The existing Internet protocols fail to operate properly over such Intermittently Connected Networks (ICNs), thus raising a variety of new challenging problems that are attracting the attention of the networking research community. Delay-Tolerant Networking emerged as a highly active area of research where networking experts compete in addressing the various ICN problems, [8]–[11]. In the open literature, the convention has been to refer to ICNs as Delay-Tolerant Networks (DTNs).

Vehicular Delay-Tolerant Networks (VDTNs) are a particular class of DTNs composed of two types of nodes: a) Information Relay Stations (IRSs) and b) Mobile nodes. IRSs are stationary nodes arbitrarily deployed along highways/roads. Very few of them, called *gateways*, are privileged by a connection to the Internet or a certain backbone network through minimal infrastructure. All others are isolated and often way apart that they cannot directly communicate. Instead, mobile nodes mounted over vehicles restricted to navigable roadways serve as opportunistic *store-carry-forward* devices that connect any arbitrary IRS pair. Imagine a scenario where three IRSs are located along the side of a highway. Only the middle IRS is connected to the Internet. At one end, some end-users deposit information data at the source *S*. At the other end, destination users are located close to *D* that is far beyond the range of *S*. Vehicles with random velocities navigate on the highway/road in the direction of *D* and enter the range of *S* at random time instants. No inter-vehicle communications may occur. *S* will therefore release data bundles to these vehicles, which in turn will deliver them to *D*. Obviously, contemporaneous end-to-end paths between such (*S*, *D*) pairs cannot be guaranteed.

In [2] a Probabilistic Bundle Relaying Scheme (PBRS) was proposed to minimize the bundle transit delay in the context of the VDTN scenario described above. Under PBRS, the source *S* utilized the probability of bundle release P_{br} in order to restrict the release of bundles to only those vehicles that contribute the most to the minimization of the mean bundle transit delay. It was shown that PBRS significantly improves the average bundle transit delay. However, this improvement was overshadowed by an unexpected tremendous increase in queueing delays leading to excessive mean end-to-end bundle delivery delays that rendered PBRS practically inefficient. Nevertheless, it was observed that the release of a bulk of bundles whenever the right opportunity arises, is a simple but yet very effective idea that may boost the performance of PBRS and render it of exceptional utility.

In this paper, we set up an analytical framework for the purpose of theoretically evaluating the performance of a source node *S* that operates under the rules of the Probabilistic Bundle Relaying Scheme with Bulk Bundle Release (PBRS-BBR). Particularly, *S* is modeled as an *M*/*M*/1 queueing system that may release groups of fixed size bundles, called *bundle bulks*, to a subset of the arriving vehicles as determined by P_{br}. Unlike queueing models existing in the open literature, our probabilistic queueing model does not rely on complete network information knowledge (*e.g.* exact vehicle arrival times, exact vehicle speeds, etc.). It is mathematically studied and validated through extensive simulations that evaluates its performance. The rest of this paper is organized as follows. In section II, we summarize a selection of major related works. Section III, describes PBRS-BBR's framework. Section IV presents a mathematical model to theoretically analyze the performance of stationary IRSs under PBRS-BBR. Section V evaluates the benefits of the proposed scheme through a simulation study. Finally, section VI concludes the paper.

II. Related Works

In [1] a joint scheduling/delay-minimization problem is studied in the above-described VDTN context. The authors solved this problem using Dynamic Programming in a complex Markov Decision Process framework and proved that it is sometimes optimal to ignore slow vehicles in present opportunities and wait for subsequent ones hoping that these latter will be faster enough to make up for the additional waiting time. Unlike [1], PBRS proposed in [2] is designed around minimal network information knowledge. It utilizes an original parameter P_{br} called the probability of bundle release that quantifies the contribution of a vehicle in a present opportunity to the minimization of the mean bundle transit delay. The performance of PBRS was compared to that of a Greedy Bundle Relaying Scheme (GBRS) counterpart. A mathematical framework was devised in [3] where the authors derived a closed-form expression for the probability of bundle release. In [4], a seminal mathematical study was devised to evaluate the performance of infrastructure-based vehicular networks in terms of two important metrics, namely, the access probability and the connectivity probability. The authors considered both a single-hop and a two-hop network scenarios and revealed the trade-offs between key system parameters, such as inter-IRS distance, vehicular density, nodal communication ranges, and analyzed their collective impact on both the access probability and connectivity probability under different communication channel models. The work in [5] investigates a multi-hop packet delivery delay in a similar low density VDTN scenario to the one described earlier. Throughout their analytical study, the authors account for the randomness of vehicular data traffic and the statistical variation of the disrupted communication channel. Using the effective bandwidth theory and the effective capacity concept, they obtain the maximum inter-IRS distance that stochastically limits the worst case packet delivery delay to a certain bound. In [6], the authors formulate a queueing model to study the performance of mobile routers in VDTNs. They investigate a scenario where some traffic sources tend to selfishly confiscate resources (*i.e.* buffer and bandwidth) thus severely impacting the performance of the network. The authors studied this competitive situation by means of a non-cooperative gaming model.

III. Problem Description and Motivation

Two simple bundle relaying schemes were investigated in [2] in the context of the scenario described earlier. Under the GBRS, the source *S* greedily releases a single bundle located at the front of its queue to every arriving vehicle. However, whenever PBRS is employed, *S* relies on the probability of bundle release P_{br} in order to opportunistically release front bundles to those vehicles that are most likely to optimally contribute to the minimization of the mean bundle transit delay. It was shown both analytically and through extensive simulations that, under GBRS and PBRS bundles suffered excessive queueing delays. Consequently, the mean end-to-end delivery delay exhibited a significantly rapid growth and hence rendered both schemes practically inefficient.

Nevertheless, it was observed that, upon the occurrence of a release opportunity, more than one bundle might be released to the arriving vehicle. In fact, given the advancement in wireless technology, today's wireless nodes utilizing one of the IEEE 802.11 protocol variants are able to transmit data at a rate in the order of tens of megabits per second while, at the physical layer, the maximum transfer data unit (MTDU) has a relatively small size. Consequently, the bundle transmission time is considerably small as compared to the vehicle dwell time (*i.e.* the amount of time a vehicle spends in the range of the source). It follows that releasing only a single bundle per opportunity will result in wasting a precious amount of residual vehicle dwell time during which the source remains idle while bundles in its queue continue to accumulate. Alternatively, releasing as many bundles as possible during the entire vehicle dwell time seems to be a promising and much more efficient approach. A group of bundles released to an in-range vehicle is referred to as a *bulk of bundles*. The size of a bulk is a random variable whose value is highly dependent on the number of existing bundles in the source's buffer and the forwarding capability to arriving vehicles. Even whenever bundle sizes are assumed to be fixed to the size of an MTDU, a Bulk Bundle Release (BBR)-enabled relaying strategy will exhibit a remarkable efficiency and perform significantly better than its non-BBR enabled counterpart. This is especially true since the release of bulks will contribute to the minimization of the mean bundle queueing delay. Ultimately, knowing that PBRS-BBR also has the luxury of efficiently releasing those bulks in a way that minimizes the mean bundle transit delay, it is expected that, PBRS-BBR will also outperform GBRS-BBR on the end-to-end delay level. It is therefore the main objective of this paper to shed the light over this improvement that PBRS-BBR has over GBRS-BBR and prove it both mathematically and through simulations as presented in the rest of this paper.

IV. Mathematical Modeling and Analysis

A. Basic Assumptions:

The below assumptions are made following the guidelines and justifications presented in [2], [3] and [1].

1) Incoming bundles follow a Poisson process with parameter λ bundles per second.
2) Vehicle arrivals follow a Poisson process with parameter μ_v vehicles per second.
3) All bundles have fixed size of S_b bytes.
4) The source node's transmission rate is T_R bps.
5) Vehicle speeds are uniformly distributed in the range $[V_{min}; V_{max}]$ meters per second.
6) The speed of a vehicle remains constant during its entire navigation period on the road/highway.
7) Release decisions are performed independently for each bulk from one opportunity to another.

B. Model Definition:

Consider the previously described VDTN scenario. Communication is to be established between a source *S* and a destination *D*. The communication range of *S* covers a distance C (meters) of the road. Both *S* and *D* are located along the roadside and are separated by a distance $d_{SD} \gg C$. Vehicles with distinct speeds navigate along the road passing by *S* in the direction of *D* as illustrated in Figure 1. We refer to the event of a vehicle entering the range of *S* as a vehicle arrival. *S* becomes aware of the speed V_i of vehicle i only at the instant t_i of arrival of this latter. As such, it computes its dwell time $D_i = \frac{C}{V_i}$. Note that the maximum dwell time is $D_{max} = \frac{C}{V_{min}}$ and the minimum dwell time is $D_{min} = \frac{C}{V_{max}}$. The probability

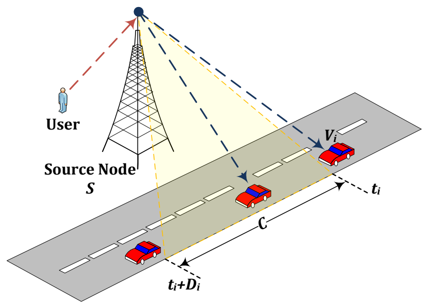


Fig. 1. Source-Vehicle communication in a two-hop VDTN.

density function of D_i may easily be proven to be given by:

$$f_{D_i}(t) = \frac{C}{(V_{max} - V_{min})t^2} \text{ , for } \frac{C}{V_{max}} \leq t \leq \frac{C}{V_{min}} \quad (1)$$

Following assumptions (2) and (3), the bundle transmission time $T_b = \frac{8S_b}{T_R}$. Therefore, knowing D_i and T_b, the source S instantaneously determines $K_i = \lfloor \frac{D_i}{T_b} \rfloor$, the maximum number of bundles that might be released to vehicle i during D_i. The parameter K_i has an upper bound $K_{max} = \lfloor \frac{D_{max}}{T_b} \rfloor$ and a lower bound $K_{min} = \lfloor \frac{D_{min}}{T_b} \rfloor$. Consequently, with a probability $P_{br,i}$, S immediately starts releasing a bulk to vehicle i. With a probability $1 - P_{br,i}$, S retains the bundles in its queue for a likely better subsequent release opportunity. $P_{br,i}$ has been derived in [3] and is given by:

$$P_{br,i} = e^{-\mu_v \left(\frac{d_{SD}}{V_i} - \frac{d_{SD}}{V_{max}} \right)} \quad (2)$$

Furthermore, the average bundle release probability over all vehicle speeds is also given by (details are found in [3]):

$$P_{br} = \frac{e^{\mu_v \frac{d_{SD}}{V_{max}}}}{V_{max} - V_{min}} \int_{V_{min}}^{V_{max}} e^{-\mu_v \frac{d_{SD}}{V_i}} dV_i \quad (3)$$

Now, the bulk size is a random variable denoted by B_i and depends on both the number of bundles (N) queued in S's buffer, and K_i. In other words, S cannot release more bundles than a vehicle can completely receive before it goes out of range. Also, a vehicle may not carry more bundles than S has in its queue. Thus, we distinguish between the following cases:

- *Case* 1: If $N = 0$, then B_i = 0.
- *Case* 2: If $0 < N \leq K_i$, then $B_i = N$.
- *Case* 3: If $N > K_i$, then $B_i = K_i$.

Based on the above observation, it is clear that, on one hand, vehicle i receives no bundles if S's buffer is empty and that on the other hand, S cannot release more than K_{max} bundles. The latter situation occurs whenever S has K_{max} or more bundles but the arriving vehicle has a speed that is as low as V_{min}. Joining the earlier discussions to the analysis of the PBRS in [3], we conclude that a source operating under PBRS-BBR is an *M*/*M*/1 queueing system with bulk bundle release. It is therefore of interest to resolve this system and derive closed-form expressions for its characteristic parameters and most importantly the number of bundles in the queue as it is directly related to the size of a departing bulk as well as the bundle queueing delay.

C. Model Resolution:

Given a known value of K_i, the queuing system under study is composed of a queue where bundles are buffered and up to K_i of them might be released. Consequently, if there exists, in the queue, a number of bundles that is less than or equal to K_i, then all of these bundles are going to be served and the queue will become empty. Otherwise, if the queue contains K_i or more bundles, only K_i of them are going to be served and all others are going to remain in the queue until the next round of service and so forth. Taking the number of bundles in the queue as a state variable, Figure 2 is found to be the state-transition-rate diagram that represents the behavior of our system. We denote by S_n (n=0,1,2...) the n^{th} state indicating that there are exactly n bundles in the queue. Observe that, in Figure 2, all states except S_0 are entered both from their left-hand neighbor upon the occurrence of a bundle arrival with a mean rate λ and their K_i^{th} neighbor to the right upon the occurrence of a bulk departure with a mean rate μ. These states are exited upon the occurrence of either an arrival or a departure. However, state S_0 can only be entered from any one of its immediate right K_i neighbors upon a departure and exited upon an arrival. To this end, it is important to note that, under PBRS-BBR, μ is a function of the mean vehicle inter-arrival time $\overline{I}$ and the bundle release probability P_{br}. As a matter of fact, on average, up to K_i bundles may be released with a probability P_{br} to a vehicle that arrives within a time interval of $\overline{I}$ seconds. Hence, the mean bundle departure rate is given by $\mu = \frac{P_{br}}{\overline{I}}$.

Let $P_{n|K_i}$ denote the equilibrium probability of finding n bundles in the system. Therefore, the diagram shown in Figure 2 leads to the following set of equilibrium equations:

$$\lambda P_{0|K_i} = \mu \sum_{i=1}^{K_i} P_{i|K_i} \text{ , for } n = 0 \quad (4)$$

$$(\lambda + \mu) P_{n|K_i} = \lambda P_{(n-1)|K_i} + \mu P_{(n+K_i)|K_i} \text{ , for } n \geq 1 \quad (5)$$

Let $\widetilde{N}(z|K_i) = \sum_{n=0}^{\infty} z^n P_{n|K_i}$ denote the p.g.f of the number of bundles in the queue. Let $\rho = \frac{\lambda}{\mu}$. Hence, through proper manipulation of (4) and identification of $\widetilde{N}(z|K_i)$ we obtain:

$$\widetilde{N}(z|K_i) = \frac{\sum_{n=0}^{K_i - 1} (z^n - z^{K_i}) P_{n|K_i}}{\rho z^{K_i+1} - (1+\rho) z^{K_i} + 1} \quad (6)$$

It can be easily shown using Rouche's Theorem that the denominator of (6) has $K_i + 1$ zeros of which exactly one occurs at $z = 1$, exactly $K_i - 1$ are such that $|z| < 1$ and only one that we denote by $z^*(K_i)$ will be such that $|z^*(K_i)| > 1$. It follows from [7] that equation (6) may be reduced to:

$$\widetilde{N}(z|K_i) = \frac{1 - \frac{1}{z^*(K_i)}}{1 - \frac{z}{z^*(K_i)}} \quad (7)$$

Inverting (7) leads to the p.m.f of the number of bundles in

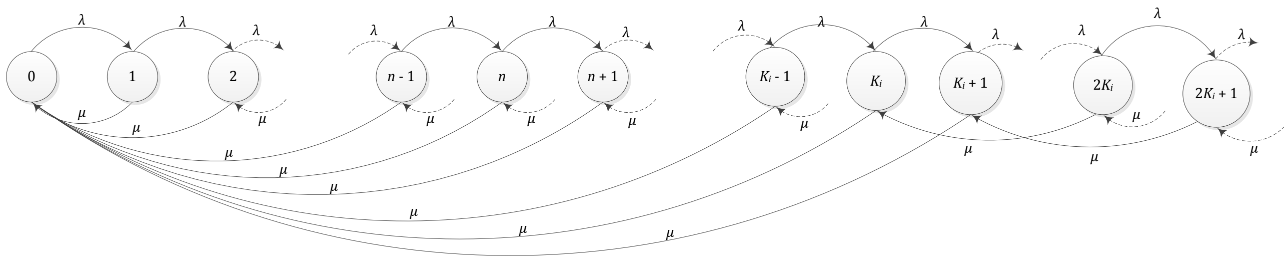


Fig. 2. State-transition-rate diagram representing the behavior of *S* under PBRS-BBR.

the queue conditioned by $K_i = k$:

$$f_{N|K_i}(n) = Pr[N = n|K_i = k] \\ = \left(1 - \frac{1}{z^*(k)}\right)\left(\frac{1}{z^*(k)}\right)^n \text{ , for } n \geq 0 \quad (8)$$

Knowing that $K_{min} \leq K_i \leq K_{max}$, therefore the unconditional probability mass function of N is given by:

$$f_N(n) = \sum_{k=K_{min}}^{K_{max}} Pr[N = n|K_i = k] \cdot Pr[K_i = k] \text{ , for } n \geq 0$$

Given that $K_i = \lfloor \frac{D_i}{T_b} \rfloor$, this means that in order for the condition $K_i = k$ to be satisfied, it is necessary that $kT_b \leq D_i \leq (k+1)T_b$. Consequently, the p.d.f of K_i is given by:

$$f_{K_i}(k) = \int_{kT_b}^{(k+1)T_b} f_{D_i}(t)dt \\ = \frac{C}{(V_{max} - V_{min})(k+1)kT_b} \text{ , for } K_{min} \leq k \leq K_{max} \quad (9)$$

Therefore equation (9) can be rewritten as:

$$f_N(n) = \frac{C}{(V_{max} - V_{min})T_b} \times \\ \sum_{k=K_{min}}^{K_{max}} \frac{1}{k(k+1)} \left(1 - \frac{1}{z^*(k)}\right)\left(\frac{1}{z^*(k)}\right)^n \text{ , for } n \geq 0 \quad (10)$$

Note, the mean number of bundles in source's queue is:

$$\overline{N} = E[N] = \sum_{n=0}^{\infty} n \cdot f_N(n) \quad (11)$$

Let D_Q represent the bundle queueing delay. Its mean can be computed using Little's Formula as:

$$\overline{D_Q} = E[D_Q] = \frac{\overline{N}}{\lambda} \quad (12)$$

According to [3], under PBRS, a single bundle is only released to the most suitable vehicle (*i.e.* the vehicle that contributes the most to the minimization of the mean bundle transit delay). In other words, from the instant it reaches the front of the queue, a bundle may witness several vehicles passing by the source while it keeps waiting until the most suitable vehicle arrives. Without loss of generality, the same will occur under PBRS-BBR, but a bulk of bundles B is concerned in this case. Nevertheless, once released, B will be subject to the same transit delay that a single released bundle would experience under PBRS. Let V_c be a random variable that represents the speed of the vehicle chosen by the source to carry B. Also, let R denote the event that B is released to an arriving vehicle. The transit delay experienced by B when released to a vehicle with speed V_c is given by $T_{d,P} = \frac{d_{SD}}{V_c}$. The probability that an arriving vehicle's speed is equal to a value v conditioned by this vehicle being the chosen carrier of B is given by:

$$Pr\left[V_c = v \middle| R\right] = \frac{Pr\left[V_c = v, R\right]}{Pr\left[R\right]} \quad (13)$$

Using Baye's Theorem, equation (13) is rewritten as:

$$Pr\left[V_c = v \middle| R\right] = \frac{Pr\left[R \middle| V_c = v\right] \times Pr\left[V_c = v\right]}{Pr\left[R\right]} \quad (14)$$

$Pr\left[R \middle| V_c = v\right] = P_{br,c}$ and $Pr\left[R\right] = P_{br}$ are given in equations (2) and (3) respectively. In addition, knowing that vehicle speeds are uniformly distributed in the range $[V_{min}; V_{max}]$, $Pr\left[V_c = v\right] = \frac{1}{V_{max} - V_{min}}$. It obviously follows that the p.d.f. of V_c is given by:

$$f_{V_c}(v) = Pr\left[V_c = v \middle| R\right] \\ = \frac{e^{-\mu_v\left(\frac{d_{SD}}{v} - \frac{d_{SD}}{V_{max}}\right)}}{(V_{max} - V_{min}) \cdot P_{br}}, \forall v \in [V_{min}; V_{max}] \quad (15)$$

Let $F_{V_c}(v)$ and $F_{T_{d,P}}(t)$ denote the respective c.d.f of V_c and $T_{d,P}$. It is easily shown that:

$$F_{T_{d,P}}(t) = 1 - F_{V_c}\left(\frac{d_{SD}}{t}\right) \quad (16)$$

The Differentiation of both sides of equation (16) leads to the p.d.f. of T_d that is given by:

$$f_{T_{d,P}}(t) = \frac{d_{SD} e^{-\mu_v\left(t - \frac{d_{SD}}{V_{max}}\right)}}{(V_{max} - V_{min}) \cdot P_{br} \cdot t^2}, \forall t \in \left[\frac{d_{SD}}{V_{max}}; \frac{d_{SD}}{V_{min}}\right] \quad (17)$$

As such, the average transit delay $\overline{T_{d,P}}$ is given by:

$$\overline{T_{d,P}} = \int_{\frac{d_{SD}}{V_{max}}}^{\frac{d_{SD}}{V_{min}}} f_{T_d}(t)dt \\ = \frac{d_{SD}}{(V_{max} - V_{min}) \cdot P_{br}} e^{\mu \frac{d_{SD}}{V_{max}}} \times \\ \left\{ \ln\left(\frac{V_{max}}{V_{min}}\right) + \sum_{m=1}^{\infty} \frac{(-\mu d_{SD})^m}{m \cdot m!} \times \right. \\ \left. \left[\left(\frac{1}{V_{min}}\right)^m - \left(\frac{1}{V_{max}}\right)^m\right] \right\} \quad (18)$$

Note that the above analysis pertains to the PBRS-BBR scheme. The analysis pertaining to the queue size and mean queueing delay under GBRS-BBR is exactly the same. However, recall that under GBRS-BBR a bulk is released to every arriving vehicle. As such, $P_{br} = 1$ in this case where we will have $\mu = \mu_v$. In addition, the transit delay under GBRS-BBR is not the same as that under PBRS-BBR. In what follows, a closed form expression is derived for the transit delay under GBRS-BBR. Let $T_{d,G}$ be a random variable representing the transit delay experienced by bundles whenever GBRS-BBR is employed. Under this scheme, a bulk is released to every arriving vehicle. Hence, following the same approach as in equations (16) and (17), it can be easily proven that the probability density function of $T_{d,G}$ is given by:

$$f_{T_{d,G}}(t) = \frac{d_{SD}}{(V_{max} - V_{min})t^2}\ , \text{for } \frac{d_{SD}}{V_{max}} \leq t \leq \frac{d_{SD}}{V_{min}} \quad (19)$$

It follows that the average transit delay is given by:

$$\overline{T_{d,G}} = \int_{\frac{d_{SD}}{V_{max}}}^{\frac{d_{SD}}{V_{min}}} t \cdot f_{T_{d,G}}(t)dt = \frac{d_{SD} \cdot \ln\left(\frac{V_{max}}{V_{min}}\right)}{V_{max} - V_{min}} \quad (20)$$

V. Simulation and Numerical Analysis

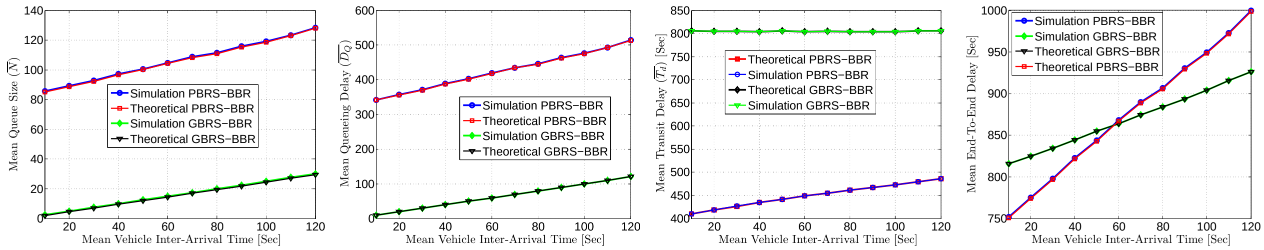
A Java-based discrete event simulator was developed to stuy and examine the delay improvement achieved by the proposed PBRS-BBR over PBRS. Whenever GBRS and GBRS-BBR are considered, their achieved delays serve as benchmarks. Delay metrics were evaluated for a total of 10^7 bundles and averaged out over multiple runs of the simulator to ensure that a 95% confidence interval is realized. The following simulation parameter values were assumed:

- The mean vehicle inter-arrival time $\overline{I} \in [10; 120]$ (sec).
- The vehicle speeds are in the range $[10; 50]$ (m/sec).
- The mean bundle inter-arrival time $\lambda = 4$ (sec).
- The source-destination distance $d_{SD} = 20$ (Km).
- The source node transmission rate $T_R = 1$ Mbps.
- The source transmission range $C = 200$ (m).

Figure 3 presents a theoretical performance evaluation of both PBRS-BBR and GBRS-BBR in terms of : (i) mean queue size, (ii) mean queueing delay, (iii) mean transit delay and (iv) mean end-to-end delay. The theoretical curves of these metrics are concurrently plotted with their simulated counterparts as a function of the mean vehicle inter-arrival time. Obviously Figures 3(a)-3(d) are tangible proofs of the validity of the mathematical analysis presented in this paper as well as the accuracy of the developed simulator. This is especially true since the curves in all of the four plots perfectly overlap with each other. The rest of the section is devoted to contrasting the performance of the PBRS-BBR and GBRS-BBR schemes with that achieved by their respective BBR-disabled counterparts. Ultimately, the metric of interest is the mean end-to-end bundle delivery delay (*i.e.* the overall delay experienced by a bundle starting from the instant it arrives to the source up until it is successfully delivered to its destination.). Obviously this delay is composed of two factors namely: (i) mean queueing delay and (ii) mean transit delay.

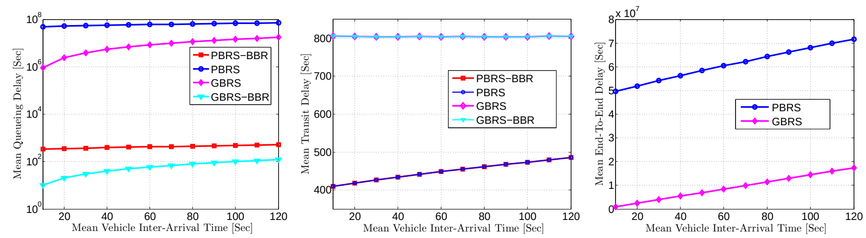
It was already shown in [2] that the queueing delays experienced by bundles under the PBRS and GBRS are excessive as shown in Figure 4(a), thus, rendering both schemes practically inefficient. Nonetheless, Figure 4(a) also shows that, indeed, the BBR extension was able to remarkably reduce the queueing delays by several orders of magnitude. Note that, for clarity purposes, Figure 4(a) was plotted using a logarithmic scale for the y-axis. The reason behind this huge improvement is the fact that, for relatively high bundle arrival rates such as the one considered in our simulations, the source IRS employing either PBRS or GBRS easily becomes unstable as, on one hand, it is subject to very rapid arrivals of bundles that accumulate in its buffers while, on the other hand, it is not able to drain them as rapidly due to the fact that vehicle arrivals are relatively more spaced out in time. The case is even worsened by the fact that, under this condition, only a single bundle is cleared out at a time. Hence, the time period during which bundles are queued will exhibit a considerably large growth. The merit of PBRS-BBR and GBRS-BBR comes from the fact that they both benefit from the arriving vehicle's residence time in the range of the source in order to clear out as many bundles as possible from the IRS's buffer before the vehicle goes out of range. Hence, this strategy, on average, will significantly reduce the number of buffered bundles and enhance the stability of the source IRS's queue but still, GBRS-BBR outperforms PBRS-BBR in terms of queueing delay. This logically follows from the fact that an IRS employing GBRS-BBR clears out bundles to every arriving vehicle. As such, not as many bundles will accumulate in its buffer during a single vehicle inter-arrival period. Under PBRS-BBR, it is often the case that the source witnesses the arrival of more than one vehicle before it finally picks up the most suitable one to carry a bulk to the destination. This extended time interval composed of multiple vehicle inter-arrival periods is sufficient to increase the delay experienced by existing bundles in the queue as well as allow a larger number of newly incoming bundles to accumulate and experience longer delays. However, it will be shown below that, on the overall end-to-end delay level, at some point, PBRS-BBR can easily outperform GBRS-BBR. Turning attention to transit delay, as stated earlier and illustrated in Figure 4(b), PBRS-BBR and GBRS-BBR will achieve the same exact performance as PBRS and GBRS. However, the probabilistic schemes considerably outperform their greedy counterparts in this regard. This is due to the fact that the greedy schemes do not differentiate between fast and slow vehicles and will release a bulk to every arriving vehicle. In contrast, the probabilistic schemes are designed to select the relatively fast vehicles in such a way to achieve the minimum possible transit delays.

On the end-to-end delay level (*i.e.* the sum of queueing and transit delays) it is obvious from Figs. 3(d) and 4(c) that the BBR schemes significantly outperform PBRS and GBRS respectively. This directly follows from the queueing delay improvement realized by the BBR option. Particularly, Figure 3(d) shows that there exists mean vehicle inter-arrival time value that constitutes a breakeven point at which both PBRS-BBR and GBRS-BBR equally perform and then GBRS-BBR will take over. This finding is quite interesting as it



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

Fig. 3. Theoretical and Simulated evaluation of PBRS-BBR and GBRS-BBR.



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

Fig. 4. Delay performance comparison between the four schemes.

sheds the lights on the mechanics of PBRS-BBR and how it adapts the release of bulks using the P_{br} parameter in order to account for trade-off between the queueing and transit delays. As a matter of fact, P_{br} has a direct impact on the stability of the IRS queue under PBRS-BBR. Notice that whenever vehicle inter-arrivals are short, meaning vehicles arrive faster to the source, as each opportunity arises, there is always an increased chance that the subsequent opportunity be better. In other words, P_{br} indicates to the source that the next arriving vehicle might be more likely to have a higher speed and achieve a lower transit delay. Consequently, the source will retain the bundles in the queue until the next opportunity arises. It is true that this will cause the queueing delays of those bundles to increase, however, it will not take long for a sufficiently fast vehicle to arrive. It is also true that, until then, more bundles may accumulate. However, the number of extra accumulating bundles is relatively small and thanks to the advances in wireless technology (*e.g.* IEEE $802.11p$) and the fast transmission rates they make possible, the source will be able to fully drain all bundles in its buffer in a single bulk to the fast arriving vehicle. As such the buffer will become empty. Under such circumstances, the IRS is highly stable and the experienced queueing delay in this case, even if larger than the one under GBRS-BBR, can be easily overshadowed by the improvement on the transit delay that PBRS-BBR incurs. As a result, PBRS-BBR outperforms GBRS-BBR. Nevertheless, as vehicle arrivals become more and more spaced out in time, the improved transit delay, eventhough optimal, will no longer be able to compensate for the increased queueing delays. As such GBRS-BBR will take over.

VI. Conclusion

A Bulk Bundle Release (BBR) extension for the Probabilistic Bundle Relaying Scheme (PBRS) and its greedy counter part (GBRS) is proposed in this paper. The mechanics of the PBRS-BBR and GBRS-BBR are similar to their BBR-disabled versions except that bulks of bundles are released per opportunity. A mathematical framework is setup for studying the performance of both PBRS-BBR and GBRS-BBR. An $M/M/1$ queueing model with bulk bundle departures was proposed to characterize source IRSs employing either of the BBR-enabled schemes. The model was verified through extensive simulations. The reported results show that PBRS-BBR significantly outperforms GBRS-BBR in terms of the mean end-to-end delay whenever the IRS queue is stable.

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