Modeling and Delay Analysis of Intermittently Connected Roadside Communication Networks

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***Abstract*—Vehicular networks outline a challenging terrestrial application of the emerging delay-tolerant networking (DTN) paradigm where wireless links experience frequent disruptions. Thus, continuous end-to-end paths are unguaranteed. Under such conditions, mobile vehicles present opportunistic relaying capabilities that promote network connectivity, particularly between stationary and isolated roadside units. In this context, we investigate a challenging information-delivery-delay minimization problem. Information is encapsulated into bundles buffered at the source, and vehicles opportunistically transport them to the destination. Consequently, bundles undergo both queueing and transit delays. We propose a probabilistic bundle release scheme (PBRS) under which a roadside unit performs typical Internet-like forwarding where a single bundle is only released to an arriving relatively high-speed vehicle. This ensures a minimized bundle transit. In contrast, under a greedy bundle release scheme (GBRS), a bundle is released to any arriving vehicle, regardless of its speed. Two queueing models are developed to characterize a roadside unit and evaluate its performance under both schemes. A simulation framework is set up to validate these models. Results indicate the inefficiency of the typical Internet packet-like release mechanism as it incurs excessive bundle queueing delays. A bulk bundle release (BBR) extension is proposed as an effective solution. We show that GBRS-BBR outperforms PBRS-BBR.**

***Index Terms*—Bundle, delay, disruption tolerant networking (DTN), intermittently connected network (ICN), performance evaluation, modelling, vehicular.**

I. Introduction

DISRUPTION-TOLERANT networking (DTN) has recently emerged as a novel communication paradigm to handle intermittent connectivity between wireless nodes in situations where the traditional networking technology fails to do so. This avant-garde networking concept precisely targets wireless ad hoc networks known as intermittently connected networks (ICNs) that are deployed in various extreme environments where they experience different levels of link disruptions, delays, and data losses depending on the severity of the operating conditions. As a result, continuous end-to-end paths between arbitrary node pairs are only available for short and unpredictable time durations [1]. To mitigate connectivity intermittence, the *store–carry–forward* mechanism (see [2]) empowers an isolated node to buffer bundles (i.e., data and control signals are combined in a single atomic entity, which is called bundle, that is transmitted across an ICN) long enough before it encounters other nodes [1]. Only then bundles may possibly be forwarded to a next hop until they finally get to their respective destinations.

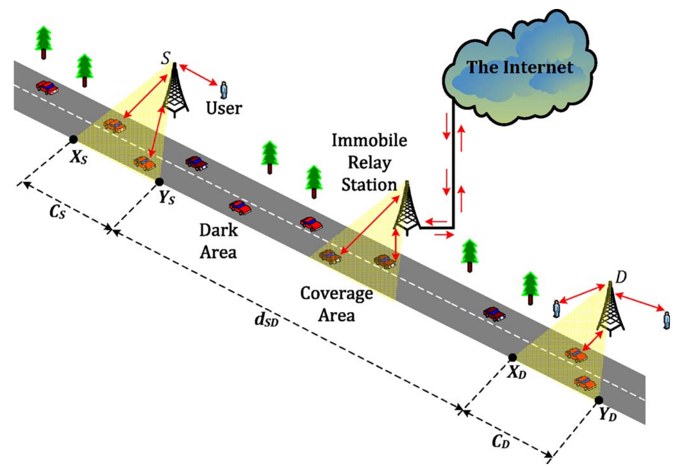

Fig. 1. Vehicular delay-tolerant network.

In this paper, we study the possibility of achieving delay-minimal data delivery in vehicular networks where connectivity is to be established between two stationary information relay stations (IRSs): a source S and a destination D that is located beyond the coverage range of S. In the absence of all kinds of fixed infrastructure that connect S to D, vehicles passing by the source (and willing to cooperate) serve as *store–carry–forward* devices that transport its data bundles to the destination. This type of data communication networks has been designed for rural regions in underdeveloped countries or for other scarcely inhabited areas where the setup of fixed infrastructure can be significantly costly [3]. A limited number of IRSs known as *gateways* are connected to the Internet through minimal infrastructure. All other IRSs are deployed anywhere along the roads and may be completely isolated. End-user data are communicated to a particular source IRS S where it is appropriately encapsulated within bundles. Those bundles are then relayed to their intended destination IRS D using the passing-by vehicles. Thus, each IRS can act as both 1) a router and 2) an access point in a hot spot.

Fig. 1 depicts the scenario of the network under study. The source S has bundles destined for D. S and D are located along a highway and are separated by a distance d_{SD} (in meters) that

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is larger than their respective coverage range. Vehicles equipped with wireless devices enter the range of S while navigating toward D. S exploits these vehicles as relays to communicate its bundles to D. Throughout this paper, intervehicular communication does not take place. This category of networks belongs to a subclass of ICNs known as *two-hop vehicular ICNs* (TH-VICNs).

In the TH-VICN scenario in Fig. 1, the bundle end-to-end delivery delay is composed of two constituents: 1) the queueing delay (i.e., the period of time a bundle is buffered at S before it gets released to a vehicle); and 2) the transit delay (i.e., the period of time spent by the bundle-transporting vehicle in traveling from S to D). Observe that the transit delay is a function of the vehicle's speed. It is assumed that S becomes aware of the vehicle's speed as soon as this latter enters its communication range.

Our primary objective is to investigate, in the given context, the possibility of minimizing the average bundle end-to-end delivery delay, which could actually be quite large. As a matter of fact, S may spend tens of seconds to a couple of minutes waiting for a vehicle to arrive. Moreover, the vehicle to which a bundle is released might travel from S to D in a few minutes to even a few hours [10]. Obviously, under such conditions, the typical Internet protocols (known to tolerate delays of a few seconds) will not work. Therefore, new protocols and bundle release schemes that meet the proper operation requirements of such networks must be developed. A number of recent publications address the performance, optimization, and operation of such ICNs [4]–[6]. In contrast, the scope of this paper is restricted to the study of a delivery-delay minimization problem in a two-hop networking scenario between S and D.

More precisely, the conducted mathematical study considers two bundle release schemes: 1) the greedy bundle release scheme (GBRS) and 2) the probabilistic bundle release scheme (PBRS). Under the GBRS, the source greedily releases a single bundle to every arriving vehicle. In contrast, under the PBRS, the *probability of bundle release* denoted by P_{br} indicates to the source which among the arriving vehicles are those that achieve relatively faster bundle transits. Consequently, the source releases bundles, one at a time, only to those vehicles. This scheme ensures the minimization of the average bundle transit delay. Simplicity and unawareness of network information are the two features that distinguish the GBRS and the PBRS from other existing schemes (e.g., in [10]). Two queueing models are developed to respectively characterize S under each scheme. Extensive simulations are conducted to examine the validity and accuracy of our analysis. Our results indicate the ineffectiveness of the traditional packet-like bundle release mechanism as it severely impacts the stability of S's buffer causing excessive queueing delays. Under such circumstances, both GBRS and PBRS become ineffective. Nevertheless, it is observed that the release of a bulk of bundles, whenever the right opportunity arises, is a very effective idea that may boost the performance of both schemes under study. Hence, the bulk bundle release (BBR) option is proposed to enhance S's queue stability under both PBRS and GBRS. Simulations are performed to test the performance of both PBRS with BBR (PBRS-BBR) and GBRS with BBR (GBRS-BBR), as well as to gauge their merits.

The rest of this paper is organized as follows. In Section II, we summarize a selection of major related works. Section III describes PBRS's framework and introduces its associated bundle release probability. Section IV presents two analytical queueing models to theoretically analyze the performance of stationary IRSs under both PBRS and GBRS. Section V presents a mathematical study of transit delays achieved under both schemes. Section VI evaluates the benefits of the schemes under study through discrete event simulation. Finally, Section VII concludes this paper.

II. Related Work

The utilization of stationary IRSs can be motivated with the help of several articles published in the open literature. For example, in DakNet (see [3]), the authors propose to provide low-cost data communication for rural regions and remote villages through the use of stationary IRSs and vehicular infrastructure. In [4], DieselNet, a VICN, where only buses were exploited as bundle transporters, was deployed over a wide urban area. In [7], Zhao and Cao investigated the possibility of using vehicles as data packet transporters to the destination with the objective of minimizing the packet delay. The utilization of ferries was suggested in [8] to improve the delay performance of these mobile networks. Throughout the analysis presented herein, it is assumed that the source and destination IRSs that store and release bundles are stationary instead of being mobile, as suggested in [8]. Goodman *et al.* [9] proposed an original idea of using infostations privileged by high bandwidth connectivity for the next-generation digital communication services. The IRSs used in the TH-VICN scenario in Fig. 1 are characterized by dual functionality: 1) data storage (similar to infostations) and 2) routers. Vehicles themselves serve as relays.

In [10], a joint scheduling/delay minimization problem is studied in the given context. Ramaiyan *et al.* 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. Throughout their study, Ramaiyan *et al.* assumed complete knowledge of network information (i.e., exact vehicle arrival times and speeds). In contrast, we propose to get away from such an assumption by introducing two novel bundle release schemes that are designed around minimal network information knowledge.

In [11], a multihop packet delivery delay is investigated in a similar low-density VICN scenario to the one described earlier. Throughout their analytical study, Abdrabou and Zhuang 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 contrast, this paper is limited to higher level protocol layers and ignores physical layer (PHY) issues. Note that this paper can be easily extended to cover PHY channel limitations. However, such extensions are left out as future work.

III. Bundle Release Probability

In the earlier described TH-VICN scenario, communication is to be established between the source S and destination D. In the absence of all sorts of networking infrastructures and backbone network connectivities, vehicles restricted to navigable roadways entering the range of S are opportunistically exploited to transport bundles to D. Intuitively, bundles may be greedily released to every arriving vehicle. This is referred to as the GBRS. In contrast, a PBRS is proposed under which S releases bundles only to the relatively faster vehicles to ensure a delay-minimal bundle transit to D. At the heart of the PBRS is the bundle release probability $P_{\mathrm{br},i}$, which is a novel decision parameter expressed as a function of the mean vehicle interarrival time and the speed V_i of a vehicle i present in the range S and the source–destination distance d_{SD}. This parameter gives S insight into the suitability of a vehicle to carry its bundles to D. More specifically, $P_{br,i}$ estimates the level of contribution of an arriving vehicle to the minimization of the overall average bundle transit delay. To the best of our knowledge, the PBRS is the first probabilistic scheme to be specifically tailored for vehicular intermittently connected networks (VICNs) similar to the one shown in Fig. 1. Here, we derive a closed-form expression for $P_{\mathrm{br},i}$.

A. Introduction of Concept

As shown in Fig. 1, the source S has a coverage range that spans a distance of C_S (in meters). S and D are separated by distance $d_{SD} \gg C_S$. Vehicles with distinct speeds enter the range of S while navigating toward D. The event of a vehicle entering the range of S is called a vehicle arrival. S becomes aware of the speed V_i of the ith vehicle only at the instant t_i of arrival of this latter. Hence, with probability $P_{\mathrm{br},i}$, S releases a *single* bundle B that occupies the topmost position of its queue to the ith vehicle. With a probability $1 - P_{\mathrm{br},i}$, it retains B for a likely better subsequent release opportunity. If B is released to the ith vehicle, it will be successfully delivered at the instant $d_i = t_i + d_{SD}/V_i$. Otherwise, if it is released to the $(i+1)$th vehicle, it will be successfully delivered at the instant $d_{i+1} = t_{i+1} + d_{SD}/V_{i+1}$. Let $I_{i+1} = t_{i+1} - t_i$ denote the $(i+1)$th-vehicle interarrival time. Thus, a better subsequent release opportunity occurs whenever

$$d_{i+1} < d_i \Rightarrow I_{i+1} + \frac{d_{SD}}{V_{i+1}} < \frac{d_{SD}}{V_i}. \tag{1}$$

Condition (1) states that not only does the $(i+1)$th vehicle has to arrive to S before the ith one has reached D, but it also has to reach D before the ith one does. Note that d_{i+1} has to be strictly less than d_i. Had there been equality, then a bundle would have been forced to wait longer in the queue with no benefits. As such, condition (1) is the only necessary and sufficient condition based on which a bundle is retained for a *possible* release whenever the next release opportunity arises. In condition (1), I_{i+1} and V_{i+1} are the only unknowns.

B. Basic Assumptions and Justifications

The mathematical framework presented herein is founded on top of the following classical assumptions that were borrowed from [14].

1) The source node has an infinite queue size.
2) Bundle interarrival times are exponentially distributed[1] with a probability density function (pdf)[2] $f_B(t) = \lambda e^{-\lambda t}$, where $t \geq 0$.
3) The bundle release decisions are independent.
4) The bundle transmission time is negligible relative to the vehicle *residence time.*[3]
5) Vehicle interarrival times are exponentially distributed with a pdf. $f_I(t) = \mu e^{-\mu t}$, where $t \geq 0$.
6) The per vehicle speed is uniformly distributed in the range $[V_{\min}; V_{\max}]$ with a pdf. $f_V(v) = 1/V_{\max} - V_{\min}$ and remains constant during the vehicle's entire navigation period on the road.

C. Conditional Bundle Release Probability

In view of the given reasoning and assumptions, the probability of retaining a bundle given that the speed of the current vehicle is $V_i = v_i$ can be expressed as

$$\Pr\left[d_{i+1} < d_i \middle| V_i = v_i\right] = \Pr\left[I_{i+1} + \frac{d_{SD}}{V_{i+1}} < \frac{d_{SD}}{V_i} \middle| V_i = v_i\right]. \tag{2}$$

Let R be the event that a bundle is released. The conditional bundle release probability $P_{\mathrm{br},i}$ is defined as the probability of occurrence of R conditioned by the current vehicle's speed being $V_i = v_i$. It is

$$\begin{aligned} P_{\mathrm{br},i} &= \Pr\left[R \middle| V_i = v_i\right] \\ &= 1 - \Pr\left[I_{i+1} + \frac{d_{SD}}{V_{i+1}} < \frac{d_{SD}}{V_i} \middle| V_i = v_i\right]. \end{aligned} \tag{3}$$

Define the two random variables $T_d = d_{SD}/V_{i+1}$ and $\Delta = I_{i+1} + T_d$. Note that $f_{I_{i+1}}(t) = f_I(t)$, as given in assumption 1. Let $f_{T_d}(t)$ denote the pdf of T_d. Following the given assumption 6, it is easy to show that $f_{T_d}(t)$ is given by

$$f_{T_d}(t) = \frac{d_{SD}}{(V_{\max} - V_{\min})t^2}, t \in \left[\frac{d_{SD}}{V_{\max}}; \frac{d_{SD}}{V_{\min}}\right]. \tag{4}$$

Let $f_\Delta(\delta)$ denote the pdf of Δ. It is given by the convolution of $f_{I_{i+1}}(t)$ and $f_{T_d}(t)$ as

$$f_\Delta(\delta) = \begin{cases} \frac{\mu d_{SD} \cdot \psi(\delta) \cdot e^{-\mu\delta}}{V_{\max} - V_{\min}}, & \text{for } \delta \in \left[\frac{d_{SD}}{V_{\max}}; \frac{d_{SD}}{V_{\min}}\right] \\ \frac{\mu d_{SD} \cdot \psi\left(\frac{d_{SD}}{V_{\min}}\right) \cdot e^{-\mu\delta}}{V_{\max} - V_{\min}}, & \text{for } \delta \in \left[\frac{d_{SD}}{V_{\min}}; +\infty\right] \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

[1]The general arrival process of typical Internet Protocol packets may also be considered. These packets are then aggregated resulting in variable-size bundles. This would highly resemble burstification, which has been investigated in the seminal work of [15] but is outside the scope of this paper.

[2]In the sequel, the terms "pdf" and "cumulative distribution function (cdf)," respectively, refer to the density and the cumulative distributions of an rv.

[3]The time period a vehicle spends in the coverage range of the source.

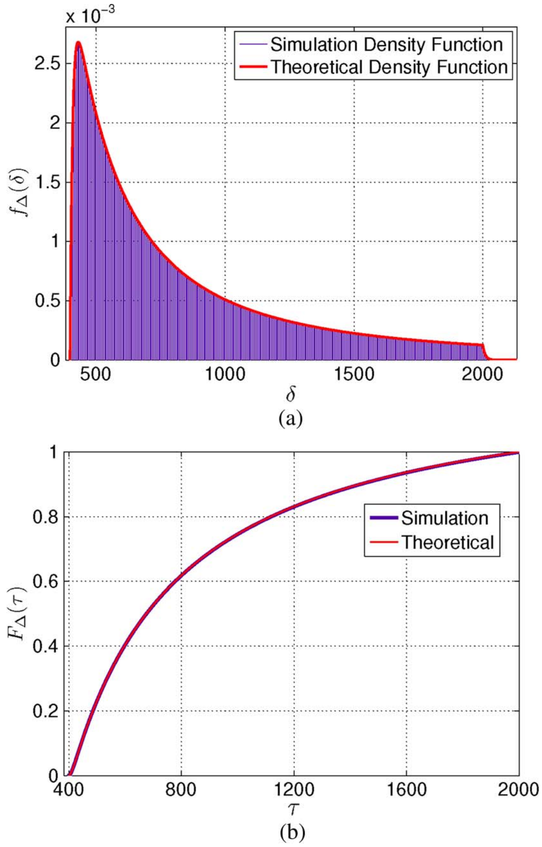


Fig. 2. Simulated versus theoretical versions of the density and cumulative distribution functions of Δ. (a) Probability density function of Δ. (b) Cumulative distribution function of Δ.

We denote by $F_\Delta(\tau)$ the cdf of Δ, as in (6), shown at the bottom of the page. The detailed derivation of $f_\Delta(\delta)$ and $F_\Delta(\tau)$ can be found in [14]. The earlier analysis is validated by carrying out a series of comparisons between numerical and simulation results. For this purpose, the simulator used in Section VI was enabled to track and record the random vehicle interarrival times and transit delays. About 10^7 samples are taken for each and averaged out over multiple runs of the simulator to ensure high accuracy. Summing those values one-to-one leads to simulated versions of Δ for which the corresponding simulated versions of the density and cumulative distribution functions can be easily obtained. In addition, the theoretical versions of these functions were computed. Both simulation and theoretical results were concurrently plotted, as shown in Fig. 2(a) and (b), respectively. With no further dwelling, the figures are tangible proofs of the validity and remarkable accuracy of our derivations as in both of them, the simulated and theoretical curves, completely overlap.

Building on the above, the conditional bundle release probability in (3) can be expressed as

$$P_{\mathrm{br},i} = 1 - F_\Delta\left(\frac{d_{SD}}{V_i}\right). \tag{7}$$

It is worth noting that since $V_i \in [V_{\min}; V_{\max}]$, then $d_{SD}/V_i \in [d_{SD}/V_{\max}; d_{SD}/V_{\min}]$. Hence, $P_{\mathrm{br},i}$ is given by

$$P_{\mathrm{br},i} = 1 - \frac{\varphi\left(\frac{d_{SD}}{V_i}\right)}{\varphi\left(\frac{d_{SD}}{V_{\min}}\right)}. \tag{8}$$

Fig. 3(a) illustrates the variations of the conditional bundle release probability given in (8) as a function of d_{SD}/v_i. Indeed, the area under the curve is exactly equal to 1, which satisfies the fundamental axiom of probability and proves the validity of the derived expression. In addition, notice that, as d_{SD}/v_i increases (i.e., v_i decreases), $P_{\mathrm{br},i}$ will decrease. This stems from the basic property of the bundle release probability that is designed to indicate to the source node those vehicles with relatively high speeds that are most suitable to transport bundles to the destination during the shortest transit period. Fig. 3(b) shows the $P_{\mathrm{br},i}$ curves for different values of the vehicle interarrival rate μ. It is quite important to highlight the fact that, whenever μ decreases, vehicle arrivals become more spaced out in time. At the bundle level, this is interpreted as waiting in the source node's buffer for a longer period of time before the occurrence of a suitable release opportunity. As such, the cumulative waiting time of a bundle in the queue becomes longer as the vehicle interarrival time increases. Nevertheless, $P_{\mathrm{br},i}$ is an adaptive parameter that will account for this situation and limit this additional waiting time by allowing a portion of slower vehicles to transport bundles from S to D. This explains why, for a fixed d_{SD}/v_i, the corresponding $P_{\mathrm{br},i}$ increases as μ increases.

Now, recall that R is the event that a bundle is released. Therefore, the average bundle release probability can be written as

$$P_{\mathrm{br}} = \Pr[R] = \int_{V_{\min}}^{V_{\max}} \frac{1}{V_{\max} - V_{\min}} P_{\mathrm{br},i}\, dv i_i. \tag{9}$$

Consequently, Fig. 3(b) and (c) show that, as the vehicle arrival rate μ increases, the average bundle release probability will decrease. This behavior is a direct result from vehicle

$$F_\Delta(\tau) = \begin{cases} \dfrac{\varphi(\tau)}{\varphi\left(\frac{d_{SD}}{V_{\min}}\right)}, & \text{for } \tau \in \left[\frac{d_{SD}}{V_{\max}}; \frac{d_{SD}}{V_{\min}}\right] \\[2ex] \dfrac{\frac{\varphi\left(\frac{d_{SD}}{V_{\min}}\right) - \psi\left(\frac{d_{SD}}{V_{\min}}\right)}{\mu}\left(e^{-\mu\tau} - e^{-\mu\frac{d_{SD}}{V_{\max}}}\right)}{\varphi\left(\frac{d_{SD}}{V_{\min}}\right) + \frac{\psi\left(\frac{d_{SD}}{V_{\min}}\right)}{\mu} e^{-\mu\frac{d_{SD}}{V_{\max}}}}, & \text{for } \tau \geq \frac{d_{SD}}{V_{\min}} \end{cases} \tag{6}$$

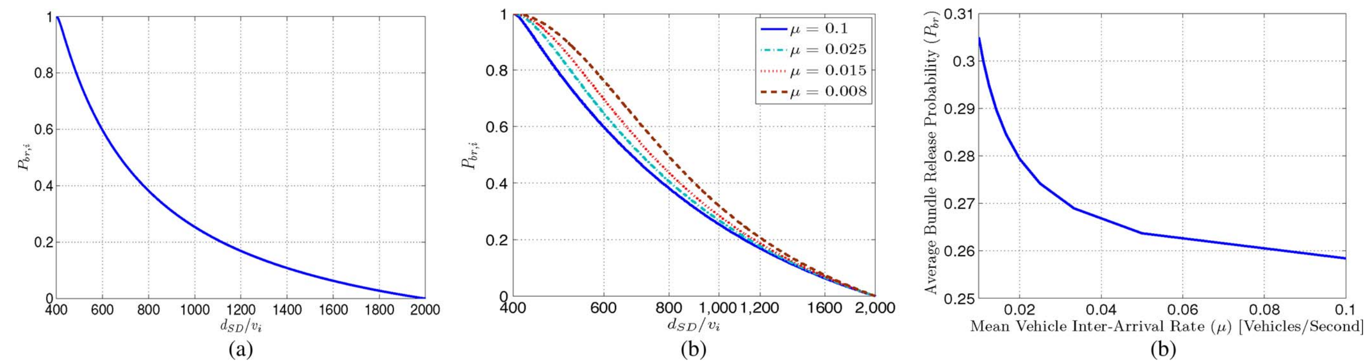


Fig. 3. Conditional and average bundle release probability.

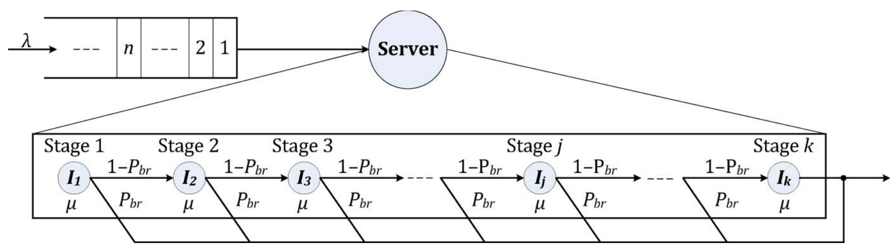


Fig. 4. Bundle service time composed of several waiting stages.

arrivals being closer in time to each other, thus causing the arrival of a relatively fast vehicle to become more probable. In fact, the shorter the vehicle interarrival time is, the faster a high-speed vehicle is expected to arrive. Hence, upon the release of a front bundle to an arriving high-speed vehicle, the additional time this bundle has spent waiting at the front of the queue is expected to be very small. It is at the expense of this little extra queueing delay that P_{br} further restricts the bundle release to only those relatively fast vehicles hoping that the achieved improvement in their transit periods from S to D will be able to compensate.

IV. Modeling and Analysis of Information Relay Station Queues

Here, two analytical queueing models are set up to represent IRS queues under both GBRS and PBRS. Mathematical expressions describing the characteristics of these models are derived. The derivation of the expression that quantifies the *bundle service time* requires particular attention.

Definition: The bundle service time, which is denoted by T_s, is the time period that elapses from the instant an arbitrary bundle reaches the top of the IRS queue until the instant it is released to an arriving vehicle.

A. GBRS Model Definition and Resolution

Recall that, under the GBRS, an IRS releases a bundle to the first arriving vehicle. As soon as a bundle B_{n-1} is released, bundle B_n will immediately occupy the front of the queue and wait for the next vehicle to arrive. Therefore, T_s, in this case, is equivalent to the vehicle interarrival time. That is, $T_s = I$ and hence is similarly exponentially distributed with mean $1/\mu$. In light of assumption 2 in Section III-B, an IRS queue under GBRS is modeled using an $M/M/1$ queue [13].

B. PBRS Model Definition and Resolution

Under the PBRS, upon the occurrence of a release opportunity, the source node S relies on the bundle release probability P_{br} to release a bundle to the vehicle that mostly contributes to the minimization of the mean bundle transit delay. Inspired by this observation, the overall service process of an arbitrary bundle B_n can be viewed as subdivided into a random number $K = k$ $(k = 1, 2 \ldots)$ of service stages [12]. While in the jth stage $(j = 1, 2 \ldots k)$, bundle B_n is said to receive partial service that is equivalent to waiting a random amount of time I_j until the next vehicle arrives. The instant when a new vehicle arrives indicates the end of a stage. The instant when S releases B_n to a vehicle passing by indicates the completion of B_n's service. After B_n is released, the bundle, which is queued behind it (i.e., B_{n+1}), advances to the queue's front. In view of this, it becomes clear that a bundle advancing to the top of the queue always passes through the first service stage as it has to wait for the next arriving vehicle. It is important to note in this regard that bundles are assumed to be serviced according to the first-in–first-out principle. After completing service at the jth stage, the bundle is either released by the source with a probability P_{br} if the present opportunity is deemed adequate or proceeds to stage $j + 1$ with a probability $1 - P_{\mathrm{br}}$. In the latter case, the bundle advances with the hope to find a better release opportunity in the subsequent stages. Following the concept explained earlier and shown in Fig. 4, a front bundle is said to receive a general type of service (i.e., the total service time of a front bundle follows a general distribution). Nevertheless, it can be easily proved that, under the PBRS, the total service time T_s, which is experienced by a bundle occupying the front position of a source IRS queue, is exponentially distributed with parameter μP_{br}. For instance, it is clear from Fig. 4 that a front bundle's total service time T_s is equal to the sum of a number of I_j random variables $(j = 1, 2 \ldots)$. For example, $T_s = I_1$ with a probability P_{br}, $T_s = I_1 + I_2$ with a probability $P_{\mathrm{br}}(1 - P_{\mathrm{br}})$, and so on. As a result, the probability that a bundle's total service time T_s is composed of k service stages is

$$f_K(k) = \Pr[K = k] = P_{\mathrm{br}}(1 - P_{\mathrm{br}})^{k-1}. \quad (10)$$

Each I_j represents a vehicle interarrival time. Given that vehicle arrivals are independent, it follows that all I_j values are independent and identically exponentially distributed with a density function $f_j(t) = f_I(t)$. In addition, given that the total service process of an arbitrary bundle is composed of $K = k$ stages, the probability that its total service time is equal to the sum of the k individual random partial service times spent at each stage can therefore be expressed as

$$\Pr\left[T_s = t = \sum_{j=1}^{k} I_j \middle| K = k\right] = f_1 * \ldots * f_K(t). \quad (11)$$

Consequently, we can express the probability density function of T_s as

$$f_{T_s}(t) = \sum_{k=1}^{\infty} [f_1 * \ldots * f_K(t)] \cdot P_{\mathrm{br}} (1 - P_{\mathrm{br}})^{k-1}. \quad (12)$$

Using Laplace transforms, it can be shown that

$$f_{T_s}(t) = \mu P_{\mathrm{br}} e^{-\mu P_{\mathrm{br}} t}, \quad \text{for } t \geq 0. \quad (13)$$

It is clear from (13) that the bundle service time is exponentially distributed with parameter μP_{br}. Consequently, given that bundle interarrival time is also exponentially distributed with parameter λ, a stationary IRS operating under the PBRS can thus be modeled as an $M/M/1$ queueing system, as studied in [13].

V. Transit Delay Analysis

Here, we derive theoretical expressions for the average transit delay under both the GBRS and PBRS.

A. Average Transit Delay Under the GBRS

Under the GBRS, when the ith vehicle having a constant speed V_i passes by the source, bundle B is released to this vehicle. The transit delay experienced by B is defined to be the amount of time that takes the vehicle carrying B to travel distance d_{SD} separating the source IRS from the destination IRS and deliver B. Obviously, this transit delay can be expressed as follows: $T_d = d_{SD}/V_i$. Note that the probability density function of T_d is given by (4). Hence, the average transit delay under the GBRS is

$$\overline{T_{d,\mathrm{GBRS}}} = E[T_d] = \frac{d_{SD}}{V_{\max} - V_{\min}} \ln\left(\frac{V_{\max}}{V_{\min}}\right). \quad (14)$$

B. Average Transit Delay Under PBRS

Under the PBRS, without loss of generality, assume that the service time of an arbitrary bundle B is composed of k stages. That is, k vehicles passed by the source with respective velocities $v_1, v_2, v_3, \ldots, v_k$. B was finally released to the kth vehicle. Let V_k be a random variable that represents the speed of the vehicle to which a bundle has been released. We denote by R the event that a bundle is released to a vehicle passing by. The transit delay of bundle B released to a vehicle having speed V_k is $T_k = d_{SD}/V_k$. Let $\overline{T_{d,\mathrm{PBRS}}} = E[T_k]$ denote the average transit delay under the PBRS. The density function of the speed V_k of a vehicle to which a bundle has been released is

$$f_{V_k}(v_k) = \frac{P_{br,k} \cdot f_V(v_k)}{\int_{V_{\min}}^{V_{\max}} P_{br,k} \cdot f_V(v_k) dv_k}, \quad \text{for } v_k \in [V_{\min}; V_{\max}]. \quad (15)$$

Let $F_{V_k}(v)$ and $F_{T_k}(t)$ denote the cumulative distribution function of the transporting vehicle speed V_k and the transit delay achieved under the PBRS T_k, respectively. It can be easily shown that

$$F_{T_K}(t) = 1 - F_{V_K}\left(\frac{d_{SD}}{t}\right). \quad (16)$$

It follows that the density function of T_k is

$$f_{T_K}(t) = \frac{d_{SD}}{t^2} f_{V_K}\left(\frac{d_{SD}}{t}\right). \quad (17)$$

Therefore, the average transit delay under the PBRS is

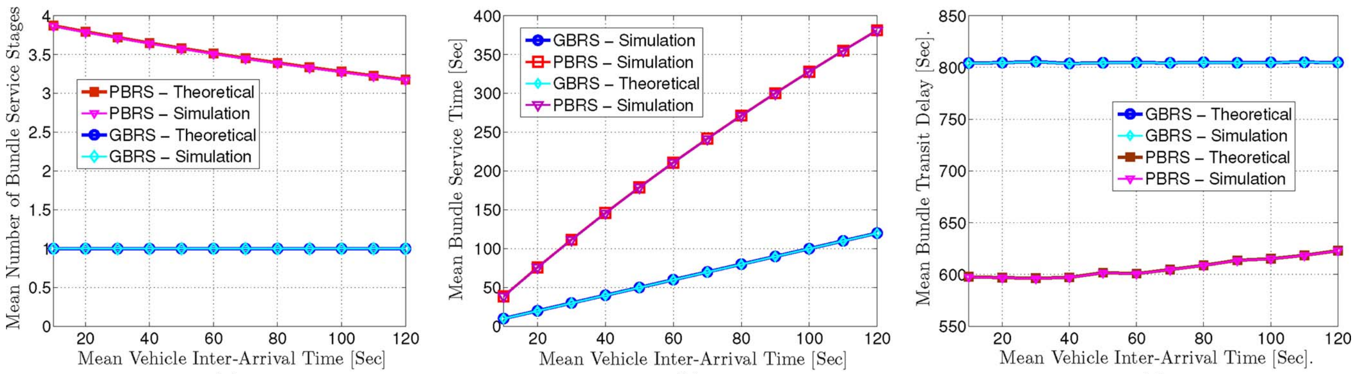
$$\overline{T_{d,\mathrm{PBRS}}} = E[T_K] = \int_{\frac{d_{SD}}{V_{\max}}}^{\frac{d_{SD}}{V_{\min}}} t \cdot f_{T_K}(t)\, dt. \quad (18)$$

VI. Simulations and Numerical Analysis

A discrete event simulation framework is developed for the purpose of examining the performance of the PBRS and the GBRS in the context of the sample VICN shown in Fig. 1.

A. Model Validation and Simulation Accuracy

Fig. 5 presents a theoretical evaluation of the performance of both PBRS and GBRS in terms of the following metrics: 1) the mean number of bundle service stages; 2) the mean bundle service time; and 3) the mean bundle transit delay. The theoretical curves of these metrics are concurrently plotted with their simulated counterparts as a function of the mean vehicle interarrival time. About 10^7 bundles were considered per simulation run. Furthermore, all of the metrics were averaged out over multiple runs of the simulator to ensure that a 95% confidence interval is realized. Following the guidelines presented in [10], the following parameter values were taken: 1) The mean vehicle interarrival time $\overline{I} \in [10; 120]$ (s); 2) the mean bundle interarrival time $\overline{B} = 4$ (s); 3) vehicle speeds are



(a) (b) (c)

Fig. 5. Theoretical and simulated performance evaluation of the PBRS and the GBRS. (a) Mean number of service stages. (b) Mean bundle service time (in seconds). (c) Mean bundle transit delay (in seconds).

in the range [10; 50] m/s; and 4) the source–destination distance $d_{SD} = 20\,000$ m.

Clearly, Fig. 5(a)–(c) shows tangible proofs of the validity and remarkable accuracy of the earlier presented queuing models and transit delay analysis. This is particularly true since the curves in all of the three plots perfectly overlap with each other. On a different note, Fig. 5(a) shows the mean number of service stages experienced by a front bundle versus the vehicle interarrival time. Recall that, under the GBRS, bundles are greedily cleared out. Therefore, a bundle that has just advanced to the front position of the queue will only have to wait for the immediate arrival of the next vehicle to which it will be released. As such, under the GBRS, a front bundle undergoes a single service stage irrespective of the time spacing between vehicle arrivals. In contrast, under the PBRS, the source releases bundles only to relatively high-speed vehicles to ensure that their transit delays are minimized. For this purpose, the bundle release probability P_{br} indicates to the source which of the arriving vehicles are relatively faster than others and more suitable to transport bundles to the destination. As such, the source with a front bundle ready to be released may witness several vehicle arrivals before it finally releases that bundle to a vehicle that P_{br} recommends. To this end, on one hand, the shorter the vehicle interarrival time is, the more likely the occurrence of a close high-speed vehicle arrival becomes. As a result, P_{br} forces the source to retain its front bundle until a vehicle that is fast enough arrives. Hence, a front bundle may experience an extended waiting time at the front of the source's queue. However, this time extension is expected to be very limited and easily compensated for by the achieved transit delay thereafter. On the other hand, once vehicle arrivals become more spaced in time, the extended waiting period of a front bundle will rapidly grow. To limit this growth, P_{br} adaptively reduces the number of waiting stages that a front bundle goes through and allows the source to release it to slower vehicles.

Now, recall from our earlier theoretical analysis that the mean bundle service time is inversely proportional to the mean vehicle interarrival time and directly proportional to the mean number of bundle service stages. This is confirmed in Fig. 5(b). On one hand, under the GBRS, the front bundle always experiences a single service stage. As a result, the mean bundle service time directly follows the mean vehicle interarrival time. On the other hand, under the PBRS, a front bundle experiences a service time that is approximately three to four times that under the GBRS. In fact, the mean vehicle interarrival time and the mean number of bundle service stages are analogous to two opposing forces where if one decreases, the other attempts to counter its effect by increasing. However, the mean vehicle interarrival time increases much faster than the mean number of service stages decreases. This directly explains the growing gap between the achieved service times under the GBRS and the PBRS.

Finally, in terms of transit delay, Fig. 5(c) shows that the PBRS remarkably outperforms the GBRS. This is due to the fact that, under the GBRS, the source node does not differentiate between slow and fast vehicles and greedily releases bundles to every arriving vehicle. Under the PBRS, however, bundles are only released to relatively high-speed vehicles. Therefore, on average, the transit delay under the PBRS is much lower than that experienced under its greedy counterpart.

B. Delay Performance of the PBRS and the GRBS

This subsection is devoted to contrasting the overall performance of the probabilistic scheme with that achieved by greedy forwarding. The adopted metric for performance evaluation is the mean bundle end-to-end delivery delay. Observe that the bundle end-to-end delivery delay is composed of 1) the bundle queueing delay[4] and 2) the bundle transit delay. Contrary to our expectations in Section VI-A, we observed throughout this paper that the vehicle interarrival time has a major impact on the source node's stability status. This is particularly true since typical Internet packet-like forwarding is adopted where only a single bundle is released at a time. Fig. 6(a) confirms this fact where, under both the probabilistic scheme and its greedy counterpart, the experienced queueing delay on average is of the order of 10^7. Indeed, this is reasonable since, in our simulations, the considered offered load to the source is relatively high with a bundle interarrival time of 4 s, whereas the minimum

[4]In the context of this paper, the bundle service time is nothing but the time period that a bundle waits at the front position of the source node's queue. As such, the overall bundle queueing delay is nothing but the sum of the bundle service time and the time period a bundle has waited in all the subsequent queue positions it passed through since the instant of its arrival.

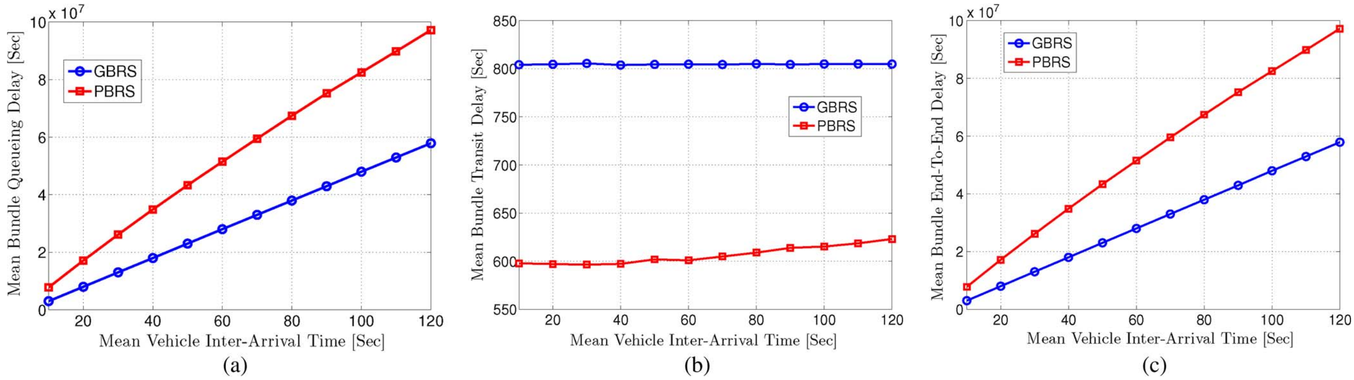


Fig. 6. Delay Performance of the PBRS versus the GBRS. (a) Mean Queueing Delay (in seconds). (b) Mean transit delay (in seconds). (c) Mean end-to-end delay (in seconds).

vehicle interarrival time is 10 s. That is, as far as the GBRS is concerned, bundles arrive to the source at a much higher rate than the one at which the source is able to clear them out. Hence, it will not take long before the queue becomes unstable; in which case, bundles will accumulate and experience uncontrollably growing queueing delays. Under the PBRS, the case is even worse since, following $P_{\rm br}$'s recommendation, bundles are forced to stay in the queue for longer times. In addition, the more vehicle arrivals become spaced out in time, the more unstable the queue will be and the larger the queueing delays grow. Although PBRS results in a significant improvement in terms of the achieved mean bundle transit delay, as shown in Fig. 6(b), this improvement, which is on the order of hundreds of seconds, becomes unable to compensate for these excessive queueing delays. In light of this, the resulting end-to-end delivery delay becomes exorbitant as it is primarily governed by the queueing delay, as shown in Fig. 6(c). It follows that, under such circumstances, both GBRS and PBRS are inefficient. Nonetheless, we observed that allowing both schemes to release a bulk of bundles, each time an opportunity presents itself, will greatly improve the performance of both of them. However, this simple yet very effective option will allow the PBRS to remarkably outperform the GBRS in terms of average end-to-end delivery delay and, hence, will become of exceptional utility. This point is investigated further in the following section.

VII. Bundle Relaying Schemes With Bulk Bundle Releases

In the VICN scenario shown in Fig. 1, notice that S has a range $C_S = 200$ m. Therefore, an arriving vehicle i with speed V_i will reside in the range of S for a period of time $D_i = C_S/V_i$. Assume that both the IRS source and vehicle implement a variant of the 802.11 protocol where the transmitted data units have a maximum size of 1500 B. Consequently, if the utilized transmission rate is the minimum of 1 Mbps, then the transmission of a bundle of the maximum size would require 12 ms. In the worst case scenario, the fastest possible vehicle $(V_i = 50\ \text{m/sec})$ will reside in the range of S for a time period $D_i = 4$ s. Under the given PBRS, only a single bundle is cleared out per release opportunity. As such, there will be 3.988 s of wasted vehicle residence time during which no bundle is released. In the context of the VICN scenario under study, this is the second major cause of the significant increase in the bundle queueing delay and has a considerable impact on the performance of the proposed probabilistic and greedy schemes. While the arrival rate of vehicles and their speeds are the two primary causes that affect the performance of the two schemes, these are uncontrollable from an operator's point of view since vehicles arrive at completely random time instants and have absolutely random speeds. In contrast, the strategy of bundle release can be wisely adjusted to become more efficient and achieve better overall performance.

To efficiently compensate for the wasted vehicle residence time, we propose an improved version of the PBRS and the GBRS, respectively, i.e., the PBRS-BBR and the GBRS-BBR. We relax the assumption that bundle sizes are fixed made in [10] and consider that the bundle size is uniformly distributed in the range [64; 1500] B. Under the PBRS-BBR, a bulk of size L may be transmitted per release opportunity. As a matter of fact, whenever vehicle i enters the range of S, this latter becomes aware of its speed and instantly computes its residence time D_i. Therefore, as long as S has bundles in its queue, it will keep on clearing them out starting from the instant that vehicle i arrives up until either the vehicle exits its communication range or its queue is emptied.

The BBR option results in a remarkable improvement of the performance of both the GBRS and the PBRS. The average queueing delay is significantly decreased, as shown in Fig. 7(a). The PBRS-BBR and the GBRS-BBR conserved the same performance as the PBRS and the GBRS in terms of the average transit delay, as shown in Fig. 7(b). However, BBR improved the performance of the PBRS with respect to the GBRS and reflected this improvement on the average end-to-end delay, as shown in Fig. 7(c). In fact, PBRS-BBR inherits from the PBRS the luxury of holding bundles in the queue for longer periods of time and hunts for the vehicle that will be able to achieve the lowest possible transit delay given a particular vehicle interarrival time. Regardless of the fact that, during this queueing time, more bundles may accumulate in the queue and contribute to the elevation of the average queueing delay, the new BBR option wisely enables the source to clear out a large number of bundles per opportunity. This has the effect of limiting the increase in the queueing delay and allows the improved transit delay to easily overshadow it and hence

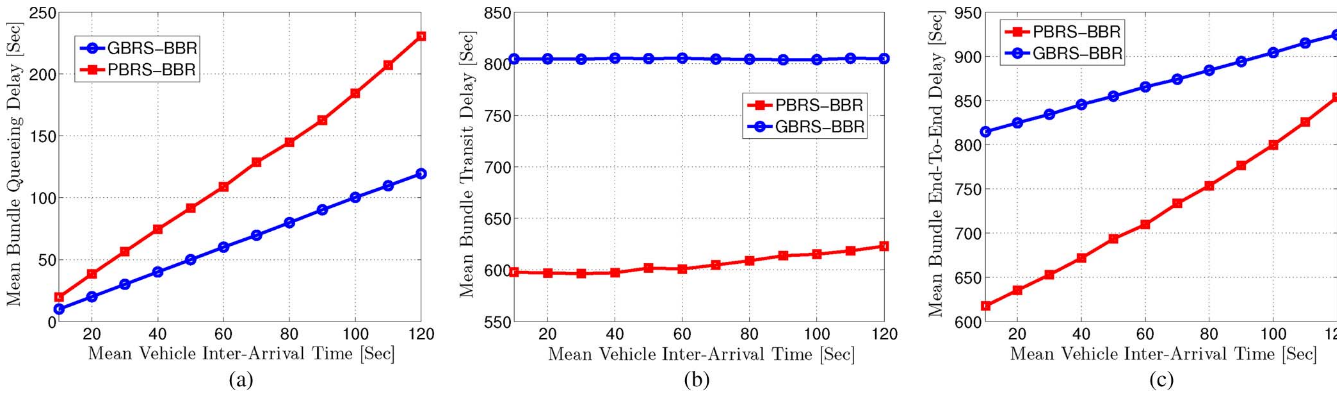


Fig. 7. Delay Performance of the PBRS-BBR versus the GBRS-BBR. (a) Mean queueing delay (in seconds). (b) Mean transit delay (in seconds). (c) Mean end-to-end delay (in seconds).

to govern the overall average end-to-end delivery delay. This latter, in turn, under the PBRS-BBR, becomes significantly lower than the one achieved under the GBRS-BBR for all considered values of mean vehicle interarrival times.

VIII. Conclusion

In this paper, we have first investigated the performance of two bundle releasing schemes in the context of a TH-VICN. The first is the GBRS under which a source IRS S greedily releases bundles to vehicles that enter its coverage range. The second scheme is the PBRS that has the luxury of holding the head-of-line bundle in S's queue while awaiting for the arrival of a relatively high-speed vehicle that best contributes to the minimization of the average bundle transit delay. A mathematical study was presented for the estimation of three delay-performance metrics: the bundle queueing, transit, and end-to-end delivery delay under both the GBRS and the PBRS. This paper has been founded on top of the unavailability of *a priori* network information. Results showed that the PBRS outperformed the GBRS in terms of average transit delay. However, the traditional Internet packet-like relaying mechanism significantly impairs the S's queue stability and incurs excessive queueing delays that overshadowed the transit delay improvements. Under such conditions, these two relaying strategies become practically inefficient. The BBR option was then introduced as an effective solution for stabilizing the S's queue and, hence, considerably improving the performance of both schemes. The PBRS-BBR was found to significantly outperform the GBRS-BBR in terms of the average end-to-end delay.

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Authors' photographs and biographies not available at the time of publication.