A Probabilistic Bundle Relay Strategy In Two-Hop Vehicular Delay Tolerant Networks

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

Abstract—**A persisting major challenge in Vehicular Delay-Tolerant Networks (VDTNs) is the delay minimization of data delivery when communicating nodes are stationary, arbitrarily deployed along roadsides and considerably apart that they cannot establish direct communication between each other. A source opportunistically releases bundles of data to cooperating vehicles passing by, hoping that they will successfully deliver them to the intended destination. Several complex strategies that tackle this problem have been proposed in the open literature. Nevertheless, these strategies often implicitly assume complete network knowledge. In this paper, we propose a rather simple Probabilistic Bundle Relay Strategy (PBRS) that relaxes the availability of complete network information. A queuing model is formulated to represent VDTN stationary sources where PBRS is deployed. We introduce the bundle release probability parameter which expresses the likelihood that a bundle is released by the source to a vehicle passing by. The proposed model is studied analytically and theoretical expressions of its characteristic parameters are all derived. In particular, we compute the time it takes to release a head-of-line bundle (referred to as the bundle's service time). Moreover, the model is validated through a simulation study that gauges its merit. The simulation results show that even with partial network knowledge the proposed queueing model can guarantee acceptable bundle delivery delay.**

Index Terms **– Delay-Tolerant Networks, vehicular networks, performance evaluation, modeling and analysis, service time, bundle.**

I. Introduction

Delay-/Disruption-Tolerant Networking (both abbreviated by DTN) recently emerged as a highly active area of research. The different networking environments where they are deployed significantly affect their operation requirements and performance rendering them heterogeneous by nature. This is why the existing network protocols fail to operate properly in the context of DTNs, thus raising a variety of new challenging problems that attract the attention of the majority of researchers in the field [4]–[7].

Wireless ad-hoc networks are often deployed in sparsely populated areas where the setup of networking infrastructures is infeasible due to its significantly high cost. Under such conditions, mobile nodes mounted over vehicles that are

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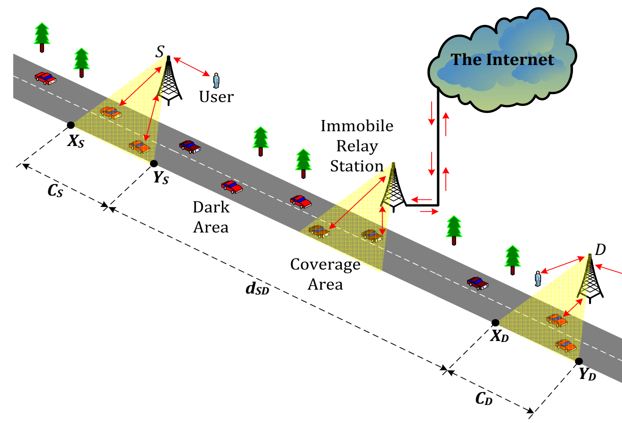


Fig. 1. Vehicular Delay-Tolerant Network

restricted to navigable roadways may be opportunistically exploited as store-carry-forward devices to establish connectivity between immobile Information Relay Stations (IRSs) located beyond the communication range of each other. Obviously, contemporaneous end-to-end paths between such fixed source-destination IRS pairs cannot be guaranteed. A number of such IRSs, called $gateways$, may be privileged by a connection to the Internet and might require minimal infrastructure. All other IRSs may be arbitrarily deployed along roadsides. Such IRSs often lack direct connectivity to other IRSs or even to any other backbone network. End users deposit information data at these IRSs which in turn relay it to vehicles passing by, hoping that these latter will successfully deliver the data to the intended destinations. These types of networks belong to the class of Vehicular Delay-Tolerant Networks (VDTNs). Figure 1 illustrates our view of these networks. The figure shows three IRSs located along the side of a road, possibly a highway. Only the middle IRS has a connection to the Internet. Assume that the source S would like to communicate with destination D that is located far beyond its communication range. Vehicles with different random velocities navigate on the road in the direction of D and enter in communication range of S at random time instants. Some of these vehicles happen to be willing to serve S and communicate its data to D. S will therefore release data bundles to these vehicles hoping that they will be delivered to D successfully.

In this paper, we consider a data delivery delay minimization problem in the context of a VDTN such as the one shown in Figure 1. We propose a new Probabilistic Bundle Relaying Scheme (PBRS) where we introduce a new parameter called the bundle release probability. This parameter expresses the likelihood that, for a present relay opportunity, a source relays a bundle occupying the front position of its queue to a suitable vehicle passing by. A mathematical queueing model is devised to evaluate the performance of PBRS. Unlike models existing in the open literature, our probabilistic queueing model (PQM) does not rely on complete network information knowledge (e.g. exact vehicle arrival times, exact vehicle speeds... etc). We capitalize on the trade-off between the waiting time of a bundle at the top of the source's queue and its transit delay. We show that increasing the waiting time of a bundle at the top of the queue and releasing it to a vehicle that is fast enough may significantly minimize its transit delay relative to a scheme that greedily releases bundles to every vehicle passing by.

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 a mathematical model to theoretically analyze the performance of stationary IRSs under PBRS. Section V evaluates the benefits of the proposed scheme through a simulation study. Finally, section VI concludes the paper.

II. Related Works

The authors in [1] studied a sequential decision problem in the context of the above-described VDTN scenario. In particular, they adopted a two-hop relay strategy where vehicles only communicate with the source and destination IRSs. The source makes a single decision π per in-range-vehicle per relay opportunity determining whether or not to release a single bundle to that vehicle. This decision is a function of the number of pending bundles, the vehicle speed and vehicle inter-arrival time. The authors aimed at minimizing the time needed to transfer a set of data from its source to its intended destination. They argued that it may be optimal to ignore slow vehicles in a present opportunity and wait for subsequent ones hoping that these latter will be fast enough to make up for the additional waiting time. The authors formulated this as an optimization problem that they solved using a complex Markov Decision Process framework in which they particularly integrated Dynamic Programming to determine their optimal decision π^*.

In [2], the authors formulate a queueing model to study the performance of mobile routers in VDTNs. Their contribution is twofold. First, the performance of such routers is assessed through the evaluation of several performance metrics such as the average number of packets in the queue, throughput and packet delivery delay. Second, a scenario where multiple traffic sources contend for the resources (i.e., buffer and bandwidth) of a mobile router is considered. Some traffic sources tend to selfishly confiscate such resources thus severely impacting the performance of the network and hence the utility of other opponents. The authors study this competitive situation by means of a non-cooperative gaming model. The solution of this game is obtained as the Nash Equilibrium which ensures that none of the traffic sources will change its packet forwarding strategy given the set of strategies adopted by the other traffic sources. Both, the queueing and non-cooperative gaming models are useful for performance evaluation and tracking the behavior of the independent entities in VDTNs.

Both [1] and [2] assume complete knowledge of network information. Therefore, this paper proposes to get away from such an assumption by introducing a novel bundle relay scheme that is designed around minimal network information knowledge.

III. Introducing The Bundle Release Probability

Consider the VDTN shown in Figure 1. Communication is to be established between the source S and destination D. The communication range of S covers a distance C_S (meters) of the road. Both S and D are located along the roadside and are separated by a distance d_{SD} (meters) much larger than C_S. Vehicles with distinct speeds navigate along the road passing by S in the direction of D. 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 the i^{th} vehicle only at the instant t_i of arrival of this latter. Hence, with a probability $P_{br,i}$, S releases a bundle B that occupies the topmost position of its queue to the present i^{th} vehicle. With a probability $1 - P_{br,i}$ it retains B for a likely better consecutive release opportunity. If B is released to the i^{th} vehicle, it will be successfully delivered at the instant $d_i = t_i + \frac{d_{SD}}{v_i}$. Otherwise, if it is released to the $(i+1)^{th}$ vehicle, it will be successfully delivered at the instant $d_{i+1} = t_{i+1} + \frac{d_{SD}}{v_{i+1}}$. A better consecutive release opportunity occurs whenever the following two conditions are simultaneously satisfied: (i) the $(i+1)^{th}$ vehicle arrives at an instant $t_{i+1} < d_i$, and (ii) the delivery instant $d_{i+1} < d_i$. However, if $t_{i+1} > d_i$, then d_{i+1} can never be less than d_i. In view of this, the probability of retaining a bundle given that the speed of the current vehicle is v_i can be mathematically expressed as:

$$Pr\left[d_{i+1} < d_i \middle| V = v_i\right] = Pr\left[t_{i+1} - t_i + \frac{d_{SD}}{v_{i+1}} < \frac{d_{SD}}{v_i} \middle| V = v_i\right] \quad (1)$$

Let R be the event that a bundle is released. Therefore, the probability of occurrence of R given that the current vehicle's speed is v_i is given by:

$$\begin{aligned} P_{br,i} &= Pr\left[R \middle| V = v_i\right] \\ &= 1 - Pr\left[t_{i+1} - t_i + \frac{d_{SD}}{v_{i+1}} < \frac{d_{SD}}{v_i} \middle| V = v_i\right] \end{aligned} \quad (2)$$

IV. Modeling And Performance Analysis Of Stationary Traffic Sources In VDTNS

In this section, we devise a mathematical model to evaluate the average delay experienced by a head of the line bundle before it is released to a vehicle passing by. This delay component will be referred to henceforth as the average bundle service time. The aim of this section is to derive a closed-form expression for the bundle service time.

A. Basic Assumptions:

The mathematical analysis is based on the following assumptions:

- Bundle transmissions are instantaneous.
- Vehicle inter-arrival times are exponentially distributed with mean $\frac{1}{\mu}$ and density function $f_I(t) = \mu e^{-\mu t}$, $t \geq 0$.
- Bundle inter-arrival times are exponentially distributed with mean $\frac{1}{\lambda}$ and density function $f_B(t) = \lambda e^{-\lambda t}$, $t \geq 0$.
- Vehicle speeds are uniformly distributed with a density function $f_V(v) = \frac{1}{V_{max}-V_{min}}$, $V_{min} \leq v \leq V_{max}$.
- A vehicle's speed remains constant during its entire navigation period on the road.
- Release decisions are performed independently for each bundle from one opportunity to another.
- The source node relays only one bundle per vehicle.

B. Closed-Form Expression of the Bundle Release Probability:

In equation (2), observe that $t_{i+1} - t_i = I_{i+1}$. Therefore equation (2) can be rewritten as:

$$P_{br,i} = 1 - Pr\left[I_{i+1} + \frac{d_{SD}}{v_{i+1}} < \frac{d_{SD}}{v_i}\middle| V = v_i\right] \qquad (3)$$

The random variables, I_{i+1} is exponentially distributed with a density function $f_{i+1}(t) = f_I(t)$ and v_{i+1} is uniformly distributed with a density function $f_V(v)$. Let us denote by $f_Y(y)$ the probability density function of the random variable $Y = \frac{d_{SD}}{v_{i+1}}$. It is easy to show that $f_Y(y)$ can be expressed as:

$$f_Y(y) = \frac{d_{SD}}{(V_{max}-V_{min})y^2}, \text{ for } \frac{d_{SD}}{V_{max}} \leq y \leq \frac{d_{SD}}{V_{min}}$$

The probability density function of the random variable $\Delta = I_{i+1} + Y$ is the convolution of $f_{i+1}(t)$ and $f_Y(y)$ and is given by:

$$\begin{aligned} f_\Delta(\delta) &= \int_{\frac{d_{SD}}{V_{max}}}^{\frac{d_{SD}}{V_{min}}} \frac{d_{SD}\mu e^{-\mu(\delta-y)}}{(V_{max}-V_{min})y^2} dy \\ &= \left[\frac{d_{SD}\mu}{V_{max}-V_{min}} \int_{\frac{d_{SD}}{V_{max}}}^{\frac{d_{SD}}{V_{min}}} \frac{e^{\mu y}}{y^2} dy\right] e^{-\mu\delta} \end{aligned}$$

We define the constant $A = \frac{d_{SD}\mu}{V_{max}-V_{min}} \int_{\frac{d_{SD}}{V_{max}}}^{\frac{d_{SD}}{V_{min}}} \frac{e^{\mu y}}{y^2} dy$. Therefore, $f_\Delta(\delta)$ is rewritten as:

$$f_\Delta(\delta) = Ae^{-\mu\delta} \text{ , for } \delta \in \left[\frac{d_{SD}}{V_{max}}; +\infty\right[$$

Let $F_\Delta(\delta)$ be the cumulative distribution function of δ. It is given by:

$$\begin{aligned} F_\Delta(\delta) &= Pr\left[\Delta < \delta \middle| \delta \geq \frac{d_{SD}}{V_{max}}\right] = \frac{\int_{\frac{d_{SD}}{V_{max}}}^{\delta} Ae^{-\mu\sigma} d\sigma}{\frac{A}{\mu} e^{-\frac{\mu d_{SD}}{V_{max}}}} \\ &= 1 - \frac{e^{-\mu\delta}}{e^{-\frac{\mu d_{SD}}{V_{max}}}} \end{aligned}$$

Building on the above, the bundle release probability given that the current vehicle speed is v_i given in equation (3) can be expressed as:

$$\begin{aligned} P_{br,i} &= 1 - F_\Delta\left(\frac{d_{SD}}{v_i}\right) = 1 - \left(1 - \frac{e^{-\frac{\mu d_{SD}}{v_i}}}{e^{-\frac{\mu d_{SD}}{V_{max}}}}\right) \\ &= \frac{e^{-\frac{\mu d_{SD}}{v_i}}}{e^{-\frac{\mu d_{SD}}{V_{max}}}} = e^{-\mu\left(\frac{d_{SD}}{v_i} - \frac{d_{SD}}{V_{max}}\right)} \end{aligned} \qquad (4)$$

Recall that R is the event that a bundle is released. Thus, it follows from equation (4) that the average bundle release probability can be written as:

$$\begin{aligned} P_{br} = Pr[R] &= \int_{V_{min}}^{V_{max}} \frac{1}{V_{max}-V_{min}} e^{-\mu\left(\frac{d_{SD}}{v_i} - \frac{d_{SD}}{V_{max}}\right)} dv_i \\ &= \frac{e^{\mu\frac{d_{SD}}{V_{max}}}}{V_{max}-V_{min}} \int_{V_{min}}^{V_{max}} e^{-\mu\frac{d_{SD}}{v_i}} dv_i \end{aligned} \qquad (5)$$

Using the appropriate integration techniques, we get:

$$\begin{aligned} P_{br} = &\frac{d_{SD} e^{\mu\frac{d_{SD}}{V_{max}}}}{V_{max}-V_{min}} \times \\ &\left\{\frac{V_{min}e^{-\mu\frac{d_{SD}}{V_{min}}}}{d_{SD}} - \frac{V_{max}e^{-\mu\frac{d_{SD}}{V_{max}}}}{d_{SD}} + \mu ln\left(\frac{V_{max}}{V_{min}}\right)\right. \\ &\left. +\mu\sum_{m=1}^{\infty}\frac{1}{m \cdot m!}\left[\left(-\mu\frac{d_{SD}}{V_{min}}\right)^m \left(-\mu\frac{d_{SD}}{V_{max}}\right)^m\right]\right\} \end{aligned} \qquad (6)$$

C. Model Definition and Resolution:

Let us designate by T the total bundle service time. As indicated earlier, T represents the time period that elapses from the instant any arbitrary bundle B_n reaches the top of the queue until the instant it hops onto a vehicle passing by. Upon the occurrence of a release opportunity, the source node S will decide whether or not to release B_n to the newly arriving vehicle. Inspired by this observation, we subdivide the overall service process of B_n can be viewed as subdivided into a random number $K = k$ ($k = 1, 2...$) of service stages. While in the j^{th} stage ($j = 1, 2...k$), B_n is said to obtain partial service that is equivalent to waiting a random amount of time I_j until the next vehicle arrives. B_n starts receiving its service at the first stage when it reaches the top of the queue. 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 queuing behind it advances to the queue's top position. 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 services according to the First-In-First-Out (FIFO) principle. After completing service at the j^{th} 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 $1-P_{br}$. In the latter case, the bundle advances with the hope to find a better release opportunity in the subsequent stages. P_{br} is the bundle release probability derived in section III-B. The concept explained above is illustrated in Figure 2.

From Figure 2, it is clear that a bundle's total service time T is equal to the sum of a number of I_j random variables ($j = 1, 2...$). For example, $T = I_1$ with a probability P_{br}. $T = I_1 + I_2$ with a probability $P_{br}(1-P_{br})$. $T = I_1 + I_2 + I_3$ with a probability $P_{br}(1-P_{br})^2$) and so on. Therefore the probability that a bundle's total service time T be composed of k service stages is given by:

$$f_K(k) = Pr[K = k] = P_{br}(1-P_{br})^{k-1}$$

It is worth mentioning that each I_j represents a vehicle inter-arrival time. Given that vehicle arrivals are independent, it follows that all I_j are independent and identically distributed (i.i.d) with a density function $f_j(t) = f_I(t)$. Under this condition, the probability that its total service time is equal to the sum of k individual random partial service times spent at each stage can therefore be expressed as follows:

$$Pr\left[T = t = \sum_{j=1}^{k} I_j \middle| K = k\right] = f_1 * ... * f_k(t) \tag{7}$$

As a result we can express the probability density function of T as:

$$\begin{aligned} f_T(t) &= \sum_{k=1}^{\infty} Pr\left[T = t = \sum_{j=1}^{k} I_j \middle| K = k\right] \cdot Pr\left[K = k\right] \\ &= \sum_{k=1}^{\infty} \left[f_1 * ... * f_k(t)\right] \cdot P_{br}\left(1-P_{br}\right)^{k-1} \end{aligned} \tag{8}$$

Knowing that the Laplace transform of equation (7) is given by:

$$L\left[f_1 * ... * f_k\left(t\right)\right] = \prod_{j=1}^{k} \frac{\mu}{s+\mu} = \left[\frac{\mu}{s+\mu}\right]^k$$

Therefore, we can express the Laplace Transform of $f_T(t)$ as:

$$\begin{aligned} F_T^*(s) &= \sum_{k=1}^{\infty} \left[\frac{\mu}{s+\mu}\right]^k \cdot P_{br}\left(1-P_{br}\right)^{k-1} \\ &= \frac{P_{br}}{1-P_{br}} \sum_{k=1}^{\infty} \left[\frac{\mu(1-P_{br})}{s+\mu}\right]^k \\ &= \frac{P_{br}}{1-P_{br}} \left(\sum_{k=0}^{\infty} \left[\frac{\mu(1-P_{br})}{s+\mu}\right]^k - 1\right) \\ &= \frac{P_{br}}{1-P_{br}} \left(\frac{1}{1-\frac{\mu(1-P_{br})}{s+\mu}} - 1\right) \\ &= \frac{\mu P_{br}}{s+\mu P_{br}} \end{aligned} \tag{9}$$

Finally, taking the inverse of the Laplace Transform of equation (9), we can express $f_T(t)$ the probability density function of the bundle service time as:

$$f_T(t) = \mu P_{br} e^{-\mu P_{br} t, \text{ for } t \geq 0} \tag{10}$$

D. *Performance Analysis of Stationary Traffic Sources:*

In light of the derivations in section III-C, it is clear from equation (10) that the bundle service time is exponentially distributed with parameter μP_{br}. It was initially assumed in section III-A that bundle inter-arrivals times are also exponentially distributed with parameter λ. Therefore a stationary Information Relay Station (IRS) can be modeled using an $M/M/1$ queue. Such queueing systems have been extensively studied, [3]. To avoid material redundancy, we will simply use the results derived in [3] to enumerate the different performance parameters characterizing a stationary traffic source in the context of the VDTN scenario under study.

- The effective bundle departure rate is $\mu_e = \mu P_{br}$.
- The total average load is $\rho = \frac{\lambda}{\mu_e}$.
- The p.d.f. of the number of bundles in the system is given by $P_n = (1-\rho)\rho^n$, for $n = 0, 1, 2...$
- The p.d.f. of the total waiting time (i.e. queuing and service) in the system is $(\mu_e - \lambda)e^{-(\mu_e-\lambda)t}$, for $t \geq 0$.
- The mean number of bundles in the system is $\overline{N_S} = \frac{\rho}{1-\rho}$.
- The mean number of bundles in the queue is $\overline{N_Q} = \frac{\rho^2}{1-\rho}$.
- The mean system delay is $\overline{W_S} = \frac{1}{\mu_e-\lambda}(sec)$.
- The mean waiting time in the queue is $\overline{W_Q} = \frac{\rho}{\mu_e-\lambda}(sec)$.
- The mean bundle service time is $\overline{T} = \frac{1}{\mu_e}(sec)$.

V. Simulation Results and Numerical Analysis:

This section evaluates the validity and the performance of the Probabilistic Bundle Relaying Strategy (PBRS) under study. An in-house Java-based discrete event simulator was developed to test various simulation scenarios relating to the VDTN shown in Figure 1. However, only one of them will be discussed due to space limitation. Following the guidelines presented in [1], the following values were used for the simulation parameters: d_{SD} = 20000 (m), C_S = 200 (m),

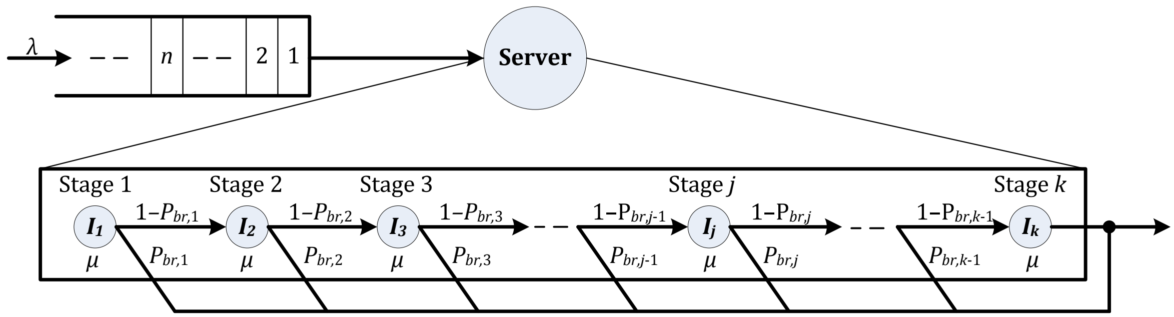


Fig. 2. Bundle service time composed of several waiting stages

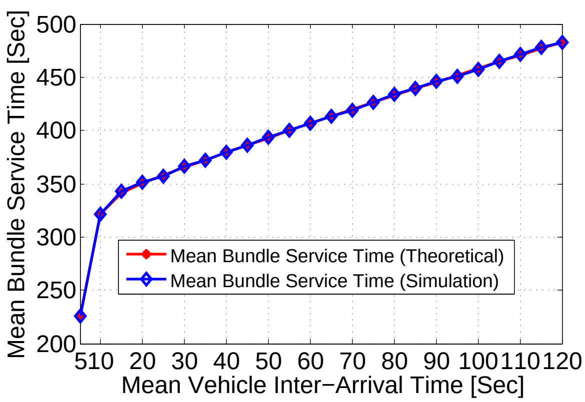
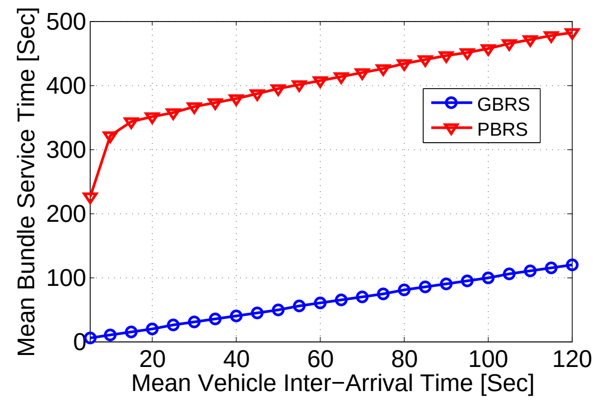
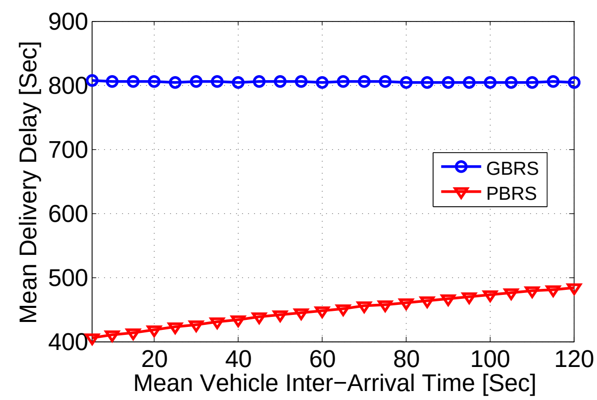


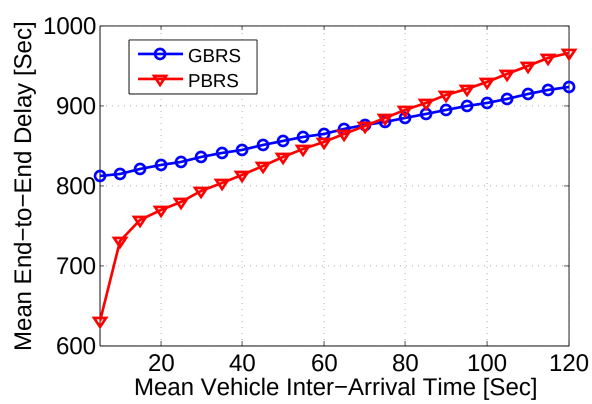
Fig. 3. Mean Bundle Service Time



(a) Mean Bundle Service Time (sec).



(b) Mean Bundle Delivery Delay (sec).



(c) Mean Bundle End-To-End Delay (sec).

Fig. 4. Delay Performance of PBRS versus GBRS.

$V_{min} = 10$ (m/sec), $V_{max} = 50$ (m/sec), $\frac{1}{\lambda} = 1$ (sec).

First, we present in Figure 3 a plot of the theoretical evaluation of the bundle service time concurrently with its simulated counterpart versus the mean vehicle inter-arrival time. This figure is a tangible proof of the validity of our queuing model as well as the accuracy of our simulation. This is especially true since the two plots overlap with each other. The following observation can be inferred from the reported results. The bundle service time is proportional to the number of service stages a bundle goes through, and an increasing function of the mean vehicle inter-arrival time. This finding can be justified as follows. Whenever vehicle arrivals become more spaced in time, this causes the front bundle to experience longer waiting times in each of its service stages. Nonetheless, the bundle release decision parameter P_{br} adaptively controls this increase in bundle service time by reducing the number of waiting stages a bundle passes through. This explains the quasi-linear growth of the mean bundle service time under PBRS as the mean vehicle inter-arrival time increases.

Second, we evaluated the performance of PBRS. For this purpose, we have developed a Greedy Bundle Relaying Strategy (GBRS) to serve as a benchmark. In the context of GBRS, a stationary source S will greedily forward a bundle to every arriving vehicle. The performance measure that will be used to evaluate the benefit of PBRS is the overall delay experienced by a head of the line bundle. The overall delay of such a bundle is composed of (i) bundle service time and (ii) transit delay (also referred to as delivery delay). Both the bundle service time and the delivery delay were evaluated for a total of 10^6 bundles and averaged out over multiple simulation runs with a view to achieving a confidence interval of 95%. The obtained results are reported in Figures 4(a)-4(c) as a function of the average vehicle inter-arrival time.

Obviously, whenever bundles are greedily cleared out, a bundle that has just occupied the front of the queue will only have to wait until the next vehicle arrives before it can be released. Therefore, in GBRS, the bundle service time strictly follows the vehicle inter-arrival time which is exponentially distributed with a mean equal to $\frac{1}{\mu}$ (sec) as shown in Figure 4(a). However, this would not be the case in PBRS where a bundle may undergo several number of service stages each of which being exponentially distributed with a mean $\frac{1}{\lambda}$ (sec) before it is released to the vehicle with the optimal speed. This justifies the longer service times experienced by the head of the line bundles when PBRS is deployed. In contrast, the results presented in Figure 4(b) confirm that PBRS is capable of achieving significantly shorter bundle transit delays relative to GBRS. When considering the overall bundle end-to-end delays given in Figure 4(c), one can observe that for some values of the mean vehicle inter-arrival time PBRS outperforms GBRS and for others GBRS presents a better performance than PBRS. This behaviour can be explained as follows. In fact, the mean vehicle inter-arrival time determines whether or not the queue in which the bundles are stored will be overloaded. More specifically, a shorter inter-arrival time results in a lower load being offered to the queue. As such, the queue becomes empty most of the time. This causes GBRS to miss most of the fast cars that are passing by since on the arrival of a fast car the queue may be empty. In contrast, PBRS has the luxury of having bundles delayed until the best relay opportunity arises reducing thus the end-to-end delay experienced by a bundle. On the other hand, under conditions of heavy load, the greedy scheme will have the upper hand. This is due mainly to the fact that under such circumstances, GBRS will always find a pending bundle to relay when a car pops up and as such will not miss any of the fast cars that pass by.

VI. Conclusion

In this paper, we proposed a new Probabilistic Bundle Relaying Strategy (PBRS) in VDTNs where stationary IRSs are modeled using an $M/M/1$ queuing model. This newly proposed model differs from typical $M/M/1$ queuing models in that it is based on a new parameter, the bundle release probability that expresses the likelihood that a fixed source S releases a bundle to a vehicle currently present in a relay opportunity. As opposed to several strategies found in the open literature, PBRS relaxes the implicitly assumed total network information knowledge. We have obtained the exact analytical expressions for both the bundle release probability and the bundle service time density function.

The performance of PBRS was evaluated through simulation where it was compared to a greedy relaying scheme GBRS that served as a benchmark. It was shown that PBRS significantly reduces the transit delay. On an end-to-end scale, PBRS was shown to outperform GBRS up until vehicle inter-arrivals become considerably spaced in time and hence the system becomes heavily overloaded. Our proposed queuing model is simple. Nevertheless, the numerical results show that it is highly accurate and useful. In summary, the relaxation of the assumed total network information availability, simplicity and great usefulness are the three major advantages of PBRS over other models found in the open literature.

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