Probabilistic Bundle Relaying Schemes in Two-Hop Vehicular Delay Tolerant Networks

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***Abstract*—One class of Vehicular Delay-Tolerant Networks consists of two node types: stationary and mobile. Stationary nodes deployed along roadsides cannot directly communicate as they are considerably distant. Mobile nodes mounted over vehicles opportunistically entering the range of a stationary source serve as relays that carry bundles to the destination. In this letter, we introduce a novel relaying scheme that probabilistically determines a vehicle's suitability to carry bundles. Hence, bundles are released to a present vehicle if and only if that latter contributes in minimizing the mean transit delay. Extensive simulations were performed to gauge the merit of the proposed scheme.**

***Index Terms*—Delay-tolerant networks, vehicular, relay, bundle.**

I. Introduction

A PARTICULAR class of wireless ad-hoc networks consists of having Stationary Relay Stations (SRSs) deployed along highways. Very few such SRSs, 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 SRS pair. Fig. 1 shows three SRSs located along the side of a highway. Only the middle SRS 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 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. Therefore, these types networks belong to the class of two-hop relay Vehicular Delay-Tolerant Networks (VDTNs) [1] and [2]. In [3] a joint scheduling/delay-minimization problem is studied in the above-described context. S is implicitly assumed to be completely aware of exact vehicle arrival instants and speeds based on which it schedules bundle releases. Only one decision is taken per relay opportunity to determine whether or not to release a single bundle to a vehicle, with a view to minimizing that the overall bundle transit delay from S to D. 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.

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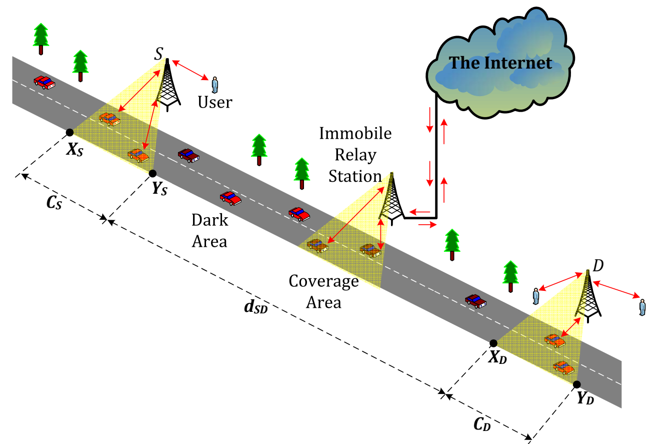


Fig. 1. Vehicular delay-tolerant network.

In this letter, we propose a novel Probabilistic Bundle Relaying Scheme (PBRS). As a distinguishing feature from the work in [3] where the authors assume complete knowledge of network information, our scheme, PBRS, is designed around minimal network information knowledge. It utilizes an original parameter P_r called the release probability. P_r quantifies the contribution of a vehicle in a present opportunity to the minimization of the overall mean bundle transit delay. A Java-based discrete event simulator was developed to study the performance of PBRS and gauge its benefits relative to a Greedy Bundle Relaying Scheme (GBRS) that releases bundles to all vehicles passing by.

II. Probabilistic Bundle Relaying Scheme

Consider the VDTN shown in Figure 1. Communication is to be established between the source S and destination D. S has a coverage range C_S (meters). Both S and D are located along the highway and are separated by a distance $d_{SD} >> C_S$. Vehicles with distinct speeds pass by S and navigate in the direction of D. We call 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_r, S releases a *single* bundle B that occupies the front of its queue to the present i^{th} vehicle. With a probability $1 - P_r$ it retains B for a likely better future release opportunity. If B is released to the i^{th} vehicle, it will be delivered to D 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 delivered at the instant $d_{i+1} = t_{i+1} + \frac{d_{SD}}{V_{i+1}}$. Let $I_{i+1} = t_{i+1} - t_i$ denote the $(i+1)^{th}$ vehicle inter-arrival time. Hence, a better consecutive 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 have to arrive to S before the i^{th} one has reached D, but it also has to reach D before the i^{th} one does. 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), only I_{i+1} and V_{i+1} are unknowns. Let $H_i(v)$ be the probability of retaining a bundle given that the speed of the i^{th} vehicle is v.

$$H_i(v) = Pr\left[I_{i+1} + \frac{d_{SD}}{V_{i+1}} < \frac{d_{SD}}{v}\middle| V_i = v\right] \tag{2}$$

We denote by H the average probability of holding a bundle. It follows from probability theory that:

$$H = \int_{\forall v} H_i(v) \times f_{V_i}(v)dv \tag{3}$$

It follows that the release probability is given by $P_r = 1 - H$. Thus, we propose a Probabilistic Bundle Relaying Scheme (PBRS) whereby each time a vehicle enters the range of the source S and its queue is found to be non-empty, S releases the head of queue bundle to the arriving vehicle with a probability P_r. Otherwise, that bundle is retained until the next vehicle arrives where the same process is repeated again. Consequently, the proposed PBRS algorithm has a running time complexity of $O(1)$ which makes it efficient and practical.

A. Simulation and Results:

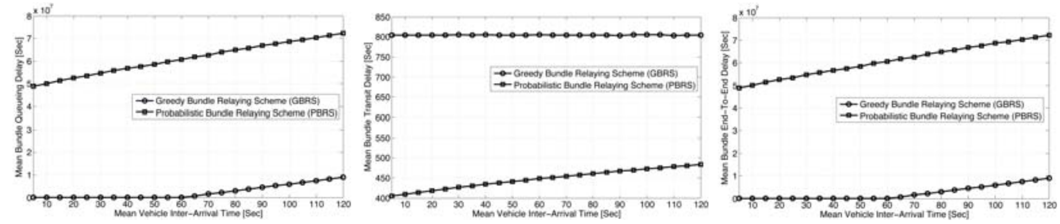
A Java-based discrete event simulator was developed to examine the improvement that the proposed PBRS incurs on the mean bundle transit delay in the context of the sample VDTN shown in Figure 1. The mean bundle transit delay achieved under a Greedy Bundle Relaying Scheme (GBRS) served as a benchmark. Under GBRS, the source greedily releases a bundle to every arriving vehicle. The transit delay was evaluated for a total of 10^6 bundles and averaged out over multiple runs of the simulator to ensure that a 95% confidence interval is realized. The following assumptions were made:

1) Bundle transmissions are instantaneous.
2) Vehicle inter-arrival time $I_i (i = 1, 2, ...)$ is exponentially distributed with mean $\frac{1}{\mu} \in [5; 120]$ (secs).
3) Bundle inter-arrival time T_B is exponentially distributed with mean $\frac{1}{\lambda} = 60$ (secs).
4) An arriving Vehicle's speed V_i is drawn from a uniform distribution over the range $[10; 50]$ (m/sec).
5) The source-destination distance d_{SD} = 20000 (m).
6) A vehicle's speed remains constant during its entire navigation period on the road.
7) Release decisions are performed independently for each bundle from one opportunity to another.
8) The source node relays only one bundle per vehicle.

The justifications for assumptions $(1.)$ and $(3.)$ through $(8.)$ were presented in [3]. In addition, we note that the Random Waypoint Model and Random Direction Mobility Traces are most suitable for use in the context of VDTN networks. However, it has been proven that such realistic mobility traces exhibit exponential-tailed distribution in terms of meeting and inter-meetig times [4]. Consequently, the exponential distribution for vehicle inter-arrival times in assumption $(2.)$ is used to first keep our model tractable, and second to parallel the mobility traces obtained from realistic models.

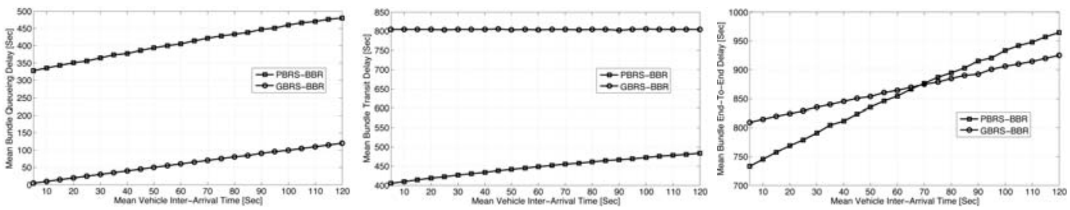
Furthermore, we observe throughout our study that vehicular density plays a major role in determining the performance level of both PBRS and GBRS. In fact, this density is determined by three parameters namely: $a)$ The vehicle inter-arrival time, $b)$ The vehicle speed, and $c)$ The coverage range of S. The ratio of C_S and V_i determines the i^{th} vehicle residence time in the range of S, R_i. Hence, if I_{i+1} is less than R_i, therefore multiple vehicles will be found in the range of the source. Recall that, V_i is uniformly drawn from a given fixed range of values that conform with the norms of allowed speeds on highways. Thus, the values of R_i vary in a fixed range and are implicitly computed within the course of the simulation process. Moreover, the values of I_{i+1} are exponentially distributed with parameter μ and have a mean $\frac{1}{\mu}$ which is a user-controlled input to the simulator that is varied from very small up to large values in order to ensure that the performances of both GBRS and PBRS are studied under high, medium and low vehicular densities. This justifies why all the simulation results are a function of the mean vehicle inter-arrival time. As illustrated in Fig. 2(a), the mean vehicle inter-arrival time has a major impact on the SRS queue's load status. Notice that, for GBRS, whenever $\frac{1}{\mu} < \frac{1}{\lambda}$, the queue is stable (i.e. underloaded) and hence bundles are subject to relatively low queueing delays. However, the queueing delay significantly increases as the queue becomes overloaded. The same occurs under PBRS. However, under PBRS, the queue is always overloaded even in the stability region. This is due to the fact that whenever vehicle inter-arrivals are short, an SRS using PBRS will hold the head-of-line bundle for much longer periods of time until the best release opportunity occurs (i.e. The arrival of a very high speed vehicle that is able to achieve the lowest transit delay). This is why the queueing delay under PBRS is significantly higher than its GBRS counterpart. Nevertheless, PBRS significantly outperforms GBRS in terms of the mean transit delay as shown in Fig. 2(b). This can be explained as follows. GBRS is a scheme that does not differentiate between slow and fast vehicles and greedily releases bundles to both irrespective of the length of the vehicle inter-arrival times. In contrast, under PBRS, vehicles to which bundles are released have relatively high speeds. This justifies the relatively low mean transit delays for PBRS in Fig. 2(b).

Observe that, under both GBRS and PBRS, bundles suffer excessive queueing delays. Clearly, the average queueing delay is several orders of magnitude greater than the mean transit delay. Particularly, the transit delay improvement of PBRS over GBRS is overshadowed by the excessive queueing delay as shown in Fig. 2(c). In fact, under such circumstances, both schemes become ineffective. However, we noticed that enabling both schemes to release a bulk of bundles each time an opportunity arises, will allow PBRS to remarkably outperform GBRS in terms of average end-to-end delay. This is investigated further in the following section.



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

Fig. 2. Delay performance of PBRS versus GBRS.



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

Fig. 3. Delay performance of PBRS-BBR versus GBRS-BBR.

III. PBRS WITH BULK BUNDLE RELEASE

In the VDTN scenario shown in Fig. 1, consider that $C_S = 200$ (m). The source and vehicle communicate using the IEEE 802.11 protocol where the maximum data unit size is $B_{max} = 1500$ (bytes), transmitted within 12 (msec) if the utilized data rate is 1 (Mbps). Recall that, under PBRS, a single bundle is released per opportunity. In the worst case, a vehicle with speed 50 (m/sec), resides in S's range for 4 (sec). As such, there will be 3.988 (sec) of wasted time during which no bundle transmissions occur. This considerably impacts PBRS's performance as the bundle queueing delay significantly increases. In this section, we propose an improved version of PBRS, the Probabilistic Bundle Relaying Scheme with Bulk Bundle Release (PBRS-BBR) that efficiently compensates for this wasted time. Furthermore, we relax the assumption of a fixed bundle size in [3] and assume it is uniformly distributed in the range [30;1500] (bytes). Under PBRS-BBR a bulk of size L may be released per opportunity. In fact, S instantly computes the residence time R_i, of the i^{th} arriving vehicle to which it keeps on releasing bundles up until either this vehicle exits its range or its queue becomes empty.

A. Simulation Results:

First Bulk Bundle Release (BBR) greatly improves the performance of both GBRS and PBRS. Fig. 3(a) and 3(b) respectively show that the queueing delay decreased significantly under both PBRS-BBR and GBRS-BBR whereas these two schemes conserved the same mean transit delay performance as PBRS and GBRS. However, BBR improved the overall mean end-to-end delay performance of PBRS relative to GBRS as reflected in Fig. 3(c). In fact, in the stability region the queue is empty most of the time or else it may contain very few bundles that all of them are often highly likely to fit within a single bulk and released in an opportunity. Originally the queueing delay for those bundles under GBRS was relatively low. Under GBRS-BBR, we cannot deny that this queueing delay is improved. However, this improvement is negligible compared to the one that the BBR-enabled version of PBRS witnesses. PBRS-BBR inherits from PBRS the luxury of holding bundles in the queue for longer time periods and hunt for the vehicle that will be able to achieve the lowest possible transit delay given a particular vehicle inter-arrival time. For low vehicle inter-arrival times, vehicles arrive at the source faster and hence PBRS-BBR will take advantage of this and hold bundles in the SRS's queue for longer periods of time. It is true that, during this waiting time, more bundles may accumulate in the queue and contribute in the overall elevation of the average queueing delay. However, PBRS-BBR will smartly compensate for this accumulation by sending as much bundles as possible in a single bulk during an opportunity. As such, the overall end-to-end delay of PBRS-BBR is significantly lower than that of GBRS-BBR.

IV. CONCLUSION

We studied the performance of the Probabilistic Bundle Relaying Scheme (PBRS) and Greedy Bundle Relaying Scheme (GBRS). While GBRS greedily releases bundles to all passing vehicles, PBRS uses vehicles that best contribute to the minimization of the mean transit delay. Simulations showed that PBRS outperforms GBRS in terms of the mean transit delay. However, the excessive bundle queueing delays experienced under both schemes rendered them practically ineffective. Bulk Bundle Release (BBR), a simple yet very lucid twist, remarkably improved the performance of PBRS and GBRS. Our reported results show that PBRS-BBR significantly outperforms GBRS-BBR in terms of the mean end-to-end delay whenever the SRS queue is stable.

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