Which Vehicle To Select?

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***Abstract*—In wireless networking, an *Opportunistic Bundle Release Mechanism* (OBRM) is a data bundle forwarding mechanism characterized by its ability to operate over Intermittently Connected Networks (ICNs) where end-to-end paths are not continuously available. Known for their intrinsic connectivity intermittence, vehicular networks constitute an ideal recreation ground for OBRMs. This letter, proposes the Optimal Vehicle Selection OBRM (OVS-OBRM) with the objective of minimizing the average bundle delivery delay.**

***Index Terms*—DTN, vehicular, performance evaluation, bundle.**

I. Introduction

VEHICULAR networking consists of transforming vehicles into intelligent mobile entities that wirelessly communicate with each other as well as with stationary roadside units (SRUs). Due to the random nature of vehicular mobility and the relatively high vehicle speeds, a vehicular network's topology becomes highly dynamic and prone to recurrent link intermittence. Hence, timely information delivery becomes a gruelling task, the realization of which intersects with several underlying challenges. This letter revolves around*Opportunistic Bundle Forwarding Mechanisms*(OBRMs) in the context of inter-SRU delay minimal information delivery. These have, thus far, received little attention and are further investigated herein. An OBRM is a bundle (*i.e.* message) forwarding mechanism where nodes are exploited as *store-carry-forward* devices whose forwarding decisions are exclusively based on the synchronic turns of events.

As opposed to typical *Mobile Ad-Hoc Networks* (MANETs), *Intermittently Connected Networks* (ICNs) operate beyond the end-to-end hypothesis. That is whenever end-to-end paths do not exist and mobility is exploited to establish time-limited connectivity. Here, conventional MANET forwarding mechanisms fail but OBRMs prevail. This is especially true since a node adopting an OBRM makes a forwarding decision based on contemporaneously available choices. Known for their intrinsic intermittent connectivity, vehicular networks set an ideal recreation ground for OBRMs.

In [1], the authors established a Markov decision process framework to minimize the transit delay. This framework is complex and unrealistically based on a complete network knowledge oracle. The authors of [2] considered infrastructure-based vehicular networks and investigated SRU placement problem and its impact on end-to-end connectivity probabilities under different communication channel models. However, they did not account for the variations of vehicle speeds as a function of density especially that these parameters have a direct impact on connectivity and channel characteristics. The work of [3] addresses the joint connectivity and delay-control problem in the context of a highly restrictive vehicular mobility model where, irrespective of the vehicular density and flow rate, vehicles navigate at only two speed levels namely, a low and a high speed.

This letter aims at achieving delay-minimal inter-SRU bundle delivery in the context of *Two-Hop Vehicular ICNs* (TH-VICNs) where SRUs are completely isolated Under such circumstances, the source SRU S will opportunistically exploit vehicles passing by as *store-carry-forward* devices that will physically transport its bundles to the destination SRU D. For this purpose, the Optimal Vehicle Selection OBRM (OVS-OBRM) is proposed. Under OVS-OBRM, every time a bundle is to be released, S wisely selects, among all vehicles present within its coverage range, the one that contributes the most to the minimization of the average bundle delivery delay.

As opposed to [1], OVS-OBRM is completely network information oblivious since vehicles are selected based solely on the instantaneous turn of events. Furthermore, OVS-OBRM enables S to continuously release bundles as long as vehicles are present. This will potentially reduce the mean queueing delay experienced by the schemes in [1]. Finally, unlike [1]–[3] this present study borrows rudimentary principles from Vehicular Traffic Theory. These principles allow the selection of appropriate traffic flow and vehicle speed distributions in order to parallel the realistic behavior of vehicular traffic. To the best of our knowledge, OVS-OBRM is the first network information unaware mechanism that is simple, practical and based on realistic modeling of vehicular traffic. To evaluate its performance, two other OBRMs namely: *i*) Random Vehicle Selection OBRM (RVS-OBRM) and *ii*) Fastest Vehicle Selection OBRM (FVS-OBRM) are developed with the same spirit and will serve as benchmarks together with the Probabilistic Bundle Relaying Scheme with Bulk Bundle Release (PBRS-BBR) that is borrowed from [7]. Due to space limitation the reader is referred to [7] for a complete description of PBRS-BBR. However, the description of the three OBRMs studied herein is detailed next.

II. Opportunistic Bundle Forwarding Mechanisms

A. Network Scenario:

Consider the scenario illustrated in Figure 1 which depicts a large uninterrupted (*i.e.* no intersections, traffic lights, STOP signs, etc.) highway segment [*EX*] experiencing light-to-medium vehicular traffic. Several SRUs are deployed along

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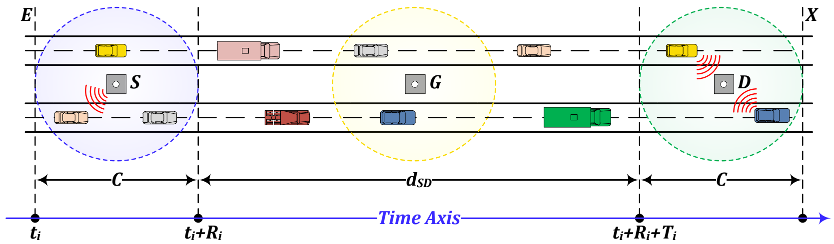

Fig. 1. Two-hop vehicular intermittently connected network scenario.

[*EX*]. Due to the elevated communication infrastructure setup costs, only a very small number of these SRUs, known as *gateways*, are connected to the Internet. The rest are completely isolated. Connectivity is to be established between two isolated SRUs, a source S and a destination D. S has a coverage range that spans a distance C of the highway. S and D are separated by a distance $d_{SD} \gg C$. In the absence of all sorts of networking infrastructures, vehicles navigating at distinct speeds enter the range of S at random times and are opportunistically exploited as *store-carry-forward* devices that transport bundles to D. No inter-vehicle communications may occur. Under such conditions, an intermittence-free S-D path does not exist. A network of this type belongs to a subclass of vehicular networks referred to as *Two-Hop Vehicular Intermittently Connected Networks* (TH-VICNs).

B. Vehicular Mobility:

Suppose that an arbitrary vehicle i ($i > 0$) with speed v_i enters the communication range of S at a random time t_i. In the sequel, such an event will be referred to as the i^{th} vehicle arrival. Subsequently, vehicle $i+1$ with speed $v_{i+1} \neq v_i$ arrives at time $t_{i+1} > t_i$. Let $I = t_{i+1} - t_i$ denote the vehicle inter-arrival time. Following the fundamental principles of traffic theory in [4] and the work of [7], I is exponentially distributed with a parameter $\mu = \rho\overline{v}$. μ is the traffic flow rate into segment [*EX*], ρ is the vehicular density and $\overline{v}$ is the average vehicle speed. Also, from [4], vehicle speeds vary as a function of ρ. The derivation details of speed-density relationship are outside the scope of this letter. However, the three major outcomes that are highly relevant to this present study are the following. First, the average speed is $\overline{v} = v_{lim}\left(1 - \frac{\rho}{\rho_{max}}\right)$ where v_{lim} is the maximum allowed speed limit and ρ_{max} is the maximum sustainable vehicular density over [*EX*]. The second important outcome is that vehicle speeds vary according to a truncated Normal distribution $\widehat{f_V}(v) = K \cdot \aleph(\mu, \sigma)$ where K is a normalization constant resulting from truncation (derivation details in [4]), $\sigma = k\overline{v}$ $(0 < k < 1)$, $v_{min} = \overline{v} - m\sigma$, $v_{max} = \overline{v} + m\sigma$ $(2 \leq m \leq 4)$ and the two-tuple (k, m) are determined based only on experimental data [6]. The third outcome is that, under light and medium traffic density, the per vehicle speed remains constant during the entire navigation period over [*EX*]. However, S becomes aware of the speed of an arriving vehicle only at the arrival time of this latter.

Vehicle i resides within S's coverage range for a time period $R_i = \frac{C}{v_i}$ and departs at time $t_i + R_i$. It is assumed that S is equipped with sensors that enable it to determine the instantaneous position of vehicle i within its range. As soon as vehicle i departs from S's coverage range, it travels during a time period $T_i = \frac{d_{SD}}{v_i}$ before it enters the coverage range of the destination D at time $t_i + R_i + T_i$. At this time, the bundle delivery may take place.

C. Description Of The OBRMs Under Study:

Unlike [1], the above acquired knowledge preserves the essence of *Delay-/Disruption-Tolerant Networking* (refer to [6]) since it pertains to vehicles that are only present within the coverage range of S. Hence, interest lies in taking as much advantage as possible of this knowledge in order to achieve delay-minimal bundle delivery. This is the objective of the OBRMs which are described next.

From [4], it is observed that the higher the vehicular density, the more likely it becomes to find multiple vehicles simultaneously within the coverage range of S. However, since S has only one radio, then it can communicate with only one vehicle at a time. For the purpose of our study we assume that S always has a bundle to transmit. Denote by N the number of vehicles within the coverage range of S. Thus, three cases are distinguished as depicted in Figure **??**, namely: 1) $N = 0$ where no bundle release can take place, 2) $N = 1$ where bundles are continuously released to the vehicle until it goes out of range and 3) $N > 1$ where, for each bundle to be released, one vehicle is selected and the bundle released to it. While cases 1 and 2 seem to be trivial, case 3 is not. In order to achieve a delay-minimal bundle delivery to the destination SRU, an intuitive but often misleading choice is to release bundles to the fastest among all currently present vehicles within S's coverage range. This is especially true since the speed alone is not sufficient to take the right release decision. Knowledge of the speed v_i of an arbitrary vehicle i has to be complemented with the knowledge of that vehicle's position x_i with respect to the entry point into the source's coverage range (*i.e.* point E in Figure 1). This enables S to determine the residual travel time τ_i of each vehicle present within its range where $\tau_i = \frac{\text{residual travel distance}}{\text{vehicle speed}} = \frac{C - x_i + d_{SD}}{v_i} = \frac{C - x_i}{v_i} + T_i$. Accordingly, among all vehicles present within the coverage range of S, the vehicle to which corresponds the minimum residual travel time is the first one to reach the destination. Hence, in order to achieve the earliest possible bundle delivery, that vehicle must keep on receiving from S one bundle after the other until either it goes out of range or possibly a new vehicle arrives and exhibits a larger contribution to the minimization of the average bundle delivery delay. We refer to the above-described bundle release procedure as the Optimal Vehicle Selection OBRM (OVS-OBRM). The term *optimal* is used to highlight the fact that, in light of the ongoing vehicular traffic conditions and given the presently available vehicles and their status (*i.e.* speed and position), the selected vehicle is the only one able to achieve the earliest bundle delivery.

In addition, two other OBRMS, namely: *i*) Fast Vehicle Selection OBRM (FVS-OBRM) and *ii*) Random Vehicle Selection OBRM (RVS-OBRM) are developed. These OBRMs perform similarly to OVS-OBRM in cases 1 and 2 but differ in handling case 3. Under the FVS-OBRM, every time *S* has a bundle to release, it selects the fastest available vehicle irrespective of its position. However, under RVS-OBRM, *S* uniformly selects one of the available vehicles to carry the bundle irrespective of its speed and position.

Note that, under the three above-presented OBRMS, an arriving vehicle associates with *S* by submitting information such as an ID, speed, position and association time using a procedure similar to the one of typical WLANs which requires minimal overhead. *S* maintains and updates information of associated vehicles until they go out of range. This is easily done without communicating with the vehicles. Also, upon vehicle selection, *S* broadcasts a bundle together with the selected vehicle's ID. This vehicle receives the bundle and carries it to *D*. This broadcast procedure has no associated overhead.

III. Simulations and Performance Evaluation

An in-house Java-based discrete event simulator was developed to examine the performance of OVS-OBRM. FVS-OBRM, RVS-OBRM and PBRS-BBR will serve as benchmarks. The average bundle end-to-end delay is used as a performance metric. This delay is composed of two components, namely: *a*) the*queueing delay* being the amount of time a bundle spends in *S*'s buffer ever since its arrival until it gets released to a vehicle and *b*) the *transit delay* being the amount of time a bundle spends in the vehicle's buffer ever since it gets released to that vehicle until it gets delivered to *D*.

The three OBRMs and PBRS-BBR are tested under light and medium vehicular traffic densities $\rho \in [0.005; 0.1]$ $\left(\frac{vehicles}{meter}\right)$. The typical IEEE 802.11 protocol is used with a data rate of 1 (*Mbps*). Increasing this rate leads to a faster bundle release to vehicles but does not alter the the OBRMs' switch-over policies. *S*'s coverage range is $C = 200$ (*meters*) and the source-destination distance $d_{SD} = 2000$ (*meters*). Bundles arrive at a rate $\lambda = 1$ $\left(\frac{bundle}{second}\right)$. The bundle size is fixed and equal to the maximum transmission unit (MTU). According to [6], $(k, m) = (0.3, 3)$. Delay metrics were evaluated for a total of 10^7 bundles and averaged out over multiple simulator runs to ensure a 95% confidence interval. Figures 2(a)-2(c) concurrently plot the queueing, transit and end-to-end delays respectively achieved by the four schemes.

Remarkably, Figure 2(a) shows that the queueing delay achieved by the three OBRMs are all equivalent and almost zero for all values of ρ. In fact, as opposed to the schemes presented in [1] and PBRS-BBR, when adopting any of the OBRMs currently under study, *S* will not waste any release opportunity. Every time *S* has a bundle to transmit and vehicles are present, then a bundle will surely be released to one of those vehicles. In other words, *S* will never hold bundles in its buffer unless there are absolutely no vehicles within its coverage range. A close examination of the simulations' input parameters and the variation of the average vehicle speed as a function of ρ leads to the conclusion that, at the lightest value of ρ, the average vehicle residence time will slightly bypass the average inter-arrival time. This means that: *a*) an arbitrary vehicle is found dwelling alone within the range of *S* during almost its entire residence time and *b*) very shortly before that vehicle departs, another vehicle comes in. Therefore, *S* is continuously supplied with bundle release opportunities. Observe that increasing ρ further will ameliorate this supply as the number of vehicles found simultaneously within the coverage range of *S* will increase to the point where, at relatively medium density values, *S* will often be able to empty its buffer. Under such conditions, an arriving bundle will readily find a vehicle to hop into and will hence experience zero queueing delay. In contrast, under PBRS-BBR, *S* will hold bundles in its buffer until the appropriate vehicle arrives. Even though, PBRS-BBR enables *S* to release bundle bulks, the amount of bundles that accumulate in *S*'s buffer until the arrival of the suitable vehicle is large. Hence, *S* can only release a subset of these bundles to the selected vehicle. The remaining bundles will have to further queue until the arrival of the next suitable vehicle. This situation arises especially under light vehicular traffic where vehicle arrivals are spaced out in time allowing more bundles to accumulate in the buffer. This explains why the achieved queueing delay under PBRS-BBR is much larger than that of the studied OBRMs respectively. As the vehicular density increases, the arrival of a suitable vehicle becomes faster causing less bundles to accumulate in the queue. As a result, the queueing delay decreases. Figure 2(a) is a tangible proof of the exclusive efficiency of the studied OBRMs in reducing queueing delays.

The curves pertaining to the transit delay performance of OVS-OBRM and the three benchmarks are concurrently plotted in Figure 2(b). This figure shows that PBRS-BBR achieves an average transit delay that is much larger than the three OBRMs under study. This is primarily due to the probabilistic nature of *S*'s decision. In other words, there are chances that, under PBRS-BBR, *S* misses precious fast vehicles only because it predicts that subsequent ones may, with a certain probability, be faster. This may turn out not to be the case. Also, since vehicle speeds follow a truncated Normal distribution, it becomes more likely that arriving vehicles have speeds that are close to the average speed. Nevertheless, the arrival of relatively higher speed vehicles is still possible with small probabilities. Missing these opportunities results in an increase in the transit delay. In addition, under PBRS-BBR the decision is taken on a per bulk basis rather than on a per bundle basis. This means that, once *S* selects a vehicle, it keeps on transmitting bundles to that vehicle until it goes out of range without accounting for the fact that during this time other faster vehicles may arrive. This increases the chances of loosing faster vehicles and further increases the transit delay.

Under RVS-OBRM, all vehicles within the range of *S* are equally likely to be chosen irrespective of their position and speed. Therefore chances are that, under RVS-OBRM, *S* chooses a slow vehicle. This choice becomes worse if the chosen slow vehicle happens to be closer than others to the entry point of the coverage range. Under FVS-OBRM

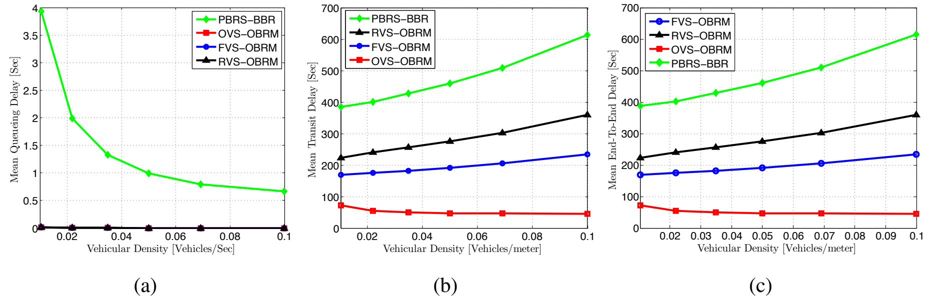

Fig. 2. Contrasted delay performance evaluation of FVS-OBRM, OVS-OBRM, RVS-OBRM and PBRS-BBR.

and OVS-OBRM slow vehicles are completely ignored unless there are no other choices (*i.e.* either all vehicles are relatively slow or there is only one present vehicle and it is slow). With regard to FVS-OBRM, S will select the fastest possible vehicle irrespective of its position. However, sometimes this vehicle may be closer to the entry point of the coverage range. Thus, even if it is the fastest, it has a longer distance to travel and might not reach the destination SRU before a vehicle that is a bit slower but located towards the exit point of the coverage range. Consequently, FVS-OBRM improves the transit delay when compared to RVS-OBRM but this improvement is not optimal. OVS-OBRM, however, exhibits the minimal transit delay since S accounts for both the residual distance and the speed of the vehicles before making the right choice. The choice will fall only on that vehicle that is determined to reach the destination before all others (*i.e.* the vehicle that has the shortest residual travel time).

Notice that, whenever ρ increases $\overline{v}$ decreases. However, the number of vehicles within the range of S will increase. The cumulative effect of these two events is an increased possibility that, under RVS-OBRM and PBRS-BBR, S's choice falls on slower vehicles. This explains the quasi-linear growth of the average transit delay achieved under these two schemes as a function of ρ. Also, as ρ increases, the transit delay achieved under FVS-OBRM increases. This increase is mainly due to the fact that S is mislead to choose the fastest vehicle irrespective of its position. The more ρ increases, the larger the fraction of such misleading choices become. Under OVS-OBRM, notice that the transit delay tends to stabilize. Recall that the range of speeds is $[v_{min}, v_{max}]$ and notice that both v_{min} and v_{max} decrease symmetrically as a function of ρ. It follows that the more ρ increases the tighter the range of speeds at which vehicles navigate becomes. Under such conditions, if an observer visualizes the roadway segment from an helicopter, it would seem that all the vehicles seem to be forcefully constrained to navigate at the same speed [4]. Due to this, and seeing that there are always vehicles that are closer to the exit point of its range, S will wisely try to compensate for the low vehicle speed and choose those vehicles since they have the least distance to travel and will reach the destination before others. Now, since the queueing delays are negligible when compared to the transit delays, the average end-to-end delays achieved by the OBRMs under study and PBRS-BBR are dominated by their achieved transit delays and exhibit similar behavioural patterns as shown in Figure 2(c).

Finally, note that this letter focuses on achieving a delay-optimal bundle transportation from S to D through an optimal vehicle selection strategy applicable at the source in the absence of any *a priori* knowledge of vehicle arrival times and speeds. However, it is worthwhile to mention that at the destination's side, multiple vehicles may be in range. All of these vehicles need to offload the carried bundles to D. This may be achieved through the use of TDMA or random access-like protocols. Being outside this letter's scope, this has been left out as a future work.

IV. Conclusion

This letter presented an empirical performance evaluation of an Optimal Vehicle Selection OBRM (OVS-OBRM) in the context of a two-hop vehicular intermittently connected network (TH-VICN) under light and medium traffic conditions. This study is founded on top of a realistic vehicle mobility model that allows for the accurate selection of vehicle inter-arrival time and speed distributions. OVS-OBRM is network information unaware as it solely adapts to the ongoing turn of events and selects the vehicle that achieves the optimal queueing-transit delay tradeoff. The PBRS-BBR scheme proposed in an earlier work and two other OBRMs, namely: *i*) Random Vehicle Selection OBRM (RVS-OBRM) and *ii*) Fast Vehicle Selection OBRM (FVS-OBRM) served as benchmarks. Under RSV-OBRM, S uniformly selects one of the presently available vehicles. However, under FSV-OBRM, the fastest available vehicle is always selected. Extensive simulations revealed that OVS-OBRM remarkably outperforms the other three benchmarks.

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