Content Downloading in Vehicular Networks: Bringing Parked Cars Into the Picture

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***Abstract*—Content access and downloading in vehicular environments is expected to heavily rely on the availability of roadside infrastructure. Although vehicle-to-vehicle communication is foreseen, data will mostly flow through roadside access points, or RSUs (RoadSide Units), which suffer from less connectivity problems. However, at least in the early stages of deployment, the RSU coverage will be spotty, or limited to main avenues in urban areas. In this paper, we try to address such shortcomings by investigating the possibility of exploiting parked vehicles to extend the RSU service coverage. Our approach leverages optimization models aiming at maximizing both the freshness of the content that downloaders retrieve and the efficiency in the utilization of radio resources. Performance evaluation highlights that the use of parked vehicles enhances the benefits of the content downloading process and leads to a significant offload of the RSUs, with respect to the case where only mobile relays are used.**

I. Introduction

Given the multitude of emerging applications in the Intelligent Transportation Systems (ITS) domain, emphasis is currently given to the integration of heterogeneous Inter-Vehicle Communication (IVC) techniques. Applications range from time-critical safety information disseminated using short range communication to entertainment applications primarily using cellular networks [1]. In this spectrum, we focus on content downloading from centralized systems to moving vehicles. We aim to show that this can also, and very efficiently, be supported using short-range communication techniques instead of relying on 3G/4G networks only. Content downloading has become the primary application in Delay Tolerant Networks (DTNs) [**?**]. It is obvious that vehicular networks will similarly benefit from this service primitive.

Short-range communication for IVC will mainly rely on the DRSC/WAVE protocol stack, using IEEE 802.11p [2] as the underlying communication protocol. DSRC/WAVE supports a number of service channels (the number depends on the allocated frequencies on the different continents) as well as a control channel. The service channel can be used for arbitrary applications (initially, the idea was to assign channels to specific applications, but given the multitude of applications, this will not be possible).

In this paper, we investigate content downloading from a central entity to moving vehicles using Roadside Units (RSUs) (frequently also called Access Points (APs)) placed along the streets following the ideas presented in [3]. Unfortunately, in realistic scenarios, it will not be possible to expect a high number of RSUs in urban scenarios, mainly due to cost restrictions but also due to the high maintenance overhead. As a novel concept, we therefore introduce the use of *parked vehicles* to support the content downloading process. Parked vehicles have been shown to be perfectly distributed in urban scenarios to support IVC [**?**], [4].

Previous work on content downloading in vehicular networks dealt with individual aspects of the process, such as the deployment of RSUs [5], [6], the performance evaluation of IVC [7], or the network connectivity [8], [9]. In our previous work [3], we quantified the actual potential of IVC based content downloading. In this paper, we aim to answer the question to what degree the use of parked vehicles helps in this process and what the associated costs are.

Given a mobility instance, we can obtain the optimal data scheduling. The ideal case (upper bound) is for a perfect mobility prediction and simplified assumptions at both the PHY and the MAC layer. Such conditions allow us to easily solve the optimization problem and carry out a qualitative study. The traces we used in the evaluation process have been generated using the Veins simulation framework and in particular the SUMO simulator [10]. We used a scenario in the city of Ingolstadt that has been carefully validated based on measurement data of road traffic flows in this city, distributing parked cars according to satellite imagery [4].

The key contributions of this paper can be summarized as follows:

- We show the potentials of using parked vehicles in addition to RSUs or APs for content downloading to moving vehicles. According to our results, the use of parked vehicles greatly benefits the content downloading process.
- We carefully study the impact of the number of parked vehicles, their ability to create a dynamic backbone infrastructure, and the impact of the locally available energy capacity for supporting the content download.

In the rest of the paper, we first present in Sec. II the system model and the optimization problems that we formulate, in order to maximize the freshness of the content that vehicular users can download, and the efficiency in the radio channel utilization. Then, in Sec. III we show the benefit of involving parked vehicles in the download process, in terms of both content freshness and channel utilization. Finally, in Sec. IV we draw our conclusions and point out future research directions.

II. System Model and Optimization

Given a vehicular mobility instance, we represent the network and its temporal and spatial dynamics as a time-expanded graph [3]. Specifically, we discretize the time into time steps, by adopting the same granularity used in the given mobility instance. Then, we represent each network node (RSUs or vehicles) at a given time step as a vertex in the graph, and wireless links existing at different time instants as directed edges connecting the vertices.

Each edge is associated to a finite weight, representing the network-layer data rate that can be achieved by transmitting over the link at the corresponding time step. In the following, we will consider the data rate to be a function of the inter-node distance (although we will employ values based on experimental results), and we will use the terms link and edge as synonyms. Also, for brevity, we will denote by I2M (I2P) the links from RSUs to moving (parked) vehicles, by M2M (P2P) the links from a moving (parked) vehicle to another, and by P2M the links from parked to moving vehicles.

We stress that edges connecting vertices that model the same RSU, or parked vehicle, over time represent the possibility that such nodes store data for a given period, while the edges modelling the same mobile over time allow us to represent the possibility that a vehicle physically carries data during its movement. Since we assume that the memory capabilities of any node are significantly larger than the content size, all edges of this type are associated to an infinite weight. Also, note that modelling the duration of the contacts between network nodes, instead of considering them as atomic, allows us to account for channel contention (see [3] for further details).

Finally, we model the server(s) (from which RSUs retrieve the data) as a vertex named α. The graph is completed with edges of infinite capacity, from α to any vertex representing an RSU.

By using such a time-expanded graph model, we study the performance of content downloading services for users travelling aboard vehicles and, more precisely, on downloading of content updates. We assume that a set of n content items are available and that a moving vehicle becomes interested in either downloading an item for the first time, or refreshing an already cached item, according to a Poisson distribution with rate λ. We also assume that the user interest lasts for a constant time period T. We refer to a vehicle that is engaged in the data retrieval process as a *downloader*.

Each content is updated at the server at time instants that are Poisson distributed with rate ρ (the extension to time-varying update rates as well as to content-depending rates is straightforward). The content update size is denoted by $S(c)$ ($c = 1, \ldots, n$). The update size, along with the weight of the edge representing a link between any two nodes, defines the content transfer time over that link. If the link fails, an interrupted transfer of a content version can be resumed through other links that may become available.

In this context, we take as metrics of interest:

- the *content freshness*: the average number of new versions of the content that each user manages to download throughout its trip across the road topology;
- the *radio resource utilization*: the efficiency in radio channel utilization during data downloading.

Thus, below, we formulate two optimization models that aim at maximizing, respectively, the content freshness and the efficiency in radio resource utilization.

A. Maximizing the content freshness

Let us focus on the generic downloader d and define the freshness associated to such a user as:

$$\phi_d = \sum_{k \in \mathcal{W}_{d,c}} \frac{1}{S_c} \sum_{v \in \mathcal{V}^k} \sum_i \left(v \cdot x_k^v(i,d)\right) \quad (1)$$

where

- $\mathcal{W}_{d,c}$ is the set including the time steps at which d is interested in content c,
- $\mathcal{V}^k$ is the set of all content versions that have become available before time step k,
- i denotes the node (RSU or vehicle) such that a link from i to d exists at time step k, and
- $x_k^v(i,d)$ is the amount of data bytes, belonging to content version v, that can be transferred on such a link.

Then, we formulate the following optimization problem so as to maximize the freshness over all downloaders:

$$\max \sum_d \phi_d \,. \quad (2)$$

Note that the above formulation could be easily extended to take into account a constraint on the maximum time for which each parked vehicle can be used.

By solving the problem in (2), we obtain the optimal scheduling of data traffic over all existing links. That is, we can derive the value of the variables $x_k^v(i,j)$'s representing the amount of data to be transferred over the network links at any time step.

B. Maximizing the radio efficiency

Next, we formulate a different optimization problem: we set a target value of freshness, Φ, to be achieved, and aim at minimizing the medium utilization.

To this end, we identify a number of "check points" across the road layout, which are located according to a regular grid with cell side equal to 100 m. At each of these locations, we compute the wireless channel utilization as seen by a node located at that position. We denote by I_p ($0 \leq I_p \leq 1$) the fraction of channel idle time observed at check point p, and pose the following non-linear optimization problem:

$$\min \sum_p (1 - I_p)^2 \quad (3)$$

$$\sum_d \phi_d \geq \Phi \quad (4)$$

where the sum in the objective function is over all selected check points, while the sum in (4) is over all downloaders.

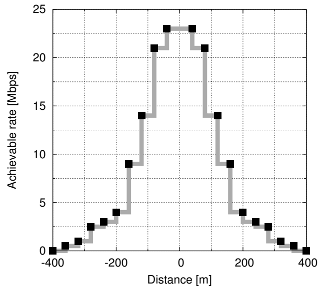


Figure 1. Characterization of the achievable network-layer rate as a function of distance, based on experimental data

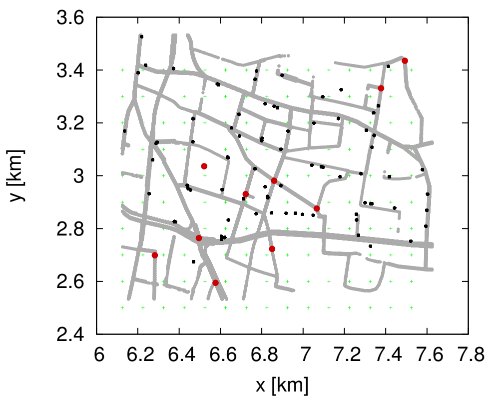


Figure 2. Road topology. Grey dots represent mobile vehicles, black dots represent parked vehicles, red ones represent RSUs. Green crosses mark the "check points".

We point out that the expression of the objective function we chose leads to a solution that reduces the channel load (i.e., $(1 - I_p)$) mainly in the most congested zones. Furthermore, since this function is convex, the problem can be solved in polynomial time.

III. Performance Evaluation

Here, we first detail the reference scenario we use to derive our performance results. Then, in Sec. III-B we show the content freshness and channel idle time that can be obtained by solving the optimization problems introduced in (2) and (3), under the following conditions: (i) an exact mobility prediction is available, and (ii) simplified assumptions on the physical and MAC layers hold. These results therefore represent an upper bound to the system performance.

A. Reference scenario

Our reference scenario is that of [4], accurately modeling road and lane topology, building layout and parking places, as well as vehicular traffic patterns in a 1.5×1 km^2 section of the urban area of Ingolstadt in Germany. Specifically, the mobility traces we used in the evaluation process have been generated using the Veins simulation framework and the SUMO simulator [10]. The scenario then has been carefully validated through measurement data of road traffic flows in the city of Ingolstadt, distributing parked cars according to satellite imagery [4].

The scenario models 963 vehicles travelling over the road topology, with an average trip time of 388 s and an average vehicle density of 69.28 vehicles/km^2. There are also 80 parked vehicles, which are present at each time step. We fix the number of available RSUs to 10. Fig. 2 shows a snapshot of the road layout, including the positions of parked (in black) and moving (in grey) vehicles, as well as RSUs (in red).

All nodes use the IEEE 802.11p technology. The value of the achievable network-layer rate between any two nodes is adjusted according to the distance between them. To this end, we refer to the experimental results in [**?**] to derive the values shown in Fig. 1, and we use them as samples of the achievable network-layer rate. Note that we limit the maximum node transmission range to 200 m, since, as stated in [**?**], this distance allows the establishment of a reliable communication in 80% of the cases.

Finally, for clarity we consider one content item only (i.e., $n = 1$), and we set $\lambda = 0.005$, $\rho = 0.02$, $T = 30$ s, and $S = 10$ Mbytes.

B. Optimal data scheduling with perfect mobility prediction

As mentioned above, we provide an upper bound to the system performance, by assuming that an exact mobility prediction is available, which is given by the aforementioned vehicular trace. Also, in order to easily solve the optimization problem and carry out our qualitative study, the physical and MAC layer aspects are represented in a simplified manner, through the time-expanded graph network model.

As a baseline scenario, we consider a network where all relays are mobile and no parked vehicles are enabled; thus, only I2M and M2M links can be exploited. Then, we include (part or all of) the parked vehicles present in the Ingolstadt trace and solve the optimization problems by exploiting links involving also such vehicles. More precisely, we consider two different ways to use parked vehicles. In the former, referred to as *no backbone*, parked vehicles can receive and transfer data using, respectively, I2P and P2M only. Instead, in the latter, referred to as *with backbone*, we assume that parked vehicles can form a backbone by exploiting P2P links among themselves, i.e., data can flow from an RSU, through one or more parked vehicles, and be eventually delivered to downloaders.

Furthermore, with the aim to investigate the impact of the available M2M links, for each of the above scenarios, we solve the optimization problems over different graphs, which are obtained by progressively removing the existing M2M links. Specifically, we solve the problems over the full graph, then we randomly remove *vertices* representing vehicles that do not request content updates but that can only relay traffic for others. Such vertices are removed till a fraction R of the original relay traffic is phased out. For a given value of R, we solve the optimization problems again, using the corresponding pruned graph.

By using the time-expanded graphs obtained as described above, we first maximize the content freshness, i.e., the formulation in (2). The level of content freshness that is attained is shown in Fig. 3 as R and the fraction of parked vehicles that can be used vary.

In the plots, the curves labeled by "no park" refer to the baseline scenario. As expected, increasing the number of involved parked vehicles and building a backbone positively affect freshness, showing the important role of parked vehicles in content downloading. In particular, when few parked vehicles are exploited, removing M2M links (i.e., $R = 0.5$) impairs the performance; however, when more than 20% of parked vehicles can be employed, they easily make up for the unavailability of mobile relays.

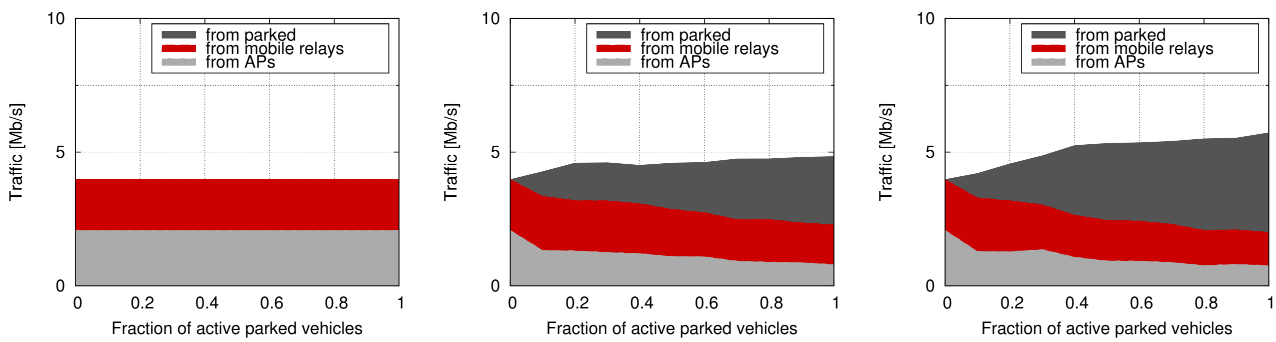
This is confirmed by the plots in Fig. 4, which depict the amount of traffic that downloaders receive directly from RSUs, other moving vehicles, or parked vehicles. Due to the limited impact of R, here we consider that all M2M links can be exploited (i.e., $R = 0$).

Consistently with the previous figure, the plots show that when parked vehicles, and especially when both P2M and P2P, can be used, the amount of data that such vehicles manage to deliver towards downloaders increases significantly. Also, as more parked vehicles can be used, less and less data traffic is originated from RSUs and the impact of mobile relays is significantly reduced.

In Fig. 5, we present the amount of data transmitted by the RSUs, split into three parts: data towards parked vehicles, mobile relays and downloaders. Comparing this figure to Figs. 3 and 4, it is clear that parked vehicles storing an information item (or part of it) are more effective relays than moving vehicles. Indeed, since they remain on the road topology much longer, they provide the same data to more than one downloader. It follows that the load on RSUs, as well as on mobile relays, can be greatly reduced while maintaining very good performance in terms of content freshness.

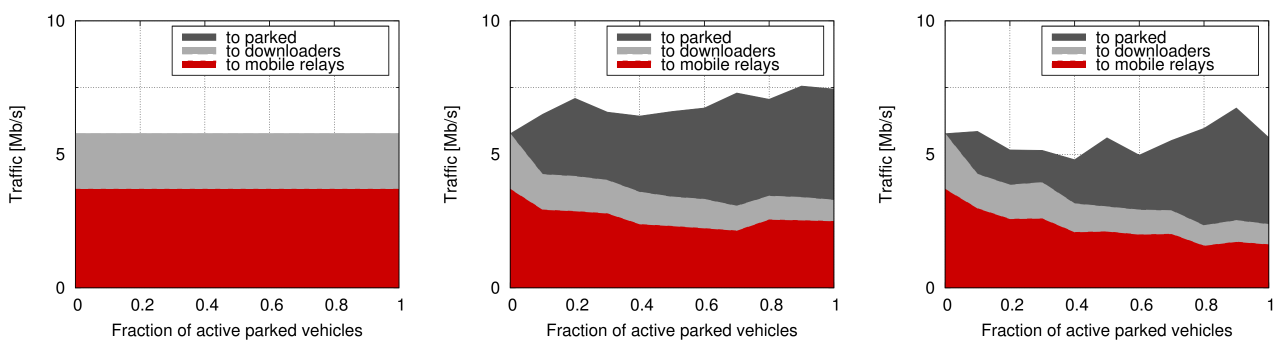
Next, we focus on maximizing the channel idle time (as in (3)), and present the results for three different target values of the freshness, Φ. Such values are set to fractions of the maximum content freshness achieved over the different scenarios (see Fig. 3). The average and 10-th percentile of the resulting fraction of idle time are depicted for both the no backbone and with backbone cases, respectively, in the top and bottom plots of Fig. 6. Note that in the "no park" case, only low-medium values of target content freshness are feasible, and that, in any case, the performance is poorer than when parked vehicles are used. Again, a backbone of parked vehicles is very beneficial, as it results in an increased idle time. Interestingly, the bottom plot underlines that such an effect is particularly evident in the most congested zones of the road topology, suggesting that the goal we aimed at while designing the objective function in (3) has been achieved.

Finally, in order to get some insight on the data delivery delay, in Fig. 7 we show the average number of hops traversed by the data, from the node storing them to the intended downloader. The top plot, which refers to the case where content freshness is maximized, highlights that the use



(a) (b) (c)

Figure 4. Traffic to downloaders for the cases "no park" (a), "no backbone" (b), and "with backbone" (c).



(a) (b) (c)

Figure 5. Traffic from RSU for the cases "no park" (a), "no backbone" (b), and "with backbone" (c).

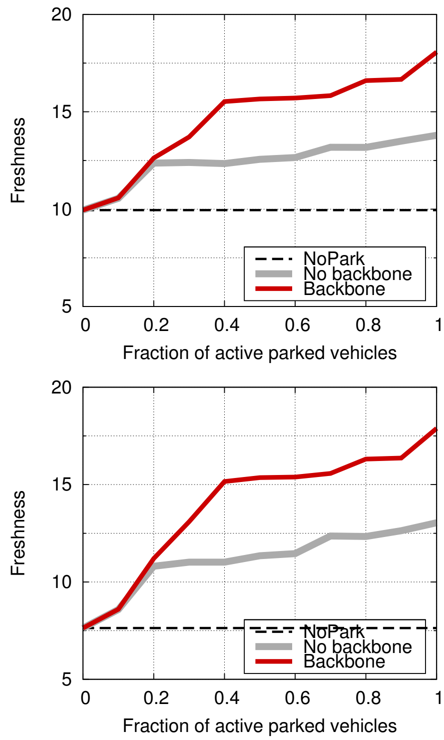


Figure 3. Freshness as a function of the maximum time period parked vehicles can be used as relays, for $R = 0$ (top) and $R = 0.5$ (bottom).

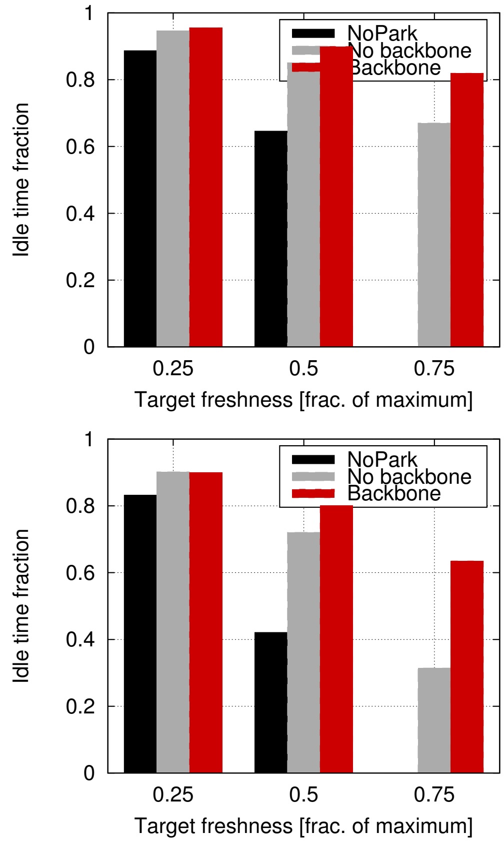


Figure 6. Average (top) and 10-th percentile (bottom) of the idle time at check points, with and without backbone and for different values of of target freshness.

of parked vehicles gives an advantage also in terms of data delay. Indeed, such vehicles can store content and provide the users with it in place of the RSU, thus speeding up the process. When a backbone is built, the number of parked vehicles that are involved in the delivery process, hence the delay, quickly increases as the fraction of parked vehicles that can be used grows. However, looking at Fig. 3, we note that this also leads to an increased content freshness. The case where the channel idle time is maximized is depicted in the bottom plot, where half of the parked vehicles can be used. Consistently with the results in the top plot, for such a scenario, the average number of hops traversed by the data is higher in presence of the backbone (but the obtained channel idle time is higher too), while the "no park" case again gives poor performance.

IV. Conclusions

We studied content downloading in vehicular network with the added twist of enlisting the support of parked cars in order to extend RSU service coverage. We proposed optimization models with the goal of maximizing the content freshness and the utilization of radio resources, showing the remarkable contribution that parked vehicles can have on vehicular downloading efficiency.

As future work, we intend to integrate the optimization framework in realistic simulations, using an imperfect mobility prediction and more accurate models for the physical and MAC layers. This will allow us to assess the existing gap between the upper bound we derived in this work and the performance that one may expect in a real-world scenario. Simulations will account for the protocol messages that enable (i) vehicles to periodically notify a central authority about the route they intend to take, (2) the optimizer to notify the suggested data flows schedule to the vehicles, and (3) downloaders to retrieve the desired content.

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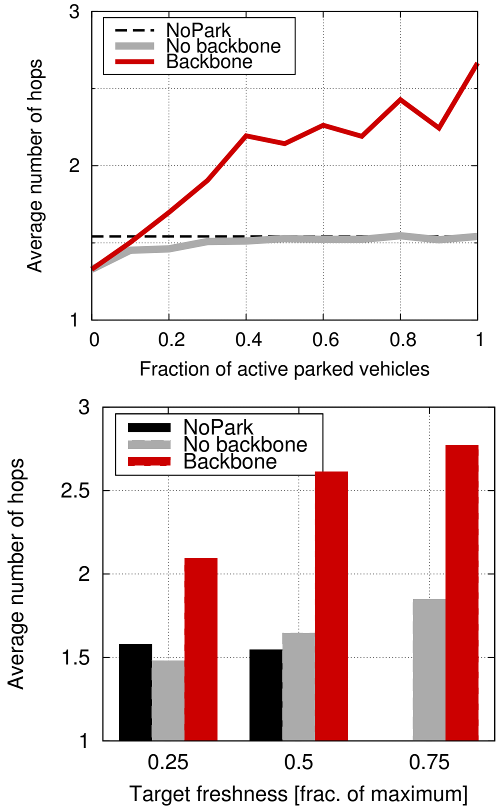

Figure 7. Average number of hops traversed by data traffic that downloaders successfully receive, when freshness (top) and idle time (bottom) are maximized.

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