Strategies to Plan the Number and Locations of RSUs for an IEEE 802.11p-based Infrastructure in Urban Environment

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ABSTRACT

In this paper, we propose different strategies to efficiently deploy RSUs in a city with the ultimate goal of having an 802.11p-based infrastructure to deliver Internet services. Unlike most existing works, (i) our strategies' only prior information is the average density of vehicles in the studied area, and (ii) they rely on the forecast of a performance model of 802.11p to assist and guide their choices regarding the location of RSUs. With the help of two simulators, namely SUMO and ns-3, we investigate the behavior of each strategy in three scenarios inspired by the street map of real-life major cities. Our findings are twofold: (i) we demonstrate that any efficient RSUs deployment is tightly tied to the specifics of the considered city (namely, the arrangement of streets and the spatial density of vehicles); (ii) the best strategy is not to position RSUs where the traffic density is at its highest, nor at the street junctions where the traffic density is often at its highest but instead where they will be able to deliver the target QoS to a maximum number of vehicles.

CCS CONCEPTS

• **Networks** → **Network simulations**; **Network performance analysis**.

KEYWORDS

IEEE 802.11p, SUMO, ns-3, vehicular networks.

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1 INTRODUCTION

The automotive industry is undergoing rapid transformation paving the way to electric, connected, and ultimately driverless vehicles. In this perspective, the deployment of a network infrastructure capable of supporting multiple services can represent a key element to improve the passengers' travel experience. As for the choice of the communication technology, 802.11p standard represents a natural potential candidate. Unlike alternatives such as cellular technologies (e.g., 5G or 6G), the frequency bands used by 802.11p are free of use and thus represent an asset for a stakeholder both in terms of cost and convenience. The infrastructure would then be primarily comprised of RSUs (Road Side Units) scattered across the area to cover and wired connected to a WAN (Wide-Area Network). Each RSU acts as a gateway to connect the nearby vehicles that have subscribed to the multi-service platform. Figure 1 illustrates the considered scenario in which RSUs scattered across a city are providing connectivity such as content streaming to passing-by vehicles. For instance, in the case of a VoD (Video on Demand) application, video frames are first transmitted from the back-end (cluster of) server(s) hosting the videos to the RSUs over high-speed wired links before being broadcasted on radio channels with 802.11p to vehicles.

There are still fundamental questions left unanswered about the implementation of a multi-service network infrastructure capable of supporting throughput-intensive applications to passing by vehicles. Among those questions are where and how many RSUs should be deployed, especially when considering a dense urban area like the downtown of a city. Should RSUs be mostly deployed in the locations where the vehicle density is at its highest? Figure 1

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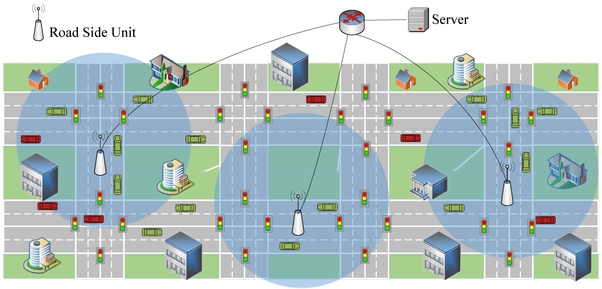


Figure 1: Overview of the considered IEEE 802.11p-based architecture to deliver connectivity to passing-by vehicles in an urban context.

illustrates a possible RSUs' deployment over an urban scenario. In recent years, several works focusing on different aspects related to the planning of vehicular networks, and specifically with the location of RSUs, have been published [8, 11, 12].

These previous works mostly differ from our current paper through their assumption regarding vehicular traffic. [8] and [11] assume the full knowledge of trajectories for each vehicle whereas in our work we will make the less restrictive/demanding assumption that only the average density of vehicles over the area of interest is known. [11] and [12] consider a multi-hop network where vehicles forward traffic for the other vehicles. In this paper, traffic is transmitted exclusively between RSUs and vehicles which is a more realistic assumption for a multi-service network providing non-free services. Note that in our previous works [2, 3], we studied the performance delivered by an infrastructure composed of RSUs through the knowledge of vehicle density as well as the use of an analytical model of 802.11p, initially introduced in [1]. However, unlike the current paper, both studies were dealing with the much simpler case of major freeways wherein vehicle trajectories are predictable. In summary, the key contributions of our proposal and the differences with respect to other studies are as follows:

- As input data, our proposed strategies only require the knowledge of the vehicle density in the areas of the city where the network infrastructure deployment should be planned.
- To the best of our knowledge, we are the first to include an analytical performance model of network communications in our strategy to assist and guide the RSUs deployment.
- As a result of the two previous items, our strategies scale well with the size of the considered areas (e.g. that can correspond to the complete downtown of a large city) and the number of vehicles.

This paper is organized as follows. In Section 2, we detail how we simulate vehicular traffic and wireless communication. Section 3 is devoted to the description of the different strategies for the deployment of RSUs. We evaluate the strategies in Section 4. Section 5 concludes this paper.

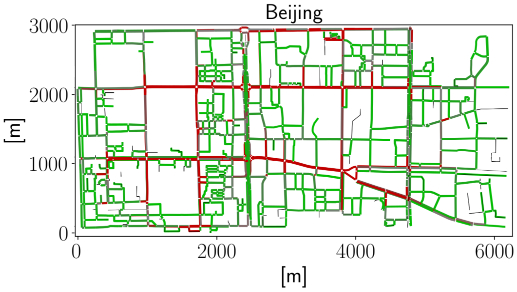


Figure 2: One of the three city maps considered in the paper. The density of vehicles is represented by the color of the street segments: Red corresponds to a high level of vehicles per space unit while Green refers to a low degree.

2 VEHICULAR MOBILITY AND NETWORK SIMULATIONS

In this work, we have used and adapted existing simulation environments. Specifically, we chose SUMO (Simulation of Urban MObility) [5] and OSM (OpenStreetMap) [7] to generate urban environments, roads and moving vehicles, and we selected the ns-3 network simulator [6] to evaluate the wireless communications using IEEE 802.11p access technology.

We consider three different excerpts of city maps, namely Beijing, Berlin, and Manhattan (see Figure 2) that we imported from OSM repositories. OSM is a free-to-use and crowd-sourced dataset that provides accurate real maps of the world. Note that we used the *Netconvert* [10] tool to convert the OSM digital maps into road network files readable by SUMO.

We use different SUMO traffic generation tools to generate vehicle trajectories in realistic urban scenarios with two types of traffic. On the one hand, we use the RT tool to generate background traffic which represents vehicle trajectories whose objective is to introduce some congestion on the map. This tool generates a set of random trips within a time interval, including the road network, simulation time, vehicle definition, and arrival rates. On the other hand, we generate deterministic traffic with OD2 and DUARouter. Deterministic traffic sets a priori the routes from an origin until a destination for specific vehicles. This deterministic traffic serves as probing traffic as we will use it to collect measurements on the corresponding vehicles and validate the forecasting model used in our deployment strategies in dense urban scenarios.

To simulate the network communication, we resort to the network simulator ns-3 version 3-29. We use the IEEE 802.11p standard, whose radio ranges and transmission rates are given in Table 1. As for the upper layer, we use a client/server video application where the video is sent by the server and played by the vehicles. To this end, we have used real traces [9]. As for the radio propagation loss model, following the recommendations of [4] for urban scenarios, we rely on the Friis model with the parameter values suggested in [4]. Table 2 summarizes the main parameters used by ns-3 for the simulation of the networking layers.

In our scenario, whenever a vehicle enters within the reach of an RSU, it starts to download traffic (as fast as it can) until it leaves the coverage range of that RSU.

Table 1: Description of the 6 communication zones of IEEE 802.11p occuring with the combination of the Ideal WiFi manager of ns-3 and the Friis propagation model.

Zone number	Length (meters)	Transmission rate, T_j (Mbps)	Achievable throughput, A_j (Mbps)
H6	60	27	12.69
H5	80	18	9.9
H4	92	12	7.5
H3	110	9	6.02
H2	126	6	4.34
H1	144	3	2.35

Table 2: Description of the networking layers.

ns-3 IP stack	Parameter	Value
Application	TCP congestion control	New Reno
MAC	MAC Helper	NqosWaveMacHelper
	Wi-Fi Manager	ns-3 Ideal Wi-Fi manager
Physical	Phy standard	802.11p
	Propagation Loss Model	Friis

Algorithm 1: Baseline of strategies

```
Inputs : Density matrix, $D$; Penetration rate, $p$; Target QoS, $q$; Covering rate, $\alpha$.
Result: A set of RSUs with their location.
1  X=0 //The current proportion of served vehicles.
2  $D = p * D$
3  Total_Density= $\sum_{(i,j)} D_{i,j}$
4  while $X < \alpha$ do
5      $(i, j) = argMax_{(i,j)} f(\text{D}, (i, j))$ //Compute the best location for the new RSU
6      $c = served(D, (i, j), q)$ //Compute the proportion of vehicles in range(i,j) that can be served
7      $veh\_cov = c \cdot \sum_{(k,l) \in range(i,j)} d_{k,l}$ //Compute the number of vehicle served
8      $X = X + \frac{veh\_cov}{Total\_Density}$
9      $D = update(D, (i, j), c)$ //Remove the vehicles that are served by the new RSU from the matrix $D$
10 end
```

3 PROPOSED STRATEGIES

To assist and guide the positioning of RSUs in an urban area, we propose and investigate three different strategies.

3.1 Forecasting the performance of 802.11p

To obtain estimates of the throughput attained by each connected vehicle for the area of interest and the locations of the RSUs, we repurpose the analytical model from [1]. Note that the model forecasts account for the different zones around an RSU in which the transmission rate negotiated between the RSU and vehicles differ (see Table 1). Despite its relative simplicity, the model was found to yield estimates that differ only by 24% with those delivered by the simulations using ns-3 and SUMO. For more details, we refer the interested reader to [3] where the same model was used for the simpler case of a major freeway. This analytical model is involved as a building block for the proposed strategies.

3.2 Key Parameters

We introduce the following key parameters and the corresponding notations.

Density matrix, D. This matrix indicates, at a fine resolution, the average density of vehicles in every part of the area of interest. More precisely, the city map is divided into small squares of equal size (e.g., 10x10 meters) in which the mean number of vehicles is measured. The corresponding measurements are ordered in a matrix, denoted by $D = (d_{i,j})$. As previously said, in our case, we use SUMO to obtain a realistic D matrix for the city maps of interest.

Penetration rate, p. Because not all vehicles will subscribe to the Internet service provided by the RSUs, we introduce a parameter for the penetration rate denoted by p ($0 < p \leq 1$). It simply indicates the proportion of vehicles that are expected to subscribe to the Internet service.

Target QoS, q. A vehicle is considered as having its QoS satisfied if it can download at a minimum rate of q Mbps. Throughout this section, we refer to vehicles able to download at a rate higher than q as being served.

Covering rate, α. An RSU deployment is considered accomplished whenever the proportion of connected vehicles that are served (i.e., can download data at a rate higher than q Mbps) exceeds α ($0 < \alpha \leq 1$).

3.3 Definition of the Strategies

The goal of any considered strategy is to find the minimum set of RSUs (and their location) so that a proportion α ($0 < \alpha \leq 1$) of the connected vehicles can download data at a rate higher than q Mbps.

We assume that the density matrix for the area of interest, D, as well as the values of the parameters p, q and α are known from the strategies.

All proposed strategies are based on a greedy algorithm that, at each iteration, positions a new RSU at the location that maximizes a given criterion. The strategies differ from each other through the definition of this criterion. Initially, the deployment is void of RSUs; the stopping criterion is met whenever a proportion α of the connected vehicles are able to download at a minimum rate of q Mbps.

Algorithm 1 describes the steps taken by each strategy at each iteration. It revolves around the following three key functions:

- $range(i, j)$ returns the set of indexes of the matrix D that are in the radio range of an RSU located at (i, j).
- $served(D, (i, j), q)$ returns the proportion of vehicles in the radio range of an RSU located at (i, j) that can receive a throughput of at least q Mbps. This proportion is computed using the performance model discussed in Section 3.1.
- $update(D, (i, j), c)$ removes a proportion c of vehicles in the radio range of an RSU located at (i, j).

While Algorithm 1 sets the general framework for an efficient RSU deployment strategy, it can be instantiated in different ways considering different definitions for the function $f(.)$ (see line 5 of Algorithm 1). We consider the three possible options for $f(.)$:

- Strategy **Max density**: Positioning a new RSU at the location where the density peaks. Hence, $f(D,(i,j)) = d_{i,j}$.
- Strategy **Max density radio range**: Positioning a new RSU at the location that maximizes the number of vehicles falling within its radio range (regardless of their performance). Hence, $f(D,(i,j)) = \sum_{(k,l)\in range(i,j)} d_{k,l}$.
- Strategy **Max vehicles served**: Positioning a new RSU at the location that maximizes the number of vehicles being served (i.e., downloading at least at q Mbps). Hence, $f(D,(i,j)) = served(D,(i,j),q) \cdot \sum_{(k,l)\in range(i,j)} d_{k,l}$.

4 NUMERICAL RESULTS

Note that looking at the throughput computation and at the strategies baseline, it is easy to notice that any RSUs deployment depends on p and q only through their product $p.q$. For this reason, we restrict our investigation to the impact of the penetration rate p on the RSUs deployments and do not consider different values for the QoS parameter q, which is set to 1 Mbps throughout this section.

4.1 Comparing the strategies

Figure 3 compares the different strategies defined in Section 3.3 for a density of 300 vehicles per km^2, a target QoS of q = 1Mbps and a penetration rate of p = 30%. We notice that the **Max vehicles served** strategy outperforms the other strategies as it requires fewer RSUs than the others regardless of the level of the covering rate α. This owes to the fact that the latter strategy directly operates on the quantity that we aim at optimizing: α which represents the proportion of vehicles served. For instance, for the city of Beijing, 223 RSUs suffice to set the value of α to 90% with **Max vehicles served** strategy, as compared to 328 and 266 RSUs with the **Max density radio range** and **Max density** strategies, respectively.

In Figure 4, we show the locations (along with their radio range) of the RSUs selected under the **Max vehicles served** strategy for the city of Beijing. Not surprisingly, RSUs are mostly positioned next to the streets, and more specifically, to those with a lot of traffic.

Figure 3 also shows that the marginal gain over the covering rate α decreases rapidly with the number of RSUs. In the case of the **Max vehicles served** strategy for the city of Berlin, the first 100 RSUs lead α to raise from 0 to 43%, while the same number of new RSUs are needed to increase α from 70 to 91%. In fact, if α were to be set at a higher value than 90%, then many additional RSUs must be deployed. Figure 3 also indicates that all strategies tend to converge for very high levels of α. Note that similar observations were made (and not been shown here for the sake of brevity) for other levels of density and target QoS q. In the remainder of the paper, we focus on the **Max vehicles served** strategy as it has proved to be the most efficient one across the considered scenarios.

4.2 Influence of the penetration rate on the RSUs deployment

Figure 5 shows the evolution of the covering rate α for the city of Beijing as a function of the number of RSUs assuming different levels of penetration rate p, namely 10, 20, and 30%. In general, different penetration rates lead to very different deployments. Indeed, if the number of vehicles to serve is higher, then one can expect a higher number of RSUs to be required. However, it is worth noting that for α =0.9, a penetration rate p of 10% or 20% leads to the same number of RSUs, namely 176. But if the penetration rate is increased to 30%, then the number of RSUs surges to 223. Overall, Figure 5 empirically shows that, along with the city structure of streets and density, the penetration rate p is also an important factor to be accounted for.

Table 3: Mean number of RSUs per kilometer to reach a covering rate, α of 0.7 and 0.9. Strategy: Max vehicles served. Density=300 vehicles per km^2. Target QoS, q=1Mbps. Penetration rate, p=30%.

	Beijing	Berlin	Manhattan
Covering rate, α = 0.7	0.485	0.457	0.384
Covering rate, α = 0.9	0.707	0.704	0.543

Table 4: Number of vehicles required in the simulation to obtain a density value equal to 400 vehicles/km².

City	Number of vehicles
Beijing	7344
Berlin	7812
Manhattan	4292

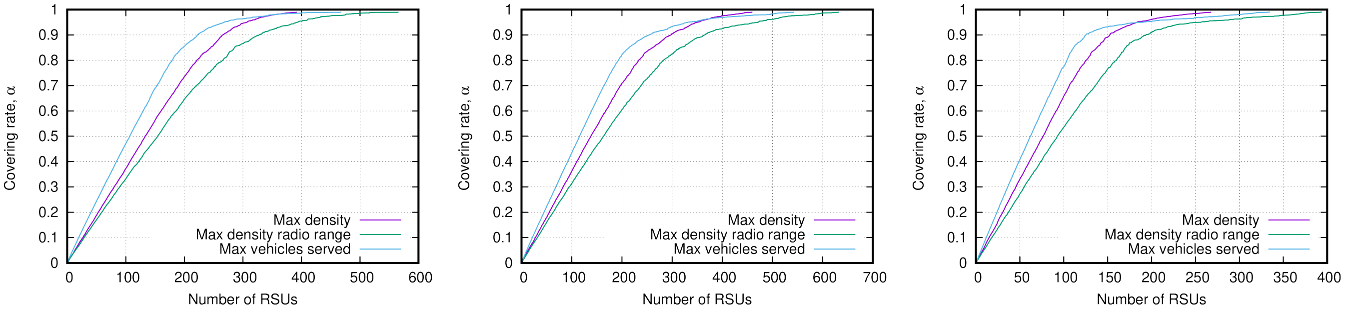
4.3 Evaluating the number of RSUs per kilometer

In Table 3, we show the number of RSUs per kilometer required to reach a covering rate α of 0.7 and 0.9 with a target QoS q of 1 Mbps for each considered city. These results were computed as the ratio of the total number of RSUs deployed in the whole excerpt of the city over the sum of the lanes' length. We observe that while Beijing and Berlin lead to similar values, Manhattan requires a significantly lower number of RSUs per kilometer. This has to do with Manhattan having less vehicles than Berlin and Beijing to obtain a same level of density (see Table 4). Overall, we can conclude from Table 3 that the number of RSUs (and their location) to be deployed strongly depends on the combination of the city map and its traffic distribution, precluding the existence of a one-size-fits-all rule.

5 CONCLUSIONS

In this paper, we proposed and investigated different strategies to efficiently deploy RSUs in a city. Unlike most existing works, we assume that strategies only prior information is the average density of vehicles. The considered strategies rely on the forecast of a performance model of 802.11p to assist and guide their choices regarding the location of RSUs. This makes the execution of these strategies fast as they do not involve time-consuming discrete simulations.

Our findings are the following: First, we demonstrate that any efficient RSUs deployment is tightly tied to the specifics of the considered city (namely, the arrangement of streets and the spatial density of vehicles). In fact, even the number of RSUs required to attain a given level of covering rate can not be forecast just by looking at the specifics of the city. Second, our simulation results consistently indicate that the best strategy is not to position RSUs



(a) Beijing **(b) Berlin** **(c) Manhattan**

Figure 3: Number of RSUs as a function of the covering rate α for the three cities and for the different strategies. Density=300 vehicles per km^2. Target QoS, q=1Mbps. Penetration rate p=30%.

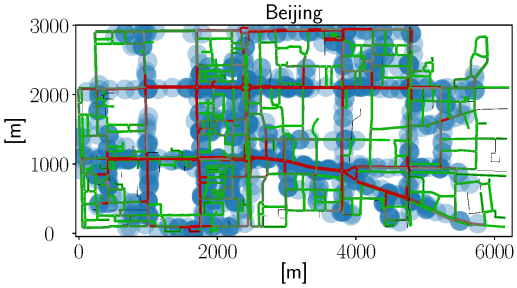


Figure 4: RSUs location in Beijing. Each blue disk represents one RSU and its radio range. Strategy: Max vehicles served. Density=300 vehicles per km^2. Penetration rate, p=30%. Target QoS, q=3Mbps. Covering rate, α=0.99.

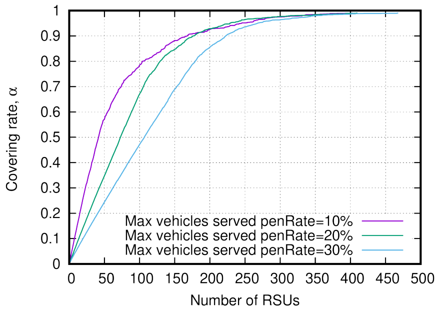


Figure 5: Number of RSUs as function of the covering rate (α) for the city of Beijing and for different penetration rate, p. Strategy: Max vehicles served. Density=300 vehicles per km^2. Target QoS, q=1Mbps.

where the traffic density is at its highest. Instead, the best strategy is to position RSUs where they will be able to deliver the target QoS to a maximum number of vehicles. In future works, we intend to extend our theoretical framework to let the infrastructure operator suggest the best trajectory taking into account the throughput that will have a vehicle entering a city. This feature could be incorporated into modern navigation systems like Waze and Google maps.

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