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Published Version:
Bazzi, A., Masini, B.M., Zanella, A., Pasolini, G. (2015). IEEE 802.11p for cellular offloading in vehicular sensor networks. COMPUTER COMMUNICATIONS, 60, 97-108 [10.1016/j.comcom.2015.01.012].

Availability:
This version is available at: https://hdl.handle.net/11585/518508 since: 2022-03-07

Published:
DOI: http://doi.org/10.1016/j.comcom.2015.01.012

IEEE 802.11p for Cellular Offloading in Vehicular Sensor Networks

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Abstract

The use of vehicles as sensors is a new paradigm to enable an efficient environment monitoring and an improved traffic management. In most cases, the sensed information must be collected at a remote control center and one of the most challenging aspects is the uplink acquisition of data from vehicles, which is presently performed through cellular networks. With the objective to offload cellular networks, in this paper we propose and discuss the adoption of the WAVE/IEEE 802.11p protocols, which represent the state of the art for short range vehicle-to-vehicle and vehicle-to-roadside communications. More specifically, we discuss the system design and assess the cellular resource saving that can be obtained in urban scenarios through the deployment of WAVE/IEEE 802.11p devices on the vehicles and roadside units, evaluating the impact of the percentage of equipped vehicles, of the number of deployed road side units, and of the adopted routing protocol. Results, obtained through an integrated simulation platform taking both realistic vehicular environments and wireless network communication aspects into account, show that the deployment of few road side units and the use of low complexity routing protocols leads to a significant reduction of cellular resource occupation, even approaching 100% with a high density of equipped vehicles.

Keywords: Vehicular sensor network (VSN); cellular networks offload; VANET; IEEE 802.11p

1. Introduction

An increasing number of vehicles traveling worldwide is equipped with sensors and wireless communication devices, denoted on board units (OBUs), aimed at collecting and transmitting information about themselves and their surroundings: the new network paradigm that arises from this scenario is known as vehicular sensor network (VSN) [1]. The vast information collected by vehicles can be used to enable a variety of new services addressing safety, traffic management, smart navigation, pollution measurements, urban surveillance, and forensic investigations. As an example, millions of vehicles are worldwide equipped with sensors (OBUs, smartphones, navigation systems) periodically collecting and storing their position and speed: data are remotely processed by a control center that infers traffic conditions used for route derivation.

This kind of services are all tolerant to some delay: information can be stored by the OBUs even for minutes before being delivered to the control center. Nonetheless, a wireless connection is required and presently only cellular networks are used. The additional data traffic generated by these

☆This manuscript has been accepted for publication in Computer Communications. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all disclaimers that apply to the journal apply to this manuscript. A definitive version will be subsequently published, DOI: 10.1016/j.comcom.2015.01.012
This work was supported in part by the CNR project ICT for smart mobility (ICT4SM).

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Preprint submitted to Computer Communications *February 2, 2015*

services, and the consequent degradation of the cellular network performance, is, therefore, a major concern for network operators and service providers [2, 3].

At the same time, several standardization processes and research activities are addressing short range vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communications [4, 5]. Presently, the wireless access in vehicular environment (WAVE)/IEEE 802.11p protocol stack [6], hereafter simply WAVE, represents the state of the art of short range vehicular communications.

It is worth noting that WAVE cannot be seen as an alternative to cellular networks: in particular, i) it is hardly feasible to equip all vehicles with such technology in short terms, and ii) a very dense roadside unit (RSU) deployment would be required to guarantee an uniform data collection in the spatial domain. On the contrary, WAVE could be used as an added technology to offload part of cellular networks.

In this paper, in particular, we explore the use of WAVE to collect as much data as possible at RSUs, thus reducing the use of cellular communications hereafter denoted vehicle-to-infrastructure (V2I) communications.[1] Numerical results, demonstrating the benefit of this solution, are obtained using an integrated simulation platform that takes into account both the vehicular mobility and the wireless network behavior, thus allowing to reproduce all the relevant aspects of VSNs, from the urban traffic to the communication protocols in their details.

1.1. Definition of Vehicular Sensor Networks and Related Work

As shown in Fig. 1, VSNs can be seen as the intersection between vehicular networks and wireless sensor networks (WSNs). As in vehicular networks, OBUs move in the scenario and the network topology changes continuously. As in WSNs, data generated in the OBUs are typically collected in a control center using wireless communications. Thanks to their mobility, OBUs (with storage capabilities) can also carry data until suitable conditions for data delivery are achieved.

[1]In this paper we will use the V2R notation to denote short range communications between OBUs and RSUs, and the V2I notation to denote the communication between OBUs and remote devices through cellular links.

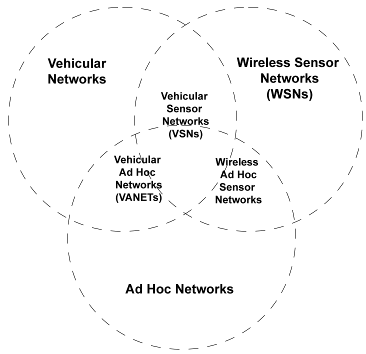


Figure 1: Relationship between various expressions related to vehicular, sensor, and ad hoc networks.

When short range communications are foreseen, VSNs could be seen as particular cases of vehicular delay tolerant networks (VDTNs), recently discussed, for example, in [7], that can be also characterized by a completely ad hoc architecture. Besides this aspect, the main differences between VSNs and VDTNs are that, in the latter, data loss might be tolerated and delivery delays can be unconstrained.

The use of vehicles as communication-enabled moving sensors opens to a number of potential applications, as pointed out in [1], where the VSN acronym firstly appeared. An interesting survey of VSNs and their applications can be found in [8]. Examples are also presented in many related works, where VSNs are envisioned, for instance, to alert upcoming vehicles when an accident is observed [9], to guarantee urban environment surveillance [10], to provide large scale pollution measurements [11], to enable traffic monitoring [12, 13], and to perform civil infrastructure monitoring and automotive diagnostics [14].

Besides possible applications, many other aspects of VSNs have been investigated so far. Data management is discussed, for instance, in [14], where Hull et al. describe the CarTel platform, which provides a simple query-oriented programming interface handling large amounts of heterogeneous data from sensors, even in intermittent and variable network connectivity conditions; security of communication is faced in [15], where a batch signature verification scheme is proposed to achieve efficient authentication, integrity, and validity in VSNs; data dissemination protocols are discussed in [16], where broadcast communication under diverse network densities is proposed to prevent the so-called broadcast storm problem and to efficiently deal with disconnected networks by relying on the store-carry-forward communication model.

In the TrafficView and MobEyes middlewares, described in [17] and [18], respectively, short range communications are exploited to exchange information and create geo-localized contents using a decentralized peer-to-peer approach. The analysis of traffic conditions is addressed in TrafficView, whereas proactive urban monitoring is addressed in MobEyes. Both these works focus on local data processing (possibly with compression and aggregation) as well as on queries and data distribution. An infrastructure-based approach, called SWIM, is proposed in [19]. In SWIM, cellular networks are not considered and the mobile nodes are used to reach the RSUs, denoted Infostations, which collect data to be delivered to a control center.

1.2. Contribution

Although several papers have been published on applications, routing algorithms, as well as performance evaluation of wireless sensor and vehicular networks [7, 20, 21, 22, 23], to the authors' knowledge the use of V2V and V2R communications to offload the cellular networks in VSNs has been only addressed in [24], where preliminary results are shown using simplifying assumptions for physical, MAC, and routing, and in [25], where the focus is on the deployment of a specific field trial.

The burden on the cellular network due to the traffic generated by VSNs is highlighted for example in [2, 26, 27]. Besides the connection costs, the foreseeable increase of the number of OBU equipped vehicles as well as of the generated data will heavily affect the performance of cellular networks, by reducing the transmission quality of both vehicular and non vehicular users. The adoption of V2V and V2R communications is thus an interesting complement to V2I communications.

More specifically, in this paper we address the following questions:

1. Are V2V and V2R short range communications efficient enough to motivate the required technological effort?
2. Is there a significant saving achievable with a limited number of RSUs, thus avoiding the need for huge infrastructure investments?
3. Which technical solutions are needed to enable this scenario? In particular, where should the RSUs be placed and which routing algorithms are suited for the considered application?

1.3. Outline of the Paper

The remainder of the paper is organized as follows. In Section 2, the technical assumptions are discussed, focusing on the application (Section 2.1), the WAVE technology (Section 2.2), the RSU placement (Section 2.3), and the routing algorithm (Section 2.4). The simulation tool and settings are then described in Section 3. In Section 4, numerical results are presented. Finally, our conclusions are drawn in Section 5.

2. Technical Assumptions

2.1. Application Requirements

As depicted in Fig. 2, we consider a scenario where OBUs are equipped with V2I, V2V, and V2R. OBUs collect some data to be delivered to a remote control center. We also assume that:

- Data cannot be modified, in terms of both content and source (data from different OBUs cannot be somehow filtered and aggregated [28]);
- A distributed processing is avoided, thus data management and the long term storage are left to the remote control center;
- Each packet must be delivered to the control center, thus packets that do not reach an RSU must be sent using V2I.

These requirements are strictly needed, for instance, whenever the data could be used for legal purposes or when they are used to derive a driving profile for insurance companies. Less stringent requirements could be foreseen for other applications; however, relaxing the first or second requirement would improve WAVE performance, thus our results can be seen as a worst case, and relaxing the third would frequently cause localized losses of data, undesirable for any VSN application.

2.2. Short Range Communication Technology

In the following, we assume that OBUs are equipped with WAVE; WAVE defines, through the IEEE 1609 specifications, the communication system architecture and the complementary set of services and interfaces for vehicular scenarios; MAC and PHY protocols are described by IEEE 802.11p.

A key feature introduced is the WAVE mode, which allows the transmission and reception of data frames with the wildcard basic service set (BSS)

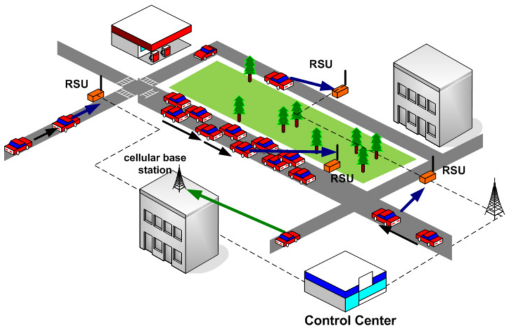


Figure 2: Scenario: vehicles equipped with OBUs integrating both cellular technology for V2I communications and V2V and V2R communication devices.

identity and without the need of belonging to a particular BSS. This feature enables very efficient communication-group setup, reducing the typical overhead required by nomadic IEEE 802.11a/g networks, and can be used for a fast exchange of contextual data. Another peculiarity is that all OBUs are expected to periodically broadcast their identity and position in packets denoted beacons, with the aim to provide each OBU with a real time knowledge of all its neighbors.

In most Countries, IEEE 802.11p will use a variable number of non overlapping channels of 10 MHz each (e.g., 7 channels are foreseen in USA and 5 in Europe), transmitted in the dedicated short range communications (DSRC) band around 5.9 GHz; one of these channels is reserved for control purposes and the others are provided as service channels. Here, we assume the parallel use of the control channel for beacon broadcasting and one service channel for data transmission. This solution guarantees that no resource reduction is caused to the control channel by the addressed service. More specifically, each OBU communicates its position in the control channel with a beacon frequency of 10 Hz, whereas collected data are delivered through the service channel.

2.3. RSU placement

Deploying the VSN, one of the main issues is the efficient location of the RSUs, a topic that has recently gained interest [29, 30, 31].

In this work, we consider and compare three algorithms. In all cases, the objective is to select where to place a fixed number N_{RSU} of RSUs among Ω possible locations L_k, $k \in [1, \Omega]$. The position of the r^{th} RSU, as ordered by the algorithm, will be then denoted RSU_r, $r \in [1, N_{RSU}]$.

1. Contacts (KP-P). This algorithm corresponds to the one denoted KP-P in [30] (the acronym follows the fact that it is a Knapsack Problem that can be solved in polynomial time). Locations are sorted based on the number of vehicles that crossed that location in a given observation time ΔT. More specifically, we denote $n_p(k)$, $k \in [1, \Omega]$, the average number of vehicles per minute that crossed L_k, and we set $RSU_r = L_{w_r}$, $r \in [1, \Omega]$, where w_r is an ordering index such that $n_p(w_1) \geqslant n_p(w_2) \geqslant \cdots \geqslant n_p(w_\Omega)$.

This algorithm requires as input only the number of vehicles crossing the locations of interest in a defined observation interval, which is an information that can be obtained with limited costs.

2. Non repeated contacts (MGP-g). This algorithm corresponds to the one denoted MCP-g in [30] (the acronym follows the fact that it solves a Maximum Coverage Problem through a greedy heuristic). Locations are selected iteratively, based on the number of *new* vehicles, i.e., those that have not been previously counted by other RSUs. More specifically, the location for the first RSU, RSU_1 is chosen like in the previous algorithm, thus $RSU_1 = L_{y_1}$, with $y_1 = w_1$. To select the r-th RSU placement, a new counter $n_p^{(r)}(k) \triangleq n_p^{(r-1)}(k) - m^{(r-1)}(k)$, $r \in [2, \Omega]$, $k \in [1, \Omega]/y_1, ..., y_{r-1}$, is calculated, with $m^{(l)}(k)$ being the number of vehicles that crossed L_k, $L_{y_1}, L_{y_2}, ..., L_{y_l}$. Then, $RSU_r = L_{y_r}$, $y_r \triangleq \{y_r \in 1, ..., \Omega/y_1, ..., y_{r-1} \text{ s.t. } n_p^{(r-1)}(y_r) = \max_{i=1,...,\Omega/y_1,...,y_{r-1}}\{n_p^{(r-1)}(i)\}\}$, with $r \in [2, \Omega]$.

Compared to KP-P, MCP-g tends to favorite the selection of locations that are far to each other and is expected to improve the connectivity level of the network. MCP-g is however harder to implement, since it requires the number of vehicles that cross each possible location as well as their identity (e.g., their license plate).

2. Connectivity improvement (CI). In addition to the previous schemes, we propose a new algorithm, denoted as CI, which aims at maximizing the connectivity level Γ, defined as the average (over time) ratio between the number of OBUs with an existing path towards an RSU (through a single or a multi hop short range connection, regardless of the capacity of the routing protocol to detect the path) and the total amount of OBUs,

$$\Gamma \triangleq \frac{1}{\Delta T} \int_{\Delta T} v_{conn}(t)/v_{tot}(t)dt \qquad (1)$$

where ΔT is the observation interval, $v_{conn}(t)$ is the number of OBUs with an existing path at time t, and $v_{tot}(t)$ is the number of vehicles in the scenario at time t; Γ is thus representative of the connectivity level provided by RSUs.

In CI, $RSU_1 = L_{z_1}$, where L_{z_1} is the location that provides the highest Γ in the case of a single RSU; then, the following RSUs are selected, one by one, in order to maximize the Γ increment. More specifically, once $RSU_1, \ldots, RSU_{r-1}$ are defined, $RSU_r = L_{z_r}$, where L_{z_r} is the location, in the set $\{1, \ldots, \Omega/z_1, \ldots, z_{r-1}\}$, that, added to the set $L_{z_1}, \ldots, L_{z_{r-1}}$, provides the largest Γ increment.

In principle, this algorithm tends to maximize the connectivity level of the network, thus better performance than KP-P and MCP-g is expected. On the other hand, differently from the other algorithms, it is not based on information available through on field measurements, but requires the use of simulations for its implementation.

2.4. Routing Algorithms

If an OBU is under coverage of any RSU, its data is directly transmitted through V2R communications. Otherwise, a routing algorithm is adopted to find the best route towards an RSU through V2V multiple hops. In particular, the routing algorithm searches for a suitable next relay among the neighbor nodes (which are known thanks to the beaconing mechanism).

Packets in the OBU buffer are sent through the V2I connection whenever one of the following "forced cellular transmission conditions", are met: (i) the number of packets inside the transmission buffer reaches a threshold N_{MAX}, or (ii) at least one of the queued packets was generated T_{MAX} seconds before the actual instant. This procedure is detailed in the flow chart shown in Fig. 3.

Concerning the routing algorithm, the peculiar aspect of VSNs is that vehicle mobility makes the wireless links between nodes rapidly varying and difficult to maintain. Differently to WSNs, vehicles carry large capacity batteries and energy is not a primary concern. To select a suitable routing algorithm for VSNs, we now discuss some necessary criteria.

Criterion A.1: anycast routing. The envisioned application requires the adoption of an anycast routing algorithm, addressing any of the deployed RSUs without caring about which one.

Criterion A.2: only unicast transmissions. It is important to minimize data loss, thus only

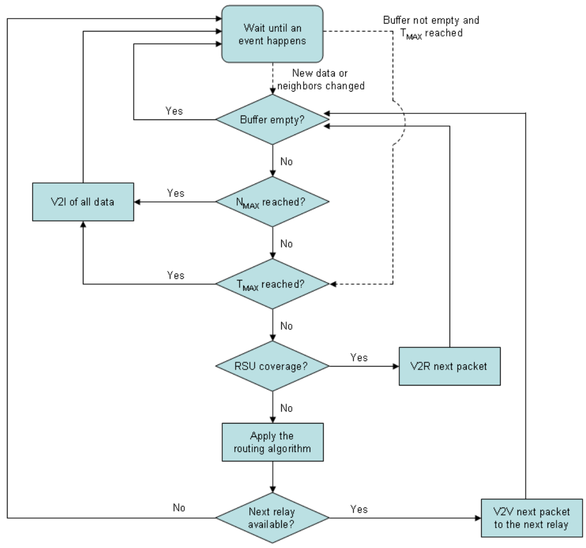


Figure 3: Flow chart description of the OBU transmission buffer management. The dashed arrows correspond to actions performed when an event occurs.

unicast transmissions with MAC level acknowledgments are acceptable.

Criterion A.3: no need for real time. Information is delay-tolerant, thus storing and carrying the messages (until better conditions are available) is possible. In any case, packets that cannot be transmitted to an RSU are transmitted via V2I cellular links when the forced cellular transmission conditions are met.

Criterion A.4: efficiency in both sparse and dense networks. Vehicle density is highly variable depending on the area and the time, thus the routing algorithm should work under all conditions.

Besides these necessary criteria, some additional (suggested) criteria are described in the following to increase the efficiency of the routing algorithms.

Criterion B.1: proactive routing. The continuous exchange of information, available thanks to the beacon frames, makes proactive algorithms implementable with reduced overhead. Moreover, reactive algorithms are less effective with continuously varying links and may suffer of scalability problems, as various experiments confirm [32].

Criterion B.2: no use of road maps. Although sophisticated processing units and memories could be easily accommodated on board of vehicles, here we assume that low cost devices are adopted. Moreover, layout accuracy of maps is guaranteed only at the cost of frequent updates. For these reasons, we avoid the use of road maps.

Criterion B.3: only a single copy per packet. Allowing the creation of multiple copies of a packet has three main drawbacks: first, the higher number of packets increases the network load; second, nodes must somehow share the list of packets in their queue to avoid useless transmissions; third, to avoid unnecessary data exchange and use of cellular resources, an acknowledgement mechanism must be foreseen to drop the copies of a packet that has been already received by the control center. The latter point is particularly critical for two reasons: a) any acknowledgment mechanism increases the network load; b) isolated OBUs cannot be reached.

These criteria exclude most of widely considered routing algorithms for vehicular ad hoc networks (VANETs), including the majority of those described in surveys [7, 33, 34]. For example, CAR [35] cannot be used due to its reactive nature, GSR [36] requires maps on board, while SPRAY&WAIT and EPIDEMIC [37, 38] foresee multiple copies.

Most of routing algorithms that respect the criteria are either based on position knowledge or hop count: in the former case, the route is selected based on the position of each node, while in the latter it is based on the estimated number of hops. For both classes we consider two protocols from the literature and we formalize a new protocol that solves some issue or simplifies the procedure.

2.4.1. Position based algorithms

To implement this class of algorithms, a location service must be available to inform OBUs of the RSU positions. As an example, a database inside the OBU could contain all the RSU positions, and updates could be performed in the case that a new RSU is deployed or an old one is removed.

Two of the position based routing algorithms that have been mostly considered for VANETs are:

- greedy forwarding (GF): the neighbor with minimum distance to destination is selected;
- greedy perimeter stateless routing (GPSR) [39], a modification of GF hereafter detailed.

GF has been widely investigated and most of its variants try to solve the so-called *local minimum problem*, that occurs in VANETs when there is a point on the road map where the distance is minimum compared to all the road segments connected to that point: an OBU near to that point will collect data from all its neighbors, without having a next relay available. GPSR is the most cited protocol trying to solve the problem of local minima: when a local minimum is detected, the OBU enters the perimeter mode to solve the problem. As shown for example in [32] and confirmed in the following numerical results, GPSR is however unable to solve the local minimum problem in vehicular scenarios. Since real time is not required and V2I is available as a backup solution, the local minimum problem might however be acceptable in our scenario.

Another issue of GF is the presence of the ping-pong effect, happening when two vehicles, for example A and B, drive in opposite directions and are not covered by an RSU. If A is going towards the RSU and B, closer than A to the RSU, is going farther, then A will uselessly transmit its data to B, and B will then send back the same data to A. To address this issue, we slightly modify GF into ***vehicular sensor greedy forwarding (VSGF)***, that works as follows (step 3 is applied to hinder the ping-pong effect).

Vehicular sensor greedy forwarding

Algorithm performed by each OBU Θ_i to determine the next hop:

1. Θ_i checks for the nearest (in the Euclidean sense) RSU R_i^*;
2. Θ_i defines the set $\{\mathcal{A}_i\}$ of the neighbor OBUs that are closer to R_i^*, marking all of them as *suitable*;
3. If and only if Θ_i is getting closer to R_i^* (as it results from the comparison of the last two couples of the global positioning system (GPS) coordinates), then it marks as *not suitable* any OBU in $\{\mathcal{A}_i\}$ that is getting farther from R_i^* (as it results from the comparison of the last two couples of coordinates received in the related beacons);
4. If $\{\mathcal{A}_i\}$ is empty or all OBUs in $\{\mathcal{A}_i\}$ are marked as *not suitable*, then no next hop is available for Θ_i. Otherwise, Θ_i assumes as next relay the OBU in $\{\mathcal{A}_i\}$, marked as *suitable*, which is the closest to R_i^*.

Limitation:

- OBUs must know the coordinates of the nearest RSUs.

2.4.2. Hop count based algorithms

This class of algorithms needs some extra fields in beacon frames to broadcast the number of hops necessary by a given OBU to reach an RSU.

Among this class, two interesting protocols are:

- HEAT [40]: it is a hop count based algorithm that weights the suitability of the neighbors as next hops also taking into account the presence of alternatives towards destination;
- the algorithm, hereafter denoted LET, based on the link expiration time (LET) metric [41], that chooses among neighbors with the same number of hops to destination the one with the highest estimated stability of the link (i.e., giving most priority to the link that is likely to last for the longest time).

As numerical results will demonstrate, the additional complexity introduced by these algorithms does not lead to a significant performance improvement. For this reason, using n_h to denote the number of hops towards the nearest RSU, we formalize the simpler ***vehicular sensor distance vector (VSDV)***, that works as follows.

Vehicular sensor distance vector

Algorithm performed by each OBU Θ_i to determine the next hop:

1. Θ_i selects among the neighbors the one θ_i^* with the lowest n_h (hereafter ${n_h}_i^*$) among those that have $\theta_{NH} \neq \Theta_i$ (*restriction 1*);
2. If there is no neighbor with $\theta_{NH} \neq \Theta_i$ or if ${n_h}_i^*$ is not lower than a threshold n_{hMAX} (*restriction 2*), then no next relay is available and Θ_i sets $n_{hi} = n_{hMAX}$ and θ_{NHi} to the default value (e.g., -1); otherwise, Θ_i assumes θ_i^* as next relay and sets $n_{hi} = {n_h}_i^* + 1$ and $\theta_{NHi} = \theta_i^*$.

Limitation:

- Two extra fields, n_h and θ_{NH}, are required in beacon frames.

Restrictions 1 and 2 aim at reducing the *count to infinity problem* that affects the distance vector based routing algorithms. More specifically, restriction 1 avoids that an OBU considers as possible next relay a neighbor that it is presently serving as next relay, since its n_h would not be updated (an approach similar to poison reverse [42]). Restriction 2 introduces a maximum count and implies that no connection to an RSU is allowed when more than n_{hMAX} hops are needed; this approach, adopted in most distance vector implementations, stops a count to infinity after a limited number of steps. The parameter n_{hMAX} is here set to 16, as in most implementations [43]. Note that, using 4 bits for n_h and 48 bits to carry the MAC address of θ_{NH}, less than 7 extra bytes are required in beacon frames.

3. Simulation tools and settings

To take into account the joint effects of vehicular mobility and wireless communications, results have been derived through simulations, performed with the use of VISSIM [44], a vehicular traffic simulator, and the simulation platform for heterogeneous interworking networks (SHINE) [45, 46]. VISSIM is a microscopic traffic simulation tool based on an origin-destination matrix, reproducing movements constrained by the three dimensional structure of vehicles and by road rules. SHINE is a wireless network simulator designed and developed in our laboratories to reproduce the whole network architecture from the application layer to the physical layer.

A summary of the main input and output figures is given in Table 1. Hereafter, all the settings and observed outputs will be detailed.

Scenario. The road-network layout of the reference scenario consists of a portion (1.6 x 1.8 km^2) of the medium sized Italian city of Bologna, as depicted in Fig. 4. For the RSU deployment, discussed in Section 2.3, the 24 junctions where at least four road segments converge are considered. These locations tend to improve radio coverage and take advantage of the presence of power supply, that is typically available for traffic lights [30].

Traffic. Both fluent and congested traffic conditions are considered. The former case is characterized by 150 vehicles/km^2 on average, whereas an average density of 230 vehicles/km^2, with car queues at some junctions, characterizes the latter case.

Sensing and delivering. A parametric portion of vehicles δ ($\delta \in [0, 1]$) is assumed equipped with an OBU. As summarized in Table 2, results will either assume a *low density* of OBUs in the scenario, due to fluent traffic and $\delta = 0.1$, or a *high density* of OBUs, due to congested traffic and $\delta = 1$. The former case corresponds to what can be expected

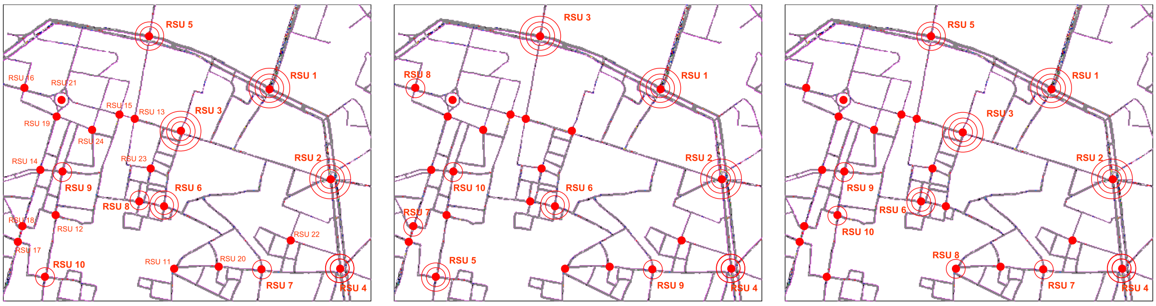
Table 1: Simulation parameters and output figures.

Inputs

Symbol	Meaning	Assumed values
$\mathcal{E}$	Effective radiated power (EIRP)	23 dBm
Pr_{min}	Receiver sensitivity	-85 dBm
G_r	Antenna gain at the receiver	3 dB
γ_{min}	Threshold signal to interference plus noise ratio	10 dB
d_{tx}	Transmission range in the absence of obstacles and interferers	Variable from 50 to 400 m (200 m if not specified)
δ	Rate of vehicles equipped with OBUs	0.1 or 1
B	Payload size of MAC frames	Variable from 50 to 1000 bytes (100 bytes if not specified)
T_s	Period of acquisition from sensors at the OBU	Variable from 0.1 to 30 s (10 s if not specified)
λ	Data generation rate	$1/T_s$ packets/s
T_{MAX}	Time limit before a cellular transmission is required	300 s
N_{MAX}	Maximum number of packets before a cellular transmission is required	1000

Outputs

Symbol	Meaning	Range
Γ	Average rate of OBUs that are connected to any RSU through one or multiple hops	$\in [0, 1]$
S_R	Rate of saved cellular resources	$\in [0, 1]$
h	Average number of hops per packet	≥ 0
Σ	Average number of bits per second collected by RSUs	≥ 0



(a) Contacts (KP-P). (b) Non repeated contacts (MCP-g). (c) Connectivity improvement (CI).

Figure 4: Locations selected for the RSU deployment with the order defined through different algorithms. One or more circles are used to point out the first ten RSUs, 2 or more circles for the first six RSUs, three circles for the first three RSUs.

in a near future inside the major cities in common traffic conditions, while the latter one refers to a wide diffusion of OBUs and rush hour conditions.

The OBU acquires from on-board sensors several vehicle parameters, referred in the following as *measured data* and generates a new packet every T_s seconds, that is, with a data generation rate $\lambda = 1/T_s$ p/s (abbreviation for packets/s). Measured data are stored in the OBU transmitter queue until transmitted to the remote control center, following the procedures and algorithms described in Section 2.4.

Channel Model. We assume that V2V and V2R communications are carried by means of WAVE, and we refer to the following propagation model

$$\mathrm{PL}(d) = \mathrm{PL}_0(1) + 10\beta \log_{10}(d) \qquad (2)$$

where $\mathrm{PL}_0(1)$ is the free space path loss at 1 meter distance, β is the path loss exponent, and d is the

Table 2: Assumed OBU densities.

Density of OBUs	Traffic conditions	δ
Low density	Fluent traffic (150 vehicles/ km^2)	0.1
High density	Congested traffic (230 vehicles/ km^2)	1

distance in meters.

A threshold model is then assumed for the packet error rate, with a shadowing effect due to buildings: a transmission between two devices is possible only if the virtual line connecting them do not cross any building and the received power P_r is higher than the receiver sensitivity $P_{r_{min}}$; a transmission successfully completes if the average signal to noise and interference ratio (SINR) is higher than a threshold γ_{min}, otherwise an error (or a collision) occurs.

This model is similar to the one adopted in previous works, such as [41] and [47], with the addition of the realistic effect of buildings, well motivated for example in [48]. Despite its simplicity, the threshold model is well suited to the characterization of

IEEE 802.11p physical layer performance in real environments, as shown in [49] where measurements are reported.

Defining the *maximum transmission range* d_{tx} as the distance that corresponds to γ_{min} in the absence of obstacles and interference, in the following various values for β (between 2.42 and 3.72) will be considered, corresponding to a different maximum transmission range d_{tx} (between 50 and 400 meters). $d_{tx} = 200$ m is used when not differently specified, corresponding to $\beta = 2.75$, coherently with measurements shown in [50].

Medium access control. The carrier sense multiple access with collision avoidance (CSMA/CA) MAC procedure foreseen by IEEE802.11p is reproduced in details, with the sensing and random access procedures, with collisions and retransmissions, and also including hidden terminals, exposed terminals, and capture effects. The payload of MAC frames is assumed of B bytes, with $B = 100$ bytes if not otherwise specified.

Output figures. The system performance is evaluated in terms of the following metrics:

- S_R, which is the ratio of cellular resources that can be saved through the use of short range transmissions,

$$S_R \triangleq 1 - \frac{\varphi_{cell}}{\varphi_{gen}} = \frac{\varphi_{RSU}}{\varphi_{gen}} \tag{3}$$

  where φ_{cell} is the number of packets transferred using the cellular network, φ_{gen} is the overall number of packets generated, and φ_{RSU} is the number of packets transferred to any RSU using V2V and V2R communications; the last equality is a consequence of criteria A.2 (unicast transmissions) and B.3 (single copy per packet), that ensure $\varphi_{gen} = \varphi_{RSU} + \varphi_{cell}$;

- h, which is the average number of hops per packet,

$$h \triangleq \frac{\varphi_{V2X}}{\varphi_{gen}} \tag{4}$$

  where φ_{V2X} is the number of successful V2V and V2R transmissions;

- Σ, which is the average amount of bits per second received by the RSUs,

$$\Sigma \triangleq \frac{\varphi_{RSU} \cdot B \cdot 8}{T_{sim}} \tag{5}$$

  where T_{sim} is the simulation duration.

All results are obtained by averaging the outputs of 30 simulation runs in the low density case and 5 simulation runs in high density case.

4. Numerical Results

The following numerical results allow considerations on the achievable connectivity level and suitability of the possible locations for RSU deployment in Section 4.1, on the validation of the proposed routing algorithms in Section 4.2, and on the cellular resource saving in Section 4.3. Finally, in Section 4.4 an adaptive algorithm taking advantage of the best of both VSGF and VSDV is proposed and validated.

4.1. Connectivity and RSU Positioning

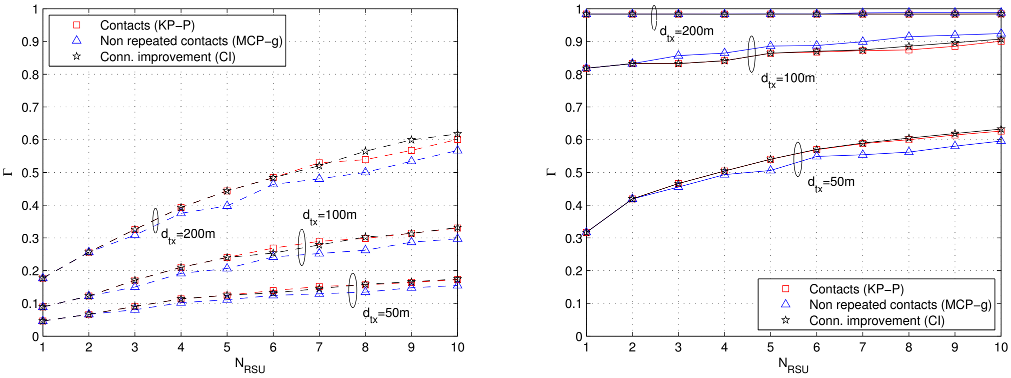
As a first step, the placement of RSUs must be defined. To achieve this objective, we applied the three algorithms of Section 2.3 to the $\Omega = 24$ possible RSU positions, with $\Delta T = T_{sim}$ and high density traffic; a transmission range of $d_{tx} = 50$ m was used for the CI algorithm.

In Fig. 4, the ordered position of the RSUs is shown for the three algorithms. In our scenario, all algorithms agree in the placement of the first, second, and forth RSUs. Compared to the simpler KP-P algorithm, MCP-g favorites locations that are farther to each other. Despite the higher complexity, CI provides the same first five positions as KP-P.

Before comparing the algorithms, n_p and Γ (with $d_{tx} = 50$ m) are shown in Fig. 5 for all the 24 candidate locations; RSUs are taken in the order provided by KP-P. It is interesting to observe that the metric n_p, which is easily measurable, shows a good agreement with Γ, which is, on the contrary, obtainable only with a more complex analysis (i.e. through simulations).

A comparison of the positioning algorithms is shown in Fig. 6, where Γ as a function of N_{RSU} is considered, for various values of d_{tx} and both high and low density conditions. In general, the increase of N_{RSU} does not linearly increase the value of Γ; on the contrary, in most cases the increase of Γ is quite smooth.

Comparing the three positioning algorithms, similar values of Γ can be observed. In spite of the additional information required to identify the vehicles crossing each junction, the MCP-g does not improve the performance of KP-P, except for the



(a) Low density.

(b) High density.

Figure 6: Impact of the number of RSUs and comparison of RSU placement algorithms. Γ versus N_{RSU} for the three placement algorithms, with various d_{tx} and for both low and high density conditions.

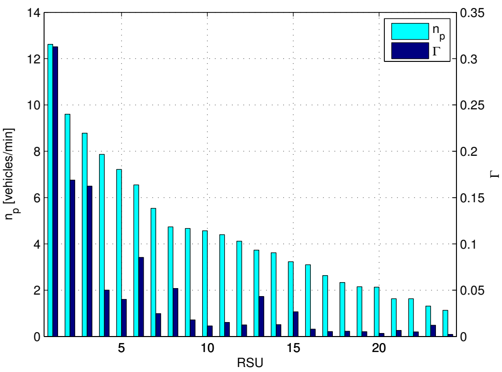


Figure 5: n_p vs. Γ for all candidate locations. $d_{tx} = 50\ m$. RSU locations are ordered through KP-P.

high density case with $d_{tx} = 100$ m. Focusing on the most complex algorithm CI, the improvement in terms of Γ compared to KP-P appears to be negligible. Similar conclusions can be obtained by observing the metric S_R, although results are not shown here for brevity. For these reasons, the RSU placement obtained through KP-P will be adopted in the following.

4.2. Performance of Routing Algorithms.

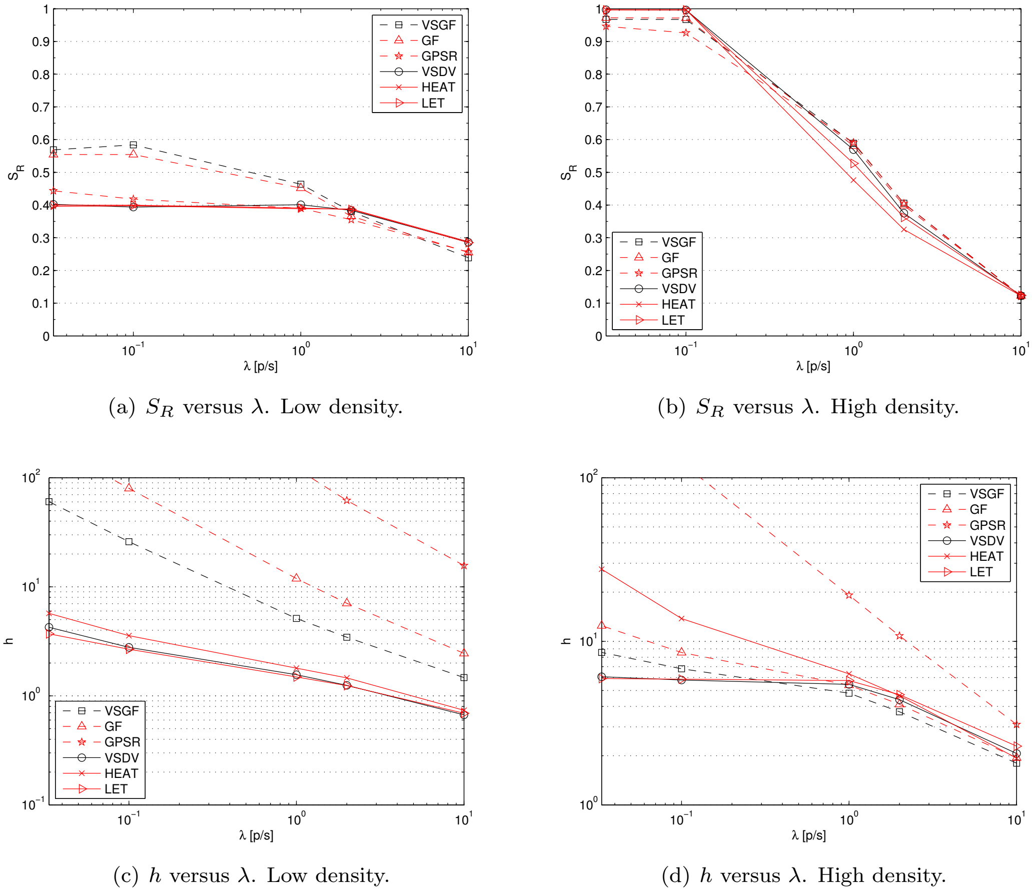
In this section, performances of VSGF and VSDV are presented and compared to those of GF, GPSR, HEAT, and LET.

Results are shown in Fig. 7 for the case of a single RSU and assuming either low or high density of OBUs. Figs. 7(a) and 7(c) refer to low density conditions, whereas Figs. 7(b) and 7(d) refer to high density conditions. In both cases, results show S_R and h, varying λ.

Starting from Fig.7(a), we can observe that hop count based algorithms (VSDV, HEAT, and LET) perform similarly, as well as position based ones (VSGF, GF, and GPSR). Significantly different performance between the two groups can be observed only for $\lambda < 1$ p/s: in such conditions, position based algorithms outperform the others. This can be explained by observing that position based algorithms get data closer to the RSUs even in the absence of a multi-hop connection to an RSU. This effect reduces with a high value of λ because performance tends to be limited by the maximum data rate supported by the RSU, that becomes the bottleneck. Furthermore, the performance difference between the two groups reduces as the OBU density increases, as evident in Fig.7(b).

The main lessons provided by Figs.7(a) and 7(b) are, however, the following: firstly, that a significant percentage of cellular resources can be saved (unless the network load is too high) and, secondly, that VSDV and VSGF, despite their simple implementation, have the same performance of their more complex siblings in the same class.

Moving the attention on the metric h, investigated in Figs. 7(c) and 7(d), we can observe that, as expected, the lowest numbers of transmissions per packet are generally achieved with hop count based algorithms. The exception represented by HEAT, that in high density conditions provides higher values of h than LET and VSDV, is due to a



(a) S_R versus λ. Low density.

(b) S_R versus λ. High density.

(c) h versus λ. Low density.

(d) h versus λ. High density.

Figure 7: Comparison of the routing algorithms. S_R and h versus λ, with $N_{RSU} = 1$.

longer time needed to update the information about neighbors when modifications occur in the topology. Figs. 7(c) and 7(d) also confirm that GPSR is not an efficient solution for the local minimum problem due to the long paths it generates.

Concerning Figs. 7(c) and 7(d) we observe that a lower value of h is obtained for high values of λ. This phenomenon is due to the fact that as λ increases, the amount of queued packets in the on-board transmitters increases as well. As a consequence, the probability that N_{max} is reached increases, this condition triggers the use of the cellular network to send the messages, and the average number of transmissions per packet tends to decrease.

Note also that VSDV and VSGF tend to provide similar (or also better) performance of the other protocols of the same group; this confirms that VSGF and VSDV are suitable solutions for the envisioned application.

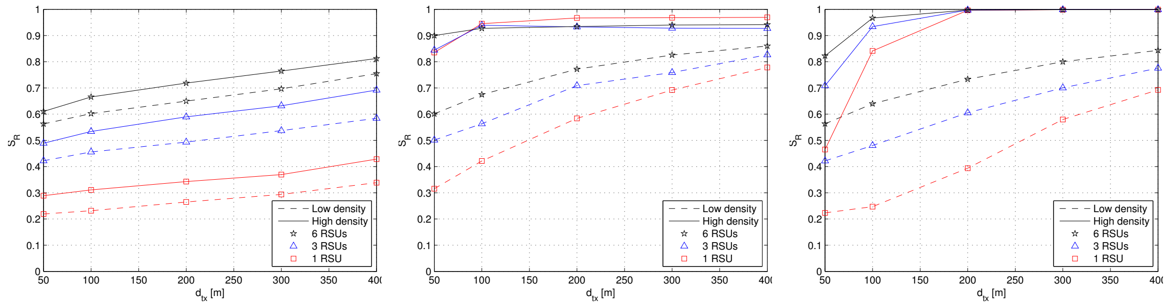
4.3. Cellular Resource Saving in VSNs

Figs. 8, 9, and 10, provide insights in cellular network saving in VSNs.

More specifically, in Fig. 8, S_R is shown as a function of d_{tx}, for different traffic conditions, RSU deployments, and routing settings. Specifically, Fig. 8(a) has been obtained considering V2I and V2R communications only (thus without V2V communications and routing algorithms), while Figs. 8(b) and 8(c) have been obtained considering also V2V communications with VSGF and VSDV routing, respectively.

In Fig. 9, S_R is shown varying the payload size B for VSGF or VSDV, with a single RSU and both low and high density conditions.

In Fig. 10, Σ is shown varying λ, with high density conditions and various deployment cases (1, 3,



(a) Only V2I and V2R (no V2V).

(b) VSGF routing.

(c) VSDV routing.

Figure 8: Impact of V2V and comparison between VSGF and VSDV. S_R versus d_{tx}. $N_{RSU} = 1$, 3, and 6.

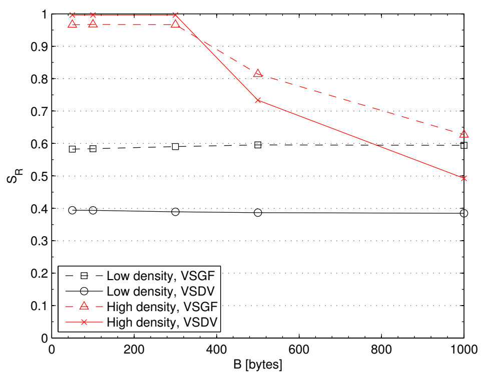


Figure 9: Impact of packet size. S_R versus B in both low and high density conditions, adopting VSGF or VSDV, with $N_{RSU} = 1$.

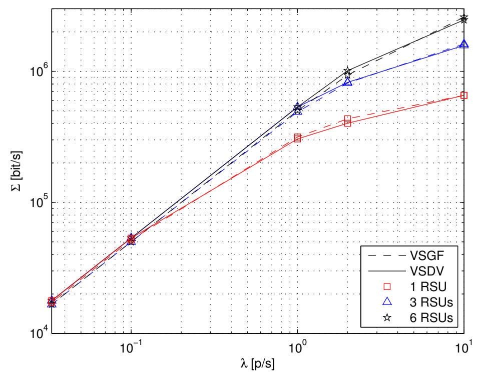


Figure 10: Impact of network load. Σ versus λ in high density conditions, adopting VSGF or VSDV, with $N_{RSU} = 1$, 3, and 6.

and 6 RSUs), for VSGF and VSDV. Σ is strictly related to S_R, and allows the quantification of the saved resources in terms of bits/s.

Looking at these figures, several conclusions can be drawn:

- The only adoption of V2I and V2R communications (Fig. 8(a)) provides a significant cellular resources saving: more than 20% of saving can be observed in the worst case of $d_{tx} = 50$ m and a single RSU, more than 70% with 6 RSUs and $d_{tx} \geqslant 200$ m;
- The density of OBUs has a limited impact on S_R in the case of exclusive use of V2I and V2R communications (Fig. 8(a)). On the contrary, it has a great impact when V2V is also considered (Figs. 8(b) and 8(c));
- In all cases, S_R increases in the presence of V2V (with both routing strategies); the difference becomes significant when a single RSU is deployed and $d_{tx} \geqslant 200$ m;
- With regard to Fig. 9, B has almost no impact on results in low density conditions; in such case, since nodes are sparse and network load is limited, the main issue is low connectivity. On the contrary, in high density conditions, a larger value of B reduces S_R, with an impact very similar to an increase of λ;
- Under low network load conditions (Fig. 8 and $\lambda \leqslant 0.1$ p/s in Fig. 10), the presence of a single RSU in a strategic position can lead to results that are comparable to those achieved with many RSUs. As the data generation rate increases, the wireless channel at the RSU tends to saturate and the number of RSUs in the scenario gets more importance (Fig. 10 with $\lambda > 0.1$ p/s);

- VSGF, that tries to get packets closer to the RSU even if a path is not available, is more effective than VSDV in sparse networks with low connectivity (Figs. 8(b) and 8(c), and low density in Fig. 9);

- As can be observed in Figs. 8(b) and 9, in high density conditions and low network load, the value of S_R obtained by VSGF is lower than 1 in most cases; this is due to the problem of local minima discussed in Section 2.4. We also observe that the impact of local minima depends on the conditions; in particular, the deployment of more RSUs do not always guarantee an increase of S_R; for example, with $d_{tx} = 200$ m and $\lambda = 0.1$ p/s in high density conditions (Fig. 8(b)), the local minima impact more with $N_{RSU} = 6$ than with $N_{RSU} = 1$;

- VSDV appears very effective in high density and low network load conditions ($\lambda \leqslant 0.1$ p/s), allowing to deliver almost the 100% of packets through RSUs when $B \leqslant 300$ bytes and $d_{tx} \geqslant 200$ m, even in a scenario with a single RSU (Figs. 8(c) and 9);

- VSGF provides the highest S_R in high density and high network load conditions (large B in Fig. 9 and high λ in Fig. 10). In this case, VSDV finds routes (towards an RSU) that tend to be longer, in terms of number of hops. This effect increases the average number of transmissions per packet, and the network tends to saturate for smaller values of λ.

4.4. Performance of an Adaptive Approach

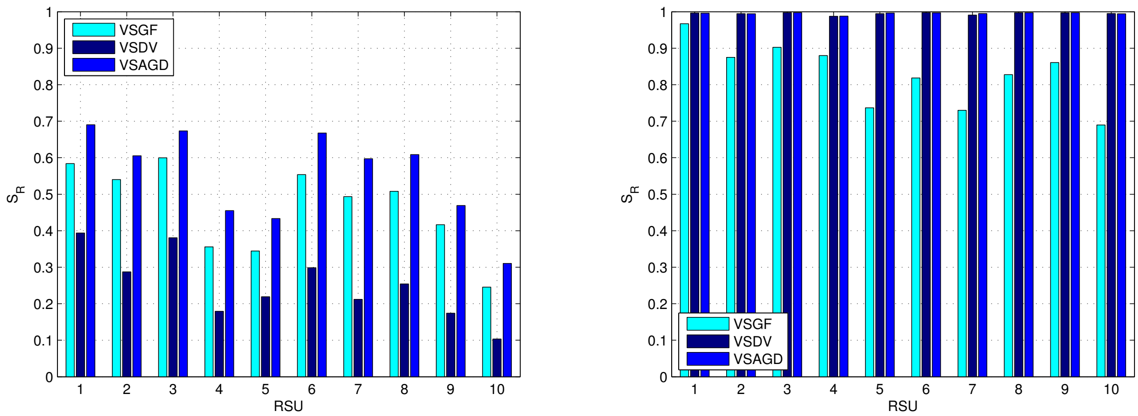
As shown in the previous sections, the two proposed algorithms are both very effective but tend to give their best performance under different conditions. In particular, VSGF suffers from the problem of local minima, preventing to reach the 100% of resource saving even in high density scenarios, whereas VSDV provides lower S_R when the network connectivity is reduced. Furthermore, in heavy network load conditions VSDV is less effective.

To adaptively take the best from both algorithms, we propose to adopt the vehicular sensor adaptive GF/DV (VSAGD) protocol, that uses VSDV whenever n_h is lower than n_{hMAX} and the network is assumed far from congested, and VSGF otherwise. More specifically, when n_h is lower than n_{hMAX}, VSAGD assumes the vehicular network overloaded (thus switching to VSGF) if more than q packets are waiting in the transmission queue. Here the value of q has been heuristically optimized to 5 for the considered scenario (simulations are not shown for brevity). Obviously, adopting VSAGD implies accepting both the limitations of VSGF and VSDV: a location service is required for the RSU positions and two new fields must be introduced in the beacon frames.

Results, comparing VSAGD to VSGF and VSDV in terms of S_R, with a single RSU and varying its position, are shown in Fig. 11, both with low and high density of OBUs. As observable, in low density conditions (Fig. 11(a)) VSAGD performs similarly to VSGF. In such case, in fact, nodes are sparse, a path towards the RSU is often not available, and VSDV is less effective. Indeed, the exploitation of the hop count by some nodes in the neighborhood of the RSU allows even a small improvement of VSAGD compared to VSGF. Fig. 11(a) also allows to observe the different S_R that are achieved varying the position of the RSU. Focusing on high density conditions (Fig. 11(b)), on the other hand, VSAGD provides a value of S_R close to 1, like VSDV. Local minima are avoided in this case: the high connectivity level characterizing the scenario makes paths often available from OBUs to the RSU, and the hop count based approach allows to easily find such paths.

The effectiveness of VSAGD is also demonstrated through Fig. 12, where S_R is shown varying N_{RSU}, with a high density of OBUs and either low or high network load ($\lambda = 0.1$ p/s and $\lambda = 2$ p/s, respectively). As observable, VSAGD provides an S_R which is always equal or even higher than VSGF and VSDV, both with $\lambda = 0.1$ p/s and $\lambda = 2$ p/s. More specifically, VSAGD exploits the hop count in low density conditions ($\lambda = 0.1$ p/s), providing an S_R close to 1. In high density conditions ($\lambda = 2$ p/s), VSGF performs better than VSDV when few RSUs are available and several OBUs are thus not able to empty their queue ($N_{RSU} < 3$), whereas the opposite is observable for a larger number of RSUs. In all cases, the performance of VSAGD is similar to the best of VSGF and VSDV.

The cellular resource saving obtainable with VSAGD is also observable in Figs. 11 and 12. Under limited network load traffic and the use of a single RSU more than 70% resources can be saved in low density conditions, and up to almost 100% in high density conditions (Fig. 11). Similar performance is also observed for high network traffic load, but at the cost of the deployment of more RSUs (Fig. 12).



(a) Low density. (b) High density.

Figure 11: Effectiveness of the adaptive algorithm VSAGD. S_R deploying a single RSU.

5. Conclusion and Future Work

In this work we discussed the use of WAVE to reduce the need of cellular networks in VSNs. More specifically, we compared various algorithms to select the positions of the WAVE RSUs and various algorithms to route packets from OBUs to RSUs through short range communications. Focusing on RSU placement, a simple algorithm based on the number of vehicles crossing the candidate locations was shown to provide as good results as more complex ones. Concerning routing, we identified the criteria that are needed for VSNs and selected two classes of protocols: distance based and hop count based schemes. We compared several algorithms of the two classes and proposed an adaptive protocol, named VSAGD, that tries to obtain the benefits of both categories.

The results showed that, in a reference urban scenario with both sparse and dense network conditions, WAVE is indeed able to significantly reduce the use of cellular networks, with simple routing protocols and few RSUs. For low and medium network load conditions, the use of VSAGD was shown to enable more than 70% saving, with a single RSU in an area of 2.88 km^2; when the node density is sufficiently high to obtain a good connectivity level, the saving approaches 100%. Under high network load conditions, the same saving is still achievable, but requires the deployment of more RSUs.

The results also reveal that, although RSU placement and routing protocols have some improvement margin, the main bottleneck, in the presence of high

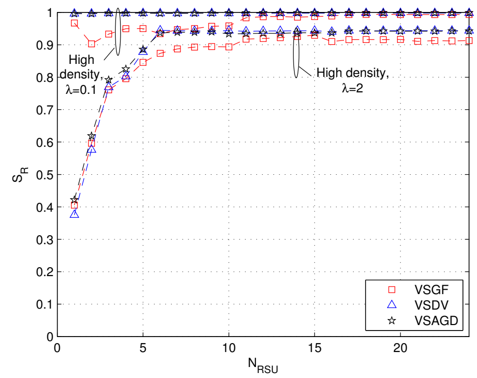


Figure 12: Achievable saving with the proposed settings and impact of N_{RSU} and network load. S_R versus N_{RSU}. High density of OBUs.

network load, appears to be the PHY and MAC layers of IEEE 802.11p standard. In particular, the overhead required by the CSMA/CA mechanism and the impact of hidden terminals tend to reduce the performance significantly. To this aim, new solutions to reduce the collision probability and improve the efficiency in the use of the channel must be foreseen; this may include modifications at the PHY layer and different mechanisms for the multiple access, with the adoption, for instance, of OFMA-based schemes.

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