Smart Navigation in Intelligent Transportation Systems: Service Performance and Impact on Wireless Networks

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***Abstract*—Wireless communications are nowadays considered as enablers of innovation in the field of smart mobility in smart cities. In this work, we focus on the smart navigation service, which is aimed at providing drivers with the best route to destination taking into account real time traffic conditions. Smart navigation is increasingly used today and expected to reduce traffic congestions, but the real impact on travel time and the cost in terms of wireless network resources are still open issues. These aspects are here discussed starting from the objectives and the outputs of the Italian project PEGASUS. More specifically, to what extent this application can reduce the travel duration and how frequently traffic information must be updated will be firstly discussed; then, the impact on wireless networks of both the uplink collection of traffic information and the downlink transmission to vehicles is shown, focusing on the UMTS cellular technology; finally, the use of short range IEEE 802.11p wireless communications technology is investigated to offload cellular networks. Through simulations performed in a dense urban scenario, it is shown that 30% to 50% travel time can be saved, that the needed information exchange might reduce the cellular network capacity available for other services of 20% or more, and that the deployment of few road side units and multi-hop transmissions can be effectively used to offload cellular networks.**

Keywords*—Smart navigation, Intelligent transportation systems (ITS), Vehicular networks (VANETs), Simulations, UMTS, IEEE 802.11p.

I. Introduction

Keeping traffic moving is a challenge that governments, industries and researchers are facing worldwide. Effective solutions can only be obtained with a capillary and continuously updated knowledge of traffic conditions: the creation of an infrastructure for communication between vehicles, service centers and sensors, is thus one of the main needs identified by international institutions, service providers and car manufacturers to address with satisfactory results the problems generated by traffic, justifying the big efforts that are being pushed both in Europe and in the rest of the world.

Many projects have been carried out in the last decade on these topics. Among the others, an interesting example is the Italian project PEGASUS [1], [2], which relies on over one million vehicles already equipped with devices periodically transmitting their position and speed to a control center. Safety, enhanced mobility, and smart navigation systems were the services targeted by the project.

With the expression *smart navigation* we refer to the best route discovery service, which is based on the collection of measurements from vehicles equipped with sensor devices, hereafter on board units (OBUs), and the provision of updated traffic information to those vehicles equipped with on board navigators, hereafter smart navigators (SNAVs). Each OBU periodically collects and sends data to a remote control center and each SNAV receives from the control center information related to the actual traveling speed on the interested road segments, exploiting this information to update the path toward its final destination. Indifferently, SNAVs can be either on-board navigation systems or personal smartphones with specific apps.

Starting from the outputs of PEGASUS, here we focus on the benefits provided by the smart navigation and its impact on the communications network. The various topics addressed by PEGASUS, discussed in [3]–[8] and summarized for the first time in [1], are here extended and discussed with an integrated approach to provide an overview of smart navigation even from the point of view of wireless communications.

More specifically, in this paper we will discuss: i) the impact of updated traffic information on travel time and the amount of data that must be transferred through the wireless networks to make the smart navigation effective, ii) the feasibility and the impact of uplink transmissions of data from a large number of OBUs through cellular networks, iii) the feasibility and the impact of downlink transmissions of updated traffic information to a large number of SNAVs through cellular networks, and iv) the feasibility and the performance of short range vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communications used to offload the cellular networks.

These issues are hereafter addressed through simulations carried out adopting a simulation platform that integrates a vehicular traffic simulator, which reproduces the urban mobility, and a wireless network simulator, which models the details of the communication protocols and the signal propagation.

The paper is organized as follows: In Section II, the envisioned application is detailed and the addressed issues are introduced. In Section III, the simulation platform is described. In Section IV, we focus on the smart navigation service and we evaluate the saved travel time. In Section V, the cellular system and the related performance in the considered scenario are investigated. In Section VI, short range communications

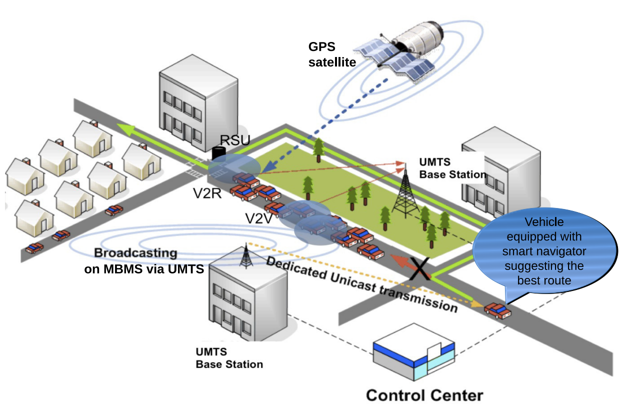


Fig. 1. Scenario: real time traffic information exchange and wireless technologies.

to offload the cellular network are presented and their performance investigated. Finally, in Section VII the conclusions are drawn and the future research activities are outlined.

II. Open Issues on Wireless Communications for the Smart Navigation Service

With the aim to study the benefits of smart navigation in terms of saved travel time and its feasibility from the communication network point of view, we consider the scenario shown in Fig. 1, where vehicles are equipped with OBUs acting as traffic sensors and periodically transmitting their position and speed to a remote control center, either through the cellular network or through multi-hop short range communications toward a road side unit (RSU). The data collected at the control center are processed in real time to estimate the actual traffic conditions (i.e., the travel time) on each monitored road segment; when the control center detects traffic conditions different from those foreseen by the static roadmap data base, it updates the roads travel times on a dynamic data base. Updated information is then transmitted from the control center to the vehicles equipped with the SNAVs through the cellular network in unicast or multicast mode. Then, the SNAVs calculate the optimal route; on a real time basis, they update their data and, in case, modify the route in order to avoid slowdowns.

From the communication technologies point of view, we need to acquire updated traffic information from OBUs (uplink) and to re-transmit processed data to the SNAVs (downlink). What amount of information needs to be transferred and which technologies to use are thus the obvious questions that arise. The first issue is strictly related to the impact of various parameters, such as the rate of data acquisition by OBUs or the rate of traffic updates provided to SNAVs, have on the effectiveness of the smart navigation service. The second issue finds cellular networks and short range wireless communication systems as possible candidates. In the short term, cellular networks appear as the only feasible solution, already guaranteeing high penetration and worldwide coverage. However, the resources needed for smart navigation are subtracted to other services, and their amount might be not negligible. A possibility to offload cellular networks could be to exploit short-range wireless communications based on wireless access in vehicular environment (WAVE) [9], which adopts IEEE 802.11p [10] at the MAC and physical layers and represents the future for V2V communications. This technology, well suited for safety applications, entertainment, gateway access, and road charging, can also be exploited in the envisioned scenario through the deployment of some RSUs and multi hop V2Vcommunications.

The above considerations motivated us to investigate several specific issues. First of all, in order to evaluate the potential benefits of updated traffic information provided by wireless communications systems, as detailed in Section IV we:

- investigate the travel time of vehicles equipped with SNAVs, periodically receiving updated traffic information, that enable to discover the best path. In particular we discuss the impact of the percentage of vehicles equipped with the OBU, the data collection rate, and traffic update timeliness.

The outcomes of these investigations are then used to discuss the role and the performance of wireless communications, both in the uplink and in the downlink, firstly focusing on the universal mobile telecommunications system (UMTS) cellular technology (in Section V) and then on the short range IEEE 802.11p technology (in Section VI). Focusing on UMTS we:

- investigate the feasibility of the acquisition of small but frequent amount of data from many OBUs (*uplink performance*);
- verify the feasibility of real-time transmissions to SNAVs of traffic information, both in unicast and multicast mode (*downlink performance*);
- investigate the impact of this service on the others already supported by the network (both in uplink and downlink).

Finally, considering IEEE802.11p-based V2V and V2R communications, we:

- investigate the impact of V2V and V2R short range communications to offload the cellular networks, with focus on the uplink delivery of measurement data generated by the OBUs.

III. Investigation Tools and Simulated Scenario

The investigation of the considered scenario requires a complete simulation of the enabling wireless networks, as well as a realistic simulation of vehicle movements. In fact, vehicular mobility significantly impacts on the performance of the telecommunication network and on the traffic redistribution itself. A realistic mobility model is thus needed, and it has to take into account all roads, with their speed limits, vehicles acceleration and deceleration, queues at traffic lights, etc. To this purpose we developed a simulation platform that integrates the VISSIM [11] vehicular traffic simulator and the SHINE [12] network simulator, that provided a realistic modeling of both the vehicular traffic (with queues, number of lanes, one

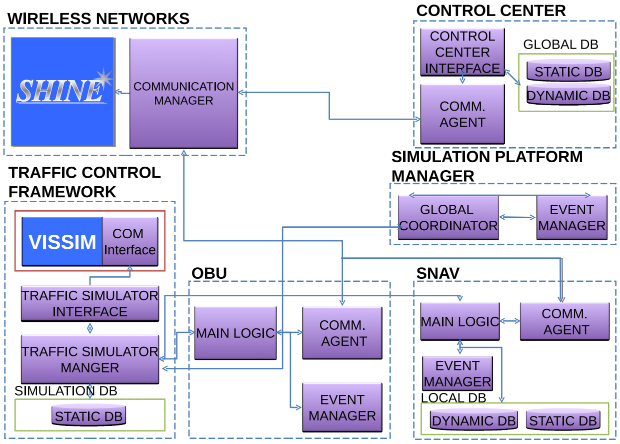


Fig. 2. Integrated platform for the simulation of smart navigation.

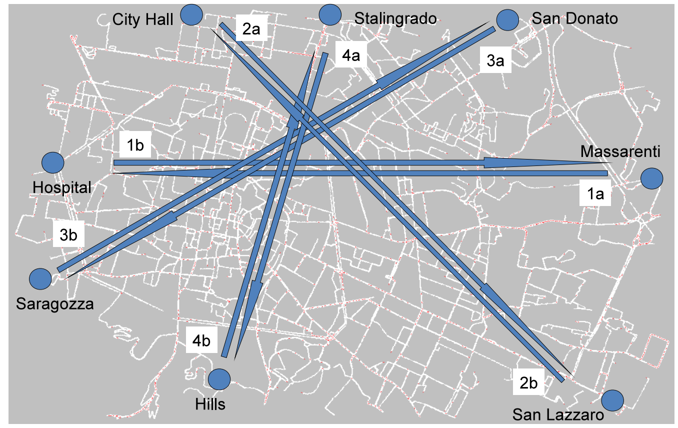


Fig. 3. Origins and destinations of the eight paths considered for the evaluation of the smart navigation impact on travel time.

way roads, etc.) and the network behavior [6]. The reasons behind this specific choice are detailed in [6], where pros and cons of several alternative vehicular traffic and wireless network simulators are discussed.

Vehicular simulator: VISSIM [11]. It is a commercial microscopic simulation tool that reproduces traffic flows in urban areas as well as interurban motorways, and allows to reproduce car-following and lane changing as in real scenarios. It uses a psycho-physical car following model for longitudinal vehicles movement and a rule-based algorithm for lateral movements. VISSIM can be controlled by external applications with the use of a component object model (COM): by the adoption of dynamic link libraries (DLL), it is possible for an application to control the movement of vehicles and to manage the whole simulation.

Wireless network simulator: SHINE [12]. It is an event driven dynamic simulator developed in our laboratories and written in C++, which allows to jointly take into account all aspects of the wireless networks related to the various layers of the network protocol pillar. SHINE has been designed to simulate heterogeneous wireless networks, according to a client-server structure; it is constituted by one server-core simulator (upper layers simulator, ULS) and one or more client simulators (lower layers simulators, LLSs), specific for the considered access technologies; among others, it includes an UMTS LLS and an IEEE 802.11p LLS.

Integrated platform. We realized a flexible architecture integrating VISSIM with SHINE, enabling the realistic simulation of vehicular traffic as well as of wireless networks [6]. This integrated platform allows the simulation of the whole smart navigation scenario: the vehicular mobility and the OBU transmissions, the data processing at the control center, the data base update with dynamic data, and the retransmission of the elaborated information to the SNAVs.

The architecture of the overall simulation platform is depicted in Fig. 2, and includes PostgreSQL databases and components written in C#; the interaction between components is provided through sockets and remote procedure calls (RCPs). More specifically, the following main blocks can be identified: *OBU*, which simulates the on board device collecting and transmitting position and speed; *SNAV*, which represents the fleet of vehicles equipped with the smart navigator, able to receive updated traffic information from the control center; *Control Center*, which is responsible of the gathering of data transmitted by the OBUs to update the dynamic data base; *Wireless Network*, which simulates the wireless network; *Traffic Control Framework*, which is based on VISSIM simulator and is in charge of controlling vehicles and their interactions; *Simulation Globals*, which manages the overall architecture. More details are available in [6].

Simulation scenario. The road-network layout of the reference scenario used for simulations consists of the medium sized Italian city of Bologna. In particular, we considered 13.636 road segments, corresponding to a length of about 600 Km. The digital-maps have been provided by TeleAtlas and given as input to VISSIM.

As detailed in the following, results concerning the cellular network performance will be obtained considering a portion of the entire scenario and assuming pedestrians that perform voice calls as background traffic added to the traffic generated by OBUs and SNAVs.

IV. Smart Navigation Impact on Travel Time

To evaluate the benefits, in terms of saved travel time, provided by timely updates of traffic information used by smart navigators, we assume that SNAVs receive updated information on the traffic conditions for each road segment from the current position to the destination and calculate the optimal route; on a timely basis, they update their data and, in case, modify the route in order to avoid slowdowns.

A. Simulation Settings and Output Figures

We consider non static traffic conditions, with a vehicle density that during each simulation varies in the range 1-10

TABLE I. SIMULATION PARAMETERS FOR THE SMART NAVIGATION SERVICE: DEFINITIONS AND NUMERICAL VALUES.

Parameter	Values
Starting instant of the journey of the monitored vehicle	600 s
Percentage of vehicles equipped with OBU ($\delta_{\text{OBU}}x100$)	0%, 1%, 3%, 5%, 10%, 20%, 50%, 100%
Interval time for the transmission of the measured data τ	10 s, 30 s, 60 s
Interval time over which measured data are averaged T_{int}	10 s
Number of last consecutive intervals to obtain the current average speed	5
Interval time after which the average speed is updated in the smart navigator T_{update}	20 s, 60 s

vehicles/Km (please note that these are average values, also including secondary roads rarely used).

A parametric percentage of vehicles is assumed equipped with OBUs ($\delta_{\text{OBU}} \times 100$, with $\delta_{\text{OBU}} \in [0,1]$); every τ seconds, each OBU transmits several parameters including the actual vehicle position and speed to the control center. Measured data are processed by the control center to estimate the actual average speed of each road segment. Specifically, measured data are averaged on a parametric T_{int} interval time.

Then, every T_{update} seconds, the control center retransmits the processed data back to vehicles equipped with smart navigators. To avoid rough estimates in those roads where no vehicles or a too low percentage of them passed, we set up an average speed equal to that given by the static roadmap provided by TeleAtlas lowered by the 30%. In addition, when the measured speed is lower than 15 Km/h, we force the measurements exactly to 15 Km/h: this avoids to overestimate the travel time in the involved road segments.

We considered four paths, with different origins and destinations, in two directions (i.e., eight routes in total), as represented in Fig. 3. Each path is denoted in the following as path Nx, with N from 1 to 4, indicating the source-destination couple, and x either equal to a or b, indicating the direction. Since a smaller number of vehicles complete their route than those that are newly generated, the overall traffic increases in time, generating queues in an increasing number of junctions. In particular, about 1000 vehicles are present after 300 s, 2000 after 800 s, and 3000 after 1800 s.

The main parameters settings and their numerical values are summarized in Table I.

B. Numerical Results

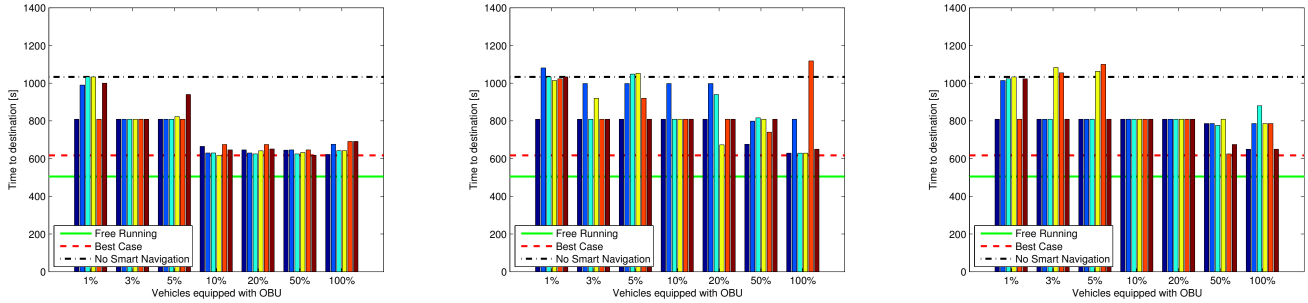
Numerical results are obtained assuming one vehicle equipped with the SNAV: this vehicle starts after 600 s and moves along one of the eight paths depicted in Fig. 3. For each path the time spent by the vehicle to reach the destination is investigated for different combinations of significant parameters (see Table I). Per each considered combination of parameters, six simulations were performed with different random variable initializations, that affect, for instance, the choice of the vehicles equipped with the OBU.

Results are presented for $T_{\text{int}} = 10$ s, $T_{\text{update}} = 20$ s and 60 s, and τ equal to 10, 30, or 60 s. Figs. 4 and 5 show the travel time, from origin to destination, of a monitored vehicle equipped with the SNAV for different percentage of vehicles equipped with the OBU and different scenarios. In each figure, results are compared with the following three cases adopted as benchmarks: i) *Free running*, referred to the case of a single vehicle moving alone on the entire scenario; ii) *Best case with smart navigation*, referred to a vehicle equipped with a smart navigator continuously updated with the best route, iii) *No smart navigation*, referred to the the same route as in Free Running in the presence of traffic (a navigator may be present, but without knowledge of real time traffic).

In Figs. 4 and 5, the travel time to destination is shown for path 1a for $T_{\text{update}} = 20$ s and 60 s, respectively. Figs. 4(a), 4(b), and 4(c) (so as Figs. 5(a), 5(b), and 5(c)) refer to three different (uplink) transmission intervals τ: 10 s, 30 s, and 60 s, respectively. For each percentage of OBU equipped vehicles, six results are presented, corresponding to six different simulations providing time and space randomness (i.e., different vehicles are equipped with OBU, and the sampling process starts at different instants). By observing Figs. 4(a), 4(b), and 4(c), it can be noted that the time to destination increases with τ, showing a not negligible impact of a timely update of road segments traffic conditions. Focusing on Fig. 4(a), the impact of the percentage of OBU equipped vehicles can be appreciated: with a frequent traffic update in the uplink ($\tau = 10$ s), the 10% of vehicles equipped with OBUs is sufficient to have a time to destination very close the best case (i.e., about 600 s). As the uplink transmission interval τ increases, the 10% of vehicles is no more sufficient to obtain optimal results, that can be instead achieved (and not all times) only when all vehicles are equipped with OBUs.

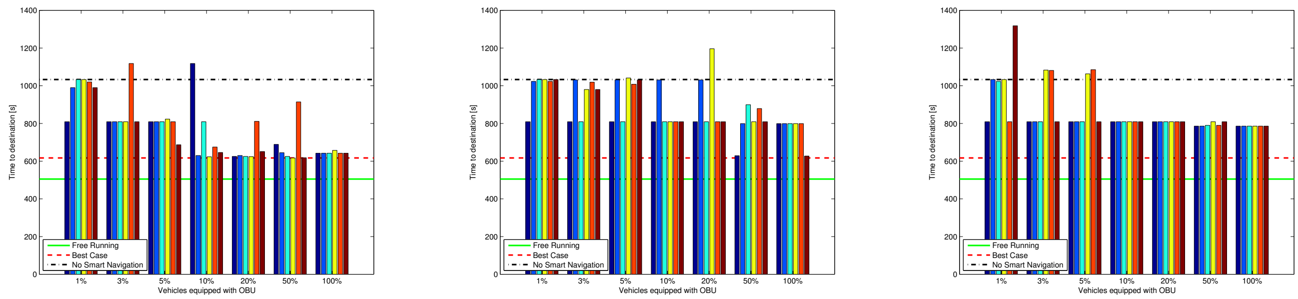
From a comparison between Fig. 4 and Fig. 5, referring to $T_{\text{update}} = 20$ s and 60 s, respectively, it can be observed that the impact of the downlink (from the control center to SNAVs) transmission interval is lower than the impact of the uplink transmission interval τ (from OBUs to the control center),

Fig. 6 summarizes the results provided in Figs. 4 and 5, showing the average travel time of the six simulations and the confidence interval, corresponding to the standard deviation of the same values. The vehicle equipped with SNAV running in path 1a encounters various slowdowns and the free run time of 505 s increases up to 1033 s under the assumed traffic conditions. Smart navigation allows a reduction of the travel time to 629 s in the best case, which corresponds to about 40% of time saving. Results show that this saving can be achieved only with a sufficient amount of collected data: specifically, 10% of vehicles equipped with OBUs and $\tau = 10$ s are required. As can be observed, a similar advantage can be achieved in some cases also for a higher τ, but it is not guaranteed and depends on which vehicles are equipped and when they collect and send their data; for example, focusing on Fig. 4 and assuming $\tau = 30$ s and $\delta_{OBU} = 1$, in the forth case (yellow bar) the SNAV suggests the best possible route, whereas in the fifth case (red bar) it suggests a route, which is worse than the one followed with no smart navigator. Furthermore, comparing Figs. 6(a) and 6(b), referring to $T_{\text{update}} = 20$ s and 60 s, respectively, a slight performance degradation can be noted when a lower update rate is assumed ($T_{\text{update}} = 60$ s), but this effect is not



(a) $\tau = 10$ s. (b) $\tau = 30$ s. (c) $\tau = 60$ s.

Fig. 4. Travel time to destination for path 1a with different percentage of vehicles equipped with OBU and $T_{\text{update}} = 20$ s.



(a) $\tau = 10$ s. (b) $\tau = 30$ s. (c) $\tau = 60$ s.

Fig. 5. Travel time to destination for path 1a with different percentage of vehicles equipped with OBU and $T_{\text{update}} = 60$ s.

TABLE II. SUMMARY OF TRAVEL TIME FOR THE SMART NAVIGATION SERVICE.

Path	Free Run [s]	No Smart Nav. [s]	TI	Best Route [s]	SNI	Parameters to Allow the Best Performance of Smart Nav.
1a	505	1033	51.1%	617	40.3%	$\tau \leq 10$ s and at least 10% of OBU
1b	577	1016	43.2%	564	44.5%	$\tau \leq 10$ s or 100% of OBU
2a	477	651	26.7%	567	12.9%	Small advantage and easily achieved.
2b	482	800	39.7%	566	29.2%	$\tau \leq 10$ s and at least 10% of OBU
3a	494	575	14.1%	552	4.0%	Smart navigation is useless.
3b	439	533	17.6%	533	0.0%	Smart navigation is useless.
4a	374	449	16.7%	390	13.1%	$\tau \leq 10$ s and more than 10% of OBU
4b	386	864	55.3%	441	49.0%	$\tau \leq 10$ s and more than 10% of OBU or $\tau \leq 20$ s and minimum 50% of OBU

as remarkable as that observed varying τ.

Similar results can be obtained for all the other paths and are summarized in Table II. In particular, the columns show:

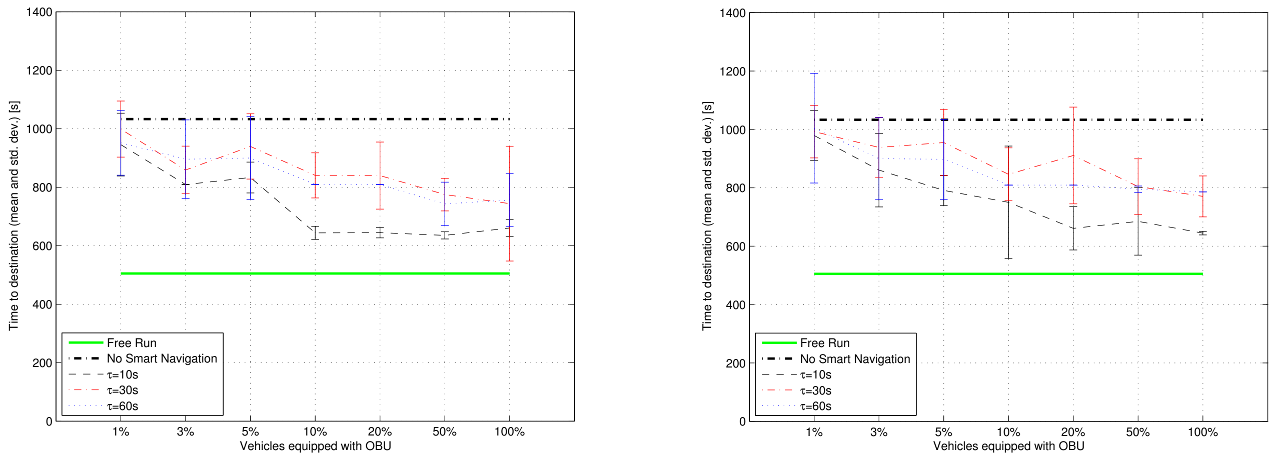
- the path name;
- the Free Run time in seconds, hereafter denoted with t_{FR};
- the No Smart Navigation time, hereafter denoted with t_{NoSN};
- the traffic impact TI evaluated through the following equation:

$$TI = \frac{t_{\text{NoSN}} - t_{\text{FR}}}{t_{\text{NoSN}}} \times 100 \quad (1)$$

where (1) corresponds to the increase of the travel time along the best route withe respect to free run conditions caused by the presence of traffic in the absence of smart navigation, normalized and expressed in percentage;
- the Best Route time, hereafter denoted with t_{BR};
- the maximum achievable benefit of smart navigation SNI evaluated through the following equation:

$$SNI = \frac{t_{\text{NoSN}} - t_{\text{BR}}}{t_{\text{NoSN}}} \times 100 \quad (2)$$

where (2) corresponds to the highest reduction of time enabled by smart navigation compared to the time needed in the same traffic conditions without smart navigation, normalized and expressed in percentage;
- a brief summary of the parameter settings that allow to achieve the maximum benefit from smart navigation,



(a) $T_{\text{update}} = 20$ s.

(b) $T_{\text{update}} = 60$ s.

Fig. 6. Mean and standard deviation of the time to destination for path 1a.

i.e., that allow the minimum travel duration with high probability.

The eight considered paths allow to compare the effect of smart navigation in various traffic conditions: when TI is high, i.e., when the traffic severely affects the travel duration (paths 1a, 1b, 2b, 4b), the smart navigation service allows to significantly reduce the travel time, with SNI between 30% and 50%; on the contrary, when TI is low (paths 2a, 3a, 3b, and 4a) the observed SNI is lower than 15%.

Another interesting conclusion arises comparing the impact of τ and T_{update}: the transmission rate from OBUs is much more important than the update rate at SNAVs. τ has, in fact, a direct impact on the traffic estimation, beacuse higher transmission rates from OBUs entail more available traffic measurements and thus better estimates, whereas T_{update} only impacts on the decision made by the SNAVs, taken at the few main junctions encountered.

Numerical results show thus that smart navigation allows the equipped vehicle to significantly reduce the travel time whenever the traffic has a significant impact on the travel duration and they highlight that a sufficient amount of data must be collected by OBUs. In particular, they show that a simple average of the collected speeds allows a good route selection when a transmission interval τ lower than 10 s is assumed and at least 10% of vehicles are equipped with OBUs. It may be possible that more sophisticated algorithms with more complex processing at either the control center or the OBUs would allow similar results with a lower τ, but the design of such algorithms is out of the scope of the present paper.

V. Cellular Communications Enabling Smart Navigation

The smart navigation service relies on wireless communications. Among all possibilities, cellular systems represent the obvious short term solution, both to collect data from OBUs (uplink) and to retransmit them to SNAVs (downlink). Due to the widespread diffusion of always-on navigators and smartphones with positioning applications, cellular systems allow the service implementation avoiding new set-ups or expensive installations [13]–[15]. Various activities are ongoing [4], [5], [16], [17], and products based on cellular technologies are already on the market.

Some studies on the performance of cellular systems in vehicular applications are coming out (see, e.g., [18]), but still few investigations focused on the impact that these new services have on other cellular services (such as voice calls) in terms of resource availability and quality of service (QoS).

Focusing on the uplink, the use of vehicles as communication-enabled moving sensors opens to a number of potential applications, as pointed out in [19]–[22]. Example applications are also presented in many related works, where vehicular ad hoc networks (VANETs) are envisioned, for instance, to alert upcoming vehicles when an accident occurs [23], to guarantee urban environment surveillance [24], to provide widespread pollution measurements [25], to enable traffic monitoring and smart navigation [4], and to perform civil infrastructure monitoring and automotive diagnostics [26]. For all these applications, cellular systems are today the unique solution. A study on the feasibility of data acquisition from vehicles through cellular systems has been carried out in the German project Aktiv CoCar [27], that defined a new protocol, called "traffic probe data protocol" (TPDP), to upload traffic data through UMTS common channels. However, results are given only in terms of cumulative distribution function (CDF) of the end-to-end delay, and no evaluation of the impact of this service on the QoS experienced by other users is given.

Focusing on the downlink, also broadcast technologies are available. A first example is represented by the traffic message channel (TMC) [28], [29], aimed at delivering traffic and travel information using the radio data system (RDS) on conventional frequency modulation (FM) radio broadcasts. However, these technologies and applications have some severe limitations. In fact, the data rate reserved for these services is limited, thus allowing the traffic conditions update for a very reduced number of roads. In addition, only the main events are described, with few approximate descriptions.

For this reason, in several Countries on-board navigation devices receive updated traffic information by means of cellular technologies [30]. Reduced data rate is sufficient until traffic information is not frequently updated nor capillary, but as the service coverage and timeliness increase the cellular network capacity and the expected QoS becomes a primary issue to be investigated.

Here, we focus on the most widely adopted cellular technology, UMTS, to collect data from OBUs and to provide updated traffic information back to SNAVs. Different strategies are considered in both directions and their impact is shown through simulations: in the uplink we compare the use of dedicated channels or random access channels, while in the downlink we compare the use of unicast or multicast transmissions. Since the quality perceived by users of other services is also of great interest, also pedestrians performing voice calls are considered.

A. Simulation Scenario and Non Vehicular Users

The portion of Bologna considered for UMTS simulations is shown in Fig. 7 and consists of a rectangular area of the city center sized 1.8 km (longitude) x 1.6 km (latitude) with 35 UMTS cells covered by 15 Nodes-B (1, 2 or 3 cells per Node-B are assumed), with a single frequency planning. This portion of the entire scenario has been considered for the assessment of the cellular network performance to avoid edge effects. Fig. 7 also shows the approximated coverage of each cell with random colors. Black segments represent roads where vehicles movements are constrained.

Concerning non vehicular users, a variable number of pedestrians randomly walking in the scenario is generated, with an uniform distribution and the same birth probability in each cell (this means that a higher density of voice users is assumed where smaller cells are considered). Hereafter, $\Lambda^{(v)}$ indicates the average offered voice load in Erlang per km^2.

As previously detailed, vehicles are constrained on roads and generated by VISSIM; a heavy traffic condition with many traffic queues is investigated, with 220 average vehicles per Km^2. A portion $\delta_{\text{OBU}} \in [0,1]$ of vehicles are equipped with the OBU, while a portion $\delta_{SNAV} \in [0,1]$ of vehicles are equipped with the SNAV.

Particular attention has been paid to all physical level aspects, including propagation, interference, and power control mechanisms. For further details on both the scenario and the UMTS simulator the reader may refer to [3].

1) Background Voice Traffic: The duration of each voice call is randomly defined with Poisson distribution and 90 s as average. In the UMTS access network, voice traffic uses a 12.2 kbit/s bearer, corresponding to a logical dedicated traffic channel (DTCH), a transport dedicated channel (DCH), and

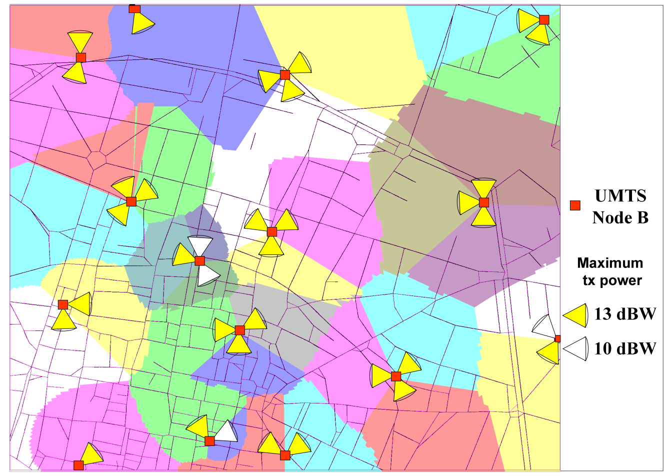


Fig. 7. UMTS planning in the considered scenario. Filled black squares correspond to Node-B locations. An approximated area of coverage is depicted for each cell with random colors.

a physical dedicated data channel (DPDCH). The DPDCH has a spreading factor (SF) equal to 64 in uplink and 128 in downlink.

Output figures. The evaluation of the QoS perceived by voice users is based on the following definitions: per each frame lasting 10 ms, a user (i.e., a voice call) is defined in outage if the BER after channel decoding of that frame is greater than 2% (uplink and downlink are evaluated independently to each other); an ended *voice call* is then considered *in outage* when either in downlink or in uplink, the outage intervals exceed a threshold of 5%. Hence, we have an outage voice call when one user is able to talk to the other party, but with poor audio quality. A voice call may also incur in the following situations: it may be blocked by the call admission control algorithm due to insufficient resources, or it may drop due to an excessive reduction of the received signal power.

Results will be presented in the following in terms of *satisfaction rate (SatR)*, that is the ratio between the number of users, which are not blocked, neither dropped, nor in outage, and the total number of call requests.

B. Uplink Acquisition from Vehicles

Among the cellular technologies, general packet radio service (GPRS) is nowadays the most adopted in vehicular scenarios for uplink measurements transmission. However, to transmit data over the GPRS network, the mobile device must first send a message on a common channel asking for a dedicated resource, with procedures requiring a not negligible access time, in the order of seconds [31]; for this reason in practical systems the OBU collects tens of measurements before transmitting them in a single packet. This approach obviously increases the data acquisition delay at the control center, and limits the effectiveness of the smart navigation service, as shown in Section IV. Differently to this, UMTS also allows the transmission of small amount of data over the shared random access channel (RACH), avoiding the set-up of dedicated resources [32]. This way, any measurement can be transmitted by the OBU as soon as it is taken, with minimum delay and reduced signaling overhead. This solution appears promising especially considering the expected increase of the number of equipped vehicles, but it clearly requires investigations on feasibility and resources occupation.

Here, we discuss the impact of real time data acquisition on the performance of cellular networks, foreseeing the realistic perspective of an explosion of the number of equipped vehicles. We consider DTCH using either dedicated or random access logical and physical channels. In the former case, a logical DCH and a DPDCH are used in uplink with a SF equal to 16, and the same channels are used in downlink with a SF equal to 32 (a dedicated channel is required also in the downlink for the TCP acknowledgment transmissions), both providing 64 kbit/s. In the latter case, a logical RACH mapped on the physical random access channel (PRACH) is used. Differently from the RACH, the dedicated transport channel is characterized by features such as fast power control, fast data rate change on a frame-by-frame basis, and soft handover. However, it has to be established each time a connection is required.

Vehicles transmit 80 byte packets every 10 seconds. When the random access is exploited in uplink, one RACH (out of the available ones) is exclusively used in each cell by the smart navigation service.

Output figures. The impact of the smart navigation service is primarily shown in terms of the effects it causes on the QoS of voice users. Besides this, the QoS of this service can be addressed investigating the probability that each measurement stored in vehicles is correctly received by the control center, independently on the specific source.

When the DCH is used, data cannot be lost due to the use of TCP at transport level and the delay introduced by the transmission over the cellular link is not very critical (the average delay remains lower than few seconds unless the network is heavily congested). Thus, observing the effect on the voice traffic is sufficient in this case.

When the RACH is used, the delay is even lower, but not all packets are delivered to the control center. In fact, a scheduled transmission fails in two cases: 1) when the RACH ramping procedure is unsuccessful, meaning that the propagation conditions and the perceived interference level are so disadvantageous that the maximum transmission power is not sufficient, and 2) when an error is detected at the receiver. In any case, the MAC layer may attempt a number of retransmissions before discarding the packet. Focusing on the smart navigation service with RACH, results are thus also expressed in terms of *packet discard rate* (R_D), that is the ratio between the number of discarded packets and the total number of packets generated by all OBUs.

UMTS Uplink: Numerical Results. The $SatR$ for voice users and the R_D for the smart navigation service with RACH are plotted in Fig. 8 and Fig. 9, respectively, as a function of $\Lambda^{(v)}$.

In Fig. 8, the $SatR$ of voice users is depicted with $\delta_{OBU} = 1$, and the case with no smart navigation service ($\delta_{OBU} = 0$) is shown for comparison. Observing Fig. 8, the presence of the smart navigation service seems not to impact on voice users, since their satisfaction remains almost unchanged. This is no more true when the dedicated channel DCH is adopted for the smart navigation service instead of RACH, that results in a $SatR$ reduction. To grant a $SatR = 0.95$, about 740 voice users could be served both in the absence of the smart navigation service or using RACH, whereas the same $SatR$ is satisfied with only 600 when the DCH is adopted (that entails a not negligible reduction of about the 20%).

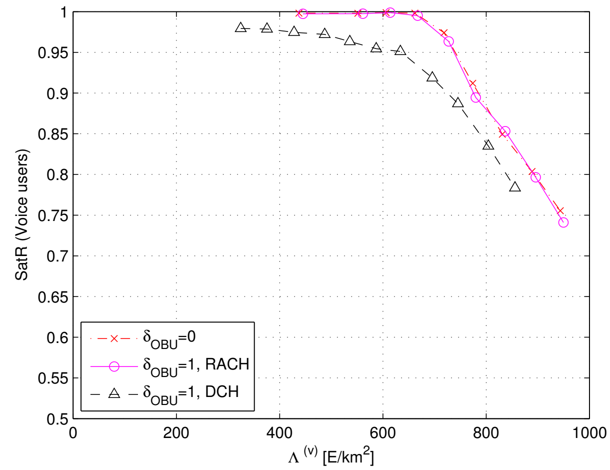


Fig. 8. Voice traffic performance: voice $SatR$ vs. the offered voice traffic $\Lambda^{(v)}$. Comparison between no smart navigation ($\delta_{OBU} = 0$), smart navigation adopting RACH, and smart navigation adopting DCH.

From this preliminary result, related to voice users only, it seems that the use of RACH does not impact the network performance: for a given $SatR$ the maximum $\Lambda^{(v)}$allowable is not affected by the underlying smart navigation service adopting RACH. However, looking at Fig. 9, where the R_D is also plotted as a function of $\Lambda^{(v)}$ for $\delta_{OBU} = 1$, this conclusion must be revised. As can be observed, the higher is the network load, the higher is the value of R_D, and the QoS of the smart navigation service results deteriorated. If $\Lambda^{(v)}$=740 (corresponding to $SatR = 0.95$) is taken as reference value, a packet loss higher than 5% can be observed, meaning that guaranteeing a $SatR = 0.95$ to voice users, does not imply that the smart navigation users are also served. To improve the QoS of the smart navigation service, a lower number of voice calls must be accepted. For instance, if R_D lower than 10^{-2} is targeted, with respect to a maximum of $\Lambda^{(v)}$=740 in the absence of the smart navigation service, a reduction of about 100 (13.4%) average voice users per Km^2 must be considered, drastically reducing the capacity left for voice users. Such reduction is, however, lower than that caused by the smart navigation service with the use of DCH.

C. Downlink Transmission to Vehicles

As far the adoption of UMTS to deliver traffic information to SNAVs is concerned, two options are available: either transmitting personalized data through unicast DCHs, or to distribute

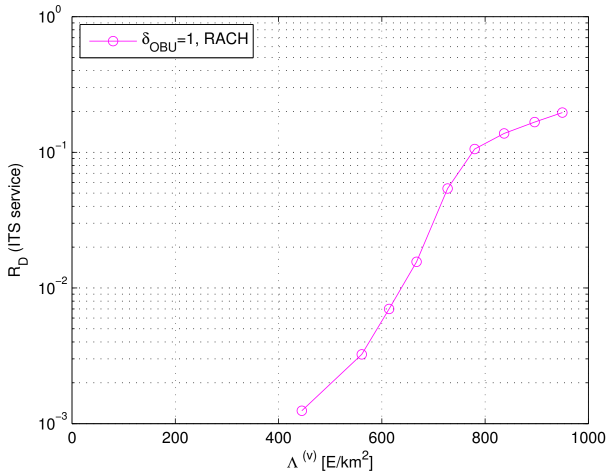


Fig. 9. Smart navigation performance: R_{D} varying the offered voice traffic $\Lambda^{(\mathrm{v})}$. $\delta_{\mathrm{OBU}} = 1$.

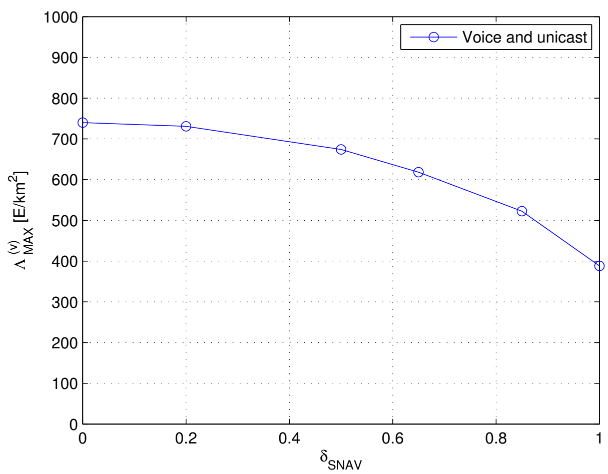


Fig. 10. Voice capacity as a function of the fraction δ_{SNAV} of vehicles receiving dedicated traffic information in unicast mode.

the same content to all users through multimedia broadcast multicast service (MBMS) channels. Hereafter, we compare these two cases, evaluating if the network can support the additional new load and the impact it has on the performance perceived by other UMTS users.

Due to the adoption of code division multiple access (CDMA) [3], the number of active channels in UMTS is a consequence of the trade-off between coverage and capacity, and the amount of resources occupied by each transmission is given in terms of used power: on the one hand, a higher data rate as well as a higher distance from the base requires a higher power for a sufficient QoS; on the other hand, a higher power reduces the cell capacity. The power is, in fact, a limited resource at the base station (in downlink) and each transmission turns into an interference to all other active communications (in both directions).

As for MBMS, it allows to share resources among many user. Hence, power is allocated to MBMS channels only once for any number of users in the cell receiving the service. When the multicast transmission is exploited in downlink, we assume that in each cell one MBMS channel is exclusively used by the smart navigation service, and that all SNAVs are enabled to join the multicast group, where traffic-related messages are distributed. It has to be remarked that MBMS uses part of the power available at the base station, thus limiting the number of DCHs that can be established. Moreover, the broadcast/multicast nature of the channel does not allow to exploit the fast power control feature that is of main importance for an interference limited system like UMTS; the base station pre-assigns a certain amount of power to MBMS services depending on the coverage planning and the desired bit rate.

The following strategies, thoroughly described in [5], are assumed for traffic updates:

- For the unicast mode, the update involves *road segments encompassed by an ellipse* whose focuses are the actual vehicle position and either an intermediate point or the final destination. This strategy avoids the transmission of information related to road segments too far from the actual vehicle position, which would be out of date when the vehicle needs it. Moreover, since only the transmission of the coordinates of two points is needed from the SNAV to the control center, the amount of data transmitted in the uplink is very small, thus limiting costs and resource occupation. Following [5], 1000 road segments are updated every 5 minutes.
- For the multicast mode, a *progressive coverage* strategy is considered, consisting in the transmission to the SNAV of the information related to the most important roads at national level and regional level, and to the minor roads at local level only. Following [5], 12000 road segments are updated in average.

Independently on the unicast or multicast communication technology, we assume the transmission of transport protocol experts group (TPEG) [33] messages at the highest layers of the protocol pillar with 60 bytes packet per each road segment [17].

1) Unicast Mode: Following the given assumptions, SNAVs receive updated traffic information through a 60000 bytes download (i.e., 1000 road segments $\times$ 60 bytes) every 5 minutes. Data are transmitted adopting the TCP protocol at the transport level, that assures data reception. A 64 kbit/s bearer is considered, corresponding to a logical DTCH, a transport DCH, and a physical DPDCH (the low amount of bytes and the relaxed delay requirements do not justify the use of more consuming bearers). The DPDCH is transmitted adopting a SF equal to 32 in downlink and 16 in uplink (note, in fact, that a dedicated unicast link is required also in the uplink direction for the TCP acknowledgment transmissions).

Output figures. A smart navigation user is satisfied if the update is received with a delay lower than 15 s (please consider that less than 10 s would be required if data were transmitted

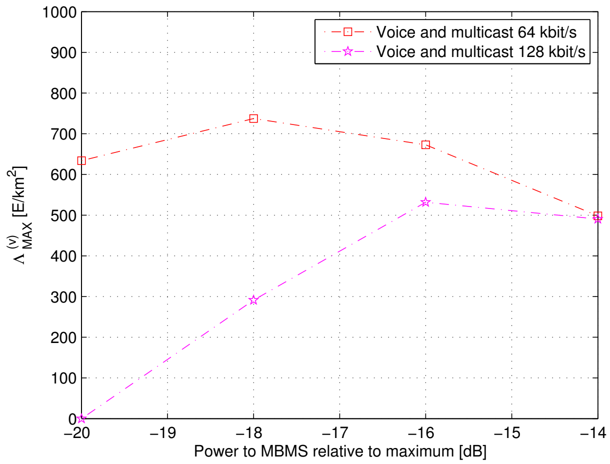


Fig. 11. Voice capacity as a function of the Node-B power dedicated to the multicast channel providing the envisioned service.

at 64 kbit/s with no errors and no TCP redundancy).

2) Multicast Mode: Data are transmitted adopting user datagram protocol (UDP) at transport level, which introduces limited redundancy but do not grant reliable communications; in this case, in fact, the absence of the uplink connection does not allow the transmission of acknowledgments. Two bearers at 64 and 128 kbit/s are considered, each corresponding to a logical MBMS transport channel (MTCH), a transport forward access channel (FACH), and a physical secondary common control physical channel (S-CCPCH). The S-CCPCH is transferred (obviously, in downlink) adopting a SF equal to 32 for 64 kbit/s and 16 for 128 kbit/s.

With the assumptions given above, all roads are updated every 90 or 45 seconds with the 64 and 128 kbit/s bearers, respectively.

Output figures. An ended smart navigation session is assumed in outage if less than the 95% of packets are correctly received. For smart navigation users the *satisfaction rate* is the ratio between the number of users that do not experience an outage and the total number of users.

UMTS Downlink: Numerical Results. In Fig. 10, the maximum $\Lambda^{(v)}$is plotted as a function of the number of equipped vehicles receiving updated traffic information via DCH. In particular, the x-axis represents the ratio δ_{SNAV} of vehicles that are equipped with the SNAV. The y-axis represents the maximum amount of voice calls that allow the system to serve both traffic classes (voice and smart navigation) with a satisfaction rate (i.e., ratio of satisfied users over the number of users of that class) greater than 95%. When the number of equipped vehicles is zero, we obtain results referred to the presence of voice only, considered as a benchmark (740 average voice calls). We can observe that, as the number of equipped vehicles receiving updated information increases, the maximum number of voice calls (i.e., the number of voice users) decreases, due to larger resources dedicated to the smart navigation service. It is however interesting to note that the decrease of $\Lambda^{(v)}_{MAX}$ is smooth for small values of δ_{SNAV}, and it becomes rapid as δ_{SNAV} approaches 1; more specifically, a reduction of only 10% voice users is observed if the 50% of vehicles are equipped with SNAVs ($\delta_{SNAV} = 0.5$), but a reduction of about 50% is observed when all vehicles are equipped ($\delta_{SNAV} = 1$).

Multicast results, shown in Fig. 11, are obtained varying the power used to transmit the S-CCPCH, which is a constant fraction of the maximum available power at the base station. Since an MBMS channel per cell is assumed independently on the number of SNAVs, the value of δ_{SNAV} is not relevant. Fig. 11 shows the maximum amount of voice calls (per km^2) that allow the system to serve both classes of traffic with at least 95% satisfaction rate as function of the fraction of Node-B power dedicated to MBMS. Multicast at 64 kbit/s and 128 kbit/s are compared. As can be observed, independently on the adopted bearer, the number of voice calls increases with the power assigned to MBMS until a maximum, then it starts decreasing: low power levels assigned to the MBMS service, in fact, require low interference (generated by voice users) in order to guarantee a full coverage to the smart navigation service, while high power levels generate strong interference that limits the number of voice calls that can be served. We can thus note that a trade off between voice and smart navigation services can be obtained for both 64 kbit/s and 128 kbit/s: -18 dB to MBMS with about 1% less average voice calls compared to the case of no smart navigation service in the former case; -16 dB to MBMS with about 30% less average voice calls in the latter case. These numbers also highlight that the adoption of a 128 kbit/s bearer greatly reduces the number of voice calls with respect to 64 kbit/s.

Comparing the unicast versus multicast approach, results show that the latter is preferable only for a high penetration of the service and only if an update every 90 s is acceptable (corresponding to a multicast channel at 64 kb/s).

VI. Short Range Communications to Offload Cellular Networks

As shown in previous sections, the increasing number of vehicles equipped with OBUs or SNAVs might overload the cellular networks, and this is particularly true in the uplink direction (acquisition of small but frequent packets from a very large number of OBUs). The use of alternative solutions, and in particular of short range V2V and V2R communications, could thus be conveniently exploited; in this case, RSUs could be deployed at proper positions and V2V and V2R could be used to collect data without the use of cellular communications.

Dealing with short range communications in vehicular scenarios, the WAVE [9]/IEEE 802.11p [10] is presently the reference standard, and several field trials and research activities are currently carried out focusing on it (see, e.g., [34]–[40]). WAVE defines the communication system architecture and the complementary set of services and interfaces for vehicular scenarios, whereas IEEE 802.11p, which is an amendment to the IEEE 802.11 standard conceived for vehicular communications at 5.9 GHz, describes the MAC and physical layer protocols. At the physical layer, IEEE 802.11p is based on the orthogonal frequency division multiplexing (OFDM) modulation, with seven non overlapping channels of 10 MHz each; one of these channels is reserved for control purposes and the other six are provided as service channels. In the control channel all OBUs are expected to periodically broadcast their identity and position (e.g., GPS coordinates) in packets denoted as beacons, so that each OBU has a real time knowledge of all its neighbors. A key amendment introduced by WAVE/IEEE 802.11p is the WAVE mode, which allows the transmission and reception of data frames with the wildcard basic service set (BSS) identity and without the need of belonging to a particular BSS. This feature enables very efficient communication-group setup without much of the overhead typically needed in nomadic IEEE 802.11a/g networks; it simplifies the BSS operations in a truly ad hoc manner for vehicular usage [10], [41], and can be used by devices for a fast exchange of data.

Here, we assume that OBUs are equipped with the WAVE/IEEE 802.11p [9], [10] communication interface with the objective to offload the cellular networks. Although it is not mandatory according to the specification, here we assume the use of two channels in parallel, with the control channel only used for beacon broadcasting and one service channel used for data exchange; this configuration guarantees that no reduction of performance is caused by the smart navigation service to safety applications. In our simulations, each OBU broadcasts its position in the control channel, with a beacon frequency of 10 Hz (in accordance with the considerations given in [42] and [43]), and transmits data in the service channel when needed.

To reduce the cellular network load, if an OBU is under the coverage of any RSU, it directly delivers its data through V2R communication. Otherwise, a routing algorithm is required to find the best route towards an RSU through V2V multiple hops. In particular, the scope of the routing algorithm is to search for a suitable next relay among the neighbor nodes. Among the many routing algorithms proposed in literature for VANETs (see, e.g., [44], [45]), here we adopt greedy forwarding (GF), which inspired most of those suited for not fully connected networks. In GF, the OBU knows the position of the nearest RSU (thanks to a location service, out of the scope of this work) and selects it as the destination; the OBU also knows the position of all its neighbors (thanks to the beaconing mechanism), and considers as possible relays those that are nearer to the destination; the OBU forwards data to the relay which is closest to the destination, if any, and stores the data otherwise.

Since an RSU or a suitable next relay are not always available and since the OBU buffer is limited and data cannot be stored for an unlimited amount of time, all packets are sent through the cellular network whenever one of the following conditions is 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 more than T_{MAX} seconds before the actual instant. N_{MAX} is related to the hardware implementation of the OBUs, while the choice of T_{MAX} is strictly related to the maximum acceptable delivery delay. Since, as shown in Section IV, the timely update of information impacts on the smart navigation effectiveness, the value of T_{MAX} is of main interest for the envisioned service.

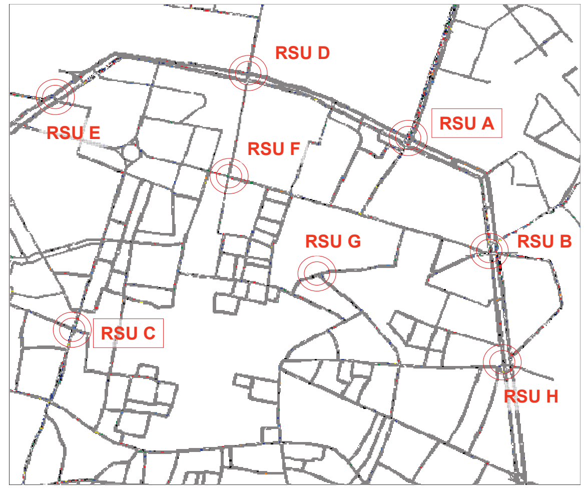


Fig. 12. RSU positions in the considered scenario.

In the following, we show the performance in terms of cellular resources that can be saved by exploiting V2V and V2R communications to deliver the sensed data to the control center through the RSUs.

A. Simulation Settings and Output Figures

As in previous sections, a parametric portion of vehicles δ_{OBU} ($\delta_{\text{OBU}} \in [0,1]$) is assumed equipped with an OBU, which acquires some measurements every τ seconds. Like in the UMTS case, simulations are performed in a portion of Bologna with an high density of vehicles, corresponding to 220 vehicles per Km^2. In this case, one or more RSUs are deployed in the scenario, in the positions shown in Fig. 12. The selected sites correspond to the mostly crowded junctions, noting that major junctions are suitable sites also owing to the likely presence of lighting, traffic lights, and therefore of power supply. RSU A is positioned, in particular, in the busiest crossroad of the whole scenario, while RSU C is in the less loaded crossroad among the eight shown in Fig. 12.

As already discussed, the maximum number of packets N_{MAX} that can be queued is related to the hardware implementation of the OBUs, and is here set to a high value, 1000. On the contrary, different values are assumed for T_{MAX}.

In short range simulations, we refer to the following propagation model:

$$\text{PL}(d) = \text{PL}_0(1) + 10\beta \log_{10}(d) \quad (3)$$

where $\text{PL}_0(1)$ is the free space path loss at 1 meter distance, β is the path loss exponent, and d is the distance in meters. A threshold model is then assumed for the packet error rate, with the shadowing effect due to buildings: a transmission between two devices is possible only if 1) the virtual line connecting them do not cross any building, 2) the received power is higher that the receiver sensitivity and 3) the signal-to-noise-plus-interference ratio is higher than a threshold. With the

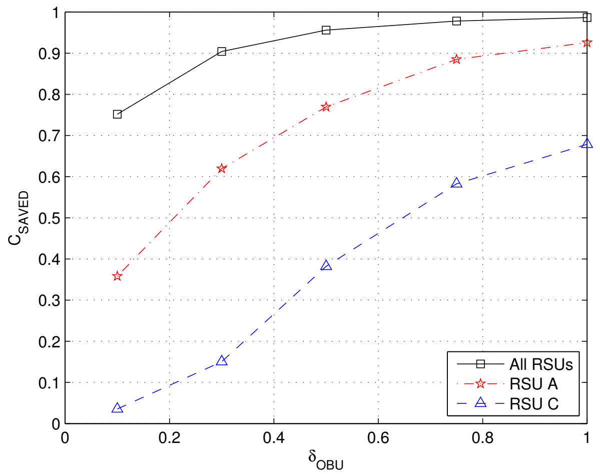


Fig. 13. Short range communications: impact of the OBU penetration δ_{OBU} and of RSU number and positions. Specifically, C_{SAVED} as a function of δ_{OBU}, with all eight RSUs, with RSU A only, and with RSU C only. $T_{MAX} = 10$ s.

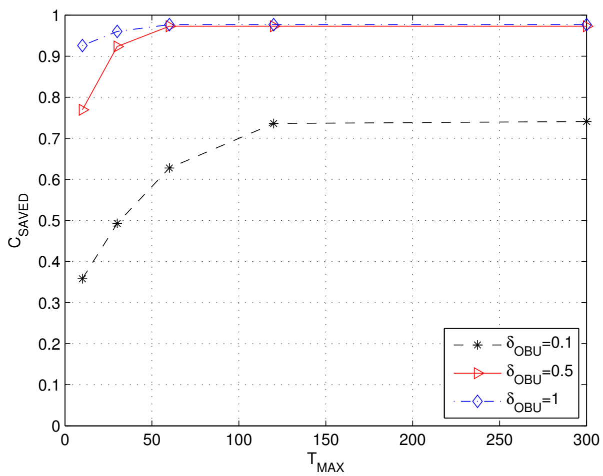


Fig. 14. Short range communications: impact of the maximum delay before transmission through the cellular link T_{MAX}. Specifically, C_{SAVED} as a function of T_{MAX}, with various values of δ_{OBU}. RSU A.

assumed parameters, the maximum communication distance in the absence of interferers is 200 m.

Numerical results are provided in terms of ratio of saved cellular resources C_{SAVED}, i.e., the ratio between the number of packets delivered through the RSUs and the number of packets generated by all vehicles.

B. Numerical results

The impact of the OBU penetration and the impact of the number and positions of RSUs are investigated in Fig. 13, where C_{SAVED} is plotted as a function of δ_{OBU}, with various RSU deployments. To guarantee an updated knowledge of traffic conditions at the control center, T_{MAX} is set to 10 s. Results show the large amount of cellular resources that can be saved through the joint adoption of V2V and V2R communications. As expected, when all the RSUs are deployed, C_{SAVED} outperforms the cases of a single RSU. However, even in case of single RSU A, C_{SAVED} is always larger than 0.3 when $\delta_{OBU} > 0.1$, even reaching 0.9 when $\delta_{OBU} = 1$; this result highlights that even a single RSU, properly positioned, can be exploited to save a large amount of cellular resources. Observing the curve that refers to RSU C, which is located in a less busy junction, it can be observed that it is less effective, owing to a reduced number of vehicles passing in its proximity. However, also in this case C_{SAVED} exceeds 0.6 when $\delta_{OBU} = 1$, with a not negligible percentage of saved cellular resources.

Fig. 14 shows C_{SAVED} as a function of T_{MAX} for various values of δ_{OBU}, when only RSU A is deployed. Allowing a greater T_{MAX} increases the probability that vehicle mobility generates new paths toward the RSUs. As can be observed, if a higher T_{MAX} is acceptable, then C_{SAVED} noticeably increases. If a T_{MAX} higher than 30 s and a δ_{OBU} higher than 0.5 are assumed, then C_{SAVED} with RSU A becomes grater than 0.9, almost fully offloading data from the cellular network.

Short range communication is thus proved to represent an interesting solution to offload the cellular network with limited costs.

VII. Conclusion and Future Work

In this work, we have discussed the smart navigation service from the wireless communication networks point of view. In particular, we have firstly evaluated the performance of the smart navigation in terms of travel time, showing that a reduction of even the 50% is possible; results have also revealed that at least 10% of vehicles providing information every 10 s are needed to enable a correct estimation in most conditions, while the update at the smart navigator is less critical. Then, the feasibility from the communication systems point of view has been discussed. To this scope, we have considered UMTS as the enabling technology for the real time acquisition and transmission of traffic information, evaluating the impact of such a communication both on other services already provided by UMTS and on the QoS of vehicular users. Furthermore, the use of dedicated channels or shared channels was compared. Our studies have highlighted that the service appears feasible and that the number of equipped vehicles does not seem a critical issue. We have also pointed out, however, a not negligible loss in capacity; in particular, it has been shown that, to guarantee a satisfactory quality of service, 15% or more resources are subtracted to the other services. Finally, the adoption of short range V2V and V2R communications have been explored to offload the cellular network in the uplink, showing that 30% to 90% data traffic can be offloaded even with few RSUs, depending on the number of vehicles equipped with such technology and the accepted delivery delay.

Besides the several aspects discussed in this paper, a number of issues are still open for future work. Concerning the benefit of smart navigation for the driver, we will extend our study to the effect of smart navigation when all vehicles are routed at the same time. Furthermore, we will investigate if the same traffic estimation can be obtained with a lower amount of information, adaptively changing the rate of both uplink collection and downlink update following traffic conditions. Regarding cellular resources, we will investigate the adoption of long term evolution (LTE) and LTE advance instead of UMTS. Focusing on short range communications, we will investigate other routing algorithms and we will also address the downlink diffusion of information from the RSUs to the SNAVs.

VIII. Acknowledgments

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References

[1] A. Bazzi, B. Masini, G. Pasolini, and O. Andrisano, "Wireless communications enabling smart mobility: Results from the project PEGASUS," in *Second International Conference on Mobile Services, Resources, and Users (MOBILITY) 2012*, Oct. 2012.

[2] PEGASUS project. Accessed on June 2013. [Online]. Available: http://pegasus.octotelematics.com

[3] A. Bazzi, B. Masini, and O. Andrisano, "On the frequent acquisition of small data through RACH in UMTS for ITS applications," *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 7, pp. 2914–2926, 2011.

[4] A. Conti, A. Bazzi, B. Masini, and O. Andrisano, *"Vehicular Networks: Techniques, Standards, and Applications"*. Auerbach Pub., CRC Press, Taylor & Francis Group, 2009, ch. Heterogeneous Wireless Communications for Vehicular Networks, pp. 63–107, ISBN: 9781420085716.

[5] A. Bazzi, B. Masini, G. Pasolini, and P. Torreggiani, "Telecommunication systems enabling real time navigation," in *Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*, 2010, pp. 1057–1064.

[6] A. Toppan, A. Bazzi, P. Toppan, B. Masini, and O. Andrisano, "Architecture of a simulation platform for the smart navigation service investigation," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2010 IEEE 6th International Conference on*, 2010, pp. 548–554.

[7] A. Bazzi and B. Masini, "Real time traffic updates via UMTS: Unicast versus multicast transmissions," in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, 2011, pp. 1–6.

[8] A. Bazzi, B. Masini, and G. Pasolini, "V2V and V2R for cellular resources saving in vehicular applications," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, 2012, pp. 3199–3203.

[9] *IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation*, Std., 2006.

[10] *Standard for Information Technology- Telecommunications and Information Exchange between Systems- Local and Metropolitan Area Networks-Specific Requirements Part 11 - Amendment 6: Wireless Access in Vehicular Environment*, IEEE Std. 802.11p, 2010.

[11] Vissim. Accessed on June 2013. [Online]. Available: http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim

[12] A. Bazzi, G. Pasolini, and C. Gambetti, "SHINE: Simulation platform for heterogeneous interworking networks," in *Communications, 2006. ICC '06. IEEE International Conference on*, vol. 12, 2006, pp. 5534–5539.

[13] C. Sommer, A. Schmidt, Y. Chen, R. German, W. Koch, and F. Dressler, "On the feasibility of UMTS-based traffic information systems," *Ad Hoc Networks*, vol. 8, no. 5, pp. 506 – 517, 2010.

[14] I. Lequerica, P. Ruiz, and V. Cabrera, "Improvement of vehicular communications by using 3G capabilities to disseminate control information," *Network, IEEE*, vol. 24, no. 1, pp. 32–38, 2010.

[15] D. Valerio, A. D'Alconzo, F. Ricciato, and W. Wiedermann, "Exploiting cellular networks for road traffic estimation: A survey and a research roadmap," in *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, 2009, pp. 1–5.

[16] The aktiv CoCar project. Accessed on June 2013. [Online]. Available: http://www.aktiv-online.org

[17] S. Cho, K. Geon, Y. Jeong, C.-H. Ahn, S.-I. Lee, and H. Lee, "Real time traffic information service using terrestrial digital multimedia broadcasting system," *Broadcasting, IEEE Transactions on*, vol. 52, no. 4, pp. 550–556, 2006.

[18] P. Belanovic, D. Valerio, A. Paier, T. Zemen, F. Ricciato, and C. Mecklenbrauker, "On wireless links for vehicle-to-infrastructure communications," *Vehicular Technology, IEEE Transactions on*, vol. 59, no. 1, pp. 269–282, 2010.

[19] A. Bazzi, B. M. Masini, A. Toppan, and O. Andrisano, "The benefits of a cellular enabled smart navigation in urban environments," in *Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International*, 2012, pp. 1044–1048.

[20] U. Lee, E. Magistretti, B. Zhou, M. Gerla, P. Bellavista, and A. Corradi, "Efficient data harvesting in mobile sensor platforms," in *Pervasive Computing and Communications Workshops, 2006. PerCom Workshops 2006. Fourth Annual IEEE International Conference on*, 2006, pp. 5 pp.–356.

[21] U. Lee and M. Gerla, "A survey of urban vehicular sensing platforms," *Computer Networks*, vol. 54, no. 4, pp. 527 – 544, 2010.

[22] F. Losilla, A.-J. Garcia-Sanchez, F. Garcia-Sanchez, J. Garcia-Haro, and Z. J. Haas, "A comprehensive approach to WSN-based ITS applications: A survey," *Sensors*, vol. 11, no. 11, pp. 10 220–10 265, 2011.

[23] B. Masini, L. Zuliani, and O. Andrisano, "On the effectiveness of a GPRS based intelligent transportation system in a realistic scenario," in *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd*, vol. 6, 2006, pp. 2997–3001.

[24] X. Yu, H. Zhao, L. Zhang, S. Wu, B. Krishnamachari, and V. Li, "Cooperative sensing and compression in vehicular sensor networks for urban monitoring," in *Communications (ICC), 2010 IEEE International Conference on*, 2010, pp. 1–5.

[25] A. R. Al-Ali, I. Zualkernan, and F. Aloul, "A mobile GPRS-sensors array for air pollution monitoring," *Sensors Journal, IEEE*, vol. 10, no. 10, pp. 1666–1671, 2010.

[26] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, A. Miu, E. Shih, H. Balakrishnan, and S. Madden, "CarTel: a distributed mobile sensor computing system," in *Proceedings of the 4th international conference on Embedded networked sensor systems*, ser. SenSys '06. New York, NY, USA: ACM, 2006, pp. 125–138.

[27] U. Dietz, "CoCar Feasibility Study: Technology, Business and Dissemination," CoCar Consortium, Report, May 2009.

[28] TMC. Accessed on June 2013. [Online]. Available: http://www.tisa.org/technologies/tmc/

[29] *Traffic and Traveller Information (TTI) TTI messages via traffic message coding Part 1: Coding protocol for Radio Data System Traffic Message Channel (RDS-TMC) using ALERT-C*, ISO Std. 14 819-1.

[30] Tom Tom. Accessed on June 2013. [Online]. Available: http://www.tomtom.com/

[31] P. Benko, G. Malicsko, and A. Veres, "A large-scale, passive analysis of end-to-end TCP performance over GPRS," in *INFOCOM 2004. Twenty-third AnnualJoint Conference of the IEEE Computer and Communications Societies*, vol. 3, 2004, pp. 1882–1892 vol.3.

[32] I. Vukovic and T. Brown, "Performance analysis of the random access channel (RACH) in WCDMA," in *Vehicular Technology Conference,*

2001. VTC 2001 Spring. IEEE VTS 53rd, vol. 1, 2001, pp. 532–536 vol.1.

[33] *Traffic and Travel Information (TTI) via Transport Protocol Expert Group (TPEG) data-streams: Parts 1 to 6*, ETSI Std. ISO 18 234.

[34] B. Bai, W. Chen, K. Letaief, and Z. Cao, "Low complexity outage optimal distributed channel allocation for vehicle-to-vehicle communications," *Selected Areas in Communications, IEEE Journal on*, vol. 29, no. 1, pp. 161–172, 2011.

[35] J. Karedal, N. Czink, A. Paier, F. Tufvesson, and A. Molisch, "Path loss modeling for vehicle-to-vehicle communications," *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 1, pp. 323–328, 2011.

[36] C. Campolo and A. Molinaro, "Vehicle-to-roadside multihop data delivery in 802.11p/WAVE vehicular ad hoc networks," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, 2010, pp. 1–5.

[37] A. Paier, D. Faetani, and C. Mecklenbrauker, "Performance evaluation of IEEE 802.11p physical layer infrastructure-to-vehicle real-world measurements," in *Applied Sciences in Biomedical and Communication Technologies (ISABEL), 2010 3rd International Symposium on*, 2010, pp. 1–5.

[38] P. Alexander, D. Haley, and A. Grant, "Cooperative intelligent transport systems: 5.9-GHz field trials," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1213–1235, 2011.

[39] V. Shivaldova, T. Paulin, A. Paier, and C. Mecklenbrauker, "Performance measurements of multi-hop communications in vehicular ad hoc networks," in *Communications (ICC), 2012 IEEE International Conference on*, 2012, pp. 7162–7166.

[40] A. Bazzi, B. Masini, A. Zanella, and G. Pasolini, "Vehicle-to-vehicle and vehicle-to-roadside multi-hop communications for vehicular sensor networks: Simulations and field trial," in *Communications, 2013. ICC '13. IEEE International Conference on*, June 2013.

[41] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," in *Vehicular Technology Conference (VTC Spring), 2008 IEEE*, 2008, pp. 2036–2040.

[42] M. van Eenennaam, W. Wolterink, G. Karagiannis, and G. Heijenk, "Exploring the solution space of beaconing in VANETs," in *Vehicular Networking Conference (VNC), 2009 IEEE*, 2009, pp. 1–8.

[43] R. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, and G. Schafer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *Network, IEEE*, vol. 24, no. 1, pp. 14–19, 2010.

[44] F. Li and Y. Wang, "Routing in vehicular ad hoc networks: A survey," *Vehicular Technology Magazine, IEEE*, vol. 2, no. 2, pp. 12–22, 2007.

[45] J. Bernsen and D. Manivannan, "Unicast routing protocols for vehicular ad hoc networks: A critical comparison and classification," *Pervasive and Mobile Computing*, vol. 5, no. 1, pp. 1 – 18, 2009.