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Visible light communications as a complementary technology for the internet of vehicles

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ABSTRACT

The paradigm of connected vehicles is moving from research to implementation, thus enabling new applications that start from safety improvement and widen to the so called Internet of vehicles (IoV). The candidate enabling technologies in the radio frequency (RF) bands are cellular and short range technologies. However, the limited bandwidth shared among several applications pushes researchers to look at new technological solutions. To this end, an option is provided by visible light communication (VLC). Based on the use of the light emission diodes (LEDs) that are already available on the majority of vehicles, VLC would enable short range communication in large, unlicensed, and uncongested bands with limited costs. In this work we first highlight the main properties of VLC in vehicular networks and revise the state of the art focusing on both the IEEE 802.15.7 standard and on the performance demonstrated by field tests that have been conducted worldwide. Then, we discuss the limitations of using VLC for pure vehicular visible light networks (VVLNs) and its application as complementary technology, to be implemented with other wireless standards in future heterogeneous vehicular networks. Finally, we show numerical results provided by simulations in a realistic urban scenario focusing, as a case study, on the crowd sensing vehicular network application with VLC added to short range IEEE 802.11p technology. Results demonstrate that the addition of VLC improves the performance of a conventional vehicular network based only on IEEE 802.11p.

1. Introduction

In the next few years, connected vehicles will travel on the roads exchanging information one with each other and with the infrastructure; the collaboration will permit safer travels, more efficient traffic management, and new services for drivers and passengers. The first steps towards this horizon are being taken in many Countries around the World. In the United States US, it is August 2014, when the National Highway Traffic Safety Administration NHTSA, one of the main agencies in the field of transportation, issues an Advance Notice to proceed with standardization of vehicle to vehicle communication for light vehicles [1]. This means that new vehicles in the US will soon be equipped with the WAVE protocol suite for short range communications, based on IEEE 802.11p at the lower levels of the protocol stack [2,3] and using the dedicated short-range communications DSRC frequency bands.

In the European Union EU, even if there is still no mandate from governments, important activities are being carried out. In particular, the so called Release 1 of the set of standards for cooperative intelligence transport systems (C-ITS) was issued in February 2014 by the European Committee for Standardization (CEN) and the European Telecommunications Standards Institute (ETSI) [4]. Differently from US, various technologies are envisioned as enabler of connected vehicles, and particular attention is being posed on cellular technologies. In the EU, the long term evolution LTE technology can thus be considered as another key enabler of connected vehicles [5,6].

The availability of wireless communications will enable the creation of vehicular networks with a wide range of new applications [7–11]. Great attention is obviously devoted to safety improvement, thanks to neighbor discovery and tracking and the immediate warning of critical events, like accidents in the proximity. In addition, connected vehicles will also form, with fixed road side units RSUs as gateways, the so called Internet of vehicles (IoV), with other data services that include traffic management improvement or entertainment applications.

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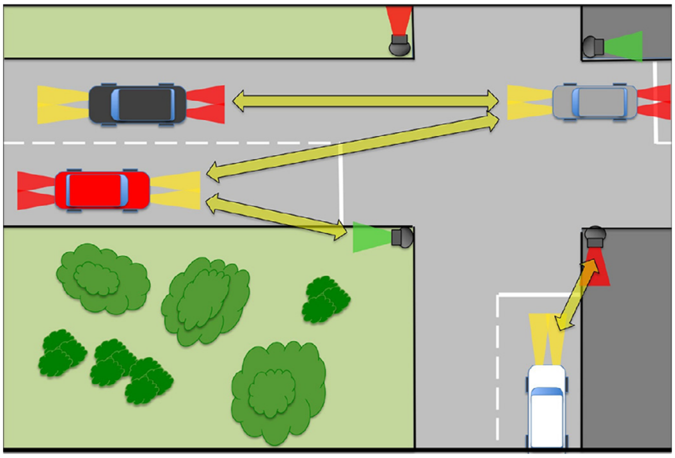


Fig. 1. Vehicular visible light networks.

Whereas presently the fight is tackled in the radio frequency RF band, with short range communications (with the IEEE 802.11p standard in the DSRC band) and cellular communications (mainly focusing on LTE), a new option is keeping the attention of researchers and engineers: visible light communication VLC. VLC exploits the low cost and high efficient light emitting diodes LEDs used for illumination purposes to also provide wireless communications.

The enormous spread of the LEDs and its huge communication potential, led in fact VLC to the introduction in the family of standards for wireless communications, by 2011, in the IEEE 802.15.7 specifications [12]. Exploiting the already mounting LED lights, VLC could be used in several application scenarios (such as underwater communications [13] or localization and tracking [14]), and also vehicles could be connected to each other to create the so called VVLNs (a.k.a. V^2LC networks [15]), as represented in Fig. 1.

Differently from RF, the visible light spectrum offers large portions of unlicensed and uncongested bands. In addition to the potentially high throughput guaranteed by the low congested frequencies, the large bandwidth, and the optimal spatial reuse, VLC is also characterized by a high directivity and a predictable channel; these aspects allow high accurate neighbors positioning without use of other technologies [16], reduce the sources of interference [17], and guarantee a high security level due to the inherently reserved channels [18,19].

The high directivity also implies, however, the need for almost clear line of sight that limits the use of VLC to the applications where no obstacles must be overtaken and only single or multiple hops between vehicles that are traveling on the same road are needed. Besides pure VVLNs, anyway, VLC can be foreseen in heterogenous vehicular networks as an addition to the RF technologies to increase the overall capacity.

The scope of this paper is thus to introduce the paradigm of VVLNs and to highlight the improvement allowed by its integration in future heterogenous vehicular networks. To this aim, results are shown focusing on the example application of CSVNs, where data collected by sensors on board of vehicles are delivered through single or multiple hops to RSUs, which act as gateways towards a remote control center. The strategies for the selection of the technology to be used is also discussed and a congestion-adaptive algorithm is proposed.

The paper is organized as follows: in Section 2, the peculiarities of VLC applied to vehicular networks, the IEEE 802.15.7 specifications that focus on VLC, and the performance demonstrated in vehicular networks by real testbeds around the world are discussed; Section 3 focuses on the use of VLC as a single technology or as a complementary technology in heterogenous vehicular networks; in Section 4 the adaptive algorithm for the technology selection is proposed and numerical results are provided; finally, in Section 5 the conclusion is drawn.

2. Vehicular visible light networks

In this section we provide an overview of the VLC technology applied to vehicular networks; after highlighting its peculiarities, the present state of the art is discussed focusing on standardization and real experimentations.

2.1. VLC peculiarities

VLC significantly differs from the reference DSRC and LTE technologies in many aspects, including the use of unlicensed and uncongested frequencies, lower coverage and high directivity, and reuse of devices that are already deployed for other scopes. These characteristics are hereafter discussed in details and summarized in Table 1.

Unlicensed and uncongested bands. One of the main advantages of VLC is that it uses an unlicensed and uncongested bandwidth, located between 380 and 800 THz. It is known that DSRC bands around 5.9 GHz have been reserved to the short range use in vehicular networks in most Countries worldwide; however, there are strong concerns and long discussions about what happens when the small number of channels provided by DSRC are used by hundreds of vehicles under congested conditions [20–22]. This issue is also present with reference to LTE, with possible hundreds of vehicles sharing resources of a single cell [23,24]. In the case of cellular networks, there is also the additional aspect of the participation of a telecom operator, with issues on who would undertake the operating costs.

Short range, high directivity and need for line of sight. The range of VLC in vehicular scenarios obtained in today experiments is in the order of the tens of meters [16,25,26]. These ranges are significantly smaller than those obtainable with DSRC and will never enable the ubiquitous coverage of cellular systems. Compared to RF technologies, VLC propagation is also more sensible to rain and fog, and even the sun position can influence the performance [15]. Furthermore, other aspects make VLC very different from the other technologies: the high directivity and low penetration capabilities. These characteristics, on the one hand require that nodes are well aligned and without obstacles in between, but on the other hand imply low interference from neighboring devices and thus lead to high spatial reuse. In addition, these peculiarities also permit high accurate positioning [16] and highly secure communications [18,19]. An interesting advantage, which is a direct consequence of the high directivity, is also that full-duplex communication with concurrent transmissions in the two directions are easily achieved in VVLN, as shown for example in [15,27]. The full duplex capability also makes the receiver able to provide an acknowledgment during the transmission, enabling a collision detection mechanism. Differently, full duplex transmissions are still a hard task for researchers in the case of RF [28,29].

Use of available LEDs as transmitters. LEDs are already available on new vehicles and they are natural transmitters for VLC. This differs from RF technologies, where optimized antenna systems [30] must be designed and implemented. Concerning the VLC receivers, various options are possible. In fact, whereas photodiodes are the most obvious solution, also LEDs themselves or cameras can be used. The use of LEDs as receivers reduces the necessity of additional components and makes the system more robust against interference from external sources (sun, lampposts) due to a narrower operational bandwidth [27]. Cameras appear instead the best option in terms of achievable throughput, which is significantly increased at the cost of an higher expense [16,26,31].

Table 1
Visible light communication vs. main RF technologies.

Feature	Short range RF	Cellular networks	VLC
Today reference	WAVE/IEEE 802.11p	3GPP LTE	IEEE 802.15.7
Frequencies	5.9 GHz	400 MHz - 3.5 GHz	380–800 THz
Use of frequencies	Reserved for ITS	Licensed	Unlicensed
Communication range	Up to 1 km	Ubiquitous	Lower than 100 m
Directionality	Normally none	Normally none	High
Obstacles effect	High impact	Medium impact	Obstructing
Spatial reuse	Limited	Limited	High
Implementation costs	Requires ad hoc devices	Requires ad hoc devices	Uses the available LEDs
V2V support	Yes	Future: D2D mode	Yes
V2I support	RSUs to be deployed	Native	Traffic lights and other light sources

Use of available infrastructure as access network. VVLN can benefit from a large number of already deployed fixed light sources that are connected or easily connectable to the Internet. Above all traffic lights, that control a significant percentage of city junctions and are oriented in the direction of approaching vehicles. In addition, there are several other light sources that could be involved in VVLN, like variable message panels and road lights. Since some modifications are required to these devices, from this point of view LTE has the advantage of the already existing infrastructure. It is however true that increasing the cellular network capacity requires an expensive deployment of more base stations [32]. In the case of IEEE 802.11p, on the contrary, a new ad hoc infrastructure is required [33].

2.2. VLC standardization: IEEE 802.15.7

The increasing interest on the VLC technology has recently led to the development of the IEEE 802.15.7 standard [12,38], which focuses on physical (PHY) and medium access control (MAC) of VLC. Although it is part of IEEE 802.15, dedicated to personal area networks, the specifications explicitly consider vehicles and illuminated roadside devices (such as trafficligths or streetlights) among the addressed applications. The specifications also include detailed procedures for flicker mitigation and dimming support. These two features, that are required while dealing with the LEDs used for illumination purposes, are added to guarantee eye safety and power efficiency [38].

The IEEE 802.15.7 specification defines three different PHY levels, with a number of possible modulations and coding schemes, that support data rate ranging from 11.67 kb/s to 96 Mb/s. Since the specifications suggest to only use PHY I in outdoor applications, the maximum data rate for vehicular communications is however presently limited to a maximum of 266.6 kb/s.

At the MAC layer four options are foreseen by IEEE 802.15.7: either beacon enabled slotted random access or non-beacon enabled unslotted random access, both with or without CSMA/CA. In VVLNs, non beacon enabled unsolved random access without CSMA/CA seem the preferable solution in most cases. Beacon enabled MAC, in fact, requires a coordinator, thus it can only be imagined when an RSU is involved in the communication; non beacon enabled communications appear to better fulfill the requirements of vehicular networks. At the same time, carrier sensing allows higher throughput and the increasing complexity required for its implementation does not appear a problem in the vehicular scenario.

2.3. VLC in vehicular scenarios: Results from field trials

In the last few years, the growing interest for VLC applied to vehicular networks motivated research groups in USA, Europe, and Asia, to implement VVLN testbeds [15,16,25,26,34–37], as summarized in Table 2. The objectives are on the one side to demonstrate the VVLN feasibility and on the other to investigate the achievable performance and push improvements beyond the IEEE 802.15.7 specifications.

Most of measurements are performed in static conditions, either indoor or outdoor [15,34–37]. Very different testbeds in terms of hardware and modulation/coding schemes demonstrated a data rate from 10 to 100 kb/s up to 100 m. For longer distances or larger throughputs, high directivity (through lenses and filters) and multiple LEDs are exploited. In [37], 5 Mb/s are demonstrated using LED fog lights up to 9 m. Three of the cited testbeds adopt commercial LED based traffic lights or car lights [35–37], and all of them use photodiodes at the receiver side. As a general achievement, the sun light was shown not to prevent the use of VLC during daytime, although it reduces the performance more than the street lamps do during night time.

Measurements with a fixed LED based transmitter and a moving receiver were also presented in [16,25] to reproduce the communication between a traffic light and a vehicle. In both cases, a throughput of few tens of kb/s was obtained with a distance of about 50 m.

Finally, on road measurements of V2V VLC based communications are presented in [16] and [26], focusing on two scooters and two cars, respectively. Whereas 10 kb/s with a distance between 10 and 15 m at 40 km/h are obtained in [16], a significantly larger 10 Mb/s throughput is shown in [26], with a distance up to 25 m at 25 km/h. Such a large throughput was obtained with high directivity and a sophisticated camera as receiver. This is obviously opposed to the aim of low cost, but might be still interesting for the car market.

The camera as a receiver is indeed an option, adopted by both the testbeds presented in [26]. This solution differs from the one used in all other experiments, that use photodiodes. These two possibilities have very different advantages and drawbacks, as already discussed in Section 2.1.

In addition to the data rates allowed by the present standard, values of throughput in the order of megabits per second have been thus already demonstrated for VVLNs and higher data rates at longer distances are expected for the future [26,39–42].

3. The role of VLC in the Internet of vehicles

In this section we discuss the use of VLC in vehicular networks. We first focus on pure VVLNs and their limitations, and then to the use of VLC in addition to other technologies towards the paradigm of heterogenous vehicular networks.

3.1. Pure vehicular visible light networks

The peculiarities of VLC make its use very interesting for vehicular networks; however, the following question arise: what services are possible if it is the only technology on board of vehicles?

Table 2
Field trials. An asterisk is used for the information that was not explicitly provided, thus inferred from the text.

Reference	Transmitter	Receiver	Modul./Coding	Conditions	Performance
[15] (USA, 2011)	120 white LEDs dissipating 120 mW, 50° half-angle	Photodiode 12° FOV with 4 × lens	OOK + Manchester	Static, indoor+outdoor*	100 kb/s @ 100 m
[34] (Italy, 2012)	White LED with lens, 9° half-angle	Photodiode with lens	OOK	Static, indoor	115.2 kb/s @ 31 m
[25] (Portugal, 2012)	240 LEDs	Photodiode	DSSS	Static transmitter, moving receiver	20 kb/s @ 50 m
[35] (France & Romania, 2013)	Commercial LED traffic light or car taillight	Photodiode	OOK + Manchester or Miller	Static, indoor	15 kb/s* @ 20 m (traffic light) or 3 m (taillight)
[36] (Republic of Korea, 2013)	Commercial LED headlamp	Photodiode with lens and color filter	4-VPPM	Static, outdoor	10 kb/s @ 20 m
[37] (Turkey, 2015)	Commercial LED fog lights	Photodiode	4-PAM + Reed-Solomon coding	Static, outdoor	5 Mb/s @ 9 m
[16] (Taiwan & Thailand & USA, 2013)	Scooter LED taillights, 20° half-angle	100 mm^2 photodetector, 90° FOV with no lens	4-VPPM	Two scooters, on the road	10 kb/s @ 10–15 m, 10–40 km/h
[26] (Japan, 2014) (2 testbeds)	32 × 32 LED array (2 × 2 LEDs per each bit), 26° half-angle	High speed camera, 1000 fps, 512 × 1024 pixels, 35 mm focal length	PWM + rate 1/2 turbo coding	Static transmitter, moving receiver	32 kb/s @ 45 m, 30 km/h
	Two red LED transmitters, 40 W optical signal, 20° half-angle	Camera receiver with an optical communication image sensor, 22 (H) × 16 (V) FOV	OOK + Manchester + BCH coding	Two vehicles, on the road	10 Mb/s @ 25 m, 25 km/h

A major role for vehicular communications is played by safety applications. Those applications that are based on communications with front and rear vehicles in visibility are indeed perfectly suited to be supported by VLC, thanks to the high reliability and low latency of the communications. Based on the list provided in the final report of an important NHTSA supported project [43], among the most relevant applications enabled by wireless communications to improve safety there are the *emergency electronic brake* and the *forward collision warning*: both of them could be perfectly supported by VLC without the need for other wireless communication technologies.

However, due to the need to overtake obstacles, there are a number of applications that are difficultly enabled, or even cannot be enabled, by VLC only, neither through multiple hops. With reference to the NHTSA list, the services of *blind spot warning and lane change warning*, the *do not pass warning*, the *control loss warning*, and the *intersection movement assist* cannot be implemented without the ability to go over the other vehicles and the walls of buildings placed on junctions.

Focusing on non-safety applications, the main drawback of VLC is that it provides a low connectivity degree. To give an idea about this issue, in Fig. 2 we show the connectivity degree allowed by VLC in different scenarios, as defined hereafter. In particular, two vehicles in a given time instant are said *connected* if there is a path from one to the other, either directly or adopting multiple hops. Considering the separated groups of connected vehicles, we then denote *connectivity degree* the number of vehicles forming the largest one, normalized by the number of vehicles in the scenario. A connectivity degree near to 1 means that most vehicles in the scenario are connected to each other, whereas a connectivity degree near to 0 means that all vehicles in the scenario are isolated or part of small groups.

Fig. 2, specifically, shows the ccdf of the connectivity degree that is calculated during the simulations. The scenarios are detailed in Appendix A and summarized in Table 3, whereas the adopted settings are later described and summarized in Table 4. Focusing, for example, on the Bologna congested scenario, there is nearly 0.2

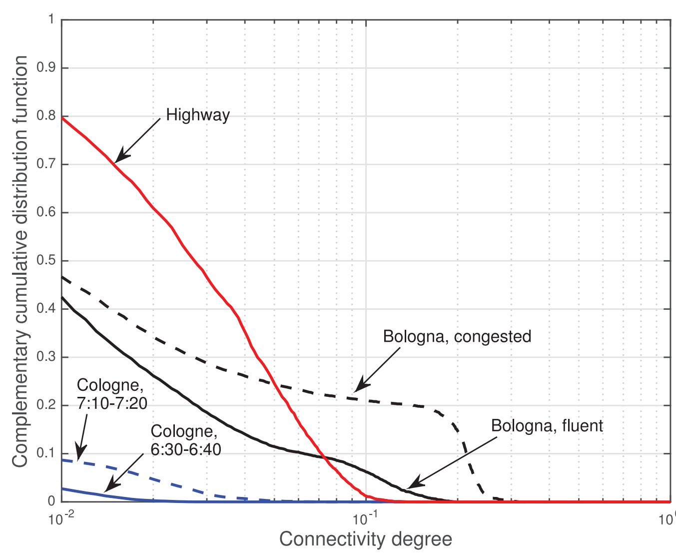


Fig. 2. Connectivity degree of the VLC technology in different vehicular scenarios.

Table 3
Size and average n. of vehicles if the considered scenarios.

Scenario	Area	Average n. of vehicles
Bologna downtown, fluent [44]	2.88 km^2	455
Bologna downtown, congested [44]		670
Cologne downtown, 6:30–6:40 a.m. [45,46]	14.35 km^2	2680
Cologne downtown, 7:10–7:20 a.m. [45,46]		4280
Highway, busy	3+3 lanes, 16 km	1995

Table 4
Simulation settings. Asterisks mean that the value is used when not differently specified.

Param.	Definition	VLC	802.11p
P_t	Transmission power	30 W	0.2 W
β	Detector responsivity	0.54 A/W	–
A	Physical area of the photodiode	1 cm^2	–
ψ_c	FOV of the receiver	30°	–
m	Order of the generalized Lambertian radiant intensity	20	–
$\gamma_{\min}$	Minimum SNR	11.4 dB	10 dB
d_{max}	LOS range	50 m	520÷1050 m (96% prob.)
R	Nominal data rate	266.6 kb/s (*)	3 Mb/s
B	Packet size	100 bytes	
λ	Packet generation rate	[0.1–10] packets/s	

probability that the largest group of vehicles connected to each other involves at least the 10% of vehicles; such probability falls below 0.015 in the Highway and Cologne scenarios.

It is thus clear that the use of pure VVLNs is not sufficient for the implementation of the whole set of safety applications and it cannot provide the full (or at least high) connectivity degree needed for real time or interactive applications. Pure VVLNs applicability is thus confined to some limited safety services and to delay tolerant applications, where an intermittent connectivity is not an issue, such as infotainment content distribution or traffic detection.

3.2. VLC as complementary technology

All in all, the limited applicability of pure VVLNs risks to never foster industries to really implement it on the vehicles. Following this observation, it is thus of major relevance to also discuss how VLC can be exploited to improve the scarce resources of the IoV, as an addition to the other technologies that can be applied to implement vehicular services.

VVLNs can, in fact, offload part of the RF networks to improve the overall performance and increase the number of implementable services. The unlicensed bandwidth, the reduced deployment costs, and the potential availability of points of access at the road side, are only some of the characteristics that make VLC suitable for this scope.

Above the other advantages, let us here remark the spatial reuse allowed by VLC, which makes the full bandwidth being used in almost all links. To give an idea of how many concurrent sources can be present in VLC and to compare it with the case of DSRC, the ccdf of the number of neighbors that are seen by the generic vehicle is shown in Fig. 3 for both VLC (Fig. 3(a)) and DSRC (Fig. 3(b)). The settings detailed in Section 4 and summarized in Table 4 are used. As observable, whereas the number of neighbors with DSRC ranges between tens to hundreds, causing a fragmentation of the available bandwidth, the probability of having more than one neighbor with VLC is less than 0.5 in a highway busy scenario and less than 0.2 in all the others.

Hence, even when the available throughput and range of VLC is normally lower than those of the RF technologies, still VVLN can provide non negligible additional resources.

Once VLC is applied as complementary technology (for instance, with respect to DSRC), the main issue is to define the strategy for the use of the joint available resources. To this aim, although several algorithms can be designed, they all lie between the two following (opposite) approaches:

1. VLC is used only in those cases where DSRC is not possible (*DSRC first* approach);
2. VLC is used anytime it is possible in order to maximally offload the DSRC network (*VLC first* approach).

The former approach makes VLC being used only when the other technology cannot be applied, while the latter makes VLC being used anytime it is possible. Which approach is preferable clearly depends on the specific conditions, such as the offloaded RF technology, its settings, and the addressed application.

For example, if VLC with the settings defined by the IEEE 802.15.7 specifications and DSRC with the settings of IEEE 802.11p are used, the use of *DSRC first* approach causes VLC to be rarely used. This is due to the fact that VLC provides smaller range and lower throughput than DSRC. If the *VLC first* approach is instead adopted, VLC can offload part of the traffic from DSRC, thus improving the overall performance.

These considerations, given in general, are hereafter explored in a specific example case. It will be shown, through simulations in a realistic urban scenario, that VLC can indeed significantly improve the capacity of the vehicular network.

4. Example results: VLC to offload DSRC in crowd sensing vehicular networks

Example results on the use of VLC to offload DSRC are obtained in the realistic scenario of Bologna, focusing on the CSVN application [46,47]. In CSVN, vehicles (hereafter smart vehicles (SVs)) are equipped with an on board unit (OBU) that periodically collects information from various sensors to be delivered to a remote control center. The SVs are all equipped with dual technology wireless systems (VLC and DSRC) and communicate to each other in order to reach, using V2V and vehicle-toroadside V2R, any of the available RSUs. The RSUs then act as gateways towards the control center. The main settings, detailed hereafter, are also summarized in Table 4.

Please note that this application plays a major role in the IoV, since the periodic generation of measurements that are then sent to a remote control center has been already implemented on millions of vehicles worldwide for insurance purposes and traffic monitoring (currently using cellular networks).

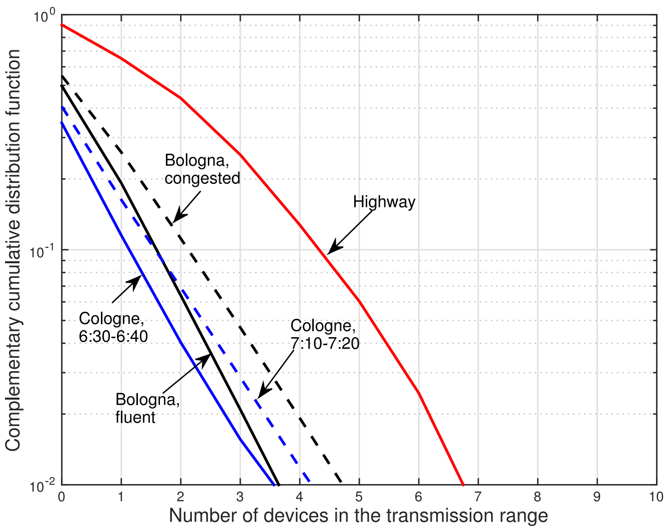
4.1. Simulation settings

Results are obtained in realistic vehicular scenarios by using the simulation platform for heterogeneous interworking networks (SHINE), which reproduces both IEEE 802.11p and IEEE 802.15.7 from the application layer down to the physical layer [48–51].

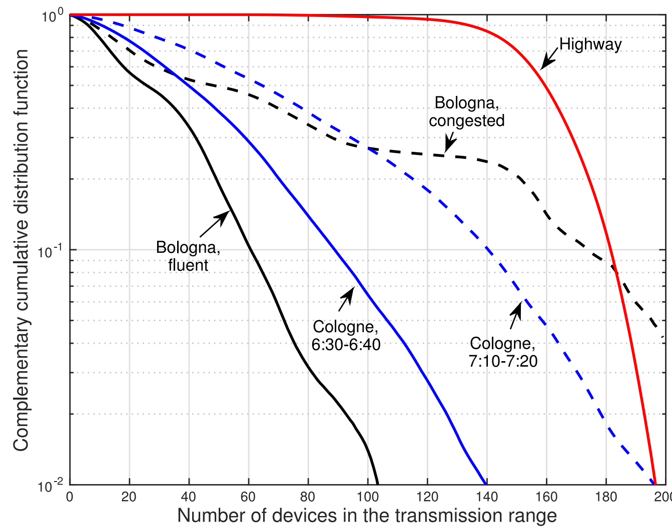
Scenario. The two Bologna scenarios, fluent and congested, are used (Table 3 and Appendix A). The road-network layout of the scenario is plotted in Fig. 4 and consists of a portion of the medium sized Italian city of Bologna of 1.8×1.6 km^2. In Fig. 4 a zoomed area of vehicular traffic simulated in the congested traffic scenario is reported to provide a visual representation of the traffic conditions nearby busy junctions. The vehicular traces, detailed in Appendix A, provide the 2D position of the SVs, that are all assumed of the same height. The length and width of all vehicles is assumed equal to 4 and 2 meters, respectively.

Application. In each SV, the OBU acquires from on-board sensors several vehicle parameters that are periodically packed into $B = 100$ byte packets every T_s seconds, that is, with a data generation rate $\lambda = 1/T_s$ packets/s. Packets are stored in the SV transmitter queue and then attempted to be delivered to any RSU through single or multi-hop communication.

RSUs. Fixed points of access are placed in the scenario, following one of these two cases:



(a) VLC.



(b) DSRC.

Fig. 3. Statistical distribution of the number of neighbors in realistic scenarios with VLC and DSRC.

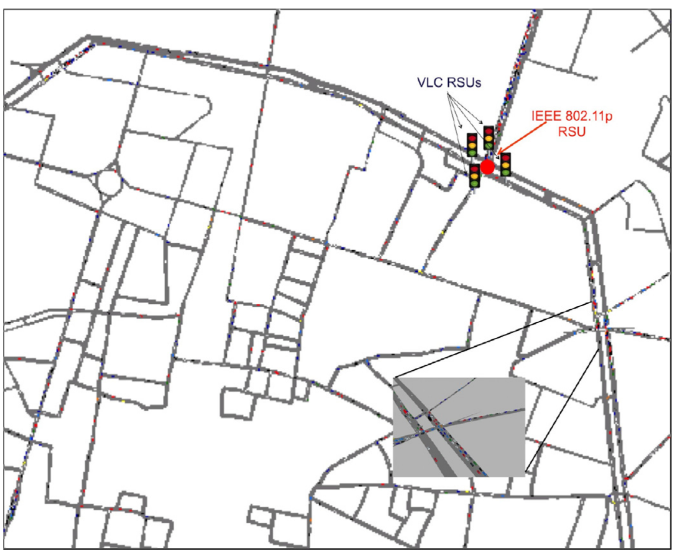


Fig. 4. Simulated scenario: part of the city center of Bologna (Italy) with one IEEE 802.11p RSU and 4 VLC RSUs represented by traffic lights at a crossroad.

1. One DSRC RSU;
2. Four traffic lights with VLC capability acting as RSU.

The four traffic lights are placed on the four directions of the mostly crowded junction of the scenario, as represented in Fig. 4; the DSRC RSU is placed in the same position as the northern traffic light of these four. RSUs are used to convey packets from vehicles and to forward them to a remote control center. The traffic lights considered as VLC RSUs are placed at one side of the road, at a height that does not allow to overcome the top of an approaching vehicle.

Communication technologies and neighbor list update. All SVs are assumed equipped with both a DSRC and a VLC interface, with LEDs used as transmitters and photodiodes as receivers. The neighboring vehicles are continuously updated thanks to the beaconing mechanism in DSRC [52] (a beacon message is periodically sent by each SV on a control channel, with information that includes the updated position) and to visible light positioning in VLC [53].

Output Figure. The system performance is evaluated in terms of

- D_R, which is the ratio of packets delivered to the control center through the RSU (i.e., using V2V and V2R),

$$D_R \triangleq \frac{\varphi_{RSU}}{\varphi_{gen}} \quad (1)$$

where φ_{gen} is the overall number of packets generated, and φ_{RSU} is the number of packets delivered to the RSUs;
- L, which is the average delay of delivered packets, in seconds.

The 95% t-based confidence interval is shown for all results. The interval is almost negligible in the majority of cases.

PHY and MAC layers. When V2V and V2R communications are carried out by means of DSRC, following [54] and [55] we assume a path loss proportional to the distance raised to the power of 2.2 in line of sight LOS conditions and we add the effect of buildings and random large-scale fading, as better detailed in Appendix B. With the considered settings, listed in Table 4, in the 96% of cases the LOS range is between 520 and 1050 m. Sensing and random access procedures, with collisions and retransmissions, are reproduced in details, also including hidden terminals, exposed terminals, and capture effects. The most reliable mode is used, thus the nominal bit rate is 3 Mb/s.

When VLC is adopted, we assume a received power inversely proportional to the distance raised to the power of four [56] and the communication impeded by the presence of any obstacle. In the case of VLC, two front and two rear LED lights are assumed, with integrated photodiodes as receivers; the angle of incidence of the transmitters and the field of view(FOV) of the receivers are all assumed of 30º. More details about the adopted model are provided in Appendix C. With the considered settings, listed in Table 4, the LOS range is 50 m. Also in the case of VLC, sensing and random access procedures, with all the consequences, are reproduced in details. Where not differently specified, the highest possible throughput as in the IEEE 802.15.7 specifications is adopted, thus the nominal bit rate is 266.6 kb/s.[1]

[1] The highest possible data rate of the IEEE 802.15.7 specifications for VLC and the lowest one of IEEE 802.11p for DSRC were adopted for Figs. 6, 7, 8 to limit the difference between the two; given the trend of research on these technologies, it is in fact expected that only the VLC data rate will increase significantly, thus a larger difference does not seem realistic.

On both interfaces, retransmissions are performed in case of packet loss up to 7 times.

Routing. Each SV attempts to forward its packets to the nearest RSU adopting the well known greedy forwarding (GF) routing algorithm [47,57]. With GF, each SV selects as next hop the neighboring SV which maximally reduces the distance from the nearest RSU. More specifically, if the SV is under coverage of an RSU, it performs a direct data transmission to that RSU. Otherwise it considers as possible relays the neighbors that are closer to the destination; the SV then selects as the next hop the relay which is closest to the destination. In the case no other SV is closer to the destination, the data is stored.

The GF routing algorithm is firstly performed for each technology separately. If no next hop is available for a given technology, the next hop of the other technology is automatically selected. Otherwise, if a DSRC next hop and a VLC next hop are both available, the adaptive procedure described in the following subsection is performed.

4.2. Congestion-adaptive VLC-DSRC selection procedure (CA-VDS)

A simple but effective algorithm named CA-VDS has been designed to manage the joint use of VLC and DSRC. The algorithm exploits the already available capabilities of the receivers and allows to investigate the performance of the two *VLC first* and *DSRC first* opposite approaches (see Section 3.2) and solutions in between, by varying a single parameter (the threshold ξ_D, hereafter discussed).

As previously detailed, the position of all DSRC and VLC neighbors are continuously updated; every time a neighbor is available as next hop for both technologies, a selection is performed as follows:

1. In every time interval of duration $T_{cm} = 0.1$ s, the DSRC channel congestion ξ_{cc} is measured by each SV;
2. DSRC is considered congested and VLC is preferred if $\xi_{cc} \geqslant \xi_D$, where ξ_D is a given threshold. If $\xi_{cc} < \xi_D$, DSRC is preferred.

CA-VDS can be implemented without an increase of the complexity of the receiver (thus without additional costs). The DSRC channel congestion ξ_{cc} is calculated, in fact, by each SV autonomously and asynchronously thanks to its sensing capabilities, similarly to [58,59]. Specifically, it is

$$\xi_{cc} = \frac{t_{busy}}{t_{busy} + t_{idle}} \qquad (2)$$

where t_{busy} is the time the DSRC medium has been sensed busy and t_{idle} the time the DSRC medium has been sensed idle. From (2) it follows that ξ_{cc} goes from 0 (free channel) to 1 (fully used channel). The threshold ξ_D defines the DSRC channel congestion level above which VLC is preferred.

As already observed, CA-VDS includes *VLC first* and *DSRC first* as special cases. Please note, in fact, that using $\xi_D = 0$, VLC is always preferred to DSRC irrespective of the channel congestion level (*VLC first*). On the opposite, when $\xi_D = 1$, DSRC is always preferred (*DSRC first*). By varying ξ_D from 0 to 1, DSRC has an increasing probability to be selected compared to VLC.

To better clarify the technology selection procedure of CA-VDS, the state transitions performed at each SV are shown in Fig. 5. Depending on the presence or not of a next hop in each of the two technologies and on the value of the DSRC channel congestion ξ_{cc}, the SV moves among three macro-states that correspond to the selection of a DSRC neighbor as next hop ("DSRC next hop selected"), a VLC neighbor as next hop ("VLC next hop selected"), and no next hop available ("No next hop"). Inside each macro-state, two or three states are possible. For example, a DSRC next hop can be selected either because $\xi_{cc} < \xi_D$ or because no VLC next hop is available; in the latter case, $\xi_{cc} < \xi_D$ and $\xi_{cc} \geqslant \xi_D$ correspond to two different states, since a different behavior follows a variation of the neighbors.

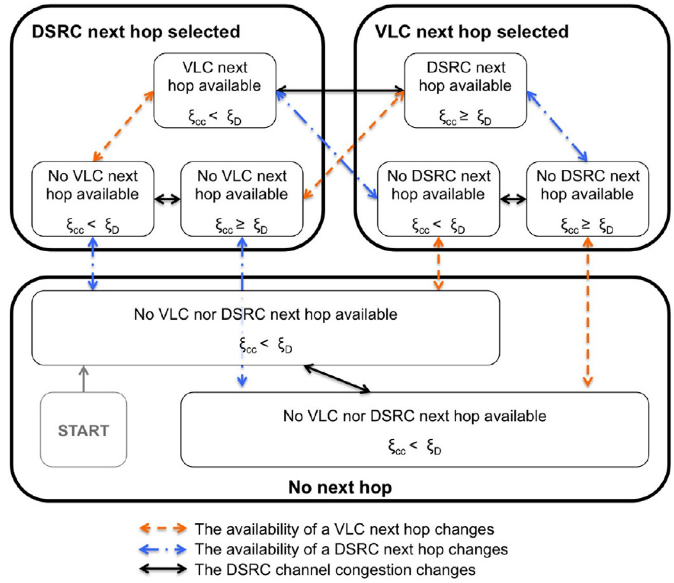


Fig. 5. State transitions of the technology selection of CA-VDS.

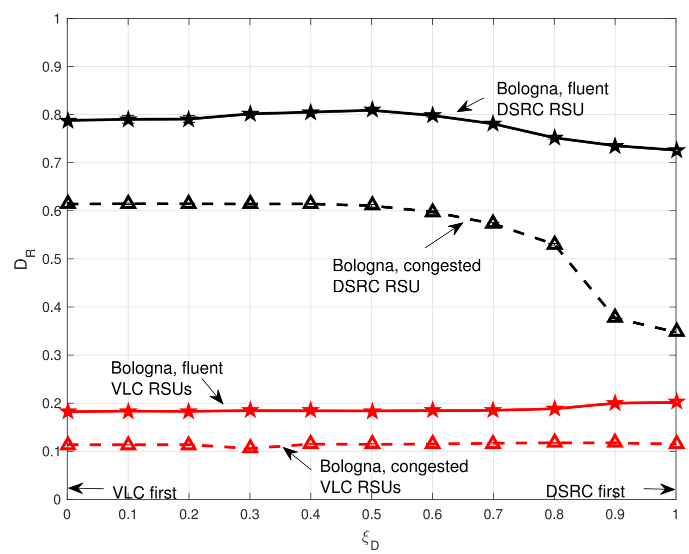


Fig. 6. Delivery rate vs. DSRC congestion threshold. $\lambda = 2$ packets/s.

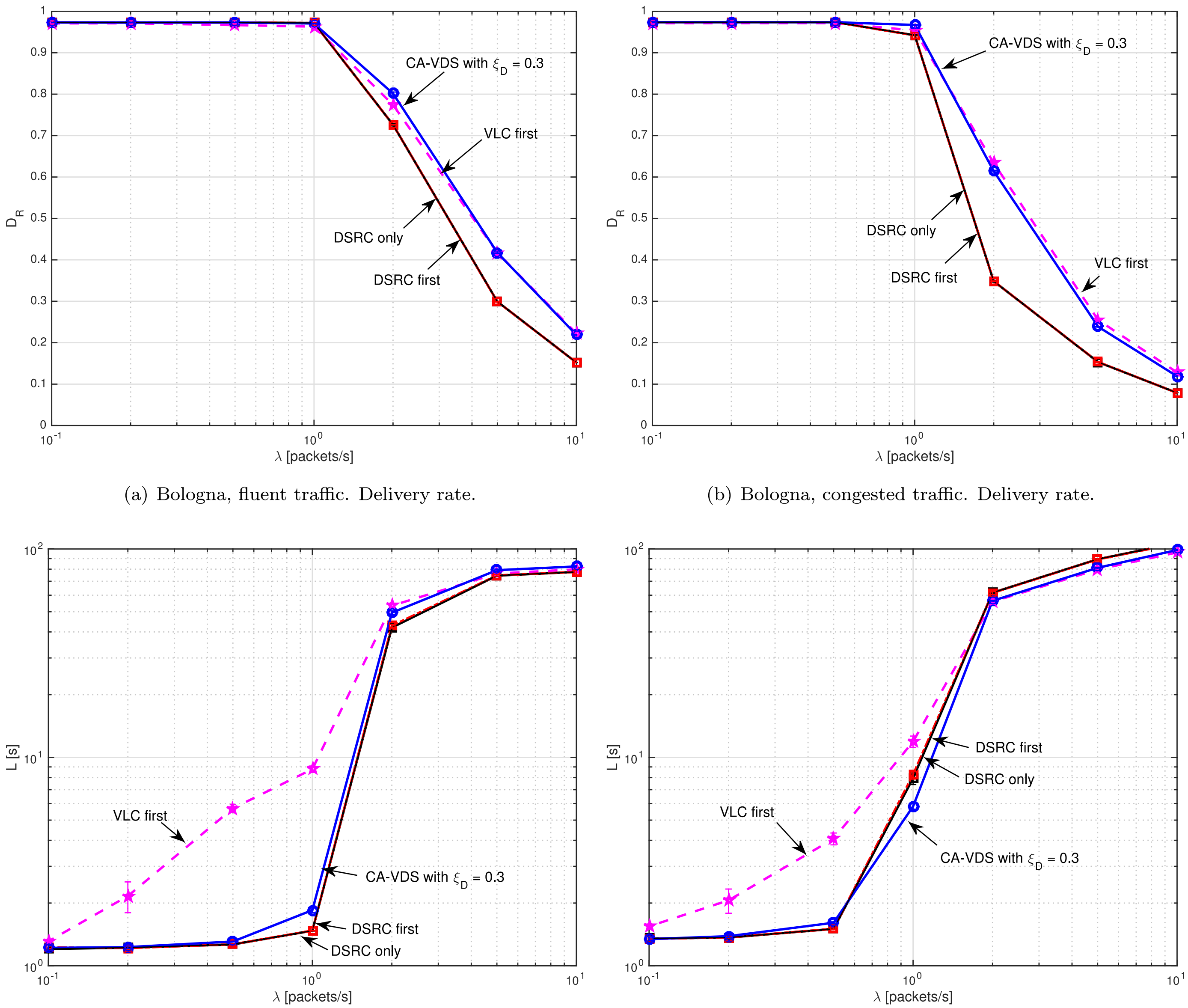
4.3. Results

Results are shown in this section firstly varying the CA-VDS threshold ξ_D, then varying the amount of data generated by each vehicle, and finally varying the data rate of VLC.

4.3.1. Effect of the threshold < upper − case > ξ_d < /upper − case >

In Fig. 6, the effect of the threshold ξ_D is shown for the two scenarios and both types of RSUs. $\lambda = 2$ packets/s is used. As already remarked, $\xi_D = 0$ means that the *VLC first* strategy is adopted; at the opposite, $\xi_D = 1$ means that the *DSRC first* strategy is adopted.

As observable in Fig. 6, when the DSRC RSU is deployed the adoption of a small ξ_D improves the delivery rate D_R, even significantly. For example, in the case of Bologna congested scenario, D_R grows of more than 75% with ξ_D changing from 1 to 0. This effect is remarkable for large values of λ, that is when the data



(a) Bologna, fluent traffic. Delivery rate.
(b) Bologna, congested traffic. Delivery rate.
(c) Bologna, fluent traffic. Average delivery delay.
(d) Bologna, congested traffic. Average delivery delay.

Fig. 7. Delivery rate and average delivery delay varying the packet generation rate with one DSRC RSU.

traffic is high and most SVs have something to transmit. The improvement is possible due to the offloading of DSRC in favor of VLC that makes less SVs contending for the DSRC medium. In fact, it is shown for example in [60] that an increase of the number of contending nodes reduces the overall capacity of a DSRC network.

In the case of VLC RSUs, the bottleneck is in the bandwidth available at the RSUs themselves, and the value of ξ_D is not so relevant. However, it is interesting to note that in the case of Bologna fluent, giving priority to DSRC ($\xi_D = 1$) allows to carry more data in the proximity of the traffic lights, with a small increase of D_R.

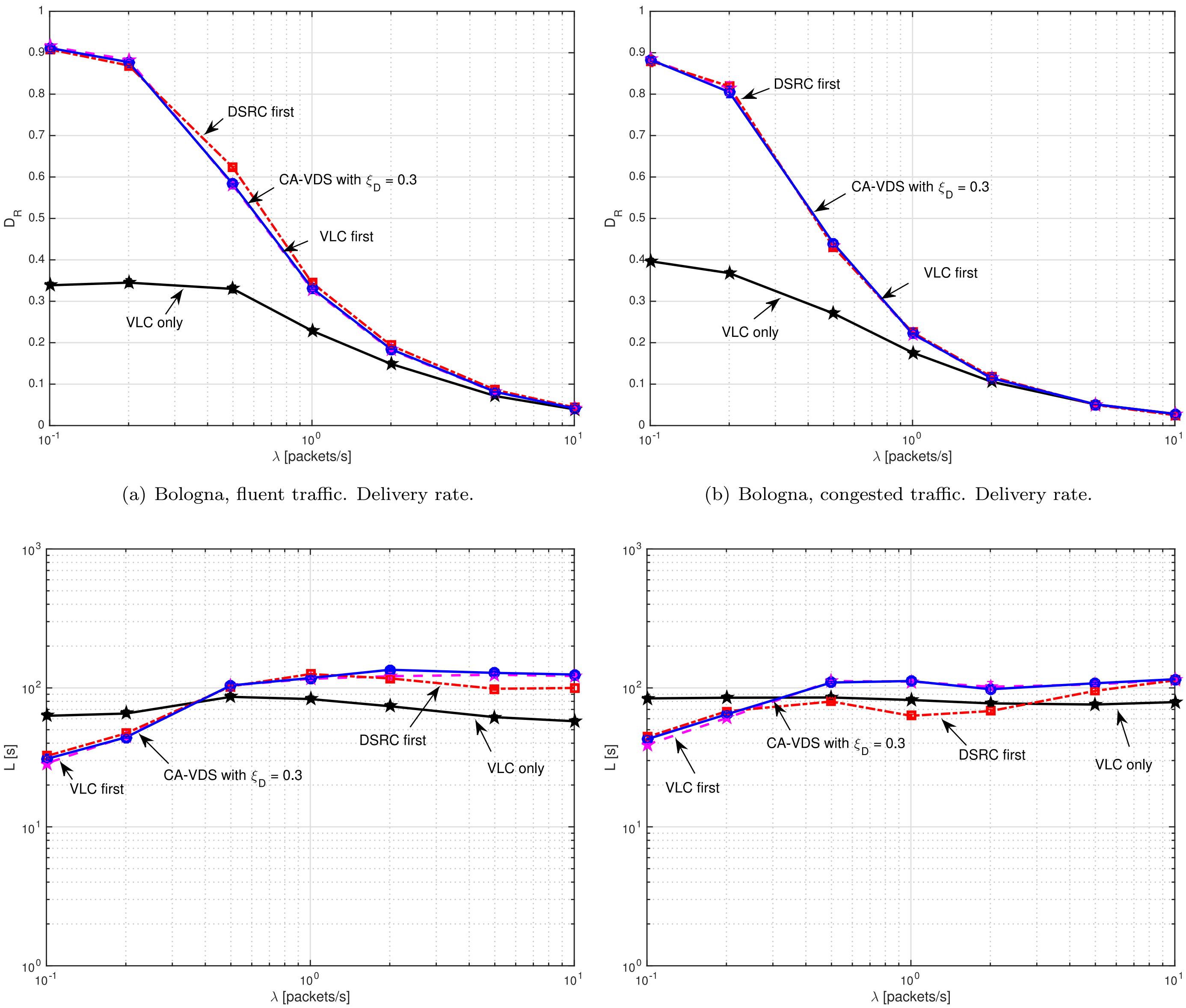
Regarding the threshold ξ_D, its optimal definition is influenced by several factors, such as the distribution of the vehicles on the road, the propagation medium and the random access mechanism including capture effect, hidden terminals and exposed terminals. However, the results shown in Fig. 6 suggest that its choice is not critical, since similar performance is achieved following small variations. It can be noted, in any case, that a value lower than 0.5 reduces the DSRC congestions and is thus preferable.

4.3.2. Effect of data traffic load

Results varying λ are then shown in Fig. 7 for the case of one DSRC RSU and in Fig. 8 for the case of four VLC RSUs, comparing the performance of:

- *DSRC* or *VLC only* (depending on the RSUs);
- *DSRC first* ($\xi_D = 0$);
- *VLC first* ($\xi_D = 1$);
- *CA-VDS with* $\xi_D = 0.3$.

In particular, assuming one DSRC RSU, the delivery rate D_R and the average delivery delay L are plotted in Fig. 7 as a function of λ, for fluent (Fig. 7(a) and (c)) and congested (Fig. 7(b) and (d)) traffic conditions.



(a) Bologna, fluent traffic. Delivery rate.

(b) Bologna, congested traffic. Delivery rate.

(c) Bologna, fluent traffic. Average delivery delay.

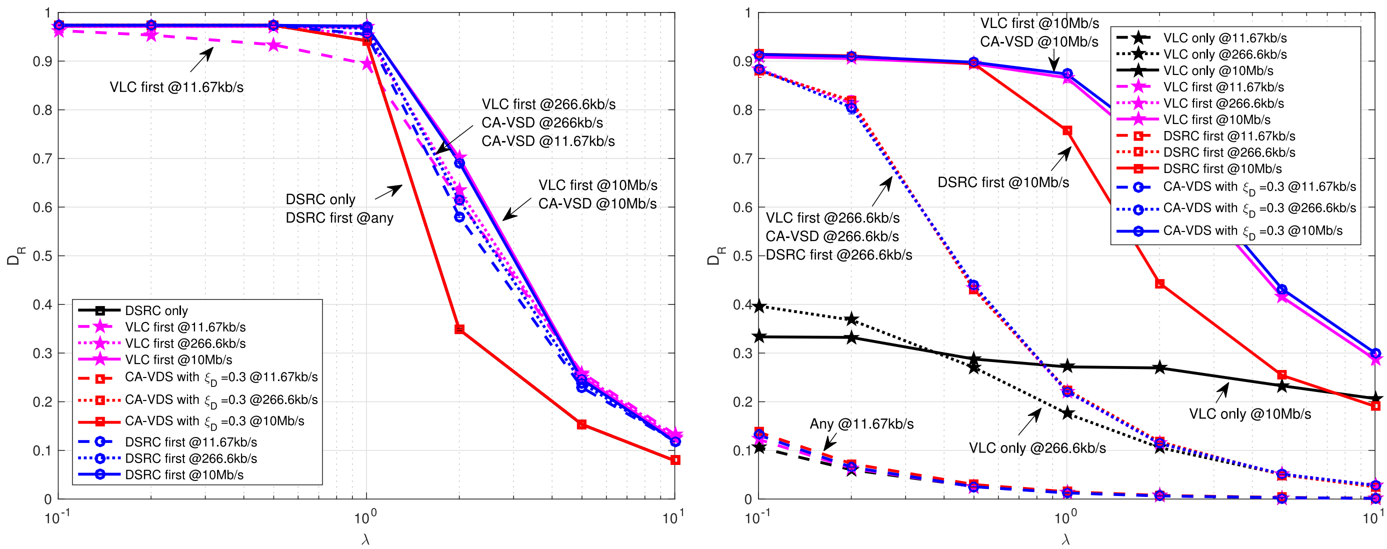
(d) Bologna, congested traffic. Average delivery delay.

Fig. 8. Delivery rate and average delivery delay varying the packet generation rate with four VLC RSUs.

Focusing on the delivery rate D_R (Fig. 7(a) and (b)), it starts from a value near to 1 (all packets delivered) when the amount of data generated is small ($\lambda \leq 1$ packets/s) and then reduces to less then 0.3 when the load is high ($\lambda = 10$ packets/s). As observable, the performance of *DSRC first* is similar to that of *DSRC only*, meaning that, due to the wider coverage provided by DSRC, the addition of VLC is ineffective if DSRC is selected first. When VLC is selected first, for values of λ greater than 1 packets/s D_R is instead higher than both the *DSRC only* and *DSRC first* cases, demonstrating the effectiveness of VLC to increase the available resources. The performance of *CA-VDS with* $\xi_D = 0.3$ is similar to that of *VLC first* in all scenarios and for any load.

Concerning the average delivery delay L (Fig. 7(c) and (d)), *DSRC only* and *DSRC first* provide smaller values than *VLC first* when the data traffic is reduced (i.e., with $\lambda \leq 1$ packets/s). If we focus on Bologna fluent and $\lambda = 1$ packets/s, for example, giving priority to VLC causes an L that is six times the one that follows the priority given to DSRC. DSRC, in fact, allows to reach the destination with fewer hops on average. Remarkably, adopting *CA-VDS with* $\xi_D = 0.3$ the delay is comparable to the cases *DSRC only* and *DSRC first* when data traffic is reduced. Please note that, when the data load increases and the delivery rate decreases, the average delivery delay becomes less relevant. In such case, in fact, the bottleneck is at the RSU receivers and part of the generated packets starve in some queue; as a consequence, if the delivery rate is the same, a higher average delivery delay only means that packets generated far from the RSUs are delivered instead of others generated near to the RSUs.

Fig. 8 then shows D_R and L as a function of λ when four VLC RSUs are supposed, both for fluent (Fig. 8(a) and (c)) and congested (Fig. 8(b) and (d)) traffic conditions. As observable, any strategy allowing the use of the heterogeneous VLC and DSRC resources improves D_R dramatically compared to the *VLC only* case. This is due to the lower connectivity level that is guaranteed by VLC in the vehicular network. In several cases, in fact, the SVs do not have a VLC next hop available, and the connectivity is guar-



(a) One DSRC RSU. (b) Four VLC RSUs.

Fig. 9. Bologna, congested traffic. Delivery rate varying the packet generation rate, for different data rates of VLC.

anteed only by the DSRC technology. It can also be observed that all the strategies perform similarly in this case; in fact, the bottleneck is represented by the VLC bandwidth of RSUs, which impacts similarly irrespective to the adopted strategy.

Comparing the use of VLC RSUs with the use of DSRC RSU, a smaller D_R is obtained in the former case for the same λ; this is expected due to the smaller data rate available at the VLC RSUs compared to the single DSRC RSU. However, the use of VLC has the great advantage to exploit the traffic lights that are already deployed on intersections; differently, DSRC RSUs require new hardware.

4.3.3. Effect of VLC data rate

In Fig. 9, the effect of VLC data rate on the delivery rate is investigated. In particular, the previous results are compared with those corresponding to 11.67 kb/s, which is the minimum data rate in the IEEE 802.15.7 specifications, and 10 Mb/s, which is the maximum throughput that has been measured in vehicular field trials [26]. The different data rates are obtained by properly modifying the duration of each transmission.

Results are shown for both the DSRC RSU and VLC RSUs cases, in the Bologna congested scenario. Again, *VLC first, CA-VSD with* $\xi_D = 0.3$, *DSRC first*, and either *VLC only* or *DSRC only* (depending on the adopted RSUs) are compared.

Focusing on the DSRC RSU case (Fig. 9(a)), it can be noted that the VLC throughput does not have a great impact on D_R, and even the use of VLC at 11.67 kb/s in addition to DSRC provides a significant gain compared to *DSRC only*. In this case, in fact, the delivery rate is limited by the RSU capacity, which depends on the DSRC data rate. Although the various links at 11.67 kb/s appear of limited capacity on a first look, the spatial reuse allows almost one link, fully available and free from collisions, per each couple of vehicles.

A slight loss of D_R is only observed if *VLC first* is applied at 11.67 kb/s, when $\lambda \leq 1$. Such a loss is anyway not observed applying *CA-VDS with* $\xi_D = 0.3$. Similarly, a slight improvement is observed if *VLC first* or *CA-VDS with* $\xi_D = 0.3$ are applied at 10 Mb/s, when $\lambda \geq 1$ and $\lambda \leq 5$.

As already discussed, *DSRC first* fails to improve the performance compared to *DSRC only* because DSRC provides higher coverage than VLC; if the VLC link is available towards a neighbor, in fact, the correspondent DSRC link is also available, and always preferred.

Overall, the improvement provided by the addition and use of VLC against *DSRC only* is up to 100% in the case of VLC at 10 Mb/s.

Differently, in the VLC RSUs case (Fig. 9(b)), the delivery rate is limited by the capacity of the VLC based RSUs. In this case, the D_R curves move to the left or the right with a decrease or an increase of the VLC throughput, respectively. Whereas no significant variation of D_R can be observed comparing *VLC first, CA-VDS with* $\xi_D = 0.3$, and *DSRC first* at 11.67 kb/s or 266.6 kb/s, both *VLC first* and *CA-VDS with* $\xi_D = 0.3$ provide a relevant D_R improvement compared to *DSRC first* at 10 Mb/s. In all the cases, the improvement of using both technologies compared to *VLC only* is remarkable.

In summary, the results shown in Fig. 9 confirm the effectiveness of the proposed algorithm, as *CA-VSD with* $\xi_D = 0.3$ provides the best D_R in both cases with all VLC data rates.

5. Conclusion

This paper focused on the adoption of VLC as supplementary technology to the RF ones for data exchanging between vehicles and between vehicles and RSUs in vehicular networks. We proposed to exploit this emergent technology in cooperation with DSRC and cellular communications to increase the overall resources available for the future IoV. Example results have been shown focusing on the crowd sensing vehicular network application, considering VLC in addition to DSRC. A cooperative algorithm to adaptively select the technology has been also proposed, with a single parameter allowing to move from VLC always preferred to DSRC to the opposite case. Simulations, performed in realistic urban scenarios with hundred of vehicles, demonstrated the significant improvement obtained by adding VLC to DSRC. The best results were obtained by giving priority to DSRC when its channel is far from congested, and preferring VLC in the other cases.

Appendix A. The scenarios

The results shown in the paper refer to the five following scenarios:

1. *Bologna downtown, fluent traffic*: a downtown area of the Italian city of Bologna which is 1.8 × 1.6 km^2; the traffic is fluent,

with few short queues at the main junctions. There are approximately 455 vehicles on average; the same scenario was used for example in [44,47];
2. *Bologna downtown, congested traffic*: the same Bologna area of 1.8×1.6 km^2, with congested traffic and queues at the main junctions. There are approximately 670 vehicles on average; the same scenario was used for example in [44,47];
3. *Cologne downtown, 6:30–6:40 a.m.*: a downtown area of the German city of Cologne which is 4.1×3.5 km^2. The traffic is fluent and there are approximately 2680 vehicles on average. It is a portion both in time and space of the traffic traces presented in [45]; more details can be found in [46];
4. *Cologne downtown, 7:10–7:20 a.m.*: the same Cologne area of 4.1×3.5 km^2. The traffic is busy and there are approximately 4280 vehicles on average. Also in this case, it is a portion both in time and space of the traffic traces presented in [45] and more details can be found in [46];
5. *Highway, busy*: a 16 km highway segment, with 3 lanes per direction; the traffic is busy, with approximately 1995 vehicles on average.

The Bologna traffic traces are available for download at [48].

Appendix B. Propagation model of DSRC

Several measurement campaigns have been carried out in the last decade in order to characterize the DSRC propagation and provide models for vehicular network simulators, such as [54,55,61–63]. In our simulator, following [54] and [55], when V2V and V2R communications are carried out by means of DSRC, we refer to the following path loss model: given one source S and its destination D, with d denoting their Euclidean distance, we consider the segment connecting S and D and check the number of buildings that are crossed [54]; we then denote with n_w the number of external walls (i.e., two per building) and with l_b the total length of the segments inside the buildings that are intersected. Then, the path loss is calculated as

$$\mathrm{PL}(d) = \mathrm{PL}_0(1) + 10\mathrm{L_e}\log_{10}(d) + \mathrm{L_w}\cdot n_\mathrm{w} + \mathrm{L_b}\cdot l_\mathrm{b} + X_\sigma \quad (3)$$

where $\mathrm{PL}_0(1)$ is the free space path loss at 1 m distance, $\mathrm{L_e}$ is the path loss exponent assumed equal to 2.2 [54], $\mathrm{L_w}$ is the loss of each external wall of a building assumed equal to 9 dB [54], $\mathrm{L_b}$ is the additional loss inside the buildings assumed equal to 0.4 dB/m [54], X_σ is a lognormal random variable with 0 mean and standard deviation equal to 1.7 [55]. With these values, the average range (when the random contribution is null) is nearly 740 m. With the random contribution, in LOS conditions the range is between 520 and 1050 m with probability 0.96.

A threshold model is then assumed for the packet error rate: a transmission between two devices is possible only if the received power P_r is higher than the receiver sensitivity $P_{r_{min}}$; a transmission successfully completes if the average SINR is higher than a threshold γ_{min}, otherwise an error (or a collision) occurs.

Appendix C. Propagation model of VLC

When VLC is adopted, we assume a Lambertian model for the signal propagation. In fact, although it was shown for example in [37,64] that the Lambertian model might not completely model the behavior of vehicular lights, this is currently the most adopted model in papers that simulate VVLNs (e.g., [16,65]). In particular, we assume a received power inversely proportional to the distance raised to the power of four [56]. In addition, a transmission between two devices is possible only if 1) they are in visibility, hence the virtual line connecting them do not cross any obstacle, (i.e., another vehicle or a building), 2) the received power P_r is higher than the receiver sensitivity $P_{r_{min}}$ and 3) the SINR is higher than a threshold γ_min. Specifically, the SINR can be evaluated as [16,66,67]

$$\mathrm{SINR} = \frac{\beta^2 P_\mathrm{r}^2}{I + \sigma^2_\mathrm{shot} + \sigma^2_\mathrm{th}} \quad (4)$$

where β is the detector responsivity, I is the interference power, σ^2_shot is the shot noise variance given by background light sources, such as sunlight and other artificial lights, and σ^2_th is the thermal noise variance, both assumed Gaussian distributed [56]. The received power P_r can be evaluated as

$$P_\mathrm{r} = H(d,\theta,\psi)P_\mathrm{t} \quad (5)$$

where P_t is the transmitted power and $H(d, \theta, \psi)$ represents the DC channel gain. Following the generalized Lambertian model, we can write [68]

$$H(d,\theta,\psi) = \begin{cases} \frac{(\mathrm{m}+1)A}{2\pi d^2}\cos^m(\theta)\cos(\psi) & \text{if } \psi < \Psi_\mathrm{C} \\ 0 & \text{otherwise} \end{cases}$$

where A is the physical area of the detector, d is the distance between the transmitter and the receiver, θ is the angle of irradiance, ψ is the angle of incidence, Ψ_C is the half width of the FOV at the receiver, $\phi_{\frac{1}{2}}$ is the half power angle, and m represents the order of the generalized Lambertian radiant intensity. The interference I is caused by all the transmitting neighbors in visibility (a device which does not transmit, does not cause interference [15]) and can be evaluated as [67]

$$I = \left(\sum_{i=1}^{N_\mathrm{int}} \beta P_{\mathrm{r}i}\right)^2 = \left(\sum_{i=1}^{N_\mathrm{int}} \beta H(d,\theta,\psi)P_{\mathrm{t}i}\right)^2 \quad (6)$$

where N_int is the number of interfering neighbors, $P_{\mathrm{r}i}$ is the power received from the i^th interferer, and $P_{\mathrm{t}i}$ is the power transmitted by the i^th interferer. Finally, in this work we assume that i) the maximum distance is fixed to a constant value varying the angle of incidence and that ii) no transmission is possible outside an angle equal to the half-power angle. Hence, denoting with δ_i the portion of time during which the i^th interfering node is transmitting, we can write

$$\mathrm{SINR} = \frac{(\beta H(d,0,0)P_\mathrm{t})^2}{\left(\sum_{i=1}^{N_\mathrm{int}} \beta H(d,0,0)P_{\mathrm{t}i}\delta_i\right)^2 + \sigma^2_\mathrm{shot} + \sigma^2_\mathrm{th}} \quad (7)$$

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