



HAL
open science

INVISIBLE2.0: an Enhanced Interference-based Handover Technique for Visible Light Communications in Vehicular Networks

Meysam Mayahi, Valeria Loscrí, Anna Maria Vegni

► **To cite this version:**

Meysam Mayahi, Valeria Loscrí, Anna Maria Vegni. INVISIBLE2.0: an Enhanced Interference-based Handover Technique for Visible Light Communications in Vehicular Networks. Elsevier Computer Networks, 2024, pp.110280. 10.1016/j.comnet.2024.110280 . hal-04476693

HAL Id: hal-04476693

<https://hal.science/hal-04476693>

Submitted on 25 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

INVISIBLE2.0: an Enhanced Interference-based Handover Technique for Visible Light Communications in Vehicular Networks

Meysam Mayahi, Valeria Loscrí, and Anna Maria Vegni

Abstract—During the last decade, the exponential growth of mobile devices and their applications, especially in the framework of the Internet of Things (IoT), induced an enormous demand for radio frequency (RF) technologies. However, the lack of sufficient resources led to the spectrum crunch phenomenon, pushing researchers to explore alternative technologies outside the RF band. Among many strategies that have been adopted to maximize the exploitation of these precious resources, Visible Light Communication (VLC) demonstrates a huge capacity to complement conventional RF technologies in plenty of applications. In this work, we investigate the coexistence of VLC and the long-term evolution (LTE) cellular network in a vehicular environment. The coordination of data transmission among different technologies is managed through a novel vertical handover mechanism, namely INVISIBLE2.0. This technique is triggered by the error probability to meet the 3GPP requirements on packet reception ratio while endorsing VLC as the preferred technology bearer. We demonstrate that INVISIBLE2.0 achieves a more stable latency, and energy efficiency based on a detailed power model represented here for VLC and LTE.

Index Terms—VLC, C-V2X, Handover, Energy Efficiency, Power Consumption Model.

I. INTRODUCTION

The total number of global mobile subscribers is expected to grow from 5.1 billion (i.e., the 66% of the world's population) in 2018 to 5.7 billion (i.e., 71% of the world's population) by the end of 2023 [1]. During the same period, connected home applications will have nearly half of Machine-to-Machine (M2M) communications in the framework of the Internet of Things (IoT), and connected car applications will grow the fastest at a Compound Annual Growth Rate (CAGR) of $\approx 30\%$. The higher cost and limited free RF spectrum able to host further mobile data traffic, ask for an alternative communication medium to offload traffic from the RF spectrum and provide more capacity.

In recent years many technologies have been presented to solve the “spectrum crunch” problem. Visible Light Communications (i.e., VLC) take place as an RF assistant technology that employs optical wireless signals in the range from 430 THz to 790 THz as a signal carrier, with the twofold aim of both illuminating and communicating simultaneously. VLC demonstrates a great capacity to complement RF systems including the huge unregulated bandwidth, a reasonable level

of immunity to interference with RF technologies, free-of-charge operations, and can be applied to many communication scenarios. For instance, VLC can be used in electromagnetic waves restricted zones such as hospitals and airplanes, or it can be applicable in underwater communications where the RF propagation is strongly affected by water [2].

Affordable and widespread applications of Light Emitting Diodes (i.e., LEDs) in the automotive industry, traffic lights, as well as broad employment of control cameras and sensors in Intelligent Transportation systems (i.e., ITS) grab the attention of VLC standardization efforts and R&D studies in this market. In ITS, vehicular communications include vehicles and other communication entities around it, such as roadside infrastructures, wireless networks, and the devices carried by individuals and pedestrians, setting up reliable and scalable communication links among Vehicles (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P) [3].

Vehicular Visible Light Communication (*VehVLC*) represents one of the most attractive paradigms for vehicular communications, relying on a fully wireless optical system. The aim of *VehVLC* is to exchange information among close vehicles and their surroundings via direct Line-of-Sight (LoS) VLC links, in order to improve the safety and driving experience on the roads. There are excellent opportunities for *VehVLC* in automobile applications, including adaptive cruise control, cooperative driving, collision avoidance, and even autonomous driving [4]. Furthermore, different from RF-based solutions that have congested licensed-band and rely on complex structures and high deployment costs, *VehVLC* is a less complex, unlicensed, low cost, reliable, low energy, efficient, secured, and interference-free solution. LoS VLC links occur among vehicles and from vehicles to fixed nodes like Road Side Units (RSUs), via V2V and V2I connectivity modes, respectively. For instance, car platooning is a popular application in vehicular communications where autonomous vehicles are accessing each other's information and are grouped within close proximity. *VehVLC* can assist the safety message dissemination in multi-platoon when the performance of the dominant radio access technology degrades due to congestion [5].

Due to the dynamic nature of the vehicular environment, *VehVLC* connectivity links are not always available and it becomes difficult to maintain active LoS links. Also, the presence of multiple interference signals, such as sunlight and artificial lights like the traffic jam, causes a degradation of the link performance, resulting in the need of considering an

Meysam Mayahi and Valeria Loscrí are with INRIA Lille Nord-Europe, France. Email: valeria.loscri@inria.fr. Anna Maria Vegni is with the Department of Industrial, Electronics, and Mechanical Engineering, Roma Tre University, Italy. Email: anna-maria.vegni@uniroma3.it

alternative communication link, if available. In the vehicular environment, cellular V2X technology (C-V2X) exploits the RF spectrum, providing a larger coverage and more stable connectivity links, as compared to VLC. The integration of C-V2X to *Veh*VLC is then expected to fully support connectivity needs in vehicular environments. How to manage the two technologies is an open challenge that needs to define first Quality of Service (QoS) requirements and then a policy for connectivity switching, also known as *handover technique*.

Following the above motivations, in this paper, we introduce a handover mechanism that guarantees seamless vehicular connectivity in a heterogeneous C-V2X and *Veh*VLC network environment. Our proposed approach has been initially presented in [6], where a preliminary handover approach is described, working for pure vehicular VLC networks only. However, due to the limitation of VLC in dynamic scenarios, in this paper, we aim to extend the handover mechanism in [6] to consider a heterogeneous network environment with both C-V2X and VLC links. We define the proposed approach as INVISIBLE 2.0, which recalls the initial approach INVISIBLE as introduced in [6] and limited to VLC networks only, now extended to heterogeneous overlapping C-V2X and VLC networks.

Main contributions

In this paper, we present the INVISIBLE 2.0 technique, an extended handover approach that considers both horizontal and vertical connectivity switching from C-V2X to VLC, and vice versa. Differently from the initial version described in [6], INVISIBLE 2.0 aims to prefer VLC connectivity over C-V2X, whenever available, due to its higher QoS performance, expressed as huge data rate and low latency, as well as reduced energy consumption. In case VLC links are not supported, C-V2X allows guaranteeing a ubiquitous service, thanks to a larger coverage. Horizontal handovers are supported among VLC links on the basis of interference metric, while vertical handovers occur in case of a lack of reliable VLC links, towards C-V2X.

This paper presents the following contributions:

- 1) A hybrid horizontal/vertical handover mechanism, namely INVISIBLE2.0, involving overlapping C-V2X and *Veh*VLC networks is proposed, in order to maintain the 3GPP requirements;
- 2) A detailed analysis of the power consumption models for VLC and V2X networks. Energy consumption is then investigated as a performance metric for the INVISIBLE2.0 approach, compared w.r.t the scenario of no handover execution;
- 3) A performance comparison of *Veh*VLC and C-V2X is carried out, expressed in terms of energy efficiency, packet latency, and Packet Reception Ratio.

The rest of this paper is organized as follows. Section II introduces the main features of C-V2X and presents recent advances on how to manage heterogeneous networks for vehicular communications. Particular emphasis is given to VLC technology. Section III presents the INVISIBLE2.0 handover mechanism, which involves connectivity switching

among VLC links in case of high interference level. Vertical handovers are also considered whenever VLC links are not available, relying on the C-V2X network cell. INVISIBLE2.0 is prospecting a robust Packet Reception Ratio (PRR) with higher power efficiency and lower latency, as compared to ad hoc C-V2X and *Veh*VLC technologies. In Section IV, we present two different energy efficiency models for C-V2X and *Veh*VLC networks, both at the transmitter and the receiver. The performance of the two technologies is then compared in Section V, for safety traffic data dissemination, called Cooperative Awareness Messages (CAMs). The performance analysis considers energy efficiency, packet latency, and PRR, carried out in different vehicular traffic scenarios and propagation modes. Based on this analysis, we evince the effectiveness of the INVISIBLE2.0 approach, providing acceptable energy consumption. Finally, conclusions are drawn at the end of this paper.

II. BACKGROUND

In an Intelligent Transportation system (ITS), Vehicular Communications (VC) include vehicles and other communication entities around it such as roadside infrastructures, wireless networks, and the devices carried by pedestrians, setting up a reliable and scalable Vehicle to Everything (V2X) communication links, in order to send and collect basic awareness information, aiming to increase safety on the road, and the driving experience [3]. In Europe, the basic awareness traffic is encapsulated in Cooperative Awareness Message (CAM), including information about speed, driving direction, vehicle characteristics, etc, and is broadcasted once:

- The vehicle has moved more than 4 m;
- The absolute velocity has changed by 0.5 m/s;
- The vehicle heading has turned at least 4°;
- The elapsed time is more than 1 s;

since previous CAM [8].

The CAM generation rules are applicable regardless of the access technology. Several Radio Access Technologies (*i.e.*, RATs) have been proposed for V2X communications, such as Dedicated Short Range Communications (DSRC), Long Term Evolution (LTE) [14], and recently fifth Generation-New Radio (5G-NR) [9]. DSRC was regulated for Wireless Access in Vehicular Environment (WAVE) based on IEEE 802.11p standard. DSRC promised higher robustness and adaptation to rapid movement in vehicular applications with a 3 Mbps data rate at the 5.9 GHz frequency band. For collision avoidance mechanism, DSRC uses CDMA/CA protocol which has rather doubtful reliability in high traffic densities [10]. After launching the early version of LTE/4G in 2008, the first standard for Cellular V2X (C-V2X) was introduced in the 3GPP release 14 and finalised in September 2016. It uses an upgraded Device-to-Device (D2D) wireless interface called ITS-G5 to enable Vehicle-to-Infrastructure (V2I) communications, while PC5-sidelink is enabling Vehicle-to-Vehicle (V2V) to share CAMs among cars [7]. The resources in LTE C-V2X are allocated by the base station (eNB) for V2I according to Mode 3, on the other hand, vehicles in Mode 4 autonomously select their sub-channels based on common sets of parameters such

as the number of sub-channels and the number of Resource Blocks (RBs) per sub-channels [11]. To this aim, vehicles use the sensing-based Semi-Persistent Scheduling (SPS) defined in [35] to reserve sub-channels for their next transmission. LTE C-V2X demonstrates superior reliability over DSRC thanks to more efficient Physical layer [12], however, its performance is degrading due to significant Doppler shift in high-speed V2X scenarios [13]. Nowadays, the evolutionary trend in V2X is moving toward complementary solutions such as 5G-NR when the Quality of Service (QoS) becomes more stringent. 3GPP release 16 has included a study item to support new applications with more stringent requirements. As a main design objective, 5G-NR V2X is neither backward compatible with LTE C-V2X, nor to replace it, but rather to supplement C-V2X in supporting those use cases that cannot be supported by LTE C-V2X [13]. Resource reservation in 5G-NR V2X is defined in centralized (*i.e.*, Mode 1) and distributed (*i.e.*, Mode 2) manners, which are similar to Mode 3 and Mode 4 of LTE C-V2X. Mode 1 uses the same sensing-based scheduling approach which has severe impacts on 5G-NR V2X performance. The sensing window increased, and obliged the receiver to detect signaling for a longer time, which in consequence increases the power consumption for signaling messages. Mode 2 random resource selection is addressed in an approved 3GPP NR Release 17 to reduce the complexity of user equipment (*i.e.*, UE) and consequently the power consumption [13]. Random resource allocation mechanism causes excessive resource collision, accordingly increasing the packet loss and the packet latency, notably in dense vehicular environment [12]. Finally, the lack of orthogonal resources in covered areas, as well as synchronized resources (infrastructures) in remote scenarios calls for an alternative paradigm to enhance the V2X performance [4].

A. Vehicular VLC

VLC represents one of the most attractive paradigms of V2X. Contradicting to RF-based VC (*e.g.*, C-V2X) Vehicular VLC (*i.e.*, *VehVLC*) is a less complex, unlicensed, low cost, reliable, low energy, efficient, secured, and interference-free solution [4]. The widespread employment of LEDs in car lamps, traffic lights as well as control cameras and sensors in ITS, lends additional motivation for researchers and industries to invest in vehicular applications using VLC. V2I communication in VLC is oriented between high-power traffic/street lights and vehicles which can achieve stable communication within a range of 50 meters [10]. Moreover, integrated VLC systems in headlights and tail lights are enabling reliable V2V links [10]. Alongside many favorable features in VC, the VLC link has a comparatively short communication range and can be blocked by obstacles like cars, therefore, reliability might be degraded in high-mobility scenarios [14]. Guaranteed coverage in VLC networks requires many Access points (APs) installation, which in dynamic scenarios (*e.g.*, VC) can result in frequent disconnectivity between mobile nodes and associated AP. In [6] new horizontal handover mechanism namely "INVISIBLE" proposes a backup VLC link based on dominant disturbance in an outdoor vehicular environment. When no AP

is available in the current network, the vehicle may maintain the connection via different networks throughout vertical handover mechanisms establishing a hybrid network [15].

B. Hybrid VLC-RF vehicular network

The hybrid VLC-RF structure is beneficial to an efficient and reliable VC [14]. A hybrid handover solution called "Li-Wi" has been proposed to address mobility and handover challenges in both Data Link and Transport layers using Multipath TCP (*i.e.*, MPTCP) for industrial indoor environment [15]. In [16], the optimal time to trigger (*i.e.*, TTT) has been found according to historical Signal to Noise Ratio (*i.e.*, SNR) by means of Q-learning algorithm in order to carry out vertical handover from LTE eNB to VLC AP. One of the pioneering field tests on the joint use of 5G and VLC was presented in [9]. Data from road sensors have been collected by a 5G network and then sent to the VLC network for diffusion to cars through traffic lights. This experiment measured an end-to-end latency equal to 9.5 ms for 5G and for VLC technology equal to 2.5 ms. Hybrid Vehicular networks assisted by VLC technology remain potential in the presence of some critical issues such as an effective handover mechanism for efficient mobility management, QoS stability through VLC integration to the vehicular radio access technologies (*e.g.*, C-V2X), as well as adaptive resource allocation and medium access process. As a matter of fact, to make VLC more operational in a real vehicular environment, an efficient design of Medium Access Control (*i.e.*, MAC) protocol is required to ensure a seamless exchange of information in a challenging V2X nature coming from high dynamicity, environmental disturbances, and co-channel interference.

However, any further enhancement in the performance of a communications protocol is ignored if it does not comply with the reliability requirements. Packet reception ratio (PRR) is defined as the number of vehicles with acceptable error probability residing within the transmitter range, to all vehicles at the baseline distant d from the transmitter, and calculated as X/Y , where X and Y are the numbers of vehicles with successful packet delivery, and the total vehicles in the range respectively [17]. The appropriate error probability is following the LTE service requirements for V2X services [18], while baseline distance is derived as a break-point from the WINNER+B1 channel model [19]. On the other hand, VLC has been selected as a primary transmission method, assisted by C-V2X. Accordingly, INVISIBLE 2.0 is developed in this paper to follow the PRR baseline of 3GPP in a hybrid VLC-RF vehicular regime.

III. INVISIBLE2.0 HANDOVER

In this section, we introduce a novel vertical handover mechanism, called INVISIBLE2.0, aiming to disseminate CAMs via VLC, acting as a preferred technology over LTE radio technology, in a vehicular heterogeneous network. Owing to the multiple advantages that have been discussed in the earlier section, INVISIBLE2.0 prefers exploiting VLC technology as the primary transmission option as compared to LTE radio technology, which is the second option for data transmission.

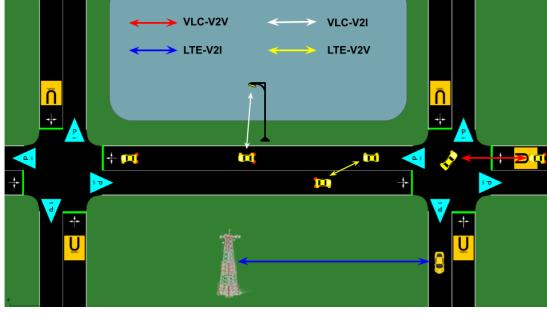


Fig. 1. Vehicular environment with heterogeneous C-V2X and *VehVLC* technologies. Both V2V and V2I communication modes are allowed.

The main trigger for vertical handover between VLC and C-V2X, and vice versa, is the link reliability, such that when the performance of the VLC link degrades below a given threshold, INVISIBLE2.0 switches to LTE to maintain an acceptable PRR level. Moreover, this handover mechanism gives a good compromise between VLC and LTE ad-hoc networks in terms of energy consumption and delay performance.

In order to provide high performance, we pose a high threshold for the Packet Error Rate (PER) *i.e.*, 95%. Furthermore, the energy consumption and the delay performance of the INVISIBLE2.0 handover mechanism represent a good compromise as compared to *VehVLC* and C-V2X. Algorithm 1 describes the main steps of the hybrid handover algorithm. CAM is transmitted in a multi-hop manner via *VehVLC*, as a preferred technology if available, as well as if the link performance is good enough as compared to the PER threshold. In case of low performance or lack of VLC connectivity link, C-V2X is used as an alternative technology, assumed as always available. Fig. 1 depicts the heterogeneous network scenario for vehicular communications. Notice the presence of RSU (e.g., street lamps and base stations) allows V2I/V2V communication links.

A heterogeneous LTE-VLC network has been simulated at vehicular applications for V2V and V2I communications in urban and highway scenarios. It is assumed that the mobile nodes are already registered in the LTE network according to the Radio Resource Control (*i.e.*, RRC) procedure. Subsequently, CAMs are generated in the mobile nodes according to the European Telecommunications Standards Institute (*i.e.*, ETSI) ITS model and delivered to the flow switch to be disseminated through the VLC link if optical intensity (e.g., SNR_o) is above the threshold, otherwise, the CAM message is sent via LTE network. When a mobile node does not have any active link, the CAM generation is prevented and new messages will be transmitted as soon as a connectivity link will be available, following the store-carry-and-forward paradigm as typical of vehicular networks.

The proposed hybrid handover mechanism considers both horizontal (HHO) and vertical (VHO) handover occurrences. In the first case, a horizontal handover is executed from a serving lighting cell to a candidate one, that overlaps with each other, selected based on the interference criteria. Specifically, the HHO technique evaluates the VLC link performance based on the prominent component of the disturbances that may

Algorithm 1: INVISIBLE2.0 Handover Mechanism

Input: N \triangleright Number of LED APs
 L \triangleright Number of VLC interferents
 i \triangleright Index for the number of LED APs
 ℓ \triangleright Index for the number of VLC interferents
 SNR_o \triangleright SNR threshold for VLC connectivity
 R_{C-V2X} \triangleright Constant C-V2X data rate
 PER \triangleright Initial value of PER
 Th \triangleright Threshold on PER set to 95%
 T \triangleright Simulation time

Output: $\mathcal{R}_{HHO/VHO}$ \triangleright Data rate in HHO/VHO

foreach $t < T$ \triangleright Simulation time **do**

if $SNR_i > SNR_o$ \triangleright A V2LC link is available **then**

if $PER_i < Th$ **then**

$\mathcal{R}_{HHO/VHO} = R_{i,VLC}$ \triangleright Access to the i -th VLC LED

Compute $INR_{Tot,i}$ \triangleright Eq. (2)

if $INR_{Tot,i} > 10$ **then**

Compute IIR \triangleright Eq. (3)

if $IIR \geq \beta$ **AND** $SNR_\ell \geq SNR_{min}$ **then**

$\mathcal{R}_{HHO} = R_{\ell,VLC}$ \triangleright HHO to the ℓ -th VLC LED

else

$\mathcal{R}_{VHO} = R_{C-V2X}$ \triangleright VHO to C-V2X

else

$\mathcal{R}_{VHO} = R_{C-V2X}$ \triangleright VHO to C-V2X

else

$\mathcal{R}_{HHO/VHO} = R_{C-V2X}$ \triangleright C-V2X connectivity link

else

$\mathcal{R}_{HHO/VHO} = R_{C-V2X}$ \triangleright C-V2X connectivity link

occur. To this end, it computes the Interference to Noise Ratio (*i.e.*, INR) of the i -th LED as follows

$$INR_{i,\ell} = \frac{(rP_{r,i})^2}{\sigma_n^2 + \mathcal{I}_\ell}, \quad (1)$$

where r is the PD responsivity, $P_{r,i}$ is the received power from the i -th LED (with $i = [1, 2, \dots, N]$), \mathcal{I}_ℓ is the interference level generated by the ℓ -th VLC signal (*i.e.*, $\ell \neq i$ and $\ell = [1, 2, \dots, L]$ with $L \leq N$), and σ_n^2 is the Additive White Gaussian Noise (AWGN), comprised of the thermal σ_t^2 and the shot noise σ_s^2 components *i.e.*, $\sigma_n^2 = \sigma_t^2 + \sigma_s^2$.

The total interference-to-noise ratio is then computed as the sum of multiple contributions of the INR at the i -th LED *i.e.*,

$$INR_{Tot,i} = \sum_{\ell}^L INR_{i,\ell}, \quad (2)$$

that is, we consider all the L interferent signals (with $L \leq N$). The i -th LED can be considered interference-dominant if the interference power is higher than the noise power. Specifically, we assume a factor 10 as a comparison, so that if $INR_{Tot,i} < 10$, the noise and the interference power are comparable, and

we treat them equally as noise. Otherwise, the i -th LED is assumed as interference-dominated, and it is possible to search for the dominant interferer by means of the IIR (Interferer to Interference Ratio) expression i.e.

$$IIR = \max_{\ell} \left(\frac{P_{r,\ell}}{\sum_{\ell} P_{r,\ell}} \right), \quad (3)$$

where $P_{r,\ell}$ is the power level of the ℓ -th interferer. Notice that lower values of IIR fit well with the Gaussian distribution assumption, while higher values of IIR prove less normal distribution and the Gaussian assumption leads to a heavier tail in the distribution. In the case that $IIR \rightarrow 1$, the only noticeable interference comes from a single dominant interferer.

At the interference dominant system, there could be single or multiple dominant interferers. The IIR is able to identify the dominant interferer if the following expression holds i.e.,

$$IIR \geq \beta, \quad (4)$$

where β is the minimum amount of IIR the system can detect and it is experimentally selected according to the node density. The interferers exhibiting the relation $IIR \leq \beta$ are not dominant and are considered as noise. On the other hand, the ℓ -th dominant interferer exhibiting the relationship in Eq. (4) will be nominated as a candidate for handover initiation, if it satisfies the QoS requirements of safety applications, expressed in terms of reliability and stability. Specifically, by fixing the maximum error probability for vehicular safety applications equal to 10^{-3} , the ℓ -th dominant interferer that verifies Eq. (4) will be nominated as a candidate lighting cell for handover if the minimum required SNR ratio is satisfied i.e.,

$$SNR_{\ell} \geq SNR_{\min}, \quad (5)$$

where SNR_{ℓ} is the SNR value of the ℓ -th dominant interferer.

Fig. 1 represents the scenario where the mobile nodes rely on VLC technology to transmit their CAMs. The INR-based handover mechanism guarantees seamless horizontal handover inside VLC coverage. When the performance of the VLC link degrades, CAMs are sent through LTE radio access technology.

CAMs are generated on the mobile nodes based on the ETSI ITS model, then they are disseminated through the VLC link if optical SNR is above the threshold (i.e., SNR_o), otherwise the CAM is sent via LTE network. It assumed that the mobile node is already registered in the LTE network according to the RRC procedure. When the mobile node does not have any active link, the CAM generation is prevented.

IV. ENERGY EFFICIENCY MODEL

The energy efficiency of communication networks is progressively attracting the research communities due to the exploding wireless technologies. The energy efficiency is usually evaluated in an extensive measurements regime using small-scale or actual devices, which increase the total cost of projects and require further expertise for implementation. In addition, new energy-saving methods and optimization techniques

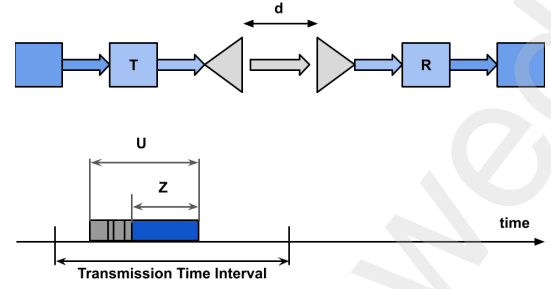


Fig. 2. Point-to-point transmission model.

proposed in academia require a comprehensive power model considering the major energy-consuming components and their performance during different phases such as transmission, reception, and ideal states.

Nokia proposed a power model which considers only radio resource configuration mode for 3GPP but it does not take into account different data rate power control at the transmitter [20]. The chip manufacturers have detailed models based on their development platforms, however, they are confidential. Launching LTE opened new horizons to empirical models. A precise model based on the LTE USB dongle has been proposed in [20], which is robust and transferable. This model describes an LTE user equipment (UE) radio modem, which is depending on power levels and data rates.

The current theoretical power model is based on the major power components of LTE and VLC systems.

A. Energy Consumption

The energy consumption occurring during a packet transmission time interval (i.e., TTI [s]), is the summation of the energy consumed at the transmitter (E_{Tx}) and the receiver (E_{Rx}) sides, as follows:

$$E_{TTI} = E_{Tx} + E_{Rx}, \quad (6)$$

whose expressions respectively are:

$$E_{Tx} = P_{Tx}^{(s)} D^{(s)} + P_{Tx}^{(i)} D^{(i)} + P_{Tx}^{(t)} D^t, \quad (7)$$

and

$$E_{Rx} = P_{Rx}^{(s)} D^{(s)} + P_{Rx}^{(i)} D^{(i)} + P_{Rx}^{(r)} D^{(r)}, \quad (8)$$

with $D^{(x)}$ [s] and $P_{Tx/Rx}^{(x)}$ [W] as the time spent and the power consumed in state x occurring at the transmitter/receiver side, respectively. Specifically, four different states are defined, named as s (sensing), i (idle), t (transmission), and r (reception). For instance, the term $P_{Rx}^{(i)}$ stands for the receiver consumption power during ideal state.

Finally, from the expressions of energy consumption, we can define the energy efficiency (i.e., E_{eff} [bit/Joule]) as the ratio of data rate R_b [bps] over the energy consumption E_{TTI} [Joule/s] i.e. [24],

$$E_{eff} = \frac{R_b}{E_{TTI}}. \quad (9)$$

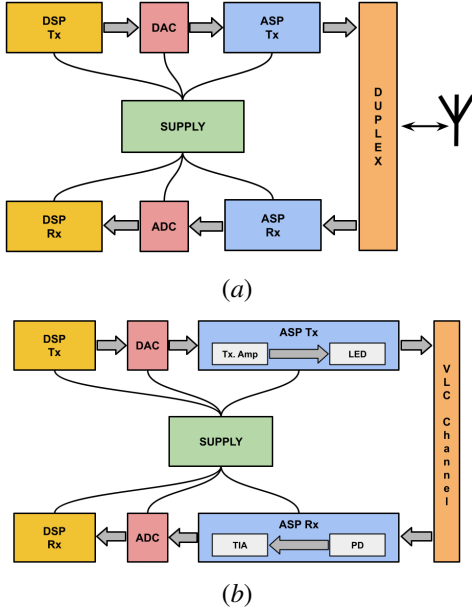


Fig. 3. Schematic of (a) LTE, and (b) VLC power consumption model, respectively.

B. LTE Power Consumption

Fig. 3 (a) shows the LTE physical layer components and the user equipment (UE) model parameters. The envisioned UE model depends on the received (Rx) and the transmitter (Tx) power levels, the uplink (UL) and downlink (DL) data rate, and RRC mode.

We can express the power consumption of an LTE UE device as:

$$P_{Total} = P_{Tx} + P_{Rx}, \quad (10)$$

where P_{Total} [Watt] is the total power consumption, while P_{Tx} [Watt] and P_{Rx} [Watt] are the transmitter and receiver power consumption, respectively, whose expressions are

$$P_{Tx} = P_{DSP,Tx} + P_{ASP,Tx} + P_{DAC}, \quad (11)$$

and

$$P_{Rx} = P_{DSP,Rx} + P_{ASP,Rx} + P_{ADC}, \quad (12)$$

where the indexes ADC and DAC refer to the Analog-to-Digital and Digital-to-Analog converter, respectively. The power consumption in ADC/DAC is represented by the offset b and the slope k of the ADC/DAC circuit design, which is further scaled with the operating bandwidth B , i.e.

$$P_{DAC/ADC} = B \cdot k_{DAC/ADC} + b_{DAC/ADC}. \quad (13)$$

Furthermore, in Eq. (11) and (12) the digital signal processing unit power consumption at the transmitter/receiver i.e., $P_{DSP,Tx/Rx}$, is assumed identical for the transmitter and the receiver [21], and can be simply defined as

$$P_{DSP} = P_{leak} \cdot P_{dyn}, \quad (14)$$

where p_{dyn} represents the power dissipation at the dynamic charging and discharging of the CMOS inherent capacitors,

and P_{leak} denotes the leakage power dissipated due to reverse leakage of the employed CMOS switches i.e.,

$$P_{leak} = \eta_{leak} \cdot P_{dyn}, \quad (15)$$

where η_{leak} stands for the leakage power ratio, which is measured in Giga Operations per Second per Watt [GOPS/W], and P_{dyn} [Watt] refers to the dynamic power at the reference bandwidth B_{ref} [Hz] i.e.,

$$p_{dyn} = \frac{O_C \cdot B}{\eta_{CMOS} \cdot B_{ref}}. \quad (16)$$

In Eq. (16), the term O_C represents the digital computational complexity function at the reference bandwidth B_{ref} , which is scaled linearly with the operating bandwidth value B . Furthermore, η_{CMOS} is the intrinsic CMOS power-efficiency factor.

The analog unit includes different elements of a transmitter and the receiver such as carrier generation, modulator, mixer, low noise amplifier (LNA), variable gain amplifier (VGA), filter, buffer, and power amplifier (PA).

The power consumption of the transmitter ASP can be modeled considering only the aggressive power consumer components of the direct conversion transmitter:

$$P_{ASP,Tx} = P_{IQ\ modulator} + P_{clock} + P_{VCO}, \quad (17)$$

where P_{VCO} is the nominal power consumption at the voltage-controlled oscillator, $P_{IQ\ modulator}$ is the in-phase and quadrature modulators power consumption, and P_{clock} is the power needed for clock generation, and buffering in [mW]. On the other hand, the power consumption of the receiver ASP is derived as

$$P_{ASP,Rx} = P_{LNA} + P_{attenuator} + P_{mixer} + P_{clock}, \quad (18)$$

where P_{LNA} stands for low-noise amplifier power consumption, $P_{attenuator}$ is the power lost in the main variable attenuator, and P_{mixer} is the dual mixer power.

C. VLC Power Consumption

A similar power consumption model is presented based on the VLC system block diagram of Fig. 3 (b), where the front-end blocks are divided into digital and analog components according to the place of DAC and ADC converters in the transmitter and the receiver sides, respectively [25]. This model accounts for the most significant power consumer VLC components, specifically:

- At the transmitter side the signals are processed digitally using **Digital Signal Processing** and then converted to an analog waveform by digital to analog converter **DAC**.
- **Transmitter Amplifier** amplifies and biases the analog signal to fit the linear region of LED transfer characteristic.
- **LED** transforms the electrical signal to visible light and then passed it to the optical wireless channel.
- At the receiver side, the **PD** is used as a passive element to convert the optical signal back to a current signal. When a bias is applied to the photodiode, the current output can

be controlled to provide thresholding, linear response, or nonlinear response.

- The trans-impedance amplifier **TIA** alters the current to a voltage signal.
- The analog voltage waveform is digitized by the analog to digital converter **ADC** and eventually delivered to **DSP** for further processing.

The analog power consumption at the transmitter can be decomposed to the power consumption at the transmitter amplifier and the power consumption of the LEDs *i.e.*,

$$P_{ASP,Tx} = P_{Tx\ Amp.} + N \cdot P_{LED}, \quad (19)$$

where the LED's power consumption P_{LED} is determined by the DC bias level and the total number of the deployed LEDs (*i.e.*, N). In the same way, the analog power consumption at the receiver part is decomposed to the PD power consumption and the trans-impedance amplifier power consumption *i.e.*,

$$P_{ASP,Rx} = m \cdot P_{PD} + P_{TIA}, \quad (20)$$

where m is the number of photodiodes and bounded trans-impedance amplifiers.

V. PERFORMANCE ANALYSIS

A vehicular environment with heterogeneous overlapping LTE-VLC networks has been simulated for the assessment of the proposed handover approach. Specifically, both V2V and V2I communications are provided, in urban and highway scenarios. The performance of INVISIBLE2.0 is evaluated in terms of PRR, latency, transmitter, and receiver energy efficiency.

Assuming the vehicular environment as depicted in Fig. 1, vehicles are generating CAMs based on the empirical model proposed in [8], which is derived from ETSI ITS communication architecture. In LTE-V2I, CAMs are generated and broadcast by the vehicle through a given wireless interface (*i.e.*, ITS-G5), while the V2V communication employs PC5 or sidelink to share CAMs among cars [7]. The on-board C-V2X units are small-scale base stations (Femto) used in cars. They use more power-efficient dedicated components compared to large base stations (*i.e.*, macro and micro), and the downscaling factor defined in [21] is used to reduce the power on smaller base stations due to less constraining space and different hardware implementation. This approach is due mainly because of (i) the number of blockages that can affect the transmission of a small base station is limited, leading to more relaxed linearity specs, and hence less power is needed, and (ii) the smaller base stations can work from a lower supply voltage, further reducing their consumption.

The main parameters for C-V2X used in our simulations are collected in Table I, which represents the power consumption of the analog components in the LTE on-board unit. In order to simulate the MAC performance of the LTE-V2X, we assume n eNBs are uniformly distributed such that the Tx-Rx distance will meet the LTE rel.14 requirements in terms of PRR, defined as the ratio of the number of vehicles with successful packet delivery over the number of total vehicles in the range, equal to 95%. In fact, in order to concentrate on

TABLE I
LTE ANALOGUE MAJOR COMPONENT'S POWER

Analogue Item	Model	Power Consumption [mW]
IQ Modulator	IDTF1650	1000
VCO	YSGM252708	170
Clock	AD9523	990
LNA	NJG1182UX2	300
Attenuator	HMC472	10
Dual Mixer	TRF37A32	1000
PA	TGA2976-SM	650

TABLE II
VLC ANALOG POWER SPECIFICATION

Analogue Item	Model	Power Consumption [mW]
LEDs	XLamp XP-E2	2000
DAC	MAX19693	1400
ADC	ADC12J4000	770
TIA	OPA1S2384	90
TA	LMH6401	345

the MAC performance we cancel the performance degradation of the physical layer (*i.e.*, propagation loss and shadowing effect) [23] following the WINNER+B1 channel model by the 3GPP [26]. The path loss [dB] for the 5.9 GHz band can be calculated in the case of LoS and NLoS, respectively as in Eq. (21) and Eq. (22), where the effective breakpoint distance d'_{BP} [m] is computed as

$$d'_{BP} = \frac{4h'_{BS}h'_{MS}f_c}{c}, \quad (23)$$

with $c = 3 \cdot 10^8$ [m/s] as the light speed and $h'_{BS/MS}$ as the effective antenna/mobile station height *i.e.*, $h'_{BS/MS} = h_{BS/MS} - 1$ [m], [17]. Based on [26], the antenna height is set to $h_{BS} = h_{MS} = 1.5$ [m] for V2V communications, while $h_{BS} = 5$ [m] and $h_{MS} = 1.5$ [m] are assumed for V2I/I2V communications.

Similarly, Table II collects the power consumption of the VLC components used in the proposed energy model. The street light poles have been used as VLC infrastructure based on global lighting design guidance [27]. In this design, the pole height varies from 8 to 10 m and the spacing between two light poles should be roughly from 2.5, to 3 times the height of the pole. This regulation allows for uniform distribution of the light poles with 25-meter spacing in highway scenarios, and 23 meters in urban scenarios.

Regarding vehicle velocity, it is defined according to the federal highway administration of the US government since the urban scenario follows the Manhattan mobility scenarios. Following this regulation, the speed in the urban areas varies from 45 to 72 [km/h], and on highways is set from 90 to 105 [km/h], [28]. Single-carrier OOK modulation has been used for its low complexity and robustness. The computational complexity factor O_C for OOK modulation is set to 505.15 GOPS at $B_{ref} = 20$ MHz reference bandwidth. According to [25], CMOS power efficiency is $3.6e + 4$ GOPS/W, while the leakage ratio was 24.3 in 2020. Additionally, under good coverage of the serving access point, the adaptive CAMs disseminates are based on ETSI ITS regulation [29].

$$PL^{(LoS)} = \begin{cases} 22.7 \log_{10} d + 27.0 + 20.0 \log_{10} f_c, & 30 < d < d'_{BP} \text{ [m]} \\ 40.0 \log_{10} d + 9 - 16.2 \log_{10} h_{BS} - 16.2 \log_{10} h_{MS} + 3.8 \log_{10} f_c, & d'_{BP} < d < 5 \text{ [km]} \end{cases} \quad (21)$$

$$PL^{(NLoS)} = (44.9 - 6.65 \log_{10} h_{BS}) \log_{10} d + 5.83 \log_{10} h_{BS} + 15.38 + 23 \log_{10} f_c. \quad (22)$$

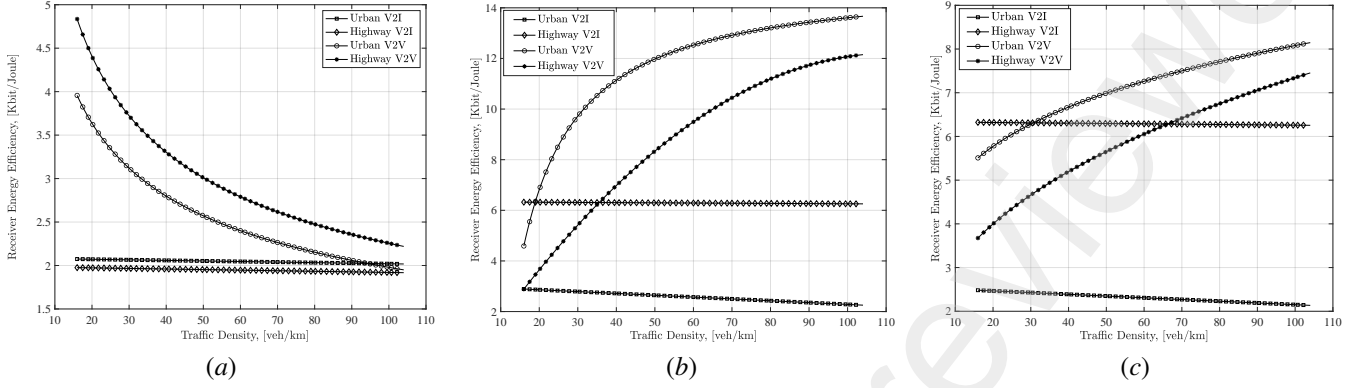


Fig. 4. Receiver energy efficiency in case of (a) *VehVLC*, (b) *C-V2X*, and (c) *INVISIBLE2.0* technique, vs. the traffic density for different communication modes and environments.

The energy efficiency model defined in Section IV-A has been implemented in the ns3 module for visible light communication in vehicular networks, and the Multi-Stack VANET framework for ns-3 (*i.e.*, *ms-van3t*) for LTE-V2X compliant application [36]. The receiver energy efficiency is expressed in [Kbits/Joule] and digitizes the amount of data received per unit of energy consumed at the receiver and it is calculated according to Eq. (9). This metric is compared versus the traffic density in Fig. 4, in case of *VehVLC*, *C-V2X*, and *INVISIBLE2.0* approach, for different traffic scenarios (*i.e.*, urban and highway) and communication links (*i.e.*, V2I and V2V). Traffic density [veh/km] describes the average number of vehicles per unit of road length per day [30]. From Fig. 4 (a), we observe the traffic density growth does not increase the infrastructure density in V2I, and so energy efficiency is independent of traffic density in the V2I scenario, which shows a flat behavior. However, the number of in-range VLC nodes increases in the dense traffic scenario, which forces the receiver to stay in the “active” mode most of the time, which in return decreases the energy efficiency. As expected, for V2V mode we can observe a reduced trend for increasing the traffic density, meaning that in crowded scenarios vehicular communications are more common, thus reducing the receiver energy efficiency.

In Fig. 4 (b) the *C-V2X* receiver energy efficiency versus the traffic density is presented. Compared to the *VehVLC* technology, the *C-V2X* approach allows for collecting more information per unit of energy. In V2V scenarios, the performance is enhanced in dense scenarios because the receiver is receiving more and more bits per unit of energy, whereas in the best case, it reaches up to 15 Kbits per Joule in high-density V2V. For V2I scenarios, the receiver energy efficiency is sustained with increasing the number of vehicles due to the central dissemination of CAM messages, which are fixed per car.

Finally, the energy efficiency at the receiver achieved with

INVISIBLE2.0 is depicted in Fig. 4 (c). We observe an improved trend, as compared to the ad-hoc *VehVLC*, especially in high traffic density. We notice that when the traffic density is growing, it has a positive effect on the V2V receiver EE, while it is less effective in V2I scenarios. Moreover, the receiver in urban V2V has the highest performance, and the lowest performance is happening in the urban V2V environment. The receiver energy efficiency in highway V2I is equivalent to the *C-V2I* curve at the same condition. It means that *INVISIBLE2.0* is mostly using LTE in highway V2I.

At the transmitter side of *VehVLC*, the energy consumption efficiency is constant in V2I communication as Fig. 5 (a) shows. The transmitter energy efficiency in the V2V scenario is worsening due to the worthless transmitter functioning in high traffic densities. The energy efficiency is less sensitive to the traffic density in the *C-V2X* transmitter. The *C-V2X* transmitters are very harsh in energy consumption such that they cannot transmit more than a few kilobytes per Joule of energy. Fig. 5 (b) shows the LTE transmitter energy efficiency in different scenarios, and we can observe the best performance of transmitter energy efficiency in the *C-V2X* is achieved at highway V2I scenario.

Finally, Fig. 5 (c) shows the energy efficiency at the transmitter side achieved with *INVISIBLE2.0* versus the traffic density. Compared to the *C-V2X*, the transmitter energy efficiency is improved in urban V2I, urban V2V, and highway V2V, and it is identical to *C-V2I* in highways. In the sparse traffic density, *INVISIBLE2.0* uses the energy more efficiently at the transmitter to send CAMs to other mobile nodes, and as the traffic density increases, the transmitter’s energy efficiency decreases. In V2I communication, the energy efficiency at the transmitter is steady but it is higher than ad-hoc *C-V2X* and *INVISIBLE2.0*.

For the PRR computation, packet accounts as delivered if the number of erroneous bits (symbol) is less than the coding threshold. Since in VLC, we do not use any channel coding

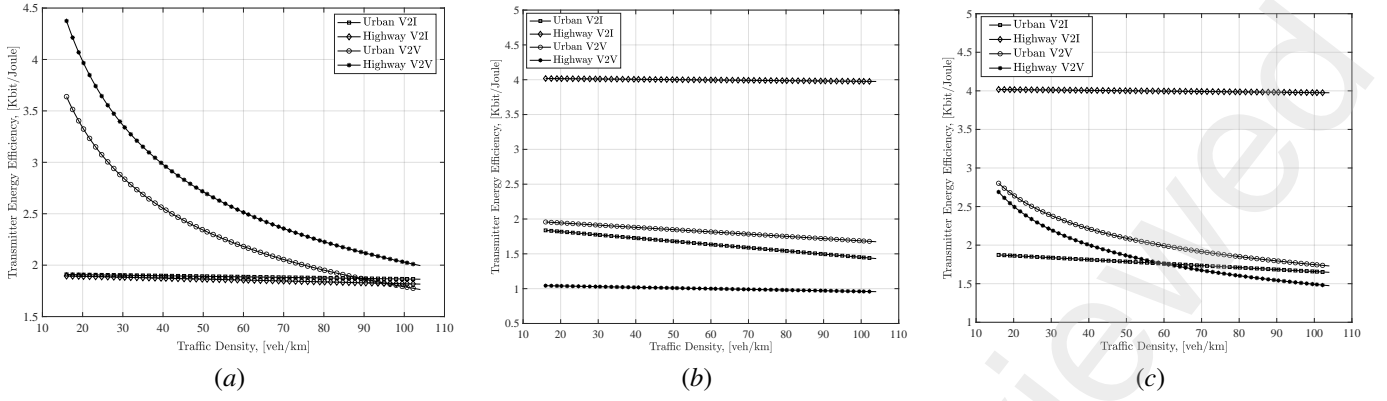


Fig. 5. Transmitter energy efficiency in case of (a) *VehVLC*, (b) *C-V2X*, and (c) *INVISIBLE 2.0* technique, vs. the traffic density for different communication modes and environments.

scheme (e.g., FEC, ARQ, etc), a packet is correctly received when all the packet's bits (symbols) are correctly detected. Assuming OOK modulation scheme [31], the Packet Error Ratio can be defined as:

$$PER = 1 - (1 - BER)^{\mathcal{M}}, \quad (24)$$

where \mathcal{M} [bit] is the packet size and BER is the bit error rate, which for the OOK modulation scheme becomes, [33]

$$BER_{OOK} = 0.5 Q(SNR_o), \quad (25)$$

with $Q(\cdot)$ as the tail probability of the standard normal distribution. In Eq. (25) the term SNR_o is the optical signal-to-noise ratio related to the link from the i -th LED transmitter to the j -th PD receiver, and is expressed as

$$SNR_o = \frac{(rP_i h_{i,j}^{LoS})^2}{\sigma_n^2}, \quad (26)$$

where $h_{i,j}^{LoS}$ is the DC channel gain in LoS expressed as

$$h_{i,j}^{LoS} = \frac{r(m+1)A}{2\pi d_{i,j}^2} \cos^m(\theta_{i,j}) \cos(\phi_{i,j}) G(\phi_{i,j}) c(\phi_{i,j}), \quad (27)$$

with $m = -\ln(2)/\ln(\cos(\theta_{1/2}))$ as the Lambertian order of the LED, r [A/W] is the receiver responsivity, A [m²] is the aperture area of the receiver, $d_{i,j}$ [m] is the Euclidean distance between the i -th LED to the j -th PD, and $\theta_{1/2}$ is the half power angle of the LED. Furthermore, $\theta_{j,i}$ is the irradiance angle of the (i,j) -th LED/PD link, $\phi_{i,j}$ is the incident angle of the (i,j) -th LED/PD link, $G(\phi_{i,j})$ is the gain of the optical filter at the receiver, and $c(\phi_{i,j})$ is the optical non-imaging concentration gain expressed as

$$c(\phi_{i,j}) = \begin{cases} \frac{\rho^2}{\sin^2(\Phi_{FoV})}, & 0 \leq \phi_{i,j} \leq \Phi_{FoV}, \\ 0, & \phi_{i,j} > \Phi_{FoV}, \end{cases} \quad (28)$$

where ρ is the refractive index of the concentration and Φ_{FoV} is the field-of-view (FoV) of the PD. Finally, we assume $G(\phi_{i,j}) = 1$.

Fig. 6 (a) demonstrates the packet reception ratio at the mobile nodes that are transmitting CAM packets using cellular long-term evolution Mode 3 and Mode 4. We observe that LTE-V2I has the best PRR performance in urban and highway scenarios regardless of the traffic density, owing to the wide

coverage and reliable resource allocation strategy of LTE. In the next world, the packet reception ratio of V2V is smaller, due to the lower coverage range of onboard modules in the vehicles compared to the eNB station at V2I scenarios. PRR is decreased by increasing the number of vehicles in V2V urban and highway scenarios. In cellular V2V, each vehicle has to manage its own communication session in a distributed way, it gives a higher chance to an individual mobile node to find a free channel for transmission at lower density, while in the higher traffic density, the completion to acquire RF resource for transmission is stronger and decrease the chance of finding a free channel, so the PRR decreases.

Fig. 6 (b) depicts the PRR of *VehVLC* scheme. The best performance belongs to V2V in the highway scenario while the lowest PRR is in highway V2V because the distance between neighboring AP is higher than urban scenario and that increases the risk of packet loss on the cell edge.

Finally, in Fig. 6 (c) we show the PRR obtained with *INVISIBLE2.0*. The 95% 3GPP baseline is always respected because the reliability (represented in PER) is the triggering metric for the *INVISIBLE 2.0* protocol. When the PER degrades below the given threshold (i.e., 10^{-3}), the mobile node uses the INR-based approach to select an alternative VLC link and then sends CAM. In case of failure, the LTE network is the final option. Furthermore, we observe that the PRR is slightly increasing in V2V communication when the traffic increases, while PRR in V2I is almost constant. The *INVISIBLE2.0* performance in V2I is higher than V2V and Highway V2I has the best PRR. Due to the fact that VLC does not fulfill the 3GPP requirement in terms of PRR, in the highway V2I, *INVISIBLE2.0* totally relies on *C-V2X* for CAM transmission.

Vehicular applications have some requirements in terms of latency. In [34] latency has been defined as the maximum time span during which vehicular traffic may be successfully delivered to the target vehicle. In our application, latency is the time delay from the CAM generated, until the successful delivery to the destination.

In Fig. 7 the latency of *C-V2X*, *VehVLC*, and *INVISIBLE2.0* is compared in multiple scenarios. Generally, the latency in LTE-V2X is much longer than the end-to-end latency in VLC. In LTE-V2V scenarios, increasing the traffic

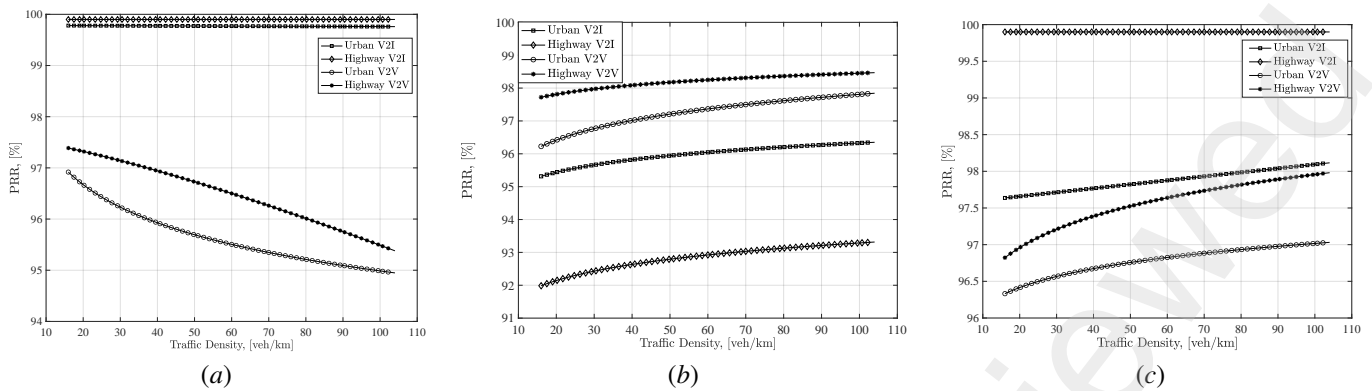


Fig. 6. PRR comparison vs. the traffic density in case of (a) C-V2X and (b) *VehVLC* technology, and (c) INVISIBLE2.0, for different communication modes and environments.

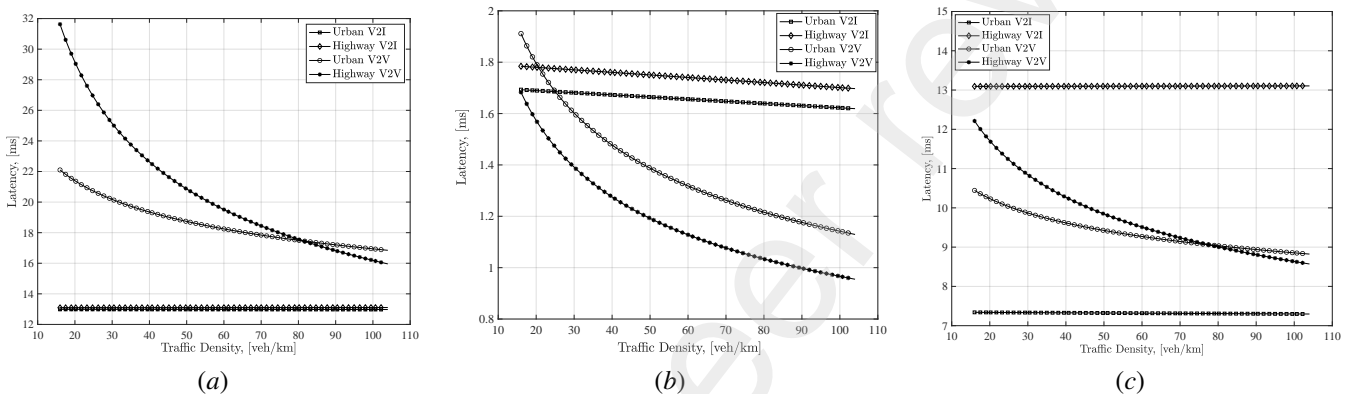


Fig. 7. Latency comparison vs. the traffic density, in case of (a) C-V2X and (b) *VehVLC* technology, and (c) INVISIBLE2.0, for different communication modes and environments.

density decreases the distance among communicating vehicles which reduces the latency by its part. However, the latency in V2I scenarios does not change significantly in dense traffic in both technologies, since the average distance between the cars and the infrastructure is constant. This distance is much lower in VLC technology i.e., the coverage range of VLC technology is lower than LTE-V2X, which makes communication faster.

Finally, the latency achieved with INVISIBLE2.0 is depicted in Fig. 7 (c) still in case of different communication modes and vehicular scenarios. We observe that with INVISIBLE2.0 the latency trend is improved by one order of magnitude as compared to ad-hoc C-V2X in the case of V2V communication mode. On the other side, in the urban V2I scenario, the latency is decreased significantly, while in highway V2I, INVISIBLE2.0 and C-V2X are identical.

VI. CONCLUSIONS

This study described the detailed power models for LTE user equipment and VLC front-end and focused on how power is scaled in vehicular scenarios. The given analysis in terms of energy efficiency, latency, and PRR motivates the design of a vertical handover mechanism where the VLC has been chosen as a primary technology to transmit cooperative awareness messages and LTE was supporting CAM dissemination when VLC does not accomplish with 3GPP packet delivery baseline. The INVISIBLE 2.0 performance has been compared to the standalone C-V2X and *VehVLC*

for V2V and V2I communications in urban and highway environments. INVISIBLE2.0 complies with the 95% PRR baseline and represents a steady energy efficiency and low packet delivery latency. Although the model was designed for simplicity, flexibility, and good accuracy, the absolute power numbers can not be guaranteed. This would require extensive physical measurements and further validation before using it to explore non-measured scenarios.

REFERENCES

- [1] Cisco Annual Internet Report (2018-2023) white paper. <https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html>, Updated: March 9, 2020.
- [2] N. Chi, Y. Zhou, Y. Wei and F. Hu, "Visible Light Communication in 6G: Advances, Challenges, and Prospects," in IEEE Vehicular Technology Magazine, vol. 15, no. 4, pp. 93-102, Dec. 2020, doi: 10.1109/MVT.2020.3017153.
- [3] A. -M. Căilean and M. Dimian, "Current Challenges for Visible Light Communications Usage in Vehicle Applications: A Survey," in IEEE Communications Surveys & Tutorials, vol. 19, no. 4, pp. 2681-2703, Fourthquarter 2017, doi: 10.1109/COMST.2017.2706940.
- [4] P. Kumar Singh, S. Kumar Nandi, and S. Nandi, "A tutorial survey on vehicular communication state of the art, and future research directions," Veh. Commun. 18, C (Aug 2019). <https://doi.org/10.1016/j.vehcom.2019.100164>.
- [5] S. Ucar, S. C. Ergen and O. Ozkasap, "Visible light communication assisted safety message dissemination in multiplatoon," 2017 IEEE International Black Sea Conference on Communications and Networking (Black-SeaCom), 2017, pp. 1-5, doi: 10.1109/BlackSeaCom.2017.8277704.

- [6] M. Mayahi, V. Loscrí, and A. Costanzo, "INVISIBLE: Enhanced Handover technique for Vehicular Visible Light Networks," 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), 2022, pp. 1-5, doi: 10.1109/VTC2022-Spring54318.2022.9860664.
- [7] J. Santa, F. Pereñíguez, A. Moragón, and A. F. Skarmeta, "Experimental evaluation of CAM and DENM messaging services in vehicular communications, Transportation Research Part C: Emerging Technologies," Volume 46, 2014, Pages 98-120, ISSN 0968-090X, <https://doi.org/10.1016/j.trc.2014.05.006>.
- [8] R. Molina-Masegosa, M. Sepulcre, J. Gozalvez, F. Berens, and V. Martinez, "Empirical Models for the Realistic Generation of Cooperative Awareness Messages in Vehicular Networks," in IEEE Transactions on Vehicular Technology, vol. 69, no. 5, pp. 5713-5717, May 2020, doi: 10.1109/TVT.2020.2979232.
- [9] D. Marabissi et al., "Experimental Measurements of a Joint 5G-VLC Communication for Future Vehicular Networks," Journal of Sensor and Actuator Networks, vol. 9, no. 3, p. 32, Jul. 2020, doi: 10.3390/jsan9030032.
- [10] A. -M. Cailean, B. Cagneau, L. Chassagne, V. Popa and M. Dimian, "A survey on the usage of DSRC and VLC in communication-based vehicle safety applications," 2014 IEEE 21st Symposium on Communications and Vehicular Technology in the Benelux (SCVT), 2014, pp. 69-74, doi: 10.1109/SCVT.2014.7046710.
- [11] R. Molina-Masegosa, J. Gozalvez and M. Sepulcre, "Comparison of IEEE 802.11p and LTE-V2X: An Evaluation With Periodic and Aperiodic Messages of Constant and Variable Size," in IEEE Access, vol. 8, pp. 121526-121548, 2020, doi: 10.1109/ACCESS.2020.3007115.
- [12] Z. Ali, S. Lagén, L. Giupponi and R. Rouil, "3GPP NR V2X Mode 2: Overview, Models and System-Level Evaluation," in IEEE Access, vol. 9, pp. 89554-89579, 2021, doi: 10.1109/ACCESS.2021.3090855.
- [13] Dino Flore 3GPP RAN Chairman, Initial Cellular V2X standard completed, <https://www.3gpp.org/news-events/3gpp-news/v2x-r14>, Sep 26, 2016.
- [14] J. Chen and Z. Wang, "Topology Control in Hybrid VLC/RF Vehicular Ad-Hoc Network," in IEEE Transactions on Wireless Communications, vol. 19, no. 3, pp. 1965-1976, March 2020, doi: 10.1109/TWC.2019.2960229.
- [15] Elnaz Alizadeh Jarchlo, Elizabeth Eso, Hossein Doroud, Bernhard Siessegger, Zabih Ghassemloooy, Giuseppe Caire, Falko Dressler, "Li-Wi: An upper layer hybrid VLC-WiFi network handover solution", Ad Hoc Networks, Volume 124, 2022, 102705, ISSN 1570-8705, <https://doi.org/10.1016/j.adhoc.2021.102705>.
- [16] Shao, Sihua, Guanxiong Liu, Abdallah Khreishah, Moussa Ayyash, Hany Elgala, Thomas DC Little, and Michael Rahaim. "Optimizing handover parameters by Q-Learning for heterogeneous radio-optical networks." IEEE Photon. J. 12, no. 1 (2020): 1-15.
- [17] Eckermann, Fabian & Kahlert, Moritz & Wietfeld, Christian. (2019). Performance Analysis of C-V2X Mode 4 Communication Introducing an Open-Source C-V2X Simulator. 1-5. 10.1109/VTCFall.2019.8891534.
- [18] 3GPP technical specification. LTE; Service Requirements for V2X Services. ETSI TS 122 185. Sophia Antipolis Cedex, FRANCE: ETSI(European Telecommunications Standards Institute, March. 2017.
- [19] 3GPP technical report. Study on LTE-based V2X Services. 3GPP TR 36.885 V14.0.0. Sophia Antipolis Cedex, FRANCE: 3rd Generation Partnership Project, 650 Route des Lucioles - Sophia Antipolis Valbonne - FRANCE, June 2016.
- [20] A.R. Jensen, M. Lauridsen, P. Mogensen, T. B. Sørensen and P. Jensen, "LTE UE Power Consumption Model: For System Level Energy and Performance Optimization," 2012 IEEE Vehicular Technology Conference (VTC Fall), 2012, pp. 1-5, doi: 10.1109/VTCFall.2012.6399281.
- [21] C. Desset et al., "Flexible power modeling of LTE base stations," 2012 IEEE Wireless Communications and Networking Conference (WCNC), 2012, pp. 2858-2862, doi: 10.1109/WCNC.2012.6214289.
- [22] H. Haas, L. Yin, Y. Wang and C. Chen, "What is LiFi?," in Journal of Lightwave Technology, vol. 34, no. 6, pp. 1533-1544, 15 March, 2016, doi: 10.1109/JLT.2015.2510021.
- [23] R. Molina-Masegosa, J. Gozalvez and M. Sepulcre, "Configuration of the C-V2X Mode 4 Sidelink PC5 Interface for Vehicular Communication," 2018 14th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN), 2018, pp. 43-48, doi: 10.1109/MSN.2018.00014.
- [24] E. Björnson, J. Hoydis, and L. Sanguinetti, "Massive MIMO networks: Spectral, energy, and hardware efficiency," *Foundations and Trends in Signal Processing*, vol. 11, no. 3-4, pp. 154-655, 2017.
- [25] L. Kong, C. Chen, Y. Wang and H. Haas, "Power Consumption Evaluation in High Speed Visible Light Communication Systems," 2018 IEEE Global Communications Conference (GLOBECOM), 2018, pp. 1-6, doi: 10.1109/GLOCOM.2018.8647711.
- [26] 3GPP. Study on LTE-based V2X services. ETSI TR 36 885. Sophia Antipolis Cedex, FRANCE: ETSI(European Telecommunications Standards Institute, Sept. 2016.
- [27] Lighting Design Guidance. <https://globaldesigningcities.org/publication/global-street-design-guide/utilities-and-infrastructure/lighting-and-technology/lighting-design-guidance/>. Posted: May 18, 2022.
- [28] Speed Limits. <https://www1.nyc.gov/html/dot/downloads/pdf/current-pre-vision-zero-speed-limit-maps.pdf>. Updated: June, 2014.
- [29] ETSI. Intelligent Transport Systems (ITS) Vehicular Communications Basic Set of Applications (Specification of Cooperative Awareness Basic Service). ETSI TS 102 637-2. Sophia Antipolis Cedex, FRANCE: ETSI(European Telecommunications Standards Institute, Mar. 2011.
- [30] Traffic Density U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-03/traffic-density-indicator-reference-sheet-20220306_0.pdf. Indicator Reference Sheet – March 6, 2022.
- [31] A. Aldalbahi, M. Rahaim, A. Khreishah, M. Ayyash and T. D. C. Little, "Visible Light Communication Module: An Open Source Extension to the ns3 Network Simulator With Real System Validation," in IEEE Access, vol. 5, pp. 22144-22158, 2017, doi: 10.1109/ACCESS.2017.2759779.
- [32] Q.-H. Dang and M. Yoo, "Handover Procedure and Algorithm in Vehicle to Infrastructure Visible Light Communication," in IEEE Access, vol. 5, pp. 26466-26475, 2017, doi: 10.1109/ACCESS.2017.2771199.
- [33] M. Rahaim and T. D. C. Little, "Optical interference analysis in Visible Light Communication networks," 2015 IEEE International Conference on Communication Workshop (ICCW), 2015, pp. 1410-1415, doi: 10.1109/ICCW.2015.7247376.
- [34] Cen B. Liu, Bahareh Sadeghi, and Edward W. Knightly. 2011. Enabling vehicular visible light communication (V2LC) networks. In Proceedings of the Eighth ACM international workshop on Vehicular inter-networking (VANET '11). Association for Computing Machinery, New York, NY, USA, 41-50. <https://doi.org/10.1145/2030698.2030705>.
- [35] 3GPP TS 36.213. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedure. ETSI TS 136 213. Sophia Antipolis Cedex, FRANCE: ETSI(European Telecommunications Standards Institute), Sept. 2019.
- [36] M. Malinverno, F. Raviglione, C. Casetti, C.F. Chiasserini, J. Mangués-Bafalluy, and M. Requena-Esteso, "A Multi-stack Simulation Framework for Vehicular Applications Testing," in Proceedings of the 10th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet '20). Association for Computing Machinery, New York, NY, USA, 17-24. <https://doi.org/10.1145/3416014.3424603>.