# CHAPTER 1

# A review on Enabling vehicular visible light communication (V2LC) networks

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## ABSTRACT

*We first develop a custom V2LC research platform on which we experimentally evaluate the feasibility of a V2LC system under working conditions in relation to link resilience to visible light noise and interference. Our experiments show that a receiver's narrow field-of-view angle makes V2LC resilient to visible light noise from sunlight and legacy lighting sources as well as to interference from active VLC transmitters. Then, by leveraging our experimental characterization as the basis of modifications to our simulator, we examine V2LC's performance in providing network services for vehicular applications. Our key findings include: (i) in dense vehicular traffic conditions (e.g., urban highway during peak hours), V2LC takes advantage of multiple available paths to reach vehicles and overcomes the effects of packet collisions; (ii) in the presence of a visible light blockage in traffic, V2LC can still have a significant number of successful transmissions by opportunistically using dynamic inter-vehicle gaps.*

***Keywords:*** *VLC, FSO technology, intelligent reflecting surfaces, V2LC etc.*

## INTRODUCTION

Visible Light Communication (VLC) is a fast-growing technology to provide data communication using low-cost and omni-present LEDs and photodiodes. In this paper, we examine the key proper-ties in enabling vehicular VLC (V2LC) networks as follows.

Next-generation mobility trends such as autonomous driving and ride sharing necessitate various vehicular connectivity schemes. On the other hand, intelligent transportation systems (ITS) harmonized with vehicular communications aim to reduce traffic congestion, accidents, air pollution, energy, and time wastage. Upto date, vehicular communications are expected to provide timely and efficient data dissemination regarding accidents, traffic jams, and road conditions beyond the drivers’ knowledge.


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Currently, RF-based IEEE 802.11p (DSRC) and LTE are the strongest candidates for V2V and vehicle to everything communications (V2X). However, regarding limited bandwidth and security vulnerabilities of RF-based communications, optical wireless communication is proposed as a complementary technology for vehicular connectivity. Utilizing redundant communication schemes for vehicular communications is expected to increase road safety while supporting safer automated driving applications.

LEDs enable flexible vehicle headlight/taillight design, while providing better illumination, low energy consumption, and longer durability. Hence, LED lights are started to be widely deployed with new production vehicles. Moreover, vehicle LED lights enable creation of various illumination patterns to prevent glare from other road users and illuminate the blind areas better [1]. LED lights illumination requirements and design guidelines are also included in the automotive light regulations [2], which paves the way for more manufacturers to utilize LED in their vehicles. Dimming capability of LED lights is another favorable feature for automotive industry, providing energy efficient vehicular lighting.

Modern vehicles are also equipped with image sensors such as PDs and cameras. PDs are utilized to detect ambient light levels and rain to automatically activate headlights or wiper blades, while the cameras are used for driver assistance systems such as lane keeping assistant, traffic sign recognition, pedestrian detection, and forward collision warning. Hence, usage of the existing vehicle LED lights and image sensors is foreseen to allow low vehicular visible light communication (V2LC) system implementation costs.

Visible light communication (VLC) systems with intensity modulation and direct detection (IM/DD) utilize signal intensity instead of signal phase information. As phase information is prone to distortions for mobility scenarios, sole dependence on signal intensity of IM/DD scheme also makes VLC a promising technology for vehicular communications.

Currently, V2V aims to transmit vehicle position and state information to enhance the road awareness of nearby vehicles. However, with the upcoming autonomous driving features, high-definition real time road maps, vehicle radar data, high-resolution image, and video data from on-board cameras are expected to be exchanged between nearby vehicles. These events driven large size data is required to be conveyed with minimum latency. Furthermore, high mobility requires higher message update rates resulting with dense message generation. In order to provide high data rates with minimum latency, hybrid schemes, utilizing various communication technologies simultaneously, are provisioned to be favorable. It has already been demonstrated that, communication degradation sourced by packet collisions and contention with the usage of single scheme such as DSRC can be avoided with a hybrid scheme employing DSRC and V2LC [3].

Upto date, VLC is reported to achieve multi-Gbit/s data rates for a few meter distances. Compared to DSRC maximum data rate support with 27 Mbps upto 1000 m distances [4], Gbit/s data rates make VLC attractive for high data rate vehicular communications. In addition to higher data rate advantages, with its immunity to malicious jamming with LoS characteristics, VLC is also foreseen to off-load RF networks while providing secure communications for safety critical applications.

In the literature, various studies investigated V2LC applications. In Ref. [5], LEDs are utilized as vehicle ambient lights and dome lights are foreseen to act as VLC transmitters. Authors in Ref. [6] implemented IEEE 802.15.7 standard to convey information using vehicle LED lights. In Ref. [7], V2LC system that is based on image sensor and high-speed camera receivers is demonstrated. PDs, PD arrays, or cameras can be employed as V2LC receivers. Depending on the sensors FOV, location and lens selection plays a key role to realize practical V2LC applications. Sunlight and artificial background lights are also supposed to be considered at the receiver side. Direct exposure to sun light causes either saturation or excess shot noise at the image sensors resulting with inability to detect intensity-modulated signals. The direct current (DC), suppressing front-end circuit usage, is proposed to suppress noise sourced by sunlight. Artificial light sources such as advertising boards and traffic signals are usually operated at the 60 Hz AC voltage and its


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harmonics. Hence, modulating V2LC LEDs in the order of at least a few hundred kHz to a few MHz is beneficial to minimize artificial light noise effects. PDs target high-rate VLC, whereas cameras are foreseen to support low-rate VLC with positioning capabilities. Current vehicles with automatic headlight and rain sensors are already equipped with PDs. On the other hand, the number of vehicles with cameras is increasing to enable features such as forward collision warning, pedestrian detection, traffic sign detection, and lane keeping. Both camera and PD sensors are located in the middle of the windshield above the rear-view mirror. Even though the already deployed image sensors can be utilized for V2LC, located the sensors, around the headlights and taillights to evaluate the performance dependence to the multi path reflections from the road.

## V2LC RECEIVERS

A V2LC system can deploy a PD or a camera image sensor to receive the optical signal transmitted by the LED-based head- and tail lamps. The intensity-modulated optical signal is converted to an electrical current signal and passed for decoding and demodulation to the rest of the receiver chain.

Both, PD and camera-based receivers have been widely considered for V2LC [V51], [V54], [V55], [V56], [V57]. As these two types of receivers differ fundamentally in terms of hardware architecture and design, the way how they “see” the optical signal and process it differs as well. Basically, this architectural difference determines the overall design of the V2LC system and its performance: Modulation and coding schemes, mitigation of noise and interference, medium access control, etc. are all designed differently depending on whether a PD or an image sensor receiver is used. In the following, section PD receivers, camera-based V2LC, and potential optical enhancements for V2LC are discussed.

## PHOTODIODE-BASED RECEIVERS

The PD is an optical-to-electrical transducer that generates an electron for each impinging photon [V58]. The generated photo current is proportional to the optical power on the PD’s surface (i.e., irradiance). The electrical power, being proportional to the square of the current, is proportional to the square of the optical power. This makes the PD a square law device. As mentioned previously, this property is a limiting factor in V2LC, as the electrical SNR for an IM/DD link is calculated as the square of the average received optical power. In contrast, in RF communication systems, it is proportional to the average received electrical power.

There are two types of PDs that are typically used for V2LC systems: PIN (p-n diode) and Avalanche Photo diode (APD).

APDs have higher sensitivity and provide better gain compared to PIN PDs. There exist high-sensitivity APDs, like the Single Photon Avalanche Diode (SPAD), which, in simulation, have been demonstrated to perform better than conventional APDs, even in adverse weather conditions [V71]. Despite this, PIN PDs are more favorable for V2LC due to the better linearity performance, high temperature tolerance, and lower cost. When choosing the PD receiver for a V2LC system, one should aim for optimal performance while considering hardware properties, such as size of the active area, adequate bandwidth, high sensitivity, low noise, and broad linearity range. These parameters can greatly impact the performance of the V2LC application. For instance, a PD with a large FOV will have higher tolerance to horizontal and vertical movement in real driving scenarios, however, it allows the reception of undesired signals, which can reduce the SNR [V55].

Most setups described in the V2LC literature prefer commercially available off-the-shelf products to demonstrate the feasibility of implementing the system both in terms of cost and effort. However, custom-built solutions are used whenever the system uses more advanced techniques. The design of low cost PD-based V2LC systems is important as, unlike image sensor-based V2LC, which can potentially be realized


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using the front and rear view cameras readily available in modern vehicles, PD-based V2LC requires the installation of new devices on the vehicle, which, in turn, increases the overall vehicle cost.

Further discussion regarding PIN PDs and APDs, including the technical differences and comparison between them, can be found in [V58]. Camera Image Sensor-based V2LC V2LC based on camera image sensor receiver falls in the domain of Optical Camera Communication (OCC) [V59], [V60].

A substantial amount of work in the V2LC literature has focused on the use of camera image sensors as receivers [V61]. Cameras are already deployed in modern vehicles for safety applications, like pedestrian detection, lane detection, and parking assist. Therefore, such cameras are ready to use for VVLC [V56], [V62]. There are many advantages of using cameras for V2LC: The rather high spatial resolution of cameras allows separation of noise and signal sources and detection of multiple transmitters and, therefore, enabling efficient MIMO V2LC [V60]. A typical OCC receiver consists of an imaging lens, an image sensor, and a readout circuit. The image sensor consists of multiple micron sized PD pixels, which generate voltage proportional to the number of impinging photons. The light from the imaging lens projected onto the image sensor is converted to binary data by the readout circuit [86, Chapter 8.1.2]. Based on the readout circuit configuration, image sensors can be classified into rolling shutter and global shutter image sensors [V69]. The global shutter technology, typically used with Charge Coupled Device (CCD) image sensors, exposes all of the pixel at once, whereas the rolling shutter technology, typically used with CMOS image sensors, reads pixels one row/column at a time. This allows comparatively higher data rate. Due to this property, rolling shutter image sensors are preferred for VLC.

An important limitation of typical CMOS image sensors is their low frame rate (typically 30–100 fps), which limits the throughput to tens of bits per second – a fairly low data rate for vehicular networking applications [V70]. As an alternative, high frame rate camera can be used, however, they are quite expensive [V68]. In addition to commercial solutions, custom designed cameras, like Optical Communication Image Sensor (OCI) and Dynamic Vision Sensor (DVS) camera, optimized for automotive applications, have been introduced [V57], [V63]–[V65]. For instance, the DVS camera offers advantages in terms of improved throughput and noise elimination [V64]. The pixels of the DVS camera only register a signal whenever there is a significant change in light intensity, otherwise they are treated as still and can easily be discarded, thus, solving noise issues.

Additionally, not having to read all of the pixels (i.e., a frame), as in commodity cameras, saves valuable bandwidth [V65]. Although custom design cameras for V2LC can deliver better performance, they do it at the expense of higher complexity and cost.

The fundamental difference in camera-based VLC is the need to use image processing techniques on the receiver side for the detection/tracking of the transmitters, and for extracting the transmitted signal. The goal here is to ensure accurate and real-time image processing in order to avoid delay penalties on the application performance, while effectively mitigating imaging-related issues like blur and perspective distortion [V66]. The distance also plays an important role. With increasing distance between the transmitter and the receiver, the number of pixels occupied by the transmitter becomes smaller and their brightness fades. This hinders the detection of the transmitter and extraction of the transmitted signal. Thorough discussion regarding camera-based VLC, also applicable to vehicular scenarios, can be found in [V67] [V59], [V60].

## LED MODULATION

The IEEE 802.15.7 standard also complies with the eye safety regulations imposed by IEEE PAR 1789, which regulates the amount flicker LED and avoid any health risks.


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White light phosphor LEDs are most commonly used in the commercial LED light fixtures. The modulation bandwidth of the white light phosphor LEDs is limited to 2 MHz. Another way to increase the bandwidth efficiency is by generating the white light by using the red-green-blue (RGB) LEDs. Then each color can be modulated separately, such that data is sent on every color wavelength separately in what known as color shift keying. Independent modulation of the colors might create different color than white or changeable light intensity over time [V2].

## ISSUES IN MODULATION TECHNIQUES:

The modulation bandwidth of phosphor-coated WLEDs is affected by the slow response time of the phosphor coating, which introduces delays and deteriorates the communication performance. To mitigate this issue, one could use a transmissive blue optical filter on the receiving side to filter out the yellow light and to focus on the blue component, which can be modulated faster. This approach can increase the modulation bandwidth to tens of MHz and to support higher data rates.

However, it does so at the expense of decreased SNR, as a large portion of the received optical power from the yellow bands is filtered out. This, in turn, can degrade the performance of multi-carrier modulation schemes.

One of the main problems on the transmitting end of VLC systems is the distortion caused by front-end nonlinearities. LEDs have a nonlinear I-V characteristic, which results in a nonlinear relation between the forward current and the radiated optical power [93]. This presents a major challenge in VLC, in particular when multi-carrier modulation schemes are used. In such cases, the intensity of the different subcarriers can be added constructively resulting in values beyond the linear range of the transmitter, thus, the signal gets distorted. A typical example of this is OFDM and its high Peak-to-Average Power Ratio (PAPR).

## RF-VLC

In Hybrid Radio-optical Wireless Networks,  most of the research on VLC is focused to demonstrate the capabilities of optical wireless communications but detached from the fact that radio communication is the dominant way of transferring information wirelessly. The radio community sees VLC as a competing technology, while indeed, optical and radio communications are highly complementary.

The flexibility, scalability and relative simplicity of radio can indeed be combined to the inherent security, safety, privacy of VLC to create a high-performance and robust

hybrid communication system. Having wireless devices or nodes equipped with both radio and optical air interfaces allow exploiting the synergy between these systems with no major impact on cost or size. A reconfigurable network selecting dynamically the best operating mode results in a high performance wireless communication system able to adapt to the radio/optical environment, use case and operating scenario. Such a system is proposed and demonstrated in [16-17]. Fig. 2 (left) illustrates the concept, where devices or nodes exploit hybrid radio-optical wireless networks.


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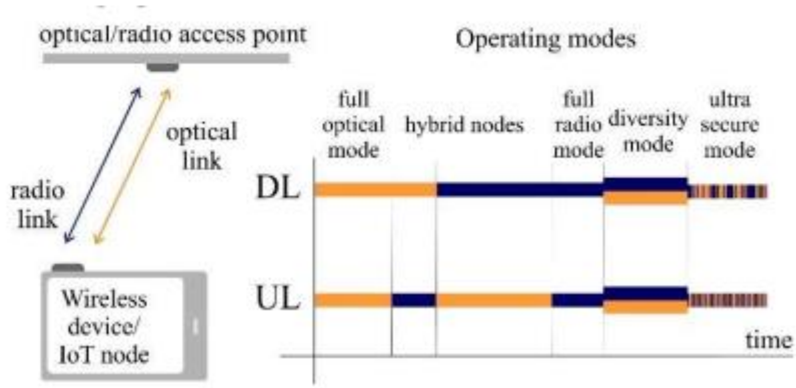


Fig. 2. Hybrid optical-radio networks and their operating modes.

Different operating modes are dynamically selected by an algorithm according to channel state information (radio/optical), scenario (e.g., local usage policies), user/operator decision, contextual information, etc. Fig. 2 (right) illustrates possible

operating modes, according on how optical and radio communications are used in uplink (UL) and downlink (DL). The most basic modes include full optical, full radio and two simple hybrid modes. In diversity mode, both optical and radio links are used for UL and/or DL, while the ultra-secure mode multiplexes the signal into radio and optical domains. To be an attractive solution, switching of the modes should be done

in a seamless manner, as demonstrated in [17]. Recently, a reconfigurable optical-radio network has been proposed as the key wireless communication network for the hospital of the future [18]. [v17]

(A) RF-VLC: The RF band lies between 3 kHz and 300 GHz of the electromagnetic spectrum. However, the range (3 kHz, 10 GHz) is widely used by the existing wireless technologies because of favorable communication properties in this range. OCC normally uses VL or IR as the communication medium. However, ultraviolet (UV) spectrum can also be used as the communication medium. The coexistence of the RF and OWC networks can effectively solve most of the limitations of individual RF-based and optical wireless communication systems [V1].

A reconfigurable network selecting dynamically the best operating mode results in a high performance wireless communication system able to adapt to the radio/optical environment, use case and operating scenario. Fig. illustrates the concept, where devices or nodes exploit hybrid radio-optical wireless networks. Different operating modes are dynamically selected by an algorithm according to channel state information (radio/optical), scenario (e.g., local usage policies), user/operator decision, contextual information, etc. Fig. illustrates possible operating modes, according on how optical and radio communications are used in uplink (UL) and downlink (DL).

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## RF-VLC OUTDOOR APPLICATION:

The Optical Wireless Channel (OWC) consists of Line-of-Sight (LOS) channel, which represents the rectilinear propagation between transmitter and receiver, and Non-Line-of-Sight (NLOS) channel, which fades severely during the propagation via reflection, scattering and so on. In outdoor scenario, there exists a lot of obstacles such as buildings, large billboard and even trees. With the help of RIS, a UAV-RIS-user link which consists of two LOS sublinks can be constructed even there exists obstacles between UAV and ground users. The use of NOMA techniques for VLC-enabled UAVs to maximize the sum rate of all users [V5].

Deploying unmanned aerial vehicles (UAVs) as flying base stations (BSs) for wireless networking is a flexible and cost-effective approach to providing on-demand communications. However, for tomorrow's ultra dense wireless networks, UAVs deployed as aerial BSs using radio frequency (RF) will interfere with ground devices, hence significantly affecting the performance of the ground network. In addition, the limited energy will restrict the applicability of UAVs using RF resource to provide high-speed communication services for ground users. These challenges can be addressed by equipping UAVs with visible light communication (VLC) capabilities.

## INTELLIGENT REFLECTIVE SURFACES (IRS):

Two different setups for intelligent reflecting surfaces in the context of VLC systems, namely, intelligent metasurface reflector (IMR) and intelligent mirror array (IMA). utilizing IRSs for non-coherent VLC systems employing intensity modulation/direct detection.[V8]

## METASURFACES:

Metasurfaces are synthesized materials composed of arrangements of sub-wavelength metallic or dielectric structures that are used to manipulate light propagation in unusual ways compared to classical optical devices. These surfaces are capable of manipulating wavelength, polarization, and phase of incident waves. The reflection governed by the generalized Snell's law of reflection as shown in the figure.

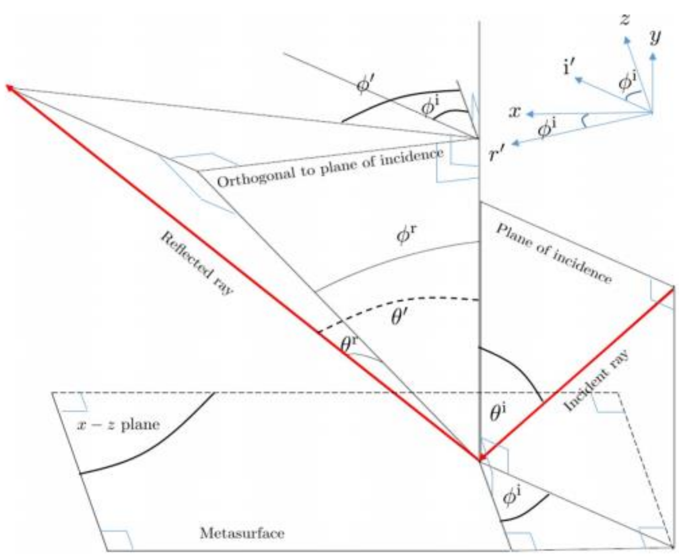


FIGURE 5. Generalized law of reflection [V8]

Hence, they can be used to realize the functionality of many classical optical devices as lenses, diffraction gratings, polarizers, and beam-splitters. Eventually, metasurfaces can provide combined conventional optical functions in addition to providing new functionalities as anomalous reflection governed by the generalized Snell's law of reflection. [v8].

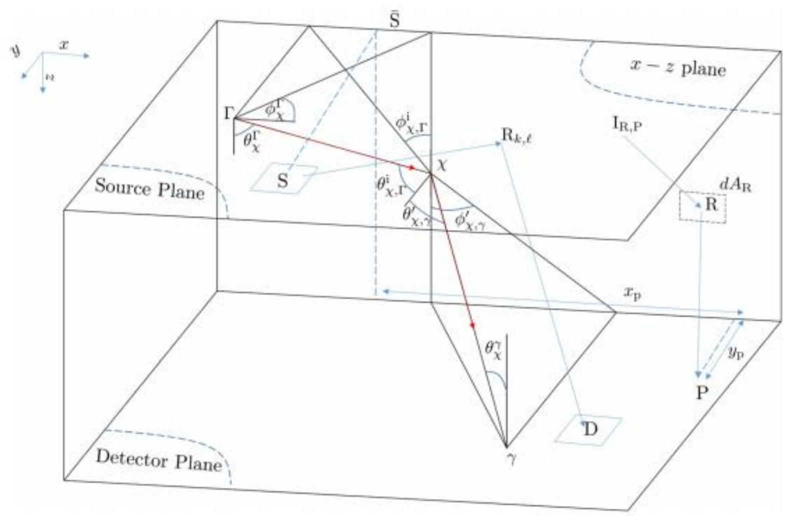


FIGURE 6. General ray tracing for metasurface-based IRS [V8]

Reflection response of a surface is highly determined by its constituting material and its geometric imperfections. Surface reflection response can be classified into: specular, diffuse, or glossy based on the roughness degree of the surface (determined by fluctuation in the height profile). Perfectly smooth surfaces act as mirrors and reflect light in a specular direction according to Snell's law of reflection while rough surfaces scatter incident light in all directions. Generally, surfaces have glossy nature where the reflected power consists of a specular component and a diffuse component.

Radiometry studies the properties of radiation energy distribution in space, which is crucial for the communications service assessment of VLC systems. On the other hand, photometry is concerned with studying the human eye perception of light, which is crucial for the assessment and design of lighting systems [V8].

## INTELLIGENT MIRROR ARRAY:

Deng et al. proposed and demonstrated a reconfigurable mirco-mirrors based beam-steering system for FSO inter-rack networks of data centers.

FIGURE 3. Mirror Array-based IRS Model [V8]

## FREE-SPACE OPTICAL (FSO) COMMUNICATIONS:


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terrestrial point-to-point OWC also known as free-space optical (FSO) communications [v75] take place at the near IR band. Using high-power high-concentrated laser beam at the transmitter, the FSO system can achieve high data rate, i.e., 10 Gbps per wavelength, over long-distance (up to 10 000 km). It offers a cost-effective solution for the backhaul bottleneck in terrestrial networks, enables cross links among space, air, and groud platforms, and facilitates high capacity inter-satellite links for the emerging LEO satellite constellation[V76].

Free space optical (FSO) communication, which takes place in the near infrared, is considered an effective approach in realizing high data rate communications over several kilometers [V77]. For example, for reasonable distances (around 1 km), FSO can achieve data rates in the order of 10 Gbps [V80]. High frequency reuse factor, physical security, and robustness against electromagnetic interference are other advantages exhibited by FSO systems, when restricting the use of a very narrow laser beam at the transmitter side [V78].

Reconfigurable Intelligent Surfaces for FSO: The existence of a LOS link constraint constitutes a major challenge in the implementation and generic deployment of FSO networks. This is due to the fact that optical links in FSO systems are usually impaired by several factors, such as atmospheric turbulence and geometric and misalignment losses [V79]. Consequently, optical reconfigurable intelligent surfaces (RIS) have emerged as an efficient solution to relax the LOS constraint in FSO networks. Different than relay, RIS is considered an energy efficient technology to extend the coverage area of FSO wireless networks at low implementation cost and complexity. Motivated by the promising potentials of RIS in FSO networks, the research community has recently started to actively investigate the integration of RIS in FSO scenarios [V78]

**LOS/NLOS LINKS:**

As for the VLC systems, IRSs are expected to participate effectively in boosting their performance, especially that most of the VLC systems rely on the existence of a line of sight (LoS)[v8].

To the best of our knowledge, most of the research has been focused on optimizing and the analysis of LOS/non-directed link configuration. Our proposal is to study the performance of using IRS for non-line of sight (NLOS) non-directed (diffuse) link . configuration. IRS are used to enhance the link performance and minimize the path loss and temporal dispersion present in diffuse links. In Table I the main differences between current studies and our proposal are summarized [V10]. Table performance metrics of IRS for non-line of sight (NLOS) non-directed (diffuse) link [V10]

## LOS DIRECTED LINK

The optical link is concentrated in a very narrow beam low power requirement indoor application is not recommended since alignment between emitter a receiver is required. in point-to-point communication links In both setups, we assume a non-coherent LED transmitter that is horizontally-oriented and mounted to the room ceiling at a vertical clearance hd from the horizontal plane containing the receiver as depicted in Fig. 2 and Fig. 3. The x, y, and z axes positive directions are oriented such that the z-axis is orthogonal to the ceiling and points towards the floor of the room, while the y-axis is normal to one of the walls and points at the source side, and the x-axis is oriented such that the three axes form a right-handed coordinate system. Moreover, we assume an extended planar source having uniform radiant emittance over its area As = wsls with ws and ls being the source span along the x-direction and y-direction, respectively. Each point on the transmitter aperture is assumed to have a generalized Lambertian radiation pattern with Lambertian order m [V8]

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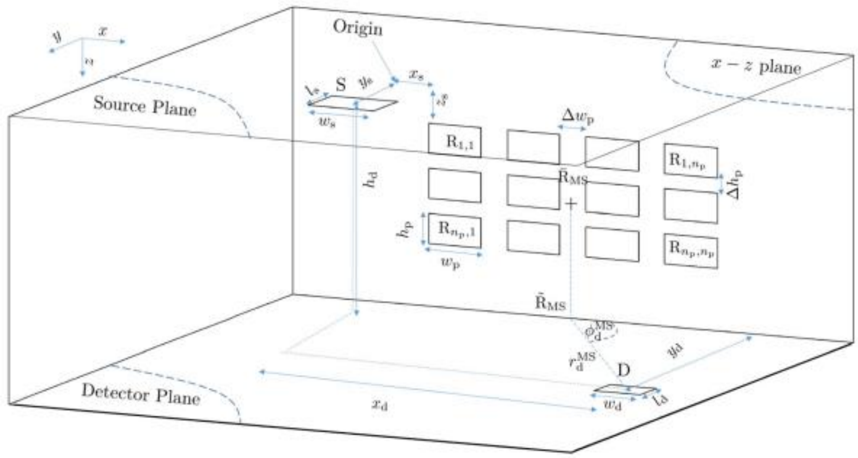


FIGURE 2. Metasurface-based IRS Model[V8]

## SECURE VEHICULAR COMMUNICATIONS THROUGH V2LC

In real-world V2LC deployment, the communication needs to be protected against predefined security attacks. Moreover, to ensure the security in V2LC, three requirements; authentication, confidentiality, and integrity must be satisfied. Authentication confirms the identity of the vehicle and gives permission to authorized vehicles to access the communication medium.

Confidentiality ensures only the participating vehicles decode the content of messages. Integrity, on the other hand, confirms that the transmitted data is not modified during over the air transmission. To enable the authentication, confidentiality and integrity for V2LC networks, physical layer protection, stenographic protection, and cryptographic key generation/management security methodologies are foreseen to be exploited [V14].

## LIMITATION OF V2LC:

VLC in vehicle platoon may degrade communication, since VLC is sensitive to environmental effects, i.e., fog, and might have short-term unreachability due to the increase in the inter-vehicle distance and/or LoS on a curvy road. Thus, IEEE 802.11p and VLC hybrid architectures are proposed to provide redundancy for better reliability in vehicular platoons.[V14]

One promising application area of V2LC is vehicular platoon where a group of cooperative adaptive cruise control (CACC) vehicles kept in close proximity through DSRC. In the vehicular platoon, inter-vehicular space gap is less than 15 m at vehicle speeds less than 100 km/h. On the other hand, VLC communication range has been demonstrated to be 100 m for headlights and 30 m for taillights. Moreover, the light directivity and impermeability of the optical signal through vehicles and obstacles provide more secure communication than DSRC by limiting the transmission area. This limited transmission area restricts the availability of the data to the attackers, while still allowing communication in the vehicular setting.

## VEHICULAR NETWORKING

V2LC is characterized by a set of generic properties owing to the physical characteristics of the light as its transmission medium, and specific properties inherent to the vehicular networking domain.[v18]

It can take advantage of the LED-equipped lighting modules and transportation infrastructure to realize V2LC,

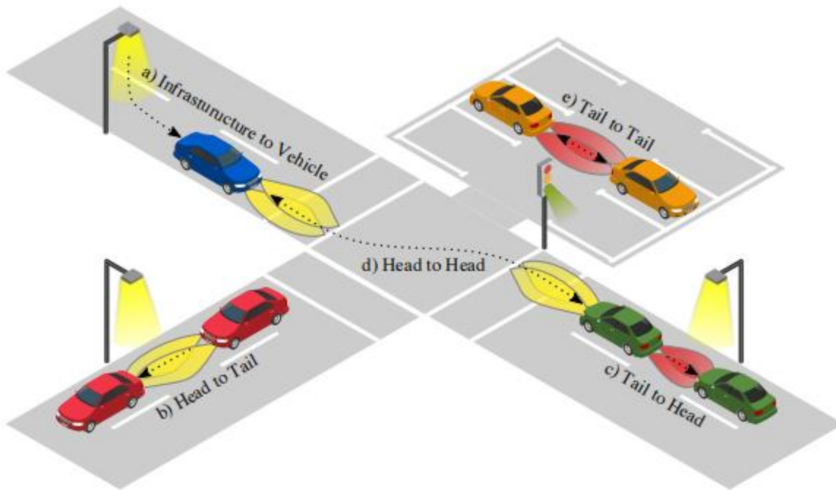


Figure . Vehicular VLC communication patterns and selected potential applications.[V18]

The truth is likely to be found in the complementary nature of both RF and V2LC. RF can make up for VLC's shortcomings, such as short communication range and inability to propagate through opaque objects and V2LC can offer high data rates with very low interference in LOS scenarios.

Considering V2LC's short communication range and directed transmission, it emerges as a viable communication technology for applications whose scope requires communication with nearby peers (e.g., platooning, emergency electronic brake light), or with a small region (e.g., intersection assistance).

V2LC can also be used for communication beyond this scope (e.g., along a trajectory, or throughout the entire network), however in that case messages need to be forwarded via multihop communication, which increases latency, thus rendering V2LC infeasible if the considered application has real-time requirements.

## V2LC NETWORK  APPLICATIONS

Cooperative Awareness: For cooperative awareness applications, like forward collision warning, or emergency vehicle warning, which require communication with the direct neighbors, V2LC can be used to exchange the messages and therefore reduce channel congestion that would be caused by RF transmissions. This can improve the application performance, except in non-optimal optical channel conditions when it is recommended to use V2LC in combination with other vehicular networking technologies due to the high reliability requirement of these applications.

Cooperative Sensing / Cooperative Perception: V2LC can also benefit cooperative sensing and cooperative perception applications, like see-through video streaming, which includes the sharing of sensory data, e.g., on-board camera, with vehicles in the vicinity, or collective collection of sensor data to perceive a bigger picture of the driving situation. In this context, headlamps and tail lamps can be used to transmit high throughput data via V2LC to the vehicles in the front and back, respectively.


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## EMERGENCY BRAKING INFORMATION:

This is a safety application that notifies the driver in case that a vehicle ahead brakes suddenly. For this application the tail to head V2LC link can be used to transmit the emergency brake messages from the vehicle ahead to the following vehicles.

Information Query: V2LC can be used for the query and dissemination of information in the scope of TIS. These applications do not have strong latency and reliability requirements, but they require high scaling and dissemination throughout the entire network. To facilitate this, in addition to V2V VLC, VLC based V2I and I2V communication can be utilized. Namely, LED-based traffic lights, traffic signs, or road lighting can disseminate the information in parts of the network where V2LC links among nearby vehicles is not possible.

## INTERSECTION ASSISTANCE:

Intersection assistance applications, like intersection collision avoidance, are used to improve the safety in intersections by providing means of coordination and warning between vehicles, other than the conventional methods, e.g., traffic lights. When vehicles face each other in an intersection, they can use the head to head V2LC link for communication with the vehicles in the opposite side of the intersection. In addition to this, LED-based traffic lights, or other elements from the infrastructure, can facilitate the communication.

Platooning: Platooning is one of the main applications that can benefit from V2LC. In platooning, the platoon members are required to exchange information in timely and frequent manner (at least 10 Hz) in order to maintain short driving distance. In the context of platooning, V2LC can be used for communication between vehicles directly following each other, while IEEE 802.11p and/or C-V2X can be used for message exchange between the leader and the rest of the platoon. This can significantly reduce the load on the RF channel, while improving the application performance.

Selected applications for V2LC and corresponding application requirements (following and adapting surveys by boban et al. [V18]

A multitude of different techniques have been used to address challenges like nonlinearities and bandwidth limitations in VLC. We focus on V2LC, therefore, a discussion regarding fundamental system-level VLC performance challenges and corresponding solutions is beyond the scope of this work.

## FACTORS INFLUENCE/PARAMETER

Impact of Lighting Module Light Distribution largely depend on the radiation pattern of the lighting module and the position of the receiver within that radiation pattern. Dirt deposition in front of the lighting modules can influence theshape of the radiation pattern The asymmetric and non-uniform property of headlights' radiation pattern poses a challenge NLOS the ground surface area between a transmitter and receiver provides the strongest NLOS components.

## LIMITATIONS IN APPLICATION:

As far as delivery latency and delivery reliability requirements are concerned, in theory, V2LC can support applications that have hard real-time requirements and demand deterministic behavior. However, in practice, this can be possible only for communication with the direct neighbors, and under favorable optical channel conditions. Therefore, for applications with stringent reliability requirements V2LC should be considered as a secondary communication channel to improve reliability and robustness. Whereas, for


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applications that can tolerate typical network delays and best-effort delivery, V2LC can be used as the only communication technology.

## CONCLUSION AND FUTURE SCOPE

In this chapter, V2LC key features such as automotive LED characteristics, PD features, dimming functionality application to vehicle LEDs, and vehicular communication security enhancement through complementary usage of V2LC are discussed. Apart from indoor VLC, V2LC requires high power LEDs with collimation and diffuse optics to fulfill long-range road illumination for all weather and ambient light conditions. High power LEDs limited switching capability, white LED usage and minimum illumination requirements for road safety upper bound the modulation frequencies.

PD or image sensor selection also plays a key role to realize V2LC practical applications. Receivers located in front of the vehicle are expected to capture taillights in red color, whereas the rear optical receiver sensors are foreseen to capture communication signals transmitted through white LEDs. Furthermore, image sensor or high-speed camera usage is also practiced with various experiments, and data rates above RF-based DSRC communications are achieved. Image sensor usage is also deemed favorable due to positioning capabilities of optical image sensors.

LEDs dimming capability enables energy savings prolong LED life and adaptive illumination for safer traffic. However, considering power and illumination limitations of outdoor environment, time domain dimming schemes providing more SNR at the receiver are regarded to be practical, despite the data rate limitations.

Hybrid usage of V2LC and RF-based DSRC enables enhanced security for vehicular communications. As both technologies can complement each other in terms of data rates, directional communications and range extension, exploiting both technologies for vehicular networks, are demonstrated to be practical in terms of security.

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