TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 09/16 pp719–728
DOI: 10.26599/TST.2022.9010020
Volume 28, Number 4, August 2023

Automotive Visible-Light Communication: Alternative Devices and Systems

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Abstract: Continuous advancements in visible-light communication (VLC) technology have paved the way for future high-capacity communication links that can simultaneously provide data transmission and illumination. VLC is being accepted as a potential complementary technology in 5G networks, and standardization efforts through IEEE 802.15.7 are on their way. Today, vehicular networking applications have become increasingly complex with tight power and performance requirements. Consequently, devices and systems that can meet diverse vehicular networking applications are in great demand. In this article, we discuss three alternatives for vehicular networking applications in (1) LED–photodiode-based active VLC, (2) VLC with a multicamera array receiver, and (3) passive VLC based on decoding information from optical backscatter. We also present our recent experimental and modeling work using our camera-based and passive VLC prototype implementations.

Key words: visible-light communications; automobile; camera communications

1 Introduction

Visible-light communication (VLC) features a number of attractive properties for enabling advanced intelligent transportation systems (ITS) with improved safety and efficiency. LEDs and cameras on modern vehicles have the potential to serve as transmitters and receivers, respectively, for vehicular communications with little additional cost. In contrast to radiofrequency (RF)-based systems, visible light occupies a large (approximately 400 THz wide) unrestricted spectrum that is available worldwide. The special reuse of highly directional optical links could accommodate an increased number of devices without interference. Moreover, VLC is resistant to electromagnetic noise. Finally, the optical link requires line-of-sight (LoS) and does not penetrate through walls. This property can be exploited for security purposes to hide data communications from potential eavesdroppers.

Within the last few years, many studies on VLC-based vehicular networking have been published[1–5]. However, these works have been very selective about how the VLC system can be useful in the automotive context and lack clear baseline agreement or standards. This paper presents three alternative VLC approaches. We describe how they can be used in vehicular communications together with our prototype design, experimental results, and modeling. We also discuss a few examples of their potential application.

- **LED-Photodiode VLC. (Can we use headlights for communication?)** We present analytical discussion with simulations on the LED-Photodiode VLC.
- **Camera communication. (Can we reuse built in cameras for networking?)** We discuss our design with experimental results of how multi-camera systems can be used for camera based vehicular communication.

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Manuscript received: 2021-11-26; revised: 2022-05-02; accepted: 2022-06-16

• **VLC backscatter. (Can we achieve battery-free operations in VLC?)** We present a physical model for the backscatter VLC channel with link budget analysis and experimental validation.

2 LED-Based Systems

While LEDs for automotive lighting come in wide varieties and shapes, most of them emit energy within approximately 20° of the direction of maximum light, and only very weak intensities can be observed beyond approximately 80° on either side. Most commercial packages include plastic lenses to spread light for a great angle of visibility. In particular, lamps, reflective devices, and associated equipment must meet specific requirements outlined in government standards, such as the Federal Motor Vehicle Safety Standards in the United States, to ensure road illumination without considerable glare for other road users, as well as the maximum or minimum light intensity. Therefore, developing precise models for capturing vehicles' light patterns on roads is challenging given a large number of parameters, such as the casing behind the LED (reflective surface) and the lens in front of the LED, which all affect the radiation pattern.

Perhaps LED emitters for narrow-angle applications should be characterized differently from those for wide-angle applications. The LED emitters used for long-distance applications need to have a narrow-angle emission pattern.

Consider a transmitter-receiver pair separated by distance D. When the transmitter–receiver distance is considerably larger than the size of the photodetector S, the received irradiance can be approximated to a constant over the detector surface. The direct current (DC) channel gain $H(0)$ can be derived as

$$H(0)=\frac{(n+1)S}{2\pi D^{\gamma}}\cos^{n}(\phi)\cos(\theta) \quad (1)$$

where n is the order of the Lambertian model, γ is the path loss exponent, ϕ is the irradiance angle with respect to the emitter, and θ is the incidence angle.

For applications involving wide-angle emission LEDs, the radiation pattern must be enhanced, usually with focal lenses, to extend the communication range. As an example, we created a simple headlamp module simulated by using LightTools (Fig. 1). CREE CXA2011 is chosen as the source in this example design because of its high flux. Of the two Fresnel lenses with a diameter of 16 mm each, the first acts as a collimating lens with a focal length of 1 mm to take the scattered light rays from the source and align them. The second Fresnel lens has a focal length of 7 mm and focuses the parallel incident rays onto the receiver screen. The receiver is placed 21 mm away. The entire system is contained in a cylinder with mirrored walls to reduce losses due to scattered rays. The LED's illuminance diagrams before and after are shown in Fig. 1. Clearly, not only is the focused LED more symmetric and less scattered, it has considerably higher peak intensity than the original LED. The units on the luminance graphs are lumens per meter squared.

On the receiving end, input light radiation is collected by a non-imaging system, often with some optical filters, for concentration onto a photodiode. This system can be integrated into taillights by using many existing components. Amplifiers can be applied later to augment the detected photocurrent. While avalanche photodiodes are used for long-range applications with weak signal strength, silicon PIN diodes are used more commonly in general because they offer linear responses and high sensitivity in their photoconductive mode.

Given that the separation distance between the LED emitter and photodiode receiver can change rapidly in vehicular applications, unsurprisingly, the photodiode can be saturated in cases of high gain. However, if the receiver gain is limited, the communication range would

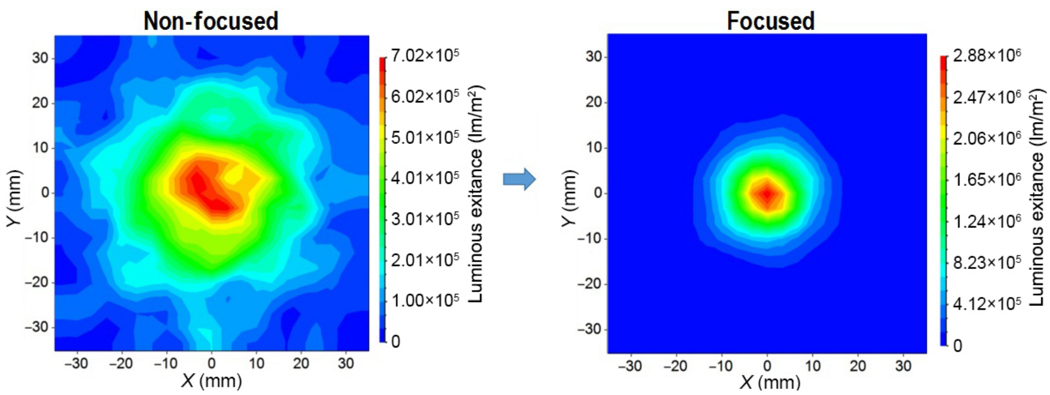

Fig. 1 A simple headlamp module simulated by using LightTools.

be reduced. In this case, an automatic gain control circuit would be necessary.

The receiver side often features large-area square-law detectors. This feature, together with its considerably shorter carrier wavelength than RF, could lead to efficient spatial diversity to prevent multipath fading, whereas large fluctuations in received signal magnitude and phase are expected in RF links. One shortcoming of VLC might be the limited path loss it can handle, given that the square of the received optical power largely determines the receiver's signal-to-noise ratio (SNR).

3 Camera and Camera Array Receiver Systems

LED-based systems often utilize existing modulation techniques, such as orthogonal frequency division multiplexing (OFDM) and on/off keying (OOK), to modulate visible-light signals to send data. On the receiver side, a network of photodetectors can demodulate messages. Such a communication system can be implemented through existing light sources, such as car headlights. Although VLC can be implemented by using LED light sources and a photodetector network, receivers in such communication systems can also be implemented through camera and camera arrays.

Cameras integrated into modern vehicles are very useful resources for communication. They enable a relatively wide field of view (FoV), allowing increased flexibility during motion through computer-vision-based tracking techniques. Tracking can include locating an optical transmitter or even another vehicle (treated as a different node in the network). A large number of highly directional receiver elements allow a long communication range because interference and noise can be selectively filtered over the spatially diverse pixel elements of the camera's image sensor. Analysis and processing can be all done with software because the pixel values are digitized and quantized. Multi-camera or camera-array systems can be very useful for vehicular networking applications from a multiple-input multiple-output system perspective. The additional cameras can help provide metadata, for example, for tracking purposes, while the primary camera can be used for active data reception. Additionally, the multi-camera setup (virtually) expands the receiving pixel array, thus enabling potential throughput scaling capability.

However, camera communication requires LoS between the transmitter and receiver. This requirement translates into the imaging of the transmitter within the FoV of the camera. Typical FoVs for off-the-shelf cameras are within the range of $\pm 60°$, which is approximately the capability to image one lane at a 12 m distance between the transmitter and camera. Cameras are also limited in their sampling rates because the typical sampling rates of off-the-shelf cameras are approximately 10–1000 Hz. The cost significantly increases for frame rates higher than 1000 frames per second and other custom cameras.

In this work, we propose the use of camera communication for vehicle-to-vehicle communication. In particular, we explore multiple vehicular camera communication wherein light emitters, such as brake/tail lights, can transmit information to be perceived and decoded by cameras on following vehicles. Our experimental platform features a stereo camera set-up to enable the dual usage of the cameras for perception and decoding, as well as distance estimation between vehicles. We estimate the movement of the vehicle through image analysis prior to decoding to address the key challenge of maintaining communication reliability during vehicular mobility.

In the remainder of this section, we discuss our experimental findings and insights into vehicle movement measurements and modeling in three dimensions: X (lateral or horizontal), Y (longitudinal or vertical), and Z (camera depth or distance between vehicles parallel to road surface).

3.1 Pilot experiment study using stereo camera setup

As a pilot study, two cameras are deployed on a car following a lead vehicle on local roads at speeds between 48–72 km/h and highways at speeds between 80–105 km/h in Atlanta, GA, USA. Figure 2 shows the experimental setup along with the device placements used in our experiment. A color chessboard presenting a Bayer RGB pattern is pasted on the back of the lead car. The chessboard is treated as the equivalent of a static-valued light transmitter. This transmitter setup is maintained identical to the setup used in the vehicle experiments in our prior work[6]. The key update from our prior work, that we highlight and discuss in this paper, is the receiver stereo camera setup with two RaspberryPis and the corresponding analysis of the depth (distance between vehicles) related information.

The transmitter car is followed by a receiver car that is stationed with two RaspberryPi3 cameras. The two

Fig. 2 Experiment setup involving the lead (transmitter from Ref. [6]) and follower (receiver) vehicle. The driving roadways are highway (speeds 80–105 km/h), local road (speeds 40–72 km/h), and parking lot (speeds 8–40 km/h).

cameras are placed at a distance of 12 cm along the horizontal (X) with zero relative height difference. The image view planes of the cameras are aligned parallel to one another. The camera is set to operate at 1920 pixel by 1080 pixel resolution and 30 frames per second. Unless otherwise specified, these are the default camera settings in our experiments.

This new stereo camera receiver setup features two RaspberryPi cameras. The cameras, which are integrated with the RaspberryPi module, are controlled remotely through a secure shell (SSH) and operated (capture image and video) synchronously. Time synchronization is ensured by enabling the network time protocol on the RaspberryPi controllers, and the parallel SSH protocol is used to operate / control the two RaspberryPi at the same time. The two vehicles are fitted with an onboard device (OBD) II vehicular diagnostic monitoring device and an Android smartphone. The OBD-II records the GPS coordinates (latitude and longitude) and car speed. The OBD-II device is paired with an Android tablet through Bluetooth and uses the TorquePro data logging application. The smartphone is stationed on the car's dashboard and records the angular rotation along three axes by using an inertial measurement unit (IMU) sensor logging application. The rotation angles along the X, Y, and Z axes are considered as the pitch, azimuth, and roll, respectively. The frequency of all the sensor measurements is set to 1 Hz on both Android devices. A SLAMTEC Rplidar A3 is used for ground-truth distance measurements. This device is a single-channel LIDAR enabled for 16 000 samples per second with a radius range of 25 m.

The field measurements involved driving the vehicles under different road conditions and driving speeds (a parking lot, local road, and highway). During the experiments, the follower car repeats the same action as the lead car while maintaining a safe driving distance. For example, if the lead car changes lanes, the follower car also changes lanes in the same direction. During this process, the cameras are set to record video footage, while the LIDAR records the distance to obstacles within a 360 degree range of the Z (depth) axis, and the other sensors log the corresponding sensor values. Overall, we collected measurements worth approximately 12 000 image frames and over 10 000 sensor data samples. The motion model is derived from this measurement dataset by using tools for computer vision, probability, and statistical error analysis.

3.2 Experiment results and insights

Consider Δ^{pixels} as the amount of motion of a specific object in the image pixel domain between successive frames. In our experiments, this motion amounts to the movement of the vehicle across frames. Given the camera-intrinsic parameters (L_{fl} is the focal-length and L_{pl} is the pixel-side-length of a pixel and image sensor center)[8], the equivalent amount of motion in world distance units (Δ^{world}) can be computed by using perspective projection theory[9].

$$\Delta^{\text{world}} = \Delta^{\text{pixels}} \frac{depth}{\left(\frac{L_{\text{fl}}}{L_{\text{pl}}}\right)} \tag{2}$$

where $depth$ is the distance between the camera center and the world object of interest (car in our example).

Equation (2) implies that the computation of the relative physical movement of the vehicles in the lateral (X) and longitudinal (Y) dimensions requires quantifying the movement along the Z dimension (or depth). In accordance with computer vision theory, a minimum of two cameras (stereo vision) setup is required to estimate depth by using the stereo correspondence algorithm[10].

In essence, the motion along the Z dimension, or depth, is measured as the spatial separation of the transmitter and receiver cars at a given time snapshot, which is equivalent to estimating the distance between the two vehicles at each time instance. We measure the baseline distance between the two cars by using the corresponding GPS coordinates by applying the haversine distance formula with GPS latitudes and longitudes. The baseline measure of the ground-truth distance between the two cars is obtained by using the synchronized LIDAR distance values.

Stereo vision theory is an alternative to distance measurement in camera depth estimation. Given the stereo camera setup, image frames from the two RaspberryPi cameras are analyzed at matching (using timestamps) time slots.

Stereo correspondence mapping is utilized to match the chessboard vertices on the stereo image pair. Five points are used in the image pairs, and the points correspond to the top left, top right, bottom left, bottom right, and centroid of a virtual box bounding the rectangular chessboard. The distance for each of these five points is computed by stereo vision, and the mode (maximally occurring) of the five distance estimates is recorded.

$$depth = \frac{f \times b}{x_l - x_r} \tag{3}$$

where f is the camera focal length, b is the baseline (distance between the two cameras in one plane), and $x_l - x_r$ is the disparity. In our setup, both cameras are aligned on the X axis. Thus, the baseline and disparity are along the horizontal. The disparity is determined by using the X coordinates of the matched corresponding point pairs.

Figrue 3 shows the distance estimated by using LIDAR and stereo vision for a snapshot from our dataset. The error bar graph illustrates errors in meters in estimated stereo distance compared with the ground distance. On the basis of our comparison between the LIDAR and stereo camera estimates, we observe an error or difference between the two estimates in the order of (absolute values) 1.2 m on average, 1.5 m median, and 6 m maximum. The goal of this analysis is not to propose a novel depth estimation algorithm but to study how appropriate the available methods for distance estimations are in our setup. We observe the following on the basis of our study:

- Upon the manual inspection of the frames with high distance estimates (peaks), we observe that the GPS method is highly susceptible to errors when the vehicle drives close to a bridge (the same applies to a tunnel). Figure 4 shows a snapshot (not shown in Fig. 3) to illustrate the high GPS inaccuracies in general.
- The disparity-based stereo vision estimates of distance deviate significantly when the two vehicles are at oblique angles from one another because the corresponding points may not lie in parallel image planes. Thus, the disparity is no longer applicable.
- The stereo method underestimates distance values in some cases when the cars are very close (in our dataset, the shortest distance between vehicles is 5 m, which is measured by using reference landmarks on Google maps).

4 Visible-Light Backscatter Systems

In our LED–LED and LED–camera setup in various automotive scenarios, both communicating parties need to be powered by external batteries. Such a requirement can limit the use of our setup in cases wherein the asymmetric link solution is favored. "Asymmetric" means that one end is designed to have ultra low power and to be potentially battery-free to reduce the cost of the deployment overhead either through wired back-haul connection or frequent battery replacement. Meanwhile, retroreflectivity appears to be a cost

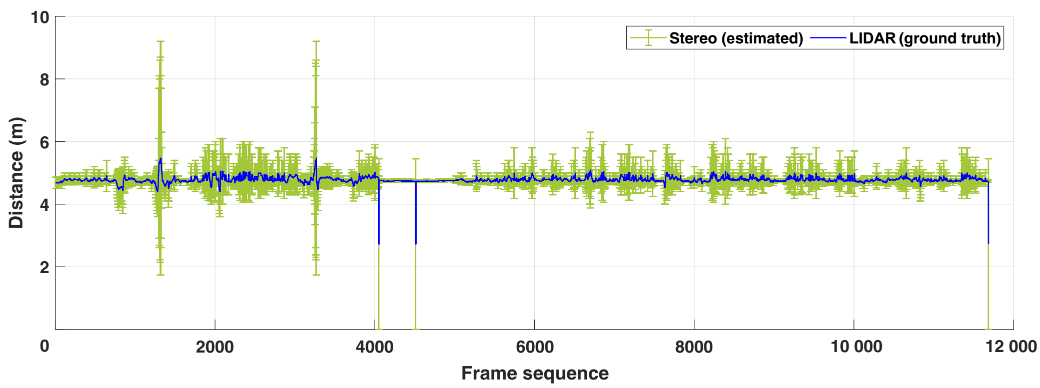

Fig. 3 A snapshot from the dataset to show the comparison between estimated distance between vehicles using stereo vision and the ground truth values (measured using the LIDAR).

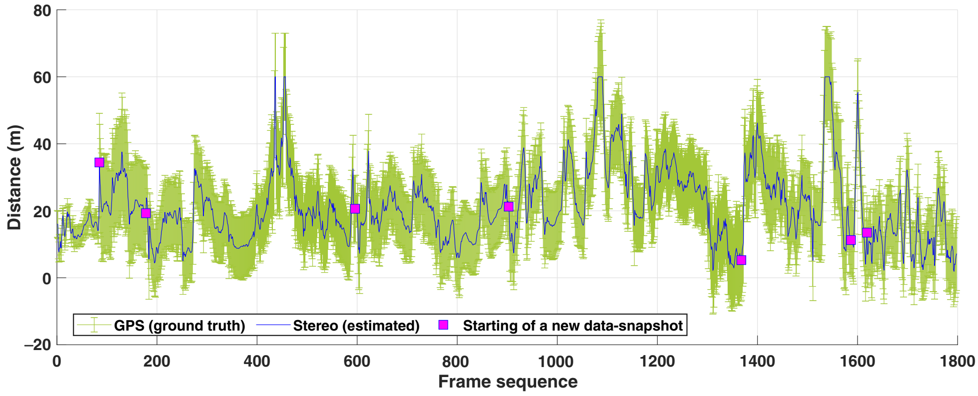

Fig. 4 A snapshot from the dataset to illustrate the disparity in distance between vehicles estimated using GPS values and stereo-estimation.

effective solution that is commonly embedded in today's road infrastructure, from static traffic signs and pavement markings to mobile objects, such as license plates. By reflecting light beams from host vehicles, these retroreflective objects improve their visibility for efficient traffic flow, driving comfort, and road safety in general, especially at night time. Enabling these retroreflective objects to talk to host vehicles in proximity, especially to deliver in-situ dynamic information, such as refined safe speed limits, points of interest, or emergency and help requests, is very exciting.

In our prior work, although we demonstrated the possibility of visible-light backscatter communication in PassiveVLC[11], we did not study how it can be used in the vehicular context. We very briefly describe the PassiveVLC before going into vehicular communications.

PassiveVLC has a reader (ViReader) residing in the lighting infrastructure and a tag (ViTag) for integration into a sensor node. Central to the PassiveVLC design is the retroreflective fabric that bounces light back to the lighting source exactly along its incoming direction. Its retroreflective nature offers two benefits. First, it helps establish an uplink over the same visible-light channel established by the high-power lighting LED, thus avoiding the use of another high-power LED on the weak end and enabling achieving the low-power design goal. Second, it not only allows flexible relative positioning between ViReader and ViTag (in contrast to the symmetric link solution) but also helps concentrate the reflected light from a scattering light source. These two favorable properties render PassiveVLC an effective and efficient visible-light backscatter communication system. At the high level, PassiveVLC works as follows. For the downlink, the LED in ViReader switches on and off at a high frequency (e.g., 1 MHz to avoid perceptible flickering), turning the illuminating light into a communication carrier. Information bits are carried by using a certain modulation method, and the light signals are picked up by the light sensor on ViTag to be decoded. For the uplink, the same carrier is leveraged via reflection. For carrying bits over the reflected light carrier, the retroreflector fabric is covered with a transparent liquid crystal display (LCD) that serves as a shutter, and OOK-based modulation is adopted over the reflected light carrier by controlling the state (pass or block) of the LCD shutter. The modulated reflected light carrier is then picked up by a photodiode on the ViReader for decoding. Specifically, PassiveVLC proposes a trend-based modulation and a miller codec design that, compared with OOK, improves the data rate by eight times to 1 Kbps.

In this paper, we describe our new work to integrate ViReader with vehicle headlights and ViTags with roadside retroreflective infrastructure because they are already installed at every place that needs one. This prerequisite serves as a solid foundation for facilitating massive deployment without extra installation costs.

In this new communication paradigm, (uplink) communication range plays a critical role in that it determines whether we have sufficient time for end-to-end message delivery. More specifically, there are several factors that contribute to the uplink communication range, including LED power P_t, tag size A, and FoV. The design of ViTag consists of a light sensor, a retroreflective fabric, a transparent LCD shutter, and the control circuits while ViReader is a typical VLC device.

As one key metric with the design, We propose a model to describe the link budget analysis. With all the model parameter defined in Table 1), our model counts in all factors of the gains and losses from the transmitter and the visible channel medium (retroreflector, LCD, lens of photodiodes, etc). $G_t \cos\theta$ is the angle distribution of light source which follows the regulations of automobile lightning. The projected area of retroreflector and photodiode is $A_r \cos\beta$ and $G_r \cos\theta$ respectively. The emitted light and retroreflected light each follows the inverse square law, and thus the light illuminance at the position of receiving photo diodes of reader shows as

$$E_u = E_{u0} \frac{P_t}{P_{t0}} \frac{A_r \cos\beta}{A_{r0}} G_t(\theta) \left(\frac{R_0}{R}\right)^2 L_m \left(\frac{R_0}{R}\right)^2 G_r \cos\theta \tag{4}$$

which increases proportionally with LED power P_t and retro reflector area A_r while decreases with distance at a speed of R^{-4}.

We also conducted experimental measurements to validate the model. In our measurements, the noise remains constant under specific temperature, given $N(T)$. Experimental result (Fig. 5) shows that SNR decreases with distance at speed of $R^{-4.2}$ which matches the theoretical value R^{-4}. A simple positioning algorithm using linear regression between distance and SNR information has an accuracy of 2.6 m with results in Fig. 5.

Table 1 Parameters in link budget analysis.

Symbol	Parameter
P_t	Transmission power of the light source
G_r	Directional gain of photodiode
L_m	Loss through LCD modulator
A_r	Area of retroreflector
R	Distance between tag and reader
θ_0	Field of view (FoV)
θ	Irradiation angle
α	Observation angle
β	Incidence angle

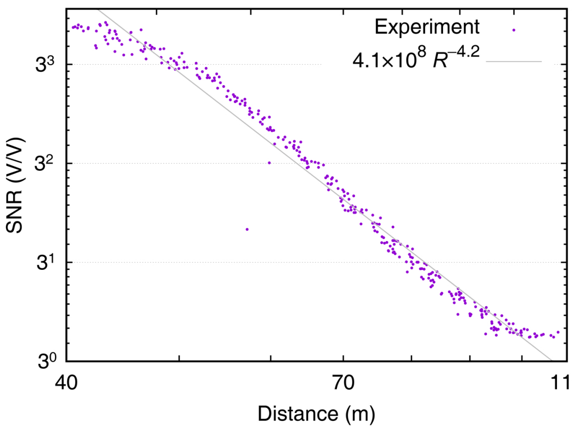

Fig. 5 SNR with-distance. We show both the scatter plot of measured values and the fitting.

With the SNR threshold for effective decoding as $\mathrm{SNR}_{\mathrm{th}}$, which varies under different transmission rates, the working range of uplink $R_{\max}$ can be calculated from Eq. (4) given the signal-to-noise ratio $\mathrm{SNR} = E_u / N(T)$ and the light source distribution $G_t(\theta) = \exp\left(-\tan^2\theta / \tan^2\theta_0\right)$.

$$R_{\max} = R_0 \sqrt[4]{\frac{E_{u_0}}{\mathrm{SNR}_{\mathrm{th}} N(T)} \frac{A_r \cos\beta}{A_{r_0}} \mathrm{e}^{-\frac{\tan^2\theta}{\tan^2\theta_0}} L_m G_r \cos\theta} \tag{5}$$

To double the working range $R_{\max}$, one would have to either increase the area of tag by 16 times or increase the LED power by 16 times. Anther method to improve working range would be reducing FoV θ_0 as well as increasing directional gain of photodiode G_r. However, it limits the working range of θ which means accurate alignment is needed for communications.

Our work can be immediately useful for road safety enhancement. By equipping the targets of interests with this technology, the car headlights take initiatives to send polling information over the light beam and retrieve the response from the reflected light carrier for object recognition, information retrieval, etc. This new communication mechanism is more effective than computer vision approach, especially in dark environments or at night.

There are a few practical considerations in deployment. For example, how far can my car talk to a remote tag, in what range and distance? How much data can I receive back? Does my driving speed matter? To answer these questions, the following key factors need to be considered carefully when adapting the PassiveVLC technology into the context of vehicle-to-infrastructure scenario. In real deployments, there are limitations (size of road sign, output power of headlight) and trade-off (larger tag size can collect more energy for communication at a longer distance, but at the same time needs more energy to be harvested; faster data rate comes at a cost of reliability; FoV of the headlight balances the communication angle and distance). Based on our link budget model analysis of the uplink/reflection link, with a normal 50 W headlight (8 degree of FoV and 10 W with 20% luminous efficiency), it can detect a tag sized 5000 cm^2 (a normal road sign) 30 m away at the rate of 240 bps.

5 Additional Application Examples

Along with the increasing demand for mobile data for 5G, VLC technology has evolved rapidly over the past few years, especially from classic indoor communications to outdoors. The public outdoor lighting infrastructure (such as street lights and traffic lights) is undergoing rapid change. Numerous cities and towns across the world are replacing conventional incandescent lamps with LED lighting. In the City of LoS Angles alone, over 140 000 incandescent lamps have been replaced with an energy savings of over 10 million US dollars per year[12]. As a result, combinations of various devices have become available for VLC-based vehicular networking, including vehicle lights and cameras, backscatter devices, traffic lights, and street lamps as roadside units (RSUs). In addition, these LED-based RSUs can be used for signaling and broadcasting a wide range of information encompassing safety to traffic and beyond.

Platooning is another interesting application of VLC devices. Given that VLC requires less frequent channel estimation and results in an overall more stable link than RF, it is particularly relevant to platooning and cooperative adaptive cruise control (C-ACC) (European Telecommunications Standards Institute (ETSI)[13]), which require continuous and stable communication links. The inherently directional motion of vehicles in a platoon will only strengthen the VLC link.

Last but not least, VLC devices can be instrumental in supporting emerging applications, such as autonomous driving. The vision sensing of the environment is critical to autonomous driving. While specific functions, such as generating blind spot warnings, lane tracking, and traffic sign recognition, are already available, the stringent demands of autonomous driving call for additional support for the robust estimation of the vehicle itself and the reconstruction of the surrounding environment. Camera-based and backscatter systems will play important roles in these applications, perhaps through robust and efficient visual simultaneous localization and mapping techniques.

6 Related Work

6.1 LED and camera based systems

There is an increasing trend in interest for the use of VLC for automotive applications. Over the last decade, there has been much interest in vehicular VLC system design and there have been a diverse set of research works conducted in this area thus far. VLC-based vehicular networking is a widely researched topic in the vehicular communication and networking communities[3–5]. Over the last few years, the interest in vehicular VLC has expanded to overall vehicular system designs and research explorations[14–18] have been cutting across different layers of the open system interconnection (OSI) stack. Even with such active research works in this area, the practical realization of vehicular VLC has been very difficult owing to open challenges presented by both the mobility of vehicles and communication constraints of VLC. In particular, camera-based VLC is limited in frame rate and thus only can work for very low data rate applications. Photodiode receivers need to incorporate robust signal tracking mechanism to sustain high SNR during mobility. Prior works have largely focused on specific improvements in a micro level, for example, in select modules of the vehicular system. Also, the theoretical and simulation estimates from prior works are yet to be validated in practice as setting up experiments representative of the exact scenarios and settings as in the analysis is challenging in reality. In this paper, we particularly target those practical challenges, and showcase preliminary works that set foundation for conducting experiments under the practical limitations. Additionally, prior works have also been very selective of how the VLC system can be useful in the automotive context and there is no clear baseline agreement or standard.

6.2 Passive VLC

Passive VLC has become a research front that leverages specially-designed devices for low-power VLC access. It can be categorized into two types depending on the modulator: the one with configurable modulators and the one with immutable modulators. Configurable modulators can be programmed to dynamically control the property of incident light. LCD is the most widely-adopted modulator and it has been extensively researched[11, 19–22]. Digital micro-mirror devices have also been exploited as modulators to achieve a faster link (up to 80 Kbps) with higher price (tens of dollars) and power consumption ($\approx$ 50 mW)[23]. In contrast, immutable modulators (e.g., a printed barcode) with different reflective properties on the “black” and “white” area show the unique signal pattern to a single photodiode. Therefore, a moving illuminated immutable modulator can be decoded by a nearby photodiode. Research progress[5, 24] has shown that such modulators achieve data rates of up to 130 bps and a communication range of 4 m. However, the immutable nature of such modulators allows limited application scenarios such as vehicle identification.

7 Conclusion

In this article, we have discussed some fundamental research issues concerning alternative devices and systems for VLC-based vehicular networking. We have shown that as vehicular networking applications become more complex, alternative devices play increasingly important roles in the system design process. Various VLC devices and systems are examined in this article, we also present our experimental explorations in multiple camera based and backscatter based systems, and propose physical models for analysis and experimental data interpretation.

Acknowledgment

This research was supported in part by the Charles A. Dana Foundation through the Dana Research Professorship program at Trinity College.

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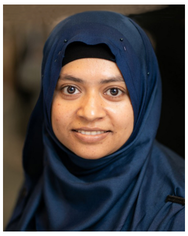

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