Enabling Vehicular Visible Light Communication (V^2LC) Networks

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ABSTRACT
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 properties in enabling vehicular VLC (V^2LC) networks as follows. We first develop a custom V^2LC research platform on which we experimentally evaluate the feasibility of a V^2LC 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 V^2LC 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 V^2LC'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), V^2LC 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, V^2LC can still have a significant number of successful transmissions by opportunistically using dynamic inter-vehicle gaps.

Categories and Subject Descriptors
C 2.1 [**Computer-Communication Networks**]: Network Architecture and Design—Wireless Communication

General Terms
Measurement, Performance, Reliability, Experimentation, Design

Keywords
Visible Light Communication, Mobility, Vehicle Safety, Vehicular Visible Light Communication

1. INTRODUCTION
Visible Light Communication (VLC) employs lighting sources as transmitters and utilizes photodiodes as receivers. This communication paradigm has drawn interest from both research and industrial communities, e.g., the Visible Light Communications Consortium [23], the IEEE task group, 802.15.7 [1], standardizing VLC for personal area network etc. The broad interest originates from the advantages VLC brings to data rate (up to 500 Mbps thus far [20]) and energy efficiency due to LEDs.

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In this paper, we examine the two key elements necessary for the realization of *vehicular VLC (V^2LC)* networks: *(i)* the feasibility of realizing V^2LC networks in working conditions under constraints posed by noise and interference sources and *(ii)* the capability of V^2LC network services to satisfy the performance requirements of vehicular applications. In particular, we make the following contributions.

First, we identify and classify a set of required V^2LC services, namely, vehicle-to-vehicle broadcasting, limited vehicle-to-vehicle broadcasting, infrastructure-to-vehicle broadcasting, vehicle-to-infrastructure anycasting, and vehicle-to/from-infrastructure unicasting. Furthermore, we develop a V^2LC prototype research platform employing three principles[1]. First, we use optical and analog techniques to increase the prototype's robustness to noise. Second, we use off-the-shelf components and achieve a feasible form factor for a vehicular environment. Third, we provide a flexible programming environment for algorithm implementation.

Second, we evaluate the feasibility of V^2LC networks to operate in working conditions via experiments with the prototype. We find that V^2LC is resilient against diurnal noise sources (i.e., sunlight) with the exception of direct exposure to the sun. This exception can only occur when vehicles have unobstructed direct line-of-sight to the sun during sunrise and sunset (i.e., when the sun makes a small angle to the horizon and falls into the VLC receiver's 12° field-of-view angle). Additionally, we find that V^2LC is robust to nocturnal noise generated by idle VLC transmitters as well as legacy lights with no data transmission abilities. When evaluating V^2LC's performance under interference from other active VLC transmitters, we determine that the VLC receiver's field-of-view angle yields a spatial binary property on the probability of successfully receiving signals. Last, we evaluate the ability of V^2LC to operate in full-duplex mode. We characterize the feasibility of full-duplex mode in relation to multipath effects created by reflective and scattering surfaces in vehicular environments and experimentally show that such effects exist only in very short distances, e.g., within 1.5 m.

Third, we examine the ability of a V^2LC system to provide the necessary network services to satisfy vehicular applications' requirements. To this end, we perform a large-scale simulation to evaluate V^2LC with respect to each of the three network services. For the simulations, we modify ns-2 [16] based on our experimental characterization of V^2LC network links, e.g., the VLC receiver's unique spatial binary property on the success of signal reception. Our results reveal two key findings. First, V^2LC takes advantage of a large number of available paths (with paths found via multihop broadcasting instead of routing protocols) to reach vehicles in dense vehicular traffic conditions. The large number of

[1] The research presented in this paper utilizes one of the VLC test platforms developed at Intel solely for research purposes, and the results presented here do not represent Intel's business strategy and direction.

paths results from V^2LC's high spatial reuse, and it overcomes the effects of packet collisions. Second, in the presence of a visible light blockage in vehicular traffic, V^2LC can opportunistically enable successful transmissions using the inter-vehicle gaps that are caused by the dynamic vehicular movements.

The rest of the paper is structured as follows. We present background information on VLC and the vehicle safety applications in Section 2. We introduce the network services and present the V^2LC research platform we developed in Section 3. We then use the prototype to experimentally investigate V^2LC links' robustness to visible light noise and interference in Section 4. We evaluate V^2LC's performance in each of the three network services in Section 5. We discuss prior work related to V^2LC networks in Section 6 and conclude in Section 7.

2. BACKGROUND

2.1 VLC

VLC uses the visible light spectrum (between 400 THz and 790 THz) as the communication medium. A VLC system consists of VLC transmitters and receivers, which are physically separated and functionally different. VLC transmitters modulate the intensities of lighting sources, e.g., LEDs, at such high frequencies that human eyes cannot perceive any difference in lighting compared to that when there is no modulation. As a result, VLC transmitters can be used for lighting and data communication simultaneously. VLC receivers consist of photodiodes either as stand-alone elements or in the form of an image sensor to receive information from varying lighting intensities.

2.2 Vehicular Applications

The Vehicle Safety Communications Project specifies vehicle safety applications and their performance requirements. Eight out of more than 75 applications were identified as high-priority and representative in terms of requirements in network services: traffic signal violation warning, curve speed warning, left turn assistant, stop sign movement assistant, lane change warning, cooperative forward collision warning, pre-crash sensing, and emergency electronic brake lights [21].

Reachability and latency are the two metrics specified for the eight applications' requirements in network services. Reachability is the ratio of the number of vehicles that can be successfully reached to the total number of vehicles that are targeted in the applications. All eight applications target 100% reachability. Latency is defined as the maximum time span during which a vehicular application needs to successfully deliver information to the targeted vehicles. All of the eight applications require a maximum latency of 100 ms except the curve speed warning and pre-crash sensing applications. The curve speed warning application requires 1000 ms latency, while the pre-crash sensing application requires 20 ms latency.

3. V^2LC SERVICES AND RESEARCH PLATFORM

In this section, we describe a V^2LC network and identify the network services V^2LC needs to provide for vehicle safety and internet access applications. We next present the principles on the design of the custom V^2LC research platform we developed and its implementation components.

3.1 V^2LC Network

A V^2LC network consists of vehicles as mobile nodes and infrastructure lighting sources as fixed gateways. Both the mobile nodes and infrastructure lightings, such as traffic lights, can be equipped with multiple transmitters and receivers which can operate simultaneously. As an example of the placement of VLC transmitters and receivers, the headlights and brake lights of a vehicle can serve as transmitters, and multiple receivers can be mounted around the vehicle. Figure 1 illustrates a V^2LC network in which vehicles can either directly communicate with the gateway infrastructure lightings or reach the gateways using other vehicles as relays. The gateways are connected by an infrastructure network, which is further connected to the internet. The information related to the vehicle safety applications is contained within the infrastructure network and vehicles. Depending on the nature of the application, it may involve none, one, or more gateways. For internet access applications, over single or multiple hops, vehicles are connected to the internet via the infrastructure network.

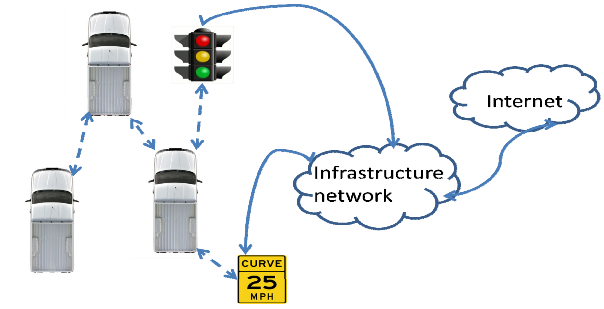

Figure 1. An illustration of a V^2LC network

3.2 V^2LC Services

Here, we identify and classify the V^2LC network services required to support the full spectrum of vehicular applications. In the vehicle-to-vehicle broadcasting, we stipulate that each vehicle acts as a relay and forwards data packets from all of its VLC transmitters following a set of rules to prevent unnecessary broadcast flooding; e.g., there is a time-to-live limit on each packet, and a packet is forwarded only once by each vehicle. This network service maximizes the chance that information is disseminated quickly and reliably among a cluster of vehicles. In vehicle safety applications, infrastructure lightings that serve as either packet sources or packet relays need to broadcast information to all targeted vehicles in range. In the infrastructure-to-vehicle broadcasting service, we stipulate that after infrastructure nodes broadcast information to vehicles, the vehicles do not forward the packets or send information back in order to avoid packet collisions at the infrastructure nodes. We also specify that vehicles anycast information to infrastructure nodes over single hops; meanwhile, the infrastructure nodes do not send information to the vehicles to avoid packet collisions.

3.3 V^2LC Research Platform

Transmitting and receiving data in the visible light spectrum require specialized hardware, which is not commercially available. Consequently, we developed a custom research platform to investigate the networking properties of V^2LC. In the development (Figure 2), we follow three design principles: robustness to noise, feasible form factor in vehicular environments using commercial components, and flexibility in protocol implementations.

First, we increase the platform's robustness to noise using optical and analog techniques. For the VLC receiver, we mount the photodiode inside of a case with an aperture, in front of which we place a 4x zoom optical lens. As a result, the receiver has a 12^o field-of-view angle, i.e., the largest angular extent that can be seen at the receiver. This field-of-view angle limits the amount of visible light noise shed onto the photodiode. The photodiode outputs electrical signals corresponding to the amplitude variations in lighting intensity. In order to reduce noise in the electrical signals, we implement a bandpass matched filter on analog circuits that can process the photodiode's signals in real time. We note that the response of the photodiode becomes nonlinear when saturated. When the photodiode is not overdriven, we verified that the spectral energy of the visible light noise was outside of the desired signal bandwidth.

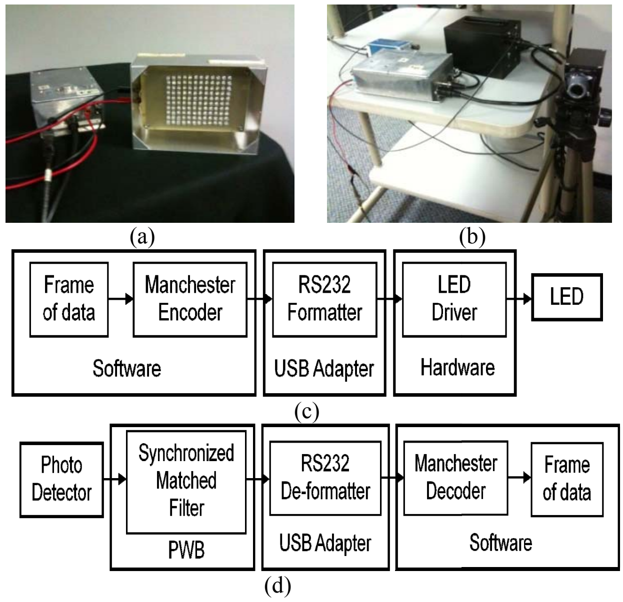

Figure 2. VLC transmitter, picture (a) and block diagram (c); VLC receiver, picture (b) and block diagram (d)

Second, we use off-the-shelf LEDs and photodiodes to construct the research platform that has a feasible form factor in vehicular environments. The VLC transmitter consists of 120 white LEDs, each having a dissipation power of 120 mW. The transmitter's half-angle (i.e., the maximum divergence of a light beam) is 50^{o}, and the form factor of the transmitter is 8" x 11". The design values lie in the range that is expected for V^2LC transmitters, such as vehicle lights and traffic lights. The VLC receiver utilizes a commercial photodiode with a spectral response range from 350 nm to 1100 nm. The design choice is again within the range expected for future low-cost V^2LC receivers that use mass produced photodiodes.

Third, we use MATLAB for flexible implementations of the modulation and coding schemes in software settings. As 802.15.7 [1] specifies, the transmitter uses on-off keying amplitude modulation, and we implement Manchester encoder and decoder at the transmitter and receiver, respectively. The modulation frequency is centered at about 115 kHz and resides in a spectral band from about 20 kHz up to about 210 kHz. We can achieve a data rate of 100 kbps. We note that different applications require a broad range of minimum data rates. While this paper's scope does not include constructing high speed VLC links, the data rate of 100 kbps is sufficient for studying vehicle safety applications.

4. FEASIBILITY OF V^2LC UNDER WORKING CONDITIONS

In this section, we use the V^2LC research platform to investigate the feasibility of V^2LC networks under working conditions. We experimentally examine V^2LC links' resilience to visible light noise and interference as well as V^2LC's capability in operating in full-duplex mode. In our experiments, we use the packet delivery ratio (PDR) as the performance measure, i.e., the ratio of the number of packets successfully received at the receiver to the total number of packets transmitted over the air. For each experiment, we repeat it 30 times and report average results. We note that for experiment values of 0% and 100% PDR, we have consistently observed these values in all repetitions of the experiments.

4.1 Robustness to Visible Light Noise

Vehicular environments are expected to encounter a high level of ambient visible light noise. Here, we evaluate the robustness of V^2LC network links to both diurnal and nocturnal visible light noise. The most prominent source of daytime noise is sunlight; in contrast, the expected sources of nighttime noise include idle VLC transmitters of other vehicles and infrastructure lightings as well as any lighting source with no data transmission capability.

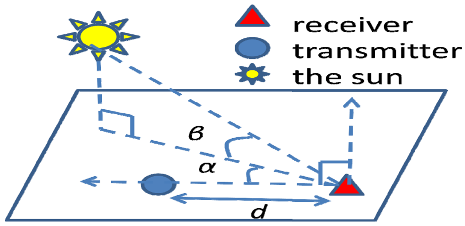

Figure 3. Experiment setup in the dominant diurnal noise scenario

Dominant Diurnal Noise Scenario. In this scenario, we investigate V^2LC's robustness to the dominant daytime noise, i.e., sunlight. There are two key cases: when the sun out of the receiver's field-of-view angle and when the sun directly within the angle. This categorization is the result of the fact that the receiver's field-of-view angle is relatively narrow, and the sun is not always directly within the field-of-view angle.

Figure 3 depicts the experiment setup for the dominant diurnal noise scenario. The angle α is the azimuth angle of the receiver to the sun, whereas the angle β is the elevation angle of the receiver to the sun. The distance between the transmitter and receiver is denoted by d. In the experiment, we vary α and β (within the range allowed by the test environment) to profile the impact of the sun with respect to its position. We also vary d to measure the achievable transmission range in the presence of sunlight.

Table 1. V^2LC robustness to the dominant diurnal noise

d	α	β	PDR
5.4 m	0^{o}	15^{o}	100%
5.8 m	30^{o}	45^{o}	100%
7.5 m	10^{o}	30^{o}	100%
16.8 m	10^{o}	10^{o}	100%
(16.8, 101] m [1]	10^{o}	10^{o}	100%
>101 m [1]	10^{o}	10^{o}	0%

[1] Due to the lack of environment space, d is obtained by reducing the transmission power of the VLC transmitter and calculated using the free space propagation model.

Table 1 summarizes the experimental results for the case that the sun is not directly in the receiver's field-of-view angle. In this scenario, the sun intensity is higher than that in the second case since it usually takes place during the day instead of during sunset and sunrise. The result shows that the packet delivery ratio is 100%

for all values of α and β with d less than 101 m. It indicates that despite the reflective and scattering surfaces in the surroundings, our VLC receiver with a 12^o field-of-view is robust to highly ambient daytime noise. While we note that the transmission range depends on the transmission power and is system-specific, we make the observation that using this V^{2}LC platform, the packet delivery ratio remains 100% for d less than 101 m. Moreover, the transmission range suffices regarding vehicular applications as these applications operate when vehicles are in the vicinity of one another.

For the second case when the sun falls directly in the field-of-view angle, we remove the optical lens from the receiver, which increases the field-of-view angle from 12^o to 50^o. Since we cannot have a clear line-of-sight to the sun during sunset and sunrise due to surrounding buildings, it is equivalent to increase the field-of-view angle for the sun to be directly seen at the receiver. Under such conditions, the packet delivery ratio is reduced to 0% because the energy of the direct sunlight saturates the photodiode. To increase robustness in this scenario, we can narrow the field-of-view angle by increasing to a higher lens zoom. Further, we can make the field-of-view angle adaptive by dynamically changing the lens zoom. Nonetheless, this case requires a clear line-of-sight to the sun, which also needs to be within 12^o of the horizon, and therefore occurs infrequently.

Dominant Nocturnal Noise Scenario. In this scenario, we evaluate V^{2}LC's robustness to two representative nighttime noise sources: an LED light source of 9.6 W and a halogen light bulb of 60 W. The LED source represents idle VLC transmitters whereas halogen light bulbs are often installed in automobiles and street lights, and exemplify lighting sources with no data transmission capabilities that generate visible light noise. Both sources emit light in the spectral response range of the VLC receiver's photodiode. Also, with LEDs' capabilities in saving power, many vehicle lights and infrastructure lights with halogen light bulbs are expected to be replaced with LEDs, e.g., [5].

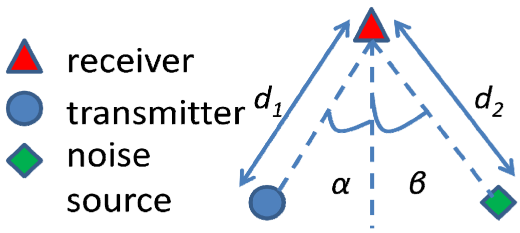

Figure 4. Experiment setup in the dominant nocturnal noise scenario (for the purpose of illustration, we depict point light sources; in reality, they emit light with an angle)

We show the experiment setup in Figure 3. In the illustration, the angle α and distance d_1 are the angle and the distance between the transmitter and the receiver, respectively. Similarly, the angle β and distance d_2 are the angle and the distance between the noise source and the receiver, respectively. In order to isolate the effects of nighttime noise from daytime noise (i.e., sunlight), we conducted these experiments in the lab environment with shades drawn to block sunlight. We fix d_1 and α to be 2 m and 3^o, respectively. We also fix β to be 3^o; i.e., both the transmitter and the noise source are in the receiver's filed-of-view angle. We vary d_2 to change the noise level at the receiver.

Table 2 shows that with the LEDs as the noise source (i.e., an idle VLC transmitter), the packet delivery ratio remains at 100% for all values of d_2. In this case, the results demonstrate that the performance of the VLC receiver is independent of the level of the nighttime noise generated by idle VLC transmitters. However, when the halogen light bulb with a significantly higher dissipation power is the noise source, the packet delivery ratio is 100% for d_2 greater than 5 m, and it decreases to 0% for d_2 less than 5 m. The reduction in the packet delivery ratio suggests that the VLC receiver's photodiode can also be saturated by a nighttime noise source, similar to what happened in the dominant diurnal noise scenario. However, the saturation due to the halogen bulb noise can be eliminated by increasing the distance between the noise source and the receiver. The separation distance needed, shown to be 5 m, is very short considering inter-vehicle distances in traffic. Additionally, we repeated the experiments with the noise sources out of the receiver's field-of-view angle (i.e., $\beta > 6^o$), and we observed that for all values of d_2, neither LEDs nor halogen bulb has any effect on PDR. Therefore, in V^{2}LC networks, the VLC receiver is also robust to the nocturnal noise generated by lighting sources with no data transmission capabilities.

Table 2. V^{2}LC robustness to the dominant nocturnal noise

d_2	Nocturnal noise source	PDR
0.1 m	LEDs	100%
>0.1 m	LEDs	100%
[0.1, 5] m	Halogen	0%
>5 m	Halogen	100%

Findings. Noise can affect V^{2}LC's performance by saturating the photodiode on our custom platform. This happens only if the noise source falls directly in the field-of-view angle of the receiver, and the noise power is significantly high, e.g., direct exposure to sunlight and close range of 5 m within a halogen light bulb. With increasing distance between the noise source and receiver as well as decreasing field-of-view angle, links become completely robust to both diurnal and nocturnal noise, e.g., sunlight and idle LED lights.

4.2 Field-of-View Angle, Interference, and Collisions

The receiver's field-of-view angle determines the largest angular extent from which the light is viewed at the receiver. Therefore, this angle has an impact on the link establishment between the transmitter and the receiver. For an interferer, we use a VLC transmitter actively sending modulated signals. This is in comparison to the idle VLC transmitter as a nocturnal noise source in Section 4.1. Here, we first examine the effects of the field-of-view angle on the success of communication between the transmitter and receiver with no interferer. Then, we investigate the field-of-view angle's effects on the collision condition for two packet transmissions from the transmitter and interferer.

Effects of Proximity of Interferer to Receiver Scenario. In this scenario, we examine the effects of the interferers being in and out of the receiver's field-of-view angle on the established link between the transmitter and the receiver. The experiment setup is similar to the one in Figure 3 except that we replace the noise source with an active VLC transmitter as the interferer. We keep d_1 and α constant at 2 m and 3^o, respectively. We conducted this scenario's experiments in-lab. We first vary d_2 and β with the interferer out of the receiver's field-of-view angle, i.e., $\beta > 6^o$ and observe that the packet delivery ratio is 100% for all values of d_2 and β. The result is expected because we find that the transmitter needs to be in the receiver's field-of-view angle in order to establish a link. This link establishment requirement also applies to the interferer and the receiver. Thus, when the interferer is out of the field-of-view angle, the receiver cannot hear any modulated signal from the interferer despite its position, and the interferer has no impact on the communication between the transmitter and the receiver.

We then locate the interferer in the receiver's field-of-view angle and keep β constant at 3^o; i.e., both the transmitter and the interferer are in the filed-of-view angle, and two data transmissions are now incident at the same receiver. In the experiment, we vary only d_2 to change the power level of the interference at the receiver. Table 3 shows that when the interferer is less than 100 m away, the receiver cannot successfully receive from the transmitter; i.e., the packet delivery ratio is 0%. When the interferer is more than 100 m away, the packet delivery ratio is 100%. We measure the SIR required for successful transmission to be over 280,000. Recall that the transmission range of the VLC transmitter is measured to be 101 m in Section 4.1. Hence, we can conclude that as long as the interferer is in the receiver's field-of-view angle, and the receiver is in the interferer's transmission range, it will be impossible for the transmitter and the receiver to communicate. We note that the on-off keying modulation used by the VLC transmitters is extremely sensitive to interference as overlapping signals can cause 0s to be detected as 1s. With use of a different modulation scheme, the results may be different. We also observed that as soon as the interferer moves within the receiver's field-of-view angle, the packet delivery ratio drops to 0% when keeping d_2 at 2 m and varying β.

Findings. (*i*) The field-of-view angle of the VLC receiver has a spatial binary indication on the success of transmissions because of the reception area's sharp boundaries; e.g., a spatial shift in a few centimeters moves the transmitter out of the field-of-view angle (12^o), and the packet delivery ratio sharply drops from 100% to 0%; (*ii*) When the interferer is out of the receiver's field-of-view angle, the communication is always successful regardless the interferer's position. Further, a small field-of-view angle significantly limits the amount of interference at the receiver.

Table 3. When the interferer in the field-of-view angle

d_2	PDR
[1, 10] m	0%
(10,100] m[1]	0%
>100 m[1]	100%

[1] The distance between the interferer and receiver, d_2, is also obtained by reducing the transmission power, similar to d in Table 1.

4.3 Full-duplex Mode Feasibility

The VLC transmitter and receiver's angular directionality along with the physical separation between the two entities yields a potential for V^2LC's operation in full-duplex mode. Compared to half-duplex mode, full-duplex has the ability to increase throughput and decrease delay. However, surrounding surfaces can reflect and scatter transmitted signals in the visible light spectrum to create multipath effects which can hinder full-duplex communication. For example, for a pair of co-located receiver and transmitter, the transmitter's signal may be reflected and scattered and appear as interference at the receiver. Here, we explore the multipath effects on the VLC link, which is essential to establish V^2LC network links' operation in full-duplex mode.

Reflection and Scattering Scenario. In vehicular environments, the main reflective and scattering objects are the surfaces of vehicles within the receiver's field-of-view angle, including their painted bodies, glass windows, and plastic covers. We use the experimental setup shown in Figure 4 to investigate the impact of multipath effects created by the vehicle surfaces on V^2LC's full-duplex operation. A vehicle was placed in front of a pair of co-located VLC transmitter and receiver. The distance between them is denoted by d. The transmitter and the receiver are kept 0.1 m apart, and we vary the distance, d. We conducted this set of experiments between 2 p.m. and 3 p.m. outside an entrance to an office building.

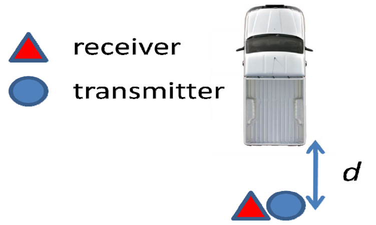

Figure 5. Experiment setup in the reflection and scattering scenario

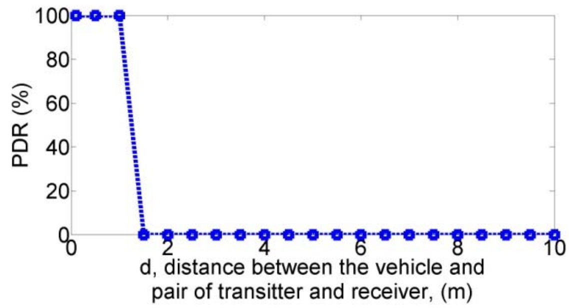

Figure 6. Multipath effects on V^2LC full-duplex mode

Figure 6 shows the packet delivery ratio as a function of d. A packet delivery ratio of 100% means that the receiver is able to receive from the transmitter because of the reflection and scattering caused by the vehicle parked in front. The results show that full-duplex operation is not feasible for d less than 1.5 m because the transmitter's signal appears as interference at the receiver, and this interference will cause packet losses as found in Section 4.2. On the other hand, a packet delivery ratio of 0% means that the receiver cannot receive from the transmitter, and the multipath effects have diminished. As a result, full-duplex operation is feasible for d greater than 1.5 m. Considering inter-vehicle distances in traffic, such a small separation always exists to allow full-duplex communication. This short distance (< 1.5 m) results from the fact that vehicles as whole entities are highly reflective rather than scattering because of their smooth surfaces. Little energy is scattered in all directions, and most of the signal's energy is reflected. Further, with an approximate 0^o reflection angle, most of the reflection is directly towards the transmitter instead of the receiver because of their 0.1 m separation distance. As a result, only a small amount of reflected and scattered signal can cause interference at the receiver, and this small amount of interference only exists within a short distance. We note that in this experiment, the receiver was moved to steer towards the reflection of the transmitter on the surface of the vehicle. In normal conditions, the receiver does not target the reflection of the transmitter, which results in reduction of interference at the receiver. In that case, multipath effects exist in significantly shorter distances than 1.5 m.

Findings. The reflected and scattered transmitter's signal can only fall in the receiver's field-of-view angle in short distances, e.g., 1.5 m while aiming the receiver at the transmitter's reflection, and does not cause interference in long distances, e.g., inter-vehicle distances in traffic. Therefore, the multipath effects are only strong in short distances and do not hinder V²LC's operation in full-duplex mode.

5. CAPABILITY OF V²LC IN PROVIDING NETWORK SERVICES

In this section, we use simulations to evaluate V²LC's capability to provide the three network services introduced in Section 3.

5.1 Evaluation Methodology and Parameters

Vehicle Clusters in Traffic. Previous research, e.g., [10], has shown that travelling vehicles form a number of co-existing, non-connected clusters at a given instant. In our evaluation, we choose the size of the vehicular network to one vehicle cluster for two reasons. First, when considering vehicle safety applications, only vehicles in the same cluster are potential communication targets because they are in the vicinity of one another via single or multiple hops. At any moment, vehicles in one cluster are considered physically distant from those in another cluster by definition. Second, the communication between one vehicle cluster and another vehicle cluster has already been studied in delay tolerant network applications, e.g., [14], but this type of communication is not suitable for vehicle safety applications due to stringent latency requirements.

Inter-Vehicle Distance. The inter-vehicle distance (or equivalently, the vehicle density) reflects different traffic conditions, and it has an impact on the performance of vehicular networks. Thus, we examine V²LC's performance in traffic conditions with different average inter-vehicle distances. The average inter-vehicle distance is defined as the mean distance between one vehicle and the next vehicle in the same lane. In [22], the U.S. Transportation Research Board uses this distance as one criterion to categorize traffic conditions measured by Level-of-Service, i.e., a qualitative measure describing operational conditions within a traffic stream. Table 4 details Level-of-Service with its corresponding inter-vehicle distances, frequent occurrences, and abilities to absorb traffic accidents.

Table 4. Level-of-Service for traffic conditions

Level-of-Service	Inter-vehicle distance range[1]	Frequent occurrence examples	Ability to absorb vehicle incidents
A	> 160 m	Rural areas	Fully absorbent
B	101—159 m	Rural highway	Absorb minor incidents
C	67 — 100 m	Urban highway	Partially absorb minor incidents
D	50 — 66 m	Urban highways peak hours	Cause short queuing
E	35 — 49 m	Roadway in large urban areas	Cause long queuing
F	< 35 m	Traffic jam	Breakdowns

[1] Inter-vehicle distance ranges are for freeways with speed limit of 75 mph. They vary for different types of roads. However, the variations are negligible compared to the sizes of ranges.

In graphs with the average inter-vehicle distance as the independent variable, we repeat the experiments 30 times and plot data points from every experiment onto the graphs. Due to the randomized vehicle movements, the average inter-vehicle distances, in contrast to time, are not directly set but rather determined. We observed that at a particular time instant, the average inter-vehicle distances in the 30 experiments vary by ± 1%.

Traffic Scenario Generation. We use the Freeway model in the IMPORTANT framework [3] to generate vehicle movements that are ported to ns-2. This tool allows us to generate realistic vehicular movements by parameterizing settings such as speed limit and vehicle acceleration. Due to the limitations of the IMPORTANT framework, traffic scenarios cannot be generated with an average inter-vehicle distance below 6.6 m. However, we make the observation that for average inter-vehicle distances less than 6.6 m, the vehicles are not very maneuverable in traffic, and therefore their relative positions to one another remains approximately the same. Based on this observation, we conducted the same set of simulations in the following sections for static scenarios with inter-vehicle distance smaller than 6.6 m. The results were similar to those obtained in the mobile simulation scenarios when vehicles are in close range of one another.

MAC Protocol. For simplicity, we use an ALOHA-based MAC protocol. We implement the MAC in ns-2 in which a transmitter waits a random amount of time before sending a packet, but does not carrier sense nor reserve the medium. The duration is uniform between zero and the ten times the packet transmission time. Acknowledgements are used only for unicast. Additionally, we implement the field-of-view angle's spatial binary property and full-duplex mode discussed in Section 4.2 and Section 4.3, respectively. Our node model enables four co-located pairs of transmitters and receivers on each vehicle's four corners, and it has a fine-grained geometric granularity in identifying vehicles' being in and out of the field-of-view angle and visible light blockage due to vehicles' physical structures.

Table 5. IMPORTANT (a) and ns-2 (b) parameters

IMPORTANT Parameters	Values
Number of vehicles	30
Acceleration	[-3, 3] m/s^2
Number of lanes	3
Vehicle length	4.5 m
Vehicle width	1.5 m
Lane width	2.5 m

(a)

ns-2 Parameters	Values
Half-angle	50°
Field-of-view angle	12°
Packet size	481 bits[1]
Data rate	100 kbps
Transmission range	101 m

(b)

[1] A representative value specified by [21].

Simulation Parameters. Table 5 lists the parameters of the Freeway model in the IMPORTANT framework and ns-2 for the vehicle-to-vehicle network scenario. The vehicle-to-vehicle scenario is used for the first two network services presented later in the section. For the last three network services that operate in the vehicle-to-infrastructure or infrastructure-to-vehicle scenarios, the following parameters are different: 29 infrastructure nodes with a spacing of 120 m placed in the rightmost lanes, and 20 vehicles travelling in the leftmost and middle lanes. The placement of the infrastructure nodes is to cover the entire distance that the vehicle cluster travels during the simulation time span. The arrangement of vehicles in two lanes establishes the vehicles in the middle lane as a visible light blockage to the communication between the vehicles in the leftmost lane and infrastructure nodes in the rightmost lane. Moreover, we apply the characteristics of our V²LC prototype in the simulation. For example, VLC transmitters and receivers have half-angle of 50° and field-of-view angle of 12°, respectively.

5.2 Vehicle-to-Vehicle Broadcasting

Scenario. The most forward vehicle in the cluster initiates the information flow, and the information is disseminated backwards by vehicle-to-vehicle broadcasting. This scenario occurs, for example, when a vehicle discovers an incident on the road and needs to warn all other vehicles behind it. In this case, we measure reachability as the percentage of vehicles receiving the information, and delay as the time difference between when the information is sent by the initiator and when iton is last received. We also investigate the effects of packet collisions on reachability and delay because they can cause certain paths to reach vehicles unusable.

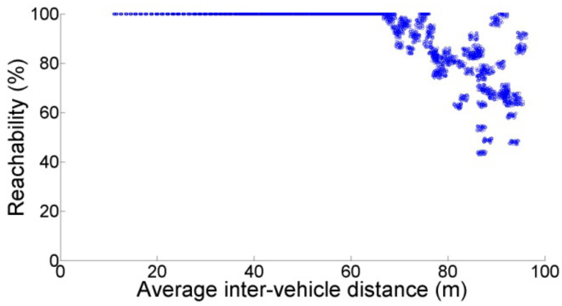

Figure 7. Reachability in vehicle-to-vehicle broadcasting

Figure 7 shows reachability as a function of the average inter-vehicle distance. Reachability is 100% for inter-vehicle distance smaller than 66 m. With inter-vehicle distance greater than 66 m, reachability shows a decreasing trend, but with high variability ranging from 40% to 100%. To avoid queue formation and vehicle chain accidents, vehicular safety applications, including cooperative forward collision warning and emergency electronic brake lights, need to reach as many proximate vehicles as possible in the back. Therefore, the result that the reachability is 100% for the inter-vehicle distance smaller than 66 m is critical to the aforementioned vehicle safety applications in preventing chain accidents when queues start forming. Figure 9 depicts the average delay for vehicle-to-vehicle broadcasting (with 95% confidence intervals) as a function of the average inter-vehicle distance. With reference to the vehicular applications' requirements in reachability and latency in Section 2.2, the delay satisfies the latency requirement (≤ 20 ms) by the vehicle safety applications that require vehicle-to-vehicle broadcasting.

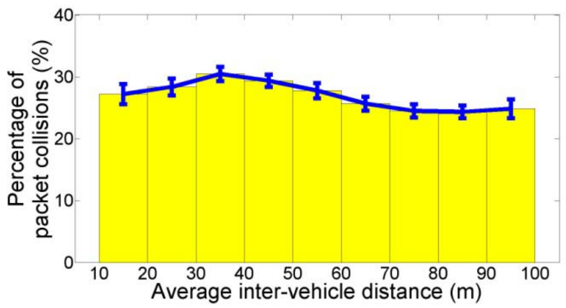

Figure 8. Percentage of packet collisions in vehicle-to-vehicle broadcasting

We plot the average percentage of collisions and 95% confidence intervals vs. average inter-vehicle distance in Figure 8. Observe that the average percentage of packet collisions, i.e., the ratio of the number of collisions to the sum of the number of collisions and the number of receptions averaged over all 30 vehicles, remains between 24% and 30%. However, collisions affect reachability significantly for inter-vehicle distance greater than 66 m. The reason is that for shorter inter-vehicle distances, there are multiple paths available to reach any vehicle. Hence, in order to decrease reachability, collisions would need to occur on all available paths, whose probability is small. As the inter-vehicle distance increases, the number of available paths to reach vehicles decreases and the probability of all the paths being affected by the collisions increases. Thus, there is a decreasing trend in reachability as the average inter-vehicle distance becomes larger. The wide variations in reachability are due to the random movements of the vehicles randomizing the number of available paths as the vehicle cluster expands.

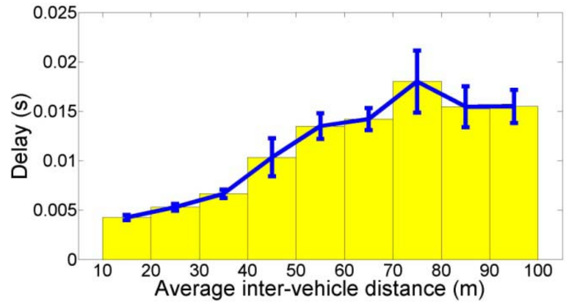

Figure 9. Delay in vehicle-to-vehicle broadcasting

Findings. (*i*) V^2LC is able to provide 100% reachability and latency as low as 20 ms in critical traffic conditions (i.e., with a Level-of-Service D or below; equivalently, an inter-vehicle distance 67 m or smaller), which do not have the ability to absorb any vehicle incidents. (*ii*) The impact of packet collisions on reachability and delay is negligible when the average inter-vehicle distance is short because there are many paths to reach each vehicle.

5.3 Limited Vehicle-to-Vehicle Broadcasting

Scenario. Every vehicle in the cluster performs limited vehicle-to-vehicle broadcasting. This scenario, for instance, occurs when the lane change warning application requires vehicles to periodically send information regarding their positions, speeds, and accelerations. We measure reachability as the percentage of neighboring vehicles which can successfully receive the information within a vehicle's proximity. Two vehicles are considered in the proximity of one another if the distance between them is 18 m (four times larger than the car length) or less, and they are in the same or adjacent lanes. The reachability is averaged over all of the 30 vehicles. We define delay in this service as the time difference between when a piece of information is sent and when it is received by the neighboring vehicles. The delay is constant at 0.0048 s, which is the packet transmission time over one hop; the propagation delay is negligible. This delay satisfies vehicle safety applications' requirements in latency which ranges from 20 ms to 1000 ms.

Figure 10 shows the reachability of V^2LC with 95% confidence interval as a function of the average inter-vehicle distance. When the inter-vehicle distance is smaller than 50 m, the mean reachability varies from 51% to 58%. With the inter-vehicle distance greater than 50 m, the mean reachability variation range is 60% to 75%. However, with the inter-vehicle distance greater than 50 m, the confidence intervals on reachability become larger. The wider range of the confidence intervals at larger inter-vehicle distances results from the fact that as the inter-vehicle distance increases, the vehicle cluster expands. Recall our node model where the VLC transmitters and receivers are co-located in vehicles' four corners and the field-of-view angle's spatial binary indication on the success of the communication between the transmitter and the receiver in Section 4.2. When the vehicle cluster is compact, vehicles can normally only hear from the vehicle lights to their front and back, but not from the vehicles to their sides, which are out of their field-of-view angle. When the vehicle cluster expands, the vehicles' random movements determine which proximate vehicles the receiver can hear, and the random movements introduce high variability to the measured reachability.

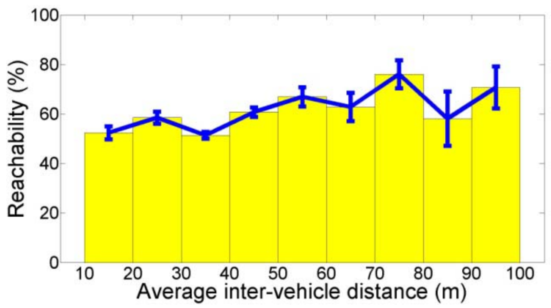

Figure 10. Reachability in limited vehicle-to-vehicle broadcasting

Given the high probability of being out of the field-of-view of the neighboring vehicles, we expect that with the vehicle-to-vehicle broadcasting limited to one hop, V^2LC cannot maintain a reachability of 100%. However, the performance of V^2LC can be improved by either allowing 2-hop broadcasting or increasing the number of transmitters/receivers on the vehicles so as to enlarge the aggregate field-of-view angle.

Findings. V^2LC on average reaches half of the target vehicles under the limited vehicle-to-vehicle broadcasting. This is a manifestation of the field-of-view angle's spatial binary indication property. The performance can be improved by extending the field-of-view of the vehicles to cover their sides as well as employing limited multihop vehicle-to-vehicle broadcasting.

5.4 Infrastructure-to-Vehicle Broadcasting

Scenario. Every infrastructure node broadcasts to vehicles within its transmission range. This service can provide last-mile connectivity for vehicular applications that require information from gateways. We measure reachability, i.e., the percentage of vehicles that successfully receive packets from the infrastructure nodes. Delay in this case is the time spent for vehicles to receive transmitted packets from infrastructure nodes. Similar to the results in Section 5.3, the delay is at the constant value of 4.8 ms since information exchange is over one hop.

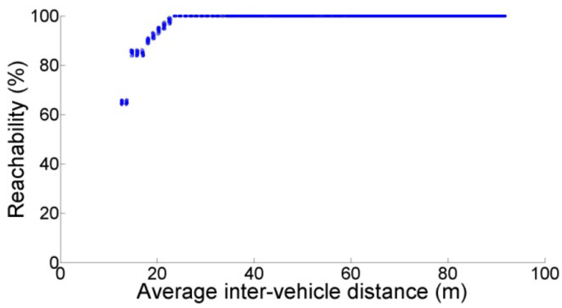

Figure 11. Reachability in infrastructure-to-vehicle broadcasting

We show reachability as a function of average inter-vehicle distance in Figure 11. For inter-vehicle distances greater than 22 m, th reachability is 100%. For the inter-vehicle distances less than 22 m, some vehicles in the leftmost lane are blocked by vehicles in the middle lane, and they cannot receive the packets transmitted by the infrastructure nodes located in the rightmost lane. Hence, reachability is less than 100%.

We observe that for average inter-vehicle distances of 22 m or larger, V^2LC opportunistically uses inter-vehicle gaps among vehicle structures in the middle lane to reach vehicles in the leftmost lane. In order to increase reachability at smaller average inter-vehicle distances, either the number of infrastructure nodes can be increased to reduce "blind spots," or infrastructure-to-vehicle broadcasting can be combined with vehicle-to-vehicle broadcasting network service to extend the coverage of the infrastructure nodes. Based on the results of Section 5.2, we expect that combining the two services would increase reachability to 100%.

Findings. Since V^2LC operates in the visible light spectrum, vehicle structures can block one another from reaching the intended vehicles and therefore affect reachability. However, in the mobile vehicular environment, the V^2LC network service can enable opportunistic transmissions via dynamic appearances of inter-vehicle gaps in a traffic stream.

5.5 Vehicle-to-Infrastructure Anycasting

Scenario. Each vehicle anycasts to the infrastructure nodes. This network service is used with a backbone network by which the infrastructure gateways are inter-connected. In this scenario, reachability is the percentage of vehicles whose transmissions are successfully received by any infrastructure node. Delay is defined as the time span that takes a packet transmitted by a vehicle to reach an infrastructure node. The information dissemination is also occurring over single hops here, and hence the delay is at the constant value of 4.8 ms.

Figure 12 shows reachability as a function of average inter-vehicle distance. When inter-vehicle distance is smaller than 26 m, vehicles in the middle lane hinder the infrastructure nodes in the rightmost lane from receiving information from vehicles in the leftmost lane. As a result, reachability is less than 100%. With inter-vehicle distances greater than 26 m, reachability is 100%.

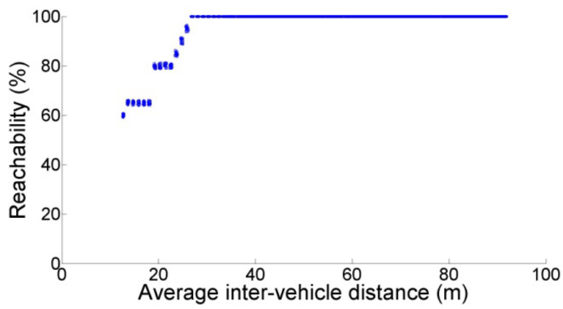

Figure 12. Reachability in vehicle-to-infrastructure anycasting

We observe similar trends in reachability results depicted in Figure 11 and 10. In infrastructure-to-vehicle broadcasting, however, the probability of collision is lower since every car is at most within transmission ranges of two infrastructure nodes, whereas in vehicle-to-infrastructure anycasting, an infrastructure node can hear packets from multiple vehicles. We note that even though there are more packet collisions in the scenario of Figure 12, in both cases, reachability of 100% has been achieved for average inter-vehicle distances larger than 26 m. Similar approaches to those in the scenario of Section 5.4 can be taken to increase reachability for smaller inter-vehicle distances.

Findings. With the same set of vehicular movements but different numbers of collisions, both V^{2}LC services achieve reachability of 100% with average inter-vehicle distances greater than 26 m. Thus, compared to packet collisions, the relative positions of transmitters and receivers are dominant factors in determining reachability.

5.6 Vehicle-to/from-Infrastructure Unicasting

Scenario. One vehicle in the leftmost lane transmits CBR traffic to a gateway infrastructure node in the rightmost lane by using AODV routing protocol. In this scenario, an acknowledgment is sent from the infrastructure gateway to the transmitters for every data packet successfully received. The simulation starts when no vehicle has reached the transmission range of the infrastructure gateway, and it ends when all vehicles have passed the gateway and are out of its transmission range. The simulation is conducted for three scenarios with different average inter-vehicle distances: 14 m, 45 m, and 67.5 m. These inter-vehicle distances are representatives of low density, medium density, and high density traffic conditions.

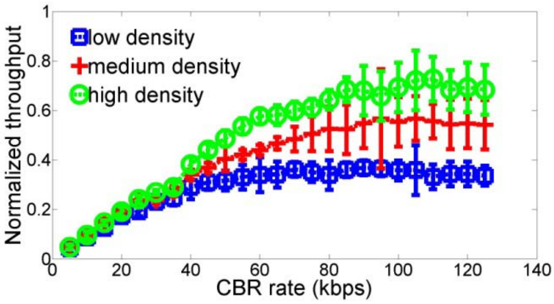

Figure 13. Normalized throughput vs. CBR rate in vehicle-to/from-infrastructure unicasting

Figure 13 shows the normalized throughput in three traffic conditions with 95% confidence intervals as a function of CBR rates, where the normalized throughput is defined as the ratio of the number of received bits to V^{2}LC data rate, 100 kbps. We observe that the normalized throughput is the highest in the high density scenario. This observation results from the fact that in denser traffic conditions, there are more routes to the gateway infrastructure node as a result of V^{2}LC's high spatial reuse. We also observe that the normalized throughput saturates at 85 kbps, lower than the data rate. We verified that the bottleneck on the throughput achievement is the high delay AODV has in finding new routes in a vehicular environment. Our results indicate that another routing protocol design can possibly improve the performance; however, the development of routing protocols is out of the scope of this paper.

Findings. Denser traffic conditions result in more available routes, which is a direct consequence of high spatial reuse in V^{2}LC networks. Therefore, the V^{2}LC network service achieves higher throughput in denser vehicular traffic conditions.

6. RELATED WORK

Vehicular RF Communications. RF solutions have been proposed to facilitate long distance and high data rate communication in vehicular environment. Prior work has examined the performance of RF technologies against vehicular application requirements. Vehicle safety applications need packets delivered by certain deadlines in real time, especially when vehicles are in the vicinity of one another and prone to be engaged in accidents. However, Eichler in [7] shows that RF solutions may not ensure time critical message dissemination because of increased RF interference in high dense vehicular traffic scenarios. The results in [4] and [11] corroborate the findings in [7] via simulations and modeling and indicate that the development of vehicular communication technologies still remains as an open problem. We explore means to satisfy vehicular application requirements via VLC and show that a V^{2}LC network is able to meet the performance specifications in reachability and latency in high dense vehicular traffic scenarios. Nevertheless, we expect VLC and RF solutions to work together and support the diverse needs from vehicular applications, e.g., utilizing VLC in dense traffic conditions while switching to RF for long distance, sparse conditions. In [15], the authors propose to use directional antennas and beam steering techniques to establish communication links between moving vehicles and roadside access points. Besides the vehicle-to/from-infrastructure communication, we also focus on the vehicle-to-vehicle scenarios which are required in vehicle safety applications. Since we find that the VLC links are very directional in transmission and reception, we contemplate that beam steering techniques may also be applied to VLC.

Additionally, ultra-wideband, short-range communication systems in the 60 GHz band have been proposed for vehicular use. Waveform selection is studied in [8], and modulation schemes are investigated in [6]. However, FCC imposed power limitations have limited transmission range to a few meters, thus decreasing the feasibility of the ultra-wideband systems in vehicular environments [9].

VLC Links. There is a large body of literature investigating VLC links. In [12], the authors provide a theoretical analysis on VLC systems based on indoor environment assumptions, such as a lack of sunlight background noise on VLC links. Under lab conditions, there have been research efforts on constructing single VLC links and increasing link speed via optical techniques and modulation schemes. Minh et al. report a VLC link speed up to 80 Mbps by using pre-equalized white LEDs [13]. In [24], the authors demonstrate a VLC link with speed up to 200 Mbps by using discrete multi-tone modulation. Recently, researchers at Siemens achieve a VLC link speed up to 500 Mbps [20]. These studies show that VLC link speed has progressively increased, and the rapid increase in data rate is the result of the unprecedented large bandwidth in visible light spectrum.

Beyond link rate, a number of single-link VLC systems have been proposed in indoor environments. The VLC Consortium in Japan demonstrates a VLC system in which two computers use lamps to communicate with each other [23]. In [18], an LCD-camera pair is used to communicate data using 2D barcodes. Besides the investigation on the LED-photodiode VLC links, prior work has also proposed to use LED-camera links. In [19] and [25], the authors present analytical results on the relation between communication distance and BER in inter-vehicle and traffic light to vehicle scenarios, respectively. More recently, the authors analyze the capacity in an LED-camera communication channel as well as the recognition and tracking algorithms for LED transmitters [2]. While the LED-camera system can tolerate more noise than the LED-photodiode, it may not achieve a data rate as high as the LED-photodiode due to the limited camera frame rate. A hybrid system of using individual photodiodes and cameras is promising in both tolerating ambient noise and improving data rate.

In contrast, our work differs from previous research in two ways. First, beyond investigating the LED-photodiode VLC link's robustness to noise and interference, we focus on networking challenges. We evaluate the capability of a V^{2}LC network with such a link robustness property to provide services for vehicular applications. We find that a V^2LC network can satisfy the applications' stringent requirements in reachability and latency in dense traffic conditions. Second, we examine VLC in vehicular environments that pose different challenges from indoor environments, such as mobility and sunlight background noise. There is only one prior experimental work that is similar to ours. In [17], data is transmitted uni-directionally from a traffic light to a vehicle. However, this work lacks the networking analysis as well as the comprehensive examination of noise and interference that we have conducted on the research platform; e.g., the VLC receiver's field-of-view angle has a spatial binary indication on transmissions and perceived interference.

7. CONCLUSIONS

In this work, we examine the key elements in realizing V^2LC networks considering the constraints imposed by outdoor environments and vehicular traffic. Specifically, on a custom research platform, we experimentally show that V^2LC network links are resilient against visible light noise and interference under working conditions. We address the unique capabilities and limits of V^2LC in relation to the requirements of vehicular applications. Via large-scale simulations, we show that V^2LC can satisfy the stringent reachability and latency requirements in dense vehicle traffic conditions.

8. ACKNOWLEDGMENTS

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