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The Case for Vehicular Visible Light Communication (V^2LC): Architecture, Services and Experiments

by

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ABSTRACT

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Visible Light Communication (VLC) is a fast-growing technology to provide data communication using low-cost and omni-present LEDs and photodiodes. In this thesis, we make the case for the use of vehicular VLC (V^2LC) as follows. We describe an architecture for V^2LC networks and introduce five network services that V^2LC needs to provide for vehicular applications. We use a custom VLC prototype developed at Intel on which we investigate the unique networking properties of V^2LC. Specifically, our experiments show that a V^2LC receiver's narrow filed-of-view angle makes V^2LC resilient to visible light noise from sunlight and legacy LED sources and interference from active VLC transmitters; further, V^2LC can operate in full-duplex mode with the exception of being subject to multipath effects at very short distances, e.g., 1.5 m in our experiment. By performing a large scale simulation study and leveraging our experimental data, we evaluate V^2LC's ability to provide network services for vehicular applications. Our results reveal two key findings: (*i*) in dense vehicle 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 because of the dynamic gaps in the blockage

caused by vehicular movements.

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Chapter 1

Introduction

Visible Light Communication (VLC) is becoming an alternative choice for next-generation wireless technology by offering unprecedented bandwidth and ubiquitous infrastructure support. As the name suggests, VLC uses the visible light spectrum as the medium to transmit and receive information. A VLC receiver consists of photodiodes, whereas a VLC transmitter can use an array of LEDs. As a result, VLC is closely coupled with the deployment of LEDs. As LEDs have become widely adopted as power-saving lighting devices, the expansion in the usage of LEDs spurs VLC to be utilized in both indoor and outdoor applications.

VLC can be applied in vehicular environments since there already exists an infrastructure with many vehicle lights and traffic lights installed with LEDs. In terms of vehicular applications, the Intelligent Transportation Systems identify internet connectivity and vehicle safety as the two main applications [1]. While RF solutions to the vehicular applications have been proposed, e.g., IEEE 802.11p [2], their capabilities to meet the requirements of the vehicular applications are still an open problem [3].

In this thesis, we make the case for the use of vehicular VLC (V^2LC) and address the unique capabilities and limits of V^2LC with respect to the requirements of the vehicle safety and internet access applications. We describe an architecture of V^{2}LC networks, in which vehicle lights as well as infrastructure lighting serve as transmitters, and receivers are co-located with the transmitters, and identify five network services V^{2}LC needs to provide for the vehicular applications. On a custom VLC research platform, we perform experiments and investigate the unique networking properties of V^{2}LC in relation to the environment and vehicular application imposing requirements, such as resilience to visible light noise and interference as well as assurance of delivering time-sensitive information. We evaluate V^{2}LC's performance in providing the network services that are re-quired by the vehicle safety and internet access applications via a large scale simulation study.

In particular, we make the following three contributions. First, we describe an architecture of V^{2}LC networks in which vehicles and infrastructure lighting can have multiple simultaneously working transmitters and receivers because of their physical separation. In order to support the requirements of the vehicular applications, we then introduce five network services that V^{2}LC needs to provide, namely, multihop inter-vehicle forwarding, limited neighbor broadcasting, infrastructure-to-vehicle one-hop broadcasting, vehicle-to-infrastructure one-hop anycasting, and vehicle-to/from-infrastructure unicasting.

Second, we are the first to identify and evaluate V^{2}LC's unique networking properties. We used the VLC prototype developed at Intel, whose design values are in range of future low-cost VLC transmitters and receivers that can be massively produced, e.g., the VLC receiver has an off-the-shelf photodiode with a 12° field-of-view angle (the largest angular extent), and the VLC transmitter with a 50° half-angle (the maximum divergence of a light beam) consists of commercially available white LEDs. On the VLC research platform, we perform experiments to evaluate V^{2}LC's networking properties with respect to robustness to visible light noise and interference as well as vehicular applications' requirements. We find that V^{2}LC is resilient against wideband noise sources (i.e., sunlight) with the exception of a direct exposure to the sun, which can only occur when vehicles with a direct line-of-sight to the sun and 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). We also find that V^{2}LC is robust to narrowband noise that is generated by idle VLC transmitters as well as legacy lights with no data transmission abilities. When considering V^{2}LC's performance under interference, we determine that the VLC receiver's field-of-view angle has a binary indication property on the success of transmissions and perceived interference, e.g., in our experiment, a shift of the transmitter for a few centimeters moves it out of the field-of-view angle (12°), and the packet delivery ratio sharply drops from 100% to 0%. Equivalently, V^{2}LC's small field-of-view angle significantly limits the impact of interference, and it results in a high spatial reuse in V^{2}LC networks. Lastly, we evaluate the ability of V^{2}LC to operate in full-duplex mode, which has the potentials to increase throughput and decrease delay for vehicular applications. We characterize the feasibility of full-duplex mode in relation to multipath effects created by reflective and scattering surfaces in vehicular environments, and we show that the effects only exist in very short distances, e.g., within 1.5 m in our experiments.

Third, using our experimental characterization of our VLC prototype and V^2LC's networking properties, e.g., four co-located pairs of transmitters and receivers that can operate in full-duplex mode on each vehicle, we perform a large scale simulation evaluation of V^2LC with respect to the five network services. We simulate vehicle movements as well as packet transmissions by following a set of physical and traffic rules: vehicles cannot pass through each other, speed limits are set on the road, packets cannot be transmitted through vehicles, etc. In dense vehicle traffic conditions that are prone to vehicle accidents (e.g., urban highways during peak hours with inter-vehicle distances less than 66 m [4]), we find that V^2LC's performance in the multihop inter-vehicle forwarding satisfies the stringent requirements of 100% reachability with latency as low as 20 ms for the vehicle safety applications. From our blockage scenario where vehicles in the middle lane hinder the communication between vehicles in the leftmost lane and infrastructure nodes in the rightmost lane, we show that with inter-vehicle distances less than 26 m, reachability is less than 100%. On the other hand, with inter-vehicle distances greater than 26 m, V^2LC can opportunistically enable successful transmissions between the vehicles in the leftmost lane and the infrastructure nodes in the rightmost lane by using the gaps among the vehicles in the middle lane, and reachability is 100%. Our results reveal two key findings: V^2LC takes advantage of a large number of available paths (paths found via multihop broadcasting, not routing protocols) to reach vehicles in dense vehicle traffic conditions, i.e., a consequence of V^2LC's high spatial reuse, to overcome the effects of packet collisions, and V^2LC can have successful transmissions in the presence of a visible light blockage in traffic because of the dynamic nature of the gaps caused by vehicular movements.

The rest of the paper is structured as follows. We first present background information on VLC and the vehicle safety applications in Chapter 2. We describe V^2LC's architectural design and introduce the network services in Chapter 3. We then use the VLC research platform to investigate V^2LC's unique networking properties in relation to robustness to visible light noise and interference as well as vehicular application requirements in Chapter 4. We evaluate V^2LC's performance in each of the five network services in Chapter 5. We discuss related work on VLC in Chapter 6 and conclude in Chapter 7.

Chapter 2

Background

In this chapter, we describe basic concepts and operations of a VLC system in transmission and reception as well as advantages of employing VLC systems. We also introduce the eight high-priority vehicle safety applications and their communication requirements in reachability and latency.

2.1 VLC System

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 different and functionally separated. The transmitter modulates information at lighting sources, such as LEDs. This modulation takes place in such high frequencies that humans' bare eyes cannot perceive any difference in lighting compared to that when there is no modulation. A VLC receiver consists of photodiodes either as stand-alone elements or in the form of an image sensor.

A VLC system inherits four advantages in data transmission from operating in the visible light spectrum and functioning with LEDs and photodiodes. First, VLC is secure for data contents because it often requires a line-of-sight for transmission and reception. Second, VLC is safe to humans and other instruments because it operates in the visible light spectrum and in low density with lighting devices. Third, VLC is cost-efficient because its components, such as LEDs and photodiodes, can be massively produced, and it is additionally power-efficient by using LEDs. Fourth, VLC has a ubiquitous infrastructure support because it can use the existing lighting infrastructure that is deployed everywhere.

2.2 Vehicle Safety Applications

The vehicle safety applications and their communication requirements are determined by the Vehicle Safety Communications Project [5]. In [5], eight out of more than 75 applications are identified as the high-priority applications, and they are representative of a range of communication requirements, namely, 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.

We give a brief description for each of the high-priority applications. All of them assist drivers with making safe de-cisions in traffic and complying with traffic regulations. The traffic signal violation warning and curve speed warning applications allow infrastructure to transmit to vehicles with traffic light states and curvature of banks, respectively. The left turn assistant application allows vehicles travelling in one direction to transmit their positions and speeds to in-frastructure, and then it allows infrastructure to transmit this information to vehicles waiting to make left turns in the opposite direction. The stop sign movement assistant application is similar to the left turn assistant application except that it allows infrastructure to retransmit information to vehicles waiting at nearby stop signs. The lane change warning application allows vehicles to gather information on their neighbors' positions and speeds. The cooperative forward collision warning application gathers and forwards information among vehicles to help identify objects and incidents as in-path or out-of-path. The pre-crash sensing application is similar to the cooperative forward collision warning application except that it also prepares the safety protection systems of vehicles that are engaged in unavoidable collisions. The emergency electronic brake lights application allows vehicles to transmit information to others whenever breaking lights are on, especially in adverse weather conditions.

We present the eight applications' communication requirements in reachability and latency. Reachability is defined as a ratio of the number of vehicles that can be suc-cessfully reached by a communication system to the total number of vehicles that are targeted in the applications. All of the eight applications require 100% reachability. Latency is defined as a maximum time span during which a communication system needs to successfully deliver information to the targeted vehicles. All of the eight applications require 100 ms latency 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.

Chapter 3

V^2LC Architecture and Services

In this chapter, we describe an architecture for V^2LC networks. We then identify the network services V^2LC needs to provide for vehicle safety and internet access applications.

3.1 V^2LC Architectural Design

A V^2LC network consists of vehicles as mobile nodes and infrastructure lighting sources as fixed gateways. Both the mobile nodes and the infrastructure lightings, such as traffic lights, can be equipped with multiple transmitters and receivers which can operate simultaneously. For example, the headlights and the brake lights of a vehicle can serve as transmitters, and multiple receivers can be mounted around the vehicles. Figure 3.1 illustrates the V^2LC network architecture. In this design, 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.

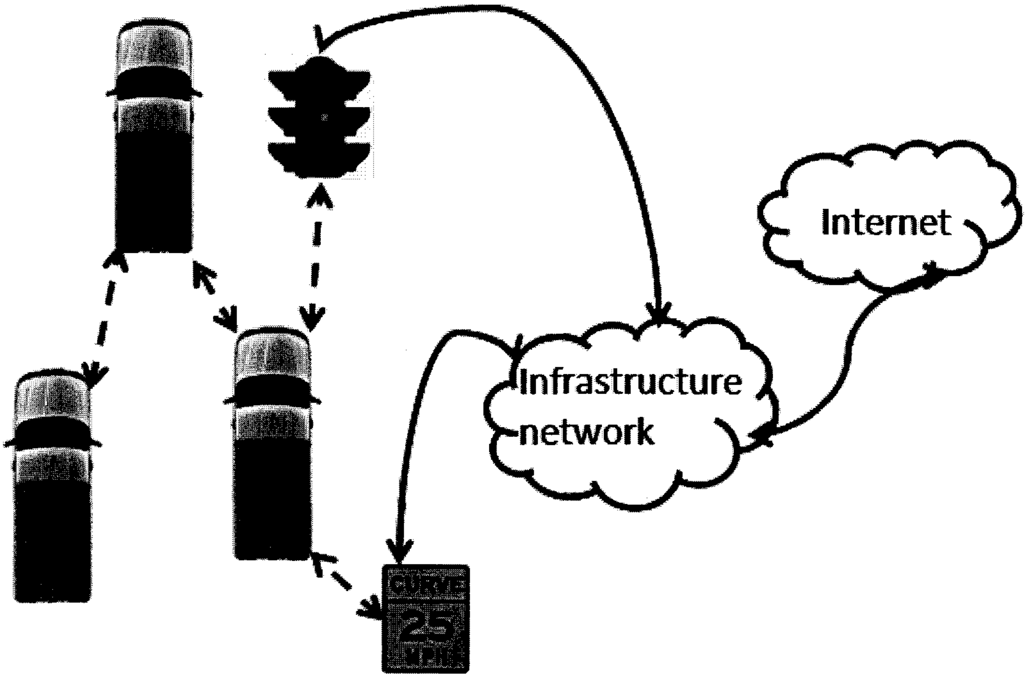

Figure 3.1 : An illustration of a V^{2}LC network architecture

3.2 V^{2}LC Network Services

Vehicular applications, including the eight high-priority vehicle safety applications and internet access applications, span different network scenarios and require a range of network services. We categorize the scenarios needed for support of these applications into three categories: vehicle-to-vehicle, infrastructure-to-vehicle, and vehicle-to-infrastructure. Furthermore, the information dissemination in these scenarios can occur over multiple hops or be limited to single hops. Based on the descriptions of the safety application operations in [5], we introduce four network services for support of the safety applications: multihop inter-vehicle forwarding, limited neighbor broadcasting, infrastructure-to-vehicle one-hop broadcasting, and vehicle-to-infrastructure one-hop anycasting. We also introduce an additional network service, vehicle-to/from-infrastructure unicasting, for vehicular internet access applications. These network services, either stand-alone or combined, provide all the services required for vehicular applications.

Multihop Inter – vehicle Forwarding. This network service works in the vehicle-to-vehicle scenario over multiple hops. 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 large number of vehicles. Therefore, it is suitable for providing service to event-triggered, urgent message delivering applications, such as cooperative forward collision warning, pre-crash sensing, and emergency electronic brake lights.

Limited Neighbor Broadcasting. The limited neighbor broadcasting network service also operates in the vehicle-to-vehicle scenario, but over single hops. Each vehicle broadcasts information from all of its transmitters to its neighboring vehicles. But, the information dissemination is limited to one hop, and the neighboring vehicles do not forward information that they receive. Thus, this network service only provides vehicles with information from close vicinity; by limiting the extent of broadcasting, it prevents network performance degradation due to high volume flooding. Thus, it can provide service to the applications that need periodic, local information. For example, the lane change warning application requires this network service because vehicles constantly need to know about the positions of the nearby vehicles when making lane changes, but information from other distant vehicles is irrelevant.

Infrastructure – to – vehicle One – hop Broadcasting. This network service works in the infrastructure-to-vehicle scenario over single hops. In this service, infrastructure nodes broadcast information to vehicles, and the vehicles do not send information back to the infrastructure nodes. The service in its stand-alone form is required by the traffic signal violation warning and curve speed warning applications because in both cases, only the infrastructure nodes need to transmit information to the vehicles. Combined with the vehicle-to-infrastructure one-hop anycasting, it can provide service for the left turn assistant, and stop sign movement assistant applications where bi-directional information exchange between the vehicles and the infrastructure nodes is required.

Vehicle – to – infrastructure One – hop Anycasting. The vehicle-to-infrastructure one-hop anycasting network service operates in the vehicle-to-infrastructure scenario over single hops. Vehicles anycast information to infrastructure nodes; meanwhile, the infrastructure nodes do not send information to the vehicles. If any infrastructure node receives the information from vehicles, then the communication is successful because the infrastructure nodes are connected by a backbone network. This network service, along with the previous infrastructure-to-vehicle one-hop broadcasting service, can be combined with the multihop inter-vehicle forwarding. In this way, the combination maximizes the utilization of the backbone infrastructure network and vehicles as relays and the chance to reach every node.

Vehicle – to/from – infrastructure Unicasting. The vehicle-to/from-infrastructure unicasting network service takes place in the vehicle-to-infrastructure and infrastructure-to-vehicle network scenarios, with each scenario providing uplink and downlink for vehicular internet access applications, respectively. This service works over single hops and multiple hops to/from a gateway infrastructure node. By using routing protocols, vehicles first find routes to a gateway infrastructure node and then start transmissions to that gateway, which may use other vehicles as relays. We note that this network service is the only one that requires routing protocols to discover routes, and other services find paths to vehicles and infrastructure nodes via single hop transmissions and multihop broadcasting.

Chapter 4

V^2LC Networking Properties

In this chapter, we use the VLC research platform developed at Intel to investigate the unique networking properties of V^2LC. We first describe the VLC platform hardware. We then examine the networking properties of V^2LC with respect to resilience to visible light noise and interference as well as requirements of vehicular applications. In our experiments, we use 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.

4.1 VLC Research Platform Hardware

Transmitting and receiving data in the visible light spectrum requires specialized hardware, which is not commercially available. Consequently, we needed a custom platform to investigate the networking properties of V^2LC.

We present Intel's V^2LC prototype. Figure 4.1 (a) and (c) show a photograph and the block diagram of the VLC transmitter. It consists of 120 off-the-shelf white LEDs, each having a dissipation power of 120 mW. The transmitter's half-angle, that is, the maximum divergence of a light beam, is 50°. The design values lie in the range that is expected for V^2LC transmitters, such as vehicle lights and traffic lights. The transmitter uses on-off keying modulation implemented in software.

Figure 4.1 (b) and (d) depict the VLC receiver which consists of a commercial photodiode with a spectral response range from 350 nm to 1100 nm, a 4x zoom optical lens, and a software-based signal processing component. The receiver has a 12° field-of-view angle, i.e., the largest angular extent that can be seen at the receiver. All of these design choices are again within the range expected for future low-cost V^2LC receivers that use massively produced photodiodes. The software for both the transmitter and the receiver is implemented in MATLAB, which runs on laptops that are connected to the hardware units with RS-232 cables.

4.2 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 to both wideband and narrowband noise. The most prominent source of wideband noise is sunlight, which contains energy in the spectral response range of the VLC receiver's photodiode. In contrast, the expected sources of narrowband noise originate from idle VLC transmitters of other vehicles and infrastructure as well as any lighting source with no data transmission capability. This source of noise is dominant during nighttime, and its energy is also distributed in the spectral response range of the photodiode.

Wideband Noise Scenario. In this scenario, we investigate V^2LC's robustness to wideband noise. There are two key cases we consider: when the sun directly

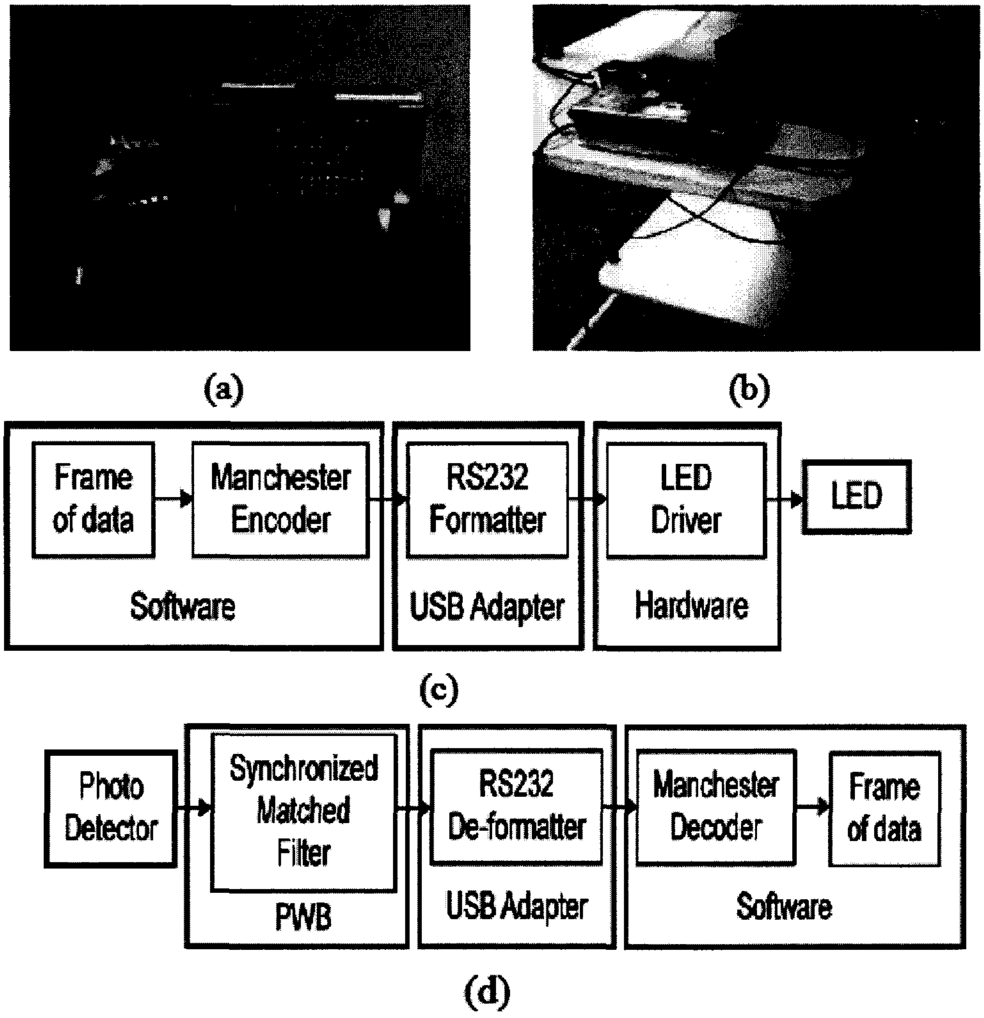

Figure 4.1 : VLC transmitter, picture (a) and block diagram (c); VLC receiver, picture (b) and block diagram (d)

within the receiver's field-of-view angle and when the sun out of 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. The former case usually happens during sunset and sunrise (i.e., when the sun makes a relatively small angle to the horizon and therefore possibly falls in the field-of-view angle) with vehicles' having a clear line-of-sight to the sun. Meanwhile, the latter case occurs much more frequently during the day since it does not place any restrictions on the sun's position or require vehicles to have a clear a line-of-sight to the sun.

Figure 4.2 depicts the experiment setup for this 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 of the VLC platform in the presence of wideband noise. We conducted our experiments between 2 p.m. and 6 p.m. on a sunny afternoon in both indoor and outdoor environments. Indoor experiments were performed on the third floor of an office building with a glass wall facing the sun. Outdoor experiments were conducted in a patio. While sunlight intensity was similar in these two environments, the indoor environment provided the elevation angles that could not be obtained in the outdoor environment due to surrounding buildings.

Table 4.1 summarizes the experimental results for the first case when the sun is

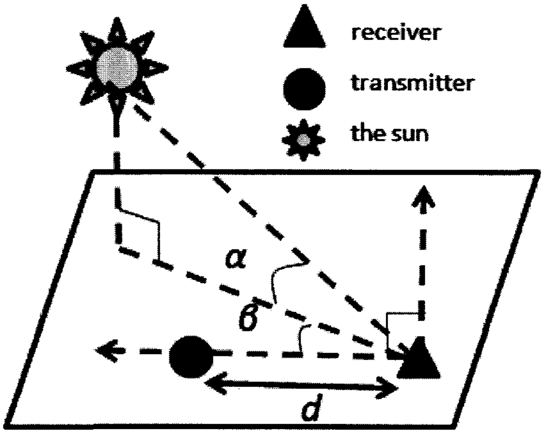

Figure 4.2 : Experiment setup in the wideband noise scenario

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 rather than during sunset and sunrise. The result shows that the packet deliver 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° field-of-view is robust to highly ambient wideband noise. While we note that the transmission range depends on the transmission power and is system-specific, we make the observation that using this VLC platform, the packet delivery ratio remains 100% for d less than 101 m.

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° to 50°. Since we cannot have a clear line-of-sight to the sun due to surrounding buildings

Table 4.1 : V^{2}LC robustness to wideband noise

d	α	β	PDR
5.4 m	0°	15°	100%
5.8 m	30°	45°	100%
7.5 m	10°	30°	100%
16.8 m	10°	10°	100%
(16.8, 101] m*	10°	10°	100%
>101 m*	10°	10°	0%

during sunset and sunrise, 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%. This is because the energy of the direct sunlight saturates the photodiode. To increase robustness in this scenario, we can narrow down the field-of-view angle by increasing the 4x zoom to a higher lens zoom. Further, we can make the field-of-view angle adaptive by dynamically changing the lens zoom. Nonetheless, this case occurs infrequently and requires a clear line-of-sight to the sun, which also needs to be within 12° of the horizon, for default.

Narrowband Noise Scenario. In this scenario, we evaluate V^{2}LC's robustness

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*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.

to two representative narrowband noise sources. They include an LED red light source of 9.6 W and a halogen light bulb of 60 W. The LED source represents idle VLC transmitters. On the other hand, the halogen light bulb is a type of incandescent light and often installed for automobiles and street lights. It is an example of lighting sources with no data transmission capabilities. Both sources emit light in the spectral response range of the VLC receiver's photodiode.

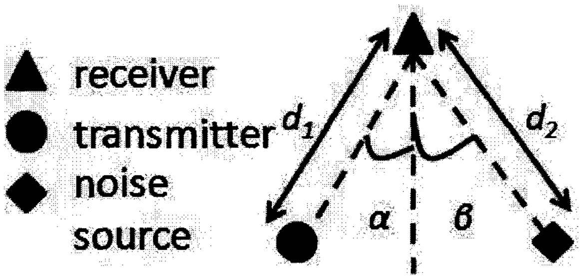

Figure 4.3 : Experiment setup in the narrowband noise scenario

We show the experiment setup in Figure 4.3. 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 narrowband noise from wideband 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°, respectively. We also fix β to be 3°, 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 4.2 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 narrowband noise generated by idle VLC transmitters. However, when the halogen light bulb with a significantly higher power is the noise source, the packet delivery ratio is 0% for d_2 less than 5 m. For d_2 greater than 5 m, the packet delivery ratio is 100%. The reduction in the packet delivery ratio suggests that the VLC receiver's photodiode can also be saturated by a narrowband noise source, similar to what happened in the wideband noise scenario. However, the saturation due to the narrowband noise can be eliminated by increasing the distance between the noise source and the receiver. The separation needed, shown to be 5 m, is very short considering inter-vehicle distances in traffic. Therefore, in V^{2}LC networks, the VLC receiver is also robust to the narrowband noise generated by lighting sources with no data transmission capabilities. Furthermore, with LEDs' capabilities in saving power, many vehicle lights and infrastructure lights with halogen light bulbs are expected to be replaced with LEDs.

Findings. Noise can affect V^{2}LC's performance by saturating the photodiode. This happens only if the noise power is significantly high, e.g., direct exposure to sunlight and close range of 5 m within a halogen light bulb, and the noise source

Table 4.2 : V^2LC robustness to narrowband noise

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

directly falls in the field-of-view angle of the receiver. With increasing distance between the noise source and the receiver and decreasing the field-of-view angle, V^2LC becomes completely robust to both wideband and narrowband noise, e.g., sunlight and idle LED lights.

4.3 The Field-of-view Angle, Interference, and Collisions

The VLC receiver's field-of-view angle determines the largest angular extent from which the light is viewed at the receiver. Therefore, it impacts the link establishment between the transmitter and the receiver. Once there is a VLC transmitter-receiver link, the field-of-view angle also affects the perceived interference at the receiver. For an interferer, we use another VLC transmitter actively sending modulated signals. This is in comparison to the idle VLC transmitter as a narrowband noise source in the previous section. Here, we first examine the effects of the field-of-view angle on the success of the communication between the transmitter and the receiver with no interferer. Then, we investigate the field-of-view angle's effects on the collision condition created by two packet transmissions from the transmitter and the interferer.

Transmitter – receiver Link Establishment

Scenario. In this scenario, we evaluate the effects of the transmitter's being in and out of the receiver's field-of-view angle on the link establishment between the transmitter and the receiver. The experiment setup is similar to the one depicted in Figure 4.3 but with only the transmitter and the receiver. We keep d_1 constant at 2 m. In the experiment, we vary α to move the transmitter in a circular motion with respect to the receiver. We conducted experiments in this scenario in the lab environment.

Figure 4.4 shows the packet deliver ratio as a function of α. The packet delivery ratio is 100% when α is smaller than 6°, i.e., when the transmitter is in the receiver's field-of-view angle. Once α becomes greater than 6°, and the transmitter falls out of the field-of-view angle of the receiver, the packet delivery ratio immediately drops to 0%. This sharp drop is observed in the granularity of 1°, i.e., a slight movement of the transmitter on the magnitude of a few centimeters can break the link with the receiver. The result implies that the field-of-view angle of the receiver is a binary indicator of the packet delivery ratio. If the transmitter is in the receiver's field-of-view angle, and the receiver is within the transmitter's transmission range, then the receiver can successfully receive all transmissions from the transmitter. If the transmitter is not in the field-of-view angle, then the receiver cannot receive from the transmitter.

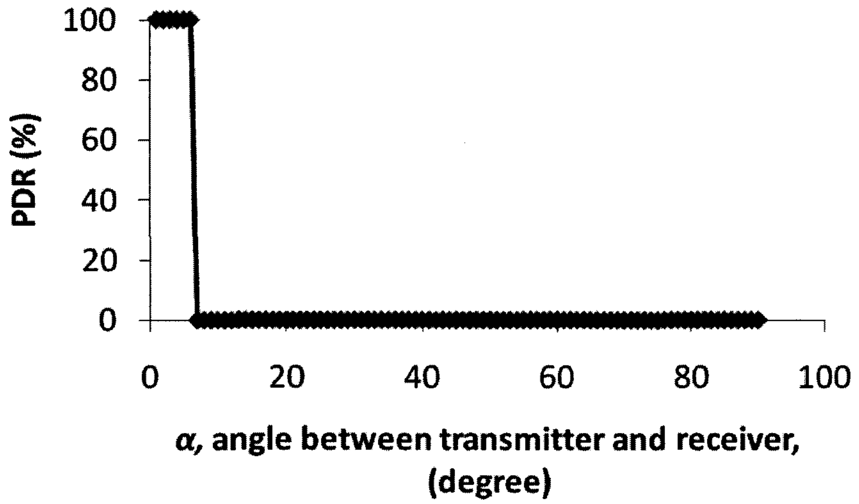

Figure 4.4 : Field-of-view angle of the receiver is a binary indicator on the transmitter's packet delivery ratio

Effects of Proximity of Interferer to Receiver

Scenario. In this scenario, we examine the effects of the interferer's 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 4.3 except that we replace the noise source with another VLC transmitter acting as the interferer. We keep d_1 and α constant at 2 m and 3°, respectively. We conducted this scenario's experiments in the lab environment.

We locate the interferer in the receiver's field-of-view angle and keep β constant at 3°, 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 4.3 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 the resilience against noise scenario. 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 0 s to be detected as 1 s. With use of a different modulation scheme, for example amplitude modulation, the results may be different. We also observe that as soon as the interferer is in 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 receiver has a binary indication on the success of transmissions because of sharp boundaries around the reception area, e.g., a spatial shift in a few centimeters of the transmitter moves it out of the field-of-view angle (12°), 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

Table 4.3 : When interferer in the field-of-view angle

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

angle significantly limits the amount of interference at the receiver.

4.4 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 full-duplex mode. Compared to half-duplex mode, full-duplex has the abilities to increase throughput and decrease delay, which are valuable assets to vehicular applications. However, the surrounding materials' reflective and scattering properties in the visible light spectrum 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 full-duplex mode.

Reflection and Scattering Scenario. In vehicular environments, the main re-

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[†] d_2 is also obtained by reducing the transmission power, similar to d in Table 4.1

flective and scattering objects are the surfaces of the nearby vehicles, including their painted bodies, glass windows, and plastic covers. We use the experiment setup shown in Figure 4.5 to investigate the impact of the surfaces of vehicles on V^2LC's full-duplex operation. A vehicle is 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.

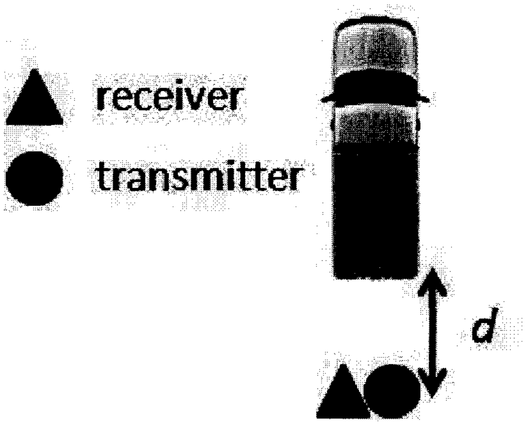

Figure 4.5 : Experiment setup in the full-duplex feasibility scenario

Figure 4.6 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 the robustness to interference section. 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. Figure 4.6 shows that 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 is the result of the fact that vehicles as whole entities are highly reflective rather than scattering. Much of the signal's energy is reflected, and little energy is scattered in all directions. Further, with an approximate 0° reflection angle, most of the reflection is directly towards the transmitter. As a result, only a small amount of reflected and scattered signal caused interference at the receiver, and this small amount of interference only exists in a short distance. We note that, in this experiment the receiver was aimed at the reflection of the transmitter on the surface of the vehicle. In normal conditions, the receiver does not necessarily target at the reflection of the transmitter, which results in reduction of interference at the receiver. In that case, the full-duplex operation is feasible in significantly shorter distances.

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 V^2LC can operate in full-duplex mode.

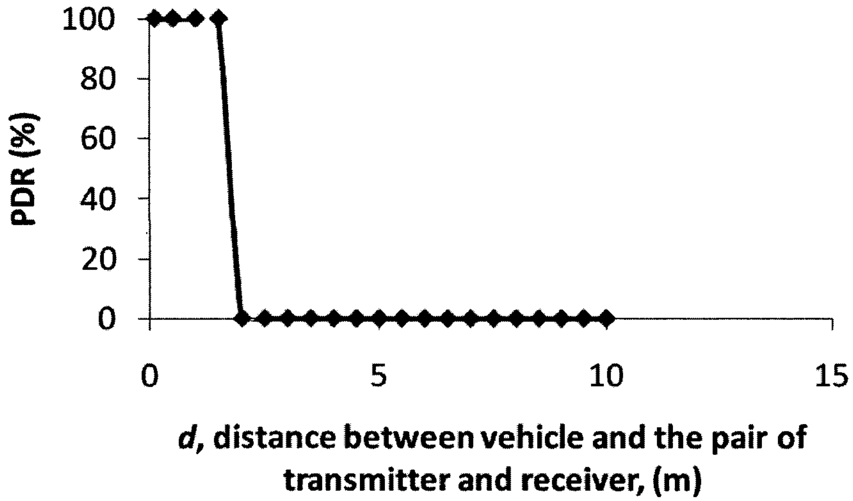

Figure 4.6 : Multipath effects on V^2LC full-duplex mode

Chapter 5

V^2LC Service Evaluation

In this chapter, we evaluate V^2LC's performance with respect to the five network services introduced in Chapter 3. We first describe our evaluation methodology and parameters. Via an extensive simulation study, we then present our results for each of the five network services.

5.1 Evaluation Methodology and Parameters

Vehicle Clusters in Traffic. Previous research, e.g., [6], 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 a vehicle cluster for two reasons. First, when considering vehicle safety applications, only vehicles in the same cluster are potential communication targets. This is because they are in the vicinity of one another via single or multiple hops. At a given instant, vehicles in one cluster are considered physically distant enough 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., [7], 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 impacts the performance of vehicular networks. Thus, we examine V^2LC'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 [4], the U.S. Transportation Research Board uses this distance as one criterion to categorize traffic conditions measured by Level-of-Service, a qualitative measure describing operational conditions within a traffic stream. Table 5.1 details Level-of-Service with its corresponding inter-vehicle distances, frequent occurrences, and abilities to absorb traffic accidents.

Traffic Scenario Generation. For the large scale simulation study of VLC, we modified the network simulator, ns-2 [8], to accommodate our experimental characterizations of V^2LC. Moreover, we use the Freeway model of the IMPORTANT tool to generate vehicle movements [9]. Due to the limitations of the IMPORTANT tool, traffic scenarios cannot be generated with an inter-vehicle distance below 6.6 m (6.6 m is the inter-vehicle distance when vehicles are uniformly distributed at the beginning; after one second, the vehicles have broken loose from the uniform pattern, and we start taking measurements). However, we make the observation that for inter-vehicle distances lower than 6.6 m, the vehicles are not much maneuverable in traffic. Thus,

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[‡] 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.

Table 5.1 : Level-of-Service for traffic conditions

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

their relative positions to one another remains approximately the same. Based on this observation, we conducted the same set of simulations for static scenarios with inter-vehicle distance smaller than 6.6 m. The results were similar to those obtained in the scenarios where vehicles are in close distance of one another and mobile.

MAC Protocol. While we acknowledge the impact of MAC on probability of collision and hence network performance, we keep MAC design and optimization for V^2LC out of the scope of this thesis and use an ALOHA based MAC protocol. We implement the MAC in ns-2 in which every vehicle waits a random amount of time before sending packets. The random amount of waiting comes from a uniform distribution, where the minimum is zero and the maximum is ten times a packet transmission time. Acknowledgments are used only in unicasting scenarios. Additionally, we implemented full-duplex mode which is established to be feasible for V^2LC in the full-duplex feasibility section, and there are four co-located pairs of transmitters and receivers on each vehicle, i.e., our node model in the simulation. We also implement the field-of-view angle's binary indication property in Chapter 4, and our MAC 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 bodies.

Simulation Parameters. Table 5.2 lists simulation parameters 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

Table 5.2 : Simulation Parameters

parameters	values	parameters	values
Num. of vehicles	30	Half-angle	50°
Acceleration	[-3,3] m/s^2	Field-of-view angle	12 °
Num. of lanes	3	Packet size	481 bits[§]
Vehicle length	4.5 m	Data rate	2 Mbps
Vehicle width	1.5 m	Trans. range	101 m
Lane width	2.5 m		

following parameters are different: 29 infrastructure nodes with a spacing of 120 m placed in the rightmost lanes, and 20 vehicles traveling 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 vehicles in the leftmost lane and infrastructure nodes in the rightmost lane, and we study V^2LC's performance with such a blockage.

[§] A representative value specified by [5]

5.2 Multihop Inter-vehicle Forwarding

Scenario. The front most vehicle in the cluster initiates the information flow, and the information is disseminated backwards by the multihop inter-vehicle forwarding. This scenario occurs, for example, when a vehicle discovers an incident on the road and needs to warn all other vehicles. In this case, we measure reachability as the percentage of vehicles receiving the information, and delay as the time difference between when this piece of information is sent by the initiator and when it is last received. We also investigate the effects of packet collisions on V^2LC's performance in reachability and delay because they can cause certain paths to reach vehicles unusable.

Figure 5.1 (trend lines in figures are provided for clarity purposes) shows the reachability as a function of the average inter-vehicle distance. The reachability is 100% for the inter-vehicle distance smaller than 66 m. With the inter-vehicle distance greater than 66 m, the reachability ranges from 40% to 100%. In order to find out the reason behind such wide variations in reachability, we draw the percentage of collisions vs. average inter-vehicle distance in Figure 5.3. We observe that the 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, remains between 20% and 33%, and yet the collisions affect the reachability significantly for the 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 impact the reachability, collisions would need to occur on all the available paths, whose probability is small. As the inter-vehicle distance increases, and the number of available paths decreases, the probability of all the paths being impacted by collision increases. Thus, there is a decrease in reachability. The variation in reachability is due to the random movements of the vehicles, which randomizes the number of available paths.

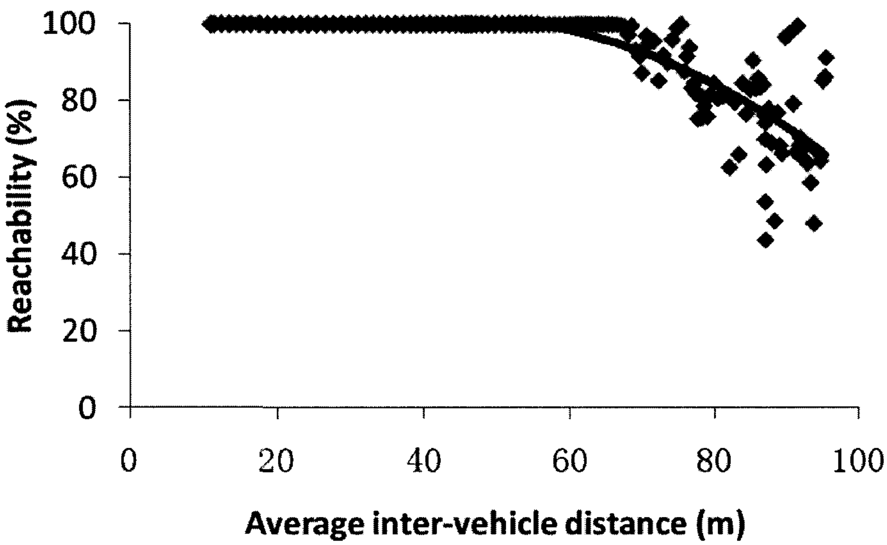

Figure 5.1 : Reachability in multihop inter-vehicle forwarding

Figure 5.2 plots the delay of V^2LC in multihop inter-vehicle forwarding as a function of the average inter-vehicle distance. We observe a generally increasing trend in delay. The increase is attributed to two factors. One factor is the rise in the number of hops required to reach vehicles as the inter-vehicle distance increases. The other factor is the effect of packet collisions as they may cause certain paths to become unavailable, and therefore a longer delay to reach vehicles is required. We also observe that as the inter-vehicle distance increases beyond 40 m, there is a variation in delay ranging from 7 ms to 27 ms. The reason for such a variation in cases of larger inter-vehicle distances is similar to that for the variations in reachability. Additionally, we find that delay is more sensitive to the impact of packet collisions than reachability, as the break point, i.e., when the wide variation occurs, is 40 m for delay as compared to 66 m for reachability. One explanation is that collisions affect when packets can arrive at the vehicles, but the reachability remains unchanged as long as packets can reach the vehicles.

Having seen that the impact of packet collisions on reachability and latency is negligible for short inter-vehicle distances, we now evaluate the effects on reachability and latency with an increase in packet collisions. In this scenario, the two most front vehicles initiate information to be sent in the multihop inter-vehicle forwarding at the same time. It almost doubles the amount of transmitted information among vehicles and the number of packet collisions. This scenario is one of the worst cases for the following two reasons. First, the initiators in the front will often observe the same event. Before vehicles retransmit information from the initiators, they should have a mechanism to first check if it is any new information. If not, the information will not be retransmitted to prevent unnecessary network flooding. Second, vehicles normally do not initiate information at the same time. As shown in Figure 5.2, if the time difference between two initiations is more than 0.03 s, one has finished its multihop inter-vehicle forwarding before the other one starts. Nevertheless, even in this worst case scenario, we did not observe any performance degradation in either reachability or latency.

Findings. (*i*) V^2LC satisfies the 100% reachability and latency as low as 20 ms requirements in critical traffic conditions, with a Level-of-Service D or below (i.e., with an inter-vehicle distance 66 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 inter-vehicle distance is short because there are a large number of paths to reach vehicles.

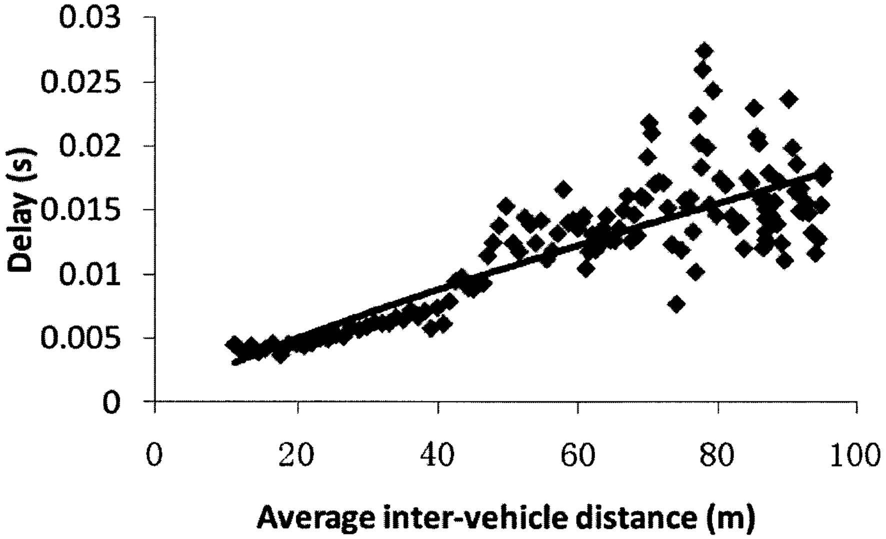

Figure 5.2 : Delay in multihop inter-vehicle forwarding

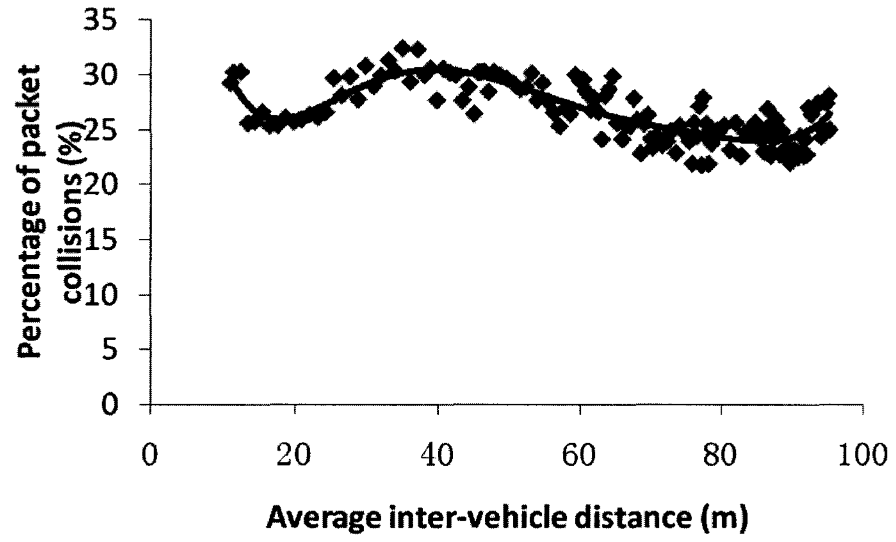

Figure 5.3 : Percentage of packet collisions in multihop inter-vehicle forwarding

5.3 Limited Neighbor Broadcasting

Scenario. Every vehicle in the cluster performs limited neighbor 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 vehicles within a vehicle's proximity which can successfully receive the information. Two vehicles are considered in proximity of one another if the distance between them is 18 m 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 0.00024 s, which is the packet transmission time over one hop; the propagation delay is negligible.

Figure 5.4 shows the reachability of V^2LC as a function of the average inter-vehicle distance. When the inter-vehicle distance is smaller than 50 m, the reachability varies from 42% to 60%. With the inter-vehicle distance greater than 50m, the reachability variation range is 25% to 98%. The wider range for larger inter-vehicle distances is a result of the fact that as the inter-vehicle distance increases, the vehicle cluster expands. Recall from Section IV that the field-of-view angle has a binary indication on the success of the communication between the transmitter and the receiver, and our node model where the VLC transmitters are vehicle headlights and brake lights, and the VLC receivers are co-located with them. When the vehicle cluster is compact, vehicles can only hear from the vehicles to their front and back, and 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 if the receiver can receive from the vehicles in their proximity.

Given the high probability of being out of the field-of-view of the neighboring vehicles, it is expected that with the neighbor 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 in such a way that the aggregate field-of-view angle is increased.

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

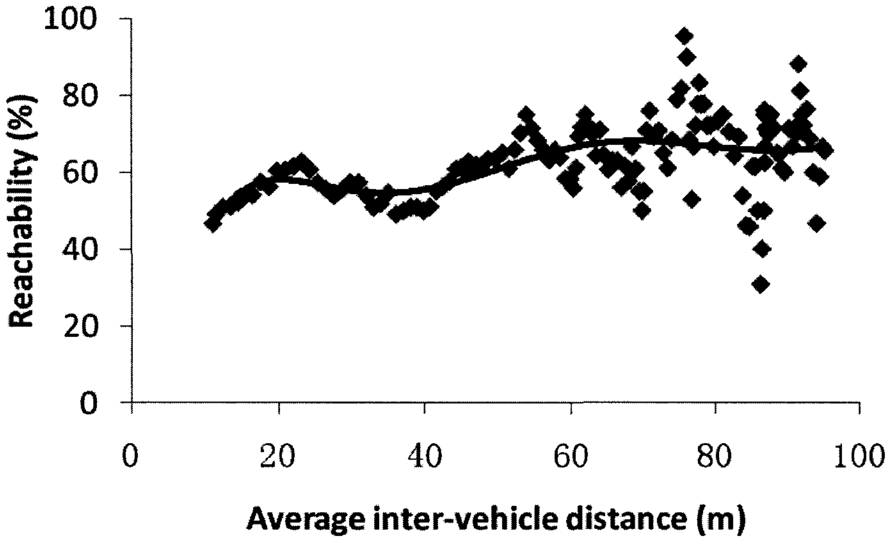

Figure 5.4 : Reachability in limited neighbor broadcasting

5.4 Infrastructure-to-vehicle One-hop Broadcasting

Scenario. Every infrastructure node broadcasts to the vehicles within its transmission range. This can serve as the last-mile connectivity for vehicular applications that require information from the gateways. We measure the 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 the previous subsection, since information exchange is over one hop, the delay is at the constant value of 0.00024 s.

We show the reachability of V^2LC as a function of the average inter-vehicle distance in Figure 5.5. For the inter-vehicle distances greater than 22 m, the reachability is 100%. For the inter-vehicle distances less than 22 m, some vehicles in the leftmost lane are blocked by the vehicles in the middle lane, and they cannot receive the packets transmitted by the infrastructure nodes located in the rightmost lane. Hence, the reachability is less than 100%.

We make the observation that for the average inter-vehicle distances of 22 m or more, although there are vehicles in the middle lane blocking the vehicles in the leftmost lane, V^2LC opportunistically uses the gaps among the vehicles in the middle lane to reach the vehicles in the leftmost lane. In order to increase the reachability of V^2LC in smaller inter-vehicle distances, either the number of the infrastructure nodes can be increased to reduce the "blind spots," or the infrastructure-to-vehicle one-hop broadcasting can be combined with the multihop inter-vehicle forwarding service to extend the coverage of the infrastructure nodes. Based on the results of the multihop inter-vehicle forwarding section, it is expected that the combining the two services would increase the reachability of V^2LC to 100%.

Findings. Since V^2LC operates in the visible light spectrum, vehicles can block one another and impact their reachability. However, the mobile nature of the vehicular environment enables opportunistic transmissions for V^{2}LC through dynamic appearances of gaps in a traffic stream.

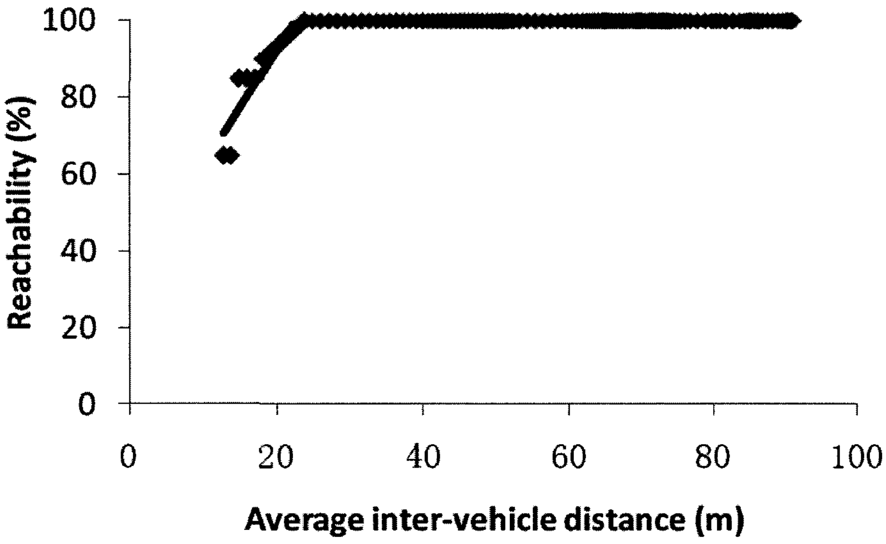

Figure 5.5 : Reachability in infrastructure-to-vehicle one-hop broadcasting

5.5 Vehicle-to-infrastructure One-hop Anycasting

Scenario. Each vehicle anycasts to the infrastructure nodes. This network service is used with a backbone network in which the infrastructure gateways are interconnected. In this scenario, the reachability is the percentage of vehicles whose transmissions are successfully received by any infrastructure node. Delay is defined as the time span that it 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 0.00024 s.

Figure 5.6 shows the reachability of V^2LC as a function of the average inter-vehicle distance. When the inter-vehicle distance is smaller than 26 m, vehicles in the middle lane hinders the infrastructure nodes in the rightmost lane from receiving information from the vehicles in the leftmost lane. As a result, the reachability is less than 100%. With inter-vehicle distances greater than 26 m, the reachability is 100%. We observe similar trends in results depicted in the previous scenario and this scenario. In the previous scenario, however, the probability of collision is lower, since every car is at most within transmission ranges of two infrastructure nodes, whereas in this scenario, an infrastructure node can hear packets from multiple vehicles. We note that even though there are more packet collisions in this scenario, in both cases reachability of 100% has been achieved for average inter-vehicle distances higher than 26 m. Similar approaches as in scenario of the previous section can be taken to increase the reachability for smaller inter-vehicle distances.

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

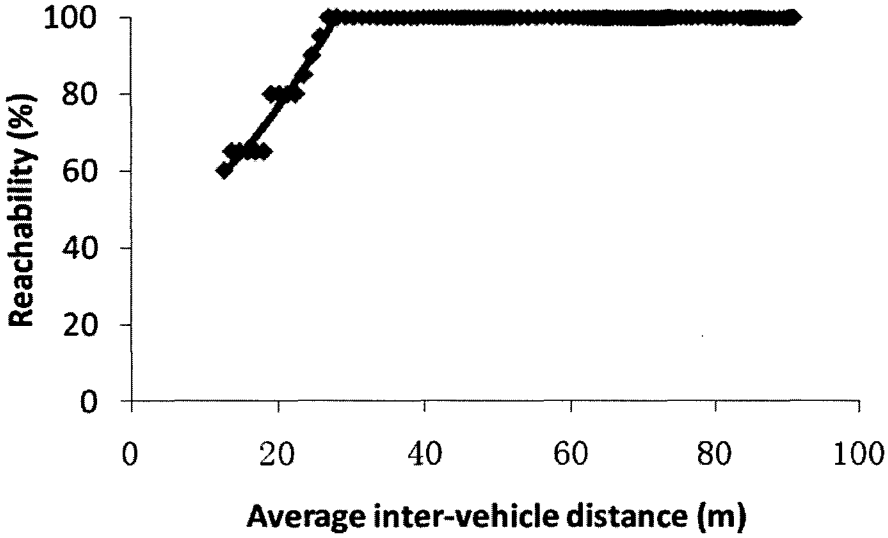

Figure 5.6 : Reachability in vehicle-to-infrastructure one-hop anycasting

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 5.7 shows the normalized throughput in three traffic conditions as a function of CBR rates, where the normalized throughput is defined as the ratio of the number of received bits to V^2LC data rate, 2 Mbps. We observe that the normalized throughput is the highest in the high density scenario. This is because in denser traffic conditions, there are more routes to the gateway infrastructure node as a result of V^2LC's high spatial reuse. We also observe that the normalized throughput saturates at 1700 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 thesis.

Findings. Denser traffic conditions result in more available routes, which is a direct consequence of high spatial reuse in V2LC networks. Therefore, V2LC achieves higher throughput.

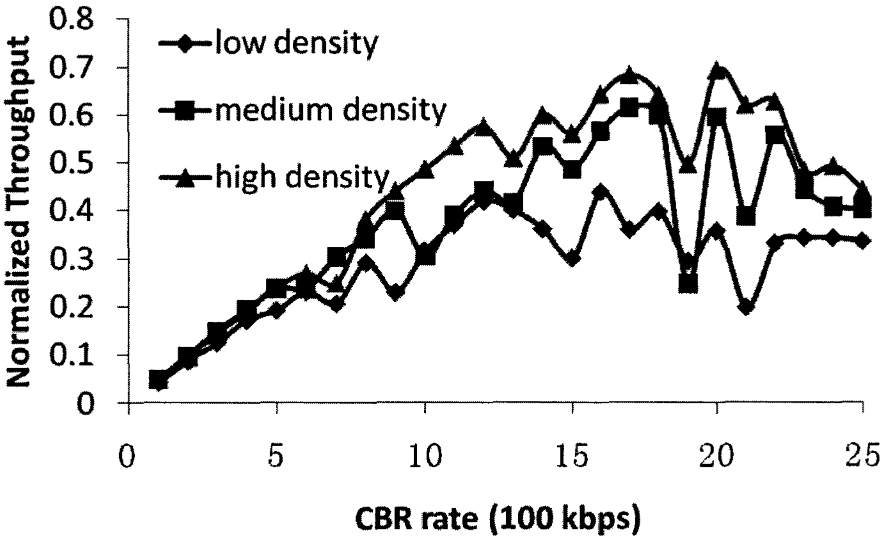

Figure 5.7 : Normalized throughput vs. CBR rate

Chapter 6

Related Work

6.1 VLC Link Speed.

Prior work has investigated constructing single VLC links and increasing the link speed via optical techniques and modulation schemes. [10] reports a VLC link speed up to 80 Mbps by using pre-equalized white LEDs. In [11], the authors demonstrate a VLC link with speed up to 200 Mbps by using discrete multi-tone modulation. Recently, researchers at Siemens achieved a VLC link speed up to 500 Mbps [12]. These studies show that the VLC link speed has progressively increased. In contrast, we have a focus on the networking properties with multiple VLC links. We show that the VLC receiver's field-of-view angle has a binary indication on transmissions and perceived interference.

6.2 VLC System Implementations.

Beyond link rate, a number of single-link VLC systems have been proposed for proof-of-concept purpose. Visible Light Communication Consortium in Japan demonstrates a VLC system, in which two computers use lamps to communicate with each other in [13]. In [14], data is transmitted uni-directionally from a traffic light to a vehicle.

These proof-of-concept systems have demonstrated that VLC is a feasible technology for data communication. In contrast, we have a focus on the introduction of V^2LC architecture. Additionally, we identify five network services that V2LC need to provide for all vehicular applications.

6.3 VLC in Indoor Environments.

A number of VLC systems have been proposed for usage in home and office settings. In [15], 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. In [16], the EU OMEGA project plans to use VLC and infrared to achieve a transmission speed at 1 Gbps in home settings. Because of an existing infrastructure in indoor lightings, VLC has garnered significant interest for indoor applications. However, our study differs from theirs in two ways. First, we study VLC in a vehicular environment that poses different challenges from indoor environments. Second, we have a focus on evaluating V^2LC's network services.

6.4 Standardization.

There are two standardization processes that are related to our work. One is 802.11p [2], and it aims to enhance 802.11's capabilities in vehicular environment. The other is 802.15.7 [17], and it standardizes PHY and MAC for VLC personal area networks. Our work is complementary to the standardization processes. On a VLC research platform, we provide experimental results on V^2LC's networking properties. Moreover, we provide simulation results on V^2LC's services for vehicle safety and internet access applications.

Chapter 7

Future Work

Although VLC is still in an infant development stage, it has become a fast burgeoning technology in the wireless world. Much of the previous work has been done on single links, such as increasing link speeds and proof-of-concept systems. We investigate VLC from a networking perspective. However, our research is still at an early stage, and we need to address several open problems. Having found that VLC has a high spatial reuse, it opens door for research on MIMO with VLC. A node can be equipped with multiple VLC transmitters and receivers, and they can transmit and receive simultaneously in a system design with MIMO. Therefore, we aim to design a more flexible VLC research platform and conduct research on VLC MAC regarding its MIMO potentials. This platform will need to provide design environment and tools for MAC and PHY layers development. For example, the WARP board developed at Rice University is good candidate. Further, we intend to evaluate VLC in real vehicular traffic environments. Such environments offer many real-world challenges, such as the visible light blockage by vehicular bodies and noise from sunlight and other lighting sources.

Chapter 8

Conclusion

In this work, we describe V^2LC networks' architecture and introduce the five network services that are needed for vehicular applications. We build a custom VLC research platform, and we are the first to investigate the unique networking properties of V^2LC. We show that V^2LC is resilient against visible light noise and interference, and it can enable full-duplex mode. Further, we show that V^2LC can satisfy the stringent reachability and latency requirements in dense vehicle traffic conditions.

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