**Visible Light Communications: The Road to Standardization and Commercialization**

Smart Automotive Lighting for Vehicle Safety

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**Abstract**

It is believed that vehicle-to-vehicle (V2V) communications and accurate positioning with sub-meter error could bring vehicle safety to a different level. However, to this date it is still unclear whether the envisioned V2V standard, dedicated short-range communications, can become available in commercially available vehicle products, while widely available consumer-grade GPS receivers do not provide the required accuracy for many safety applications. In this article, combining visible light communications and visible light positioning, we propose the use of smart automotive lighting in vehicle safety systems. These lights would be able to provide the functions of illumination and signaling, reliable communications, and accurate positioning in a single solution. The proposed solution has low complexity, and is shown to be scalable in high vehicle density and fast topology changing scenarios. In this article, we also present several design guidelines for such a system, based on the results of our analytic and empirical studies. Finally, evaluation of our prototype provides evidence that the system can indeed detect potential risks in advance and provide early warnings to the driver in real-world scenarios, lowering the probability of traffic accidents.

**Introduction**

The conventional paradigm for vehicle safety has been an “independent” approach — to incorporate a large number of sensors in each vehicle so that sufficient coverage can be provided to identify neighboring objects that could cause accidents. The main downside of such an approach is the high cost of the system as a result of the large number of sensors. Recent advances of communication and networking technologies have enabled a new cooperative paradigm for vehicle safety systems, in which, via direct vehicle-to-vehicle (V2V) communication links, vehicles not only share information about their current status such as positions and speed, but also what they observe of neighboring objects at different locations. The advantages of the new paradigm include:

- Wireless communications and networks can penetrate or route around (i.e., utilizing multihop communications) obstacles blocking line-of-sight (LOS), effectively extending the sensor coverage to include all of those neighboring vehicles.
- Cooperation among vehicles can reduce uncertainty of measurements [1], such as the position and the speed of a certain vehicle, in multiple ways:
  - *Self-information* of a vehicle is more accurate than observations from neighboring vehicles.
  - *Observations from a nearby vehicle* are more accurate than observations from a distant vehicle.\(^1\)
- *Combining observations* of the same object from multiple vehicles can reduce the noise in the measurements.
- The system can have lower cost as a direct result of the lower required number of sensors in each vehicle — information does not have to be only from on-board sensors, but also from sensors in neighboring vehicles.

**The Cooperative Paradigm Requires Reliable V2V Communications**

Dedicated short-range communications (DSRC) is often considered the most promising V2V technology [2]. The technology incorporates a set of physical, data link, and higher layer standards that use the 5.9 GHz radio spectrum to enable V2V and vehicle-to-infrastructure (V2I) communications. Although the standards in DSRC have been drafted or ratified for more than a few years, to this date there is still no commercial adoption of the technology. The future of DSRC is not clear as of today. For example, the U.S. government will make a decision regarding the technology at the end of 2013.

\(^1\) For example, when estimating the distance to a vehicle using a camera.
based on real-world tests carried out in the past two years [3]. The main reason that V2V technology has not yet seen its adoption is that there is very low incentive for early adopters to purchase a new vehicle with the technology. Many envisioned applications that use multihop communications require a minimum market penetration rate of 10 percent or more [4].

The implication of the 10 percent minimum market penetration is that even if every new vehicle were equipped with a new V2V radio starting from today, it will still take more than two years before these applications can be functional on the road. As a result, early adopters do not gain any benefit in purchasing a V2V-equipped vehicle, which has a higher price tag. To jumpstart the initial market penetration rate, we believe the key directions include:

- To discover applications that can immediately provide benefits to the driver on the day they obtain the new vehicle
- To lower the complexity of the technology so that the added cost to the vehicle product is minimized, and we do not rely on a large sale quantity to bring down the costs. This implies that the communications technology should be designed to fulfill the requirements of only a small set of key applications.

Visible light communications (VLC) utilize modulated optical radiation in the visible light spectrum to carry digital information in free space. A VLC system usually uses an LED as the transmitting component and a photodiode as the receiving component. Over the past five years, LED has become very common in automotive lighting due to its long service life, high resistance to vibration, and better safety performance due to its short rise time. Today, LEDs can be found in center high mount stop lamps (third brake lights), brake lights, turn signals, and headlamps in many commercial vehicles. As a result, VLC becomes a new and attractive solution to realize V2V communications [5–7] in a completely different way.

In this article, we propose the use of VLC in vehicles for several key safety applications, creating smart automotive lighting that combines the functions of illumination and signaling, communications, and positioning. As shown in Fig. 1, in the case of cars, a VLC transmitter is connected to each of the two headlamps and two taillights to create four VLC-capable lights transmitting the same signal; a photodetector is placed next to each of these four lights and connected to a VLC receiver. Additional photodetectors can be installed on the rear facing side of each of the two side rearview mirrors to provide communication coverage to vehicles on the side. In the case of motorcycles or scooters, both the headlamp and the taillight are connected to the VLC transmitters, creating two VLC-capable lights transmitting the same signal, and a photodetector is installed right next to each of these two lights and connected to VLC receivers. As the optical signal is modulated at a high frequency, persistence of vision causes these optical signals to be invisible to human eyes. Therefore, the VLC-capable lights can still retain their original illumination and signaling functions.

The unique properties of optical propagation and VLC present many advantages over conventional radio frequency (RF) communications for safety applications:

**Low complexity and low cost**: The design of the VLC transmitter and receiver is much less complex than a comparable RF transceiver, due to a much less severe multipath effect. Combined with simple modulation schemes and the fact that the main transmitting component, LED, already exists in vehicles, this minimizes the additional cost to realize smart automotive lighting.

**Scalability**: In scenarios with high vehicle density, conventional V2V communications using RF typically experience longer delay and lower packet reception rate due to the large number of nodes that participate in channel contention. An adaptive transmission power scheme can be used to mitigate the problem, but requires high overhead to accurately estimate the number of nodes in the neighborhood, which could also reduce the reliability. On the other hand, in the case of VLC, only a small number of nodes within direct LOS of the receiver are in the same contention domain, and those nodes are of the most importance since they are the vehicles most likely to collide with the receiving vehicles. This filtering mechanism depends on the optical propagation property, does not require any overhead, and hence is highly scalable.

**Positioning capability**: Due to the high directivity of visible light propagation, it is possible to perform accurate relative positioning between vehicles [8]. Compared to a typical positioning error of up to 10 m with GPS [9], the positioning error of visible light positioning (VLP) is on the order of only tens of centimeters, much more suitable for vehicle safety applications.

**Security**: For a malicious attacker to send falsified information or jam a VLC receiver, due to the closer operation range and the LOS-only propagation property of VLC, the attacker has to be in visual range of the victim vehicle for an extended period of time, which renders the action less likely compared to when using conventional RF communications. In addition, the positioning capability can be used to provide an additional layer of security by verifying whether the received message is sent from a correct or possible position.

VLC also presents a few challenges when used in outdoor environments, most of which have been investigated in existing literature [10].

**Severe weather conditions**: Heavy fog, rain, or snow could create additional attenuation to the transmitted optical signal, shortening the operation range. However, existing work [11] has shown that a VLC receiver has better sensitivity than human eyes; this implies that, in these drastic weather conditions, VLC will be able to receive a message before human eyes can perceive the light from the same transmitting light, proving the usefulness of VLC.

**Sunlight and ambient light**: Direct sunlight or strong ambient light could saturate the VLC receiver. This is usually addressed by utilizing a frequency higher than 1 kHz and a high pass filter to eliminate the majority of the solar radiation power. However, the shot noise induced by...
Combining the communication and positioning capabilities of smart automotive lighting and integrating them into the vehicle safety system, each vehicle can build a map which has the relative positions, as well as the speed, the brake status, the heading, etc., of all surrounding vehicles that has a direct path to it.

The rest of this article is organized as follows. We present a few applications that are enabled or enhanced by smart automotive lighting. We present the evidence that VLC is more scalable to vehicle density and rapid topology change than RF communications for vehicle safety applications. We show the results from a numerical analysis to quantify the positioning error performance of VLP for vehicles. We present the design of our smart automotive lighting prototype on two scooters and the results of a real-world evaluation of our prototype. Finally, concluding remarks and future work directions are given. In addition, a brief overview of the VLC link budget model is presented in the appendix.

APPLICACIONS

COLLISION WARNING AND AVOIDANCE

Combining the communication and positioning capabilities of smart automotive lighting and integrating them into the vehicle safety system, each vehicle can build a map that has the relative positions, as well as the speed, brake status, heading, and so on of all surrounding vehicles that has a direct path to it (and thus the VLC transmission is not blocked). The relative positions can be obtained by VLP, while the others can be obtained from packets sent via VLC by other vehicles. The map with the estimated positions of these vehicles can be presented to the driver so that he/she can adjust the vehicle’s heading or speed to avoid collisions. The system can also provide early detection of stopped and overtaking vehicles. In addition, the information can be used to estimate the trajectories of these vehicles in the next few seconds; if the projected paths of two vehicles cross with each other, a warning can be presented to the driver to take appropriate evasive actions or slow down. Cooperative forward collision warning, which utilizes the same concept, is identified as one of the eight high-priority and representative vehicle safety applications enabled by DSRC [12], [12] also identifies the requirements for the application: the maximum required communication range is 150 m, the latency needs to be less than 100 ms, and the size of the application payload is 419 bits (53 bytes). Smart automotive lighting can certainly satisfy these requirements and offer a low-cost alternative to DSRC, while it can also provide more accurate positioning than GPS.

LANE CHANGE ASSISTANCE/WARNING

Similar to the collision warning and avoidance application, a map with the positions and speed of all surrounding vehicles is created in each vehicle, including those in nearby lanes. When the driver indicates that he/she will change to a different lane by switching on the turning signal, the system can provide indication of when the lane change can take place based on the map, and can provide a warning if the driver starts to turn the steering wheel while the trailing vehicle in the target lane does not have a sufficient gap from its preceding vehicle for the vehicle to move into that lane. This application requires very accurate positioning to identify the lane in which each surrounding vehicle is traveling, which cannot be provided by GPS. The high positioning accuracy of VLP makes smart automotive light an attractive solution for this application. VLC can also satisfy the communication requirements: a maximum required communication range of 150 m, a latency lower than 100 ms, and a payload size of 36 bytes [12].

COOPERATIVE ADAPTIVE CRUISE CONTROL

An adaptive cruise control (ACC) system automatically adjusts the speed of the vehicle according to the readings of an onboard ranging sensor, typically a radar or a laser imaging detection and ranging system (lidar), which reports the distance of the preceding vehicle. One of the most important design goals of ACC is to increase road capacity by shortening the gaps between vehicles, but without compromising road safety. However, it has been shown that the inaccuracy and processing delay introduced by the ranging sensor severely limit the potential of ACC. Today, commercially available ACC systems are usually offered as an automatic system at a high price of a few thousand U.S. dollars, which further decreases the driver’s incentive to adopt such a system. A cooperative adaptive cruise control (CACC) system, in addition to the onboard ranging sensor data, incorporates the more accurate self-information transmitted from the preceding vehicle (e.g., acceleration, and braking capability) via a V2V communication link. Studies show that such a system could overcome the aforementioned limitations and is capable of operating CACC with a time gap of 0.6 to 1.1 s between vehicles as opposed to 1.1 to 2.2 s for ACC [13]. This translates to an 80 percent increase in road capacity at 100 percent market penetration rate [1] compared to the saturated road capacity (2200 vehicles/lane/h) when not using any automatic system. We believe that the proposed smart automotive lighting system is perfect for use in a CACC system. As a communication system to carry the information from the preceding vehicle, VLC has more than sufficient data rate and delay performance for CACC. In addition, VLP offers the positioning capability that can be used to determine the distance to the preceding vehicle, eliminating the need to have a separate high-cost ranging sensor.

SCALABILITY

For vehicle safety applications, the main concern is collision with nearby vehicles. Therefore, the driver’s situational awareness should be confined to a small potential collision area. Vehicles in this area, to which we refer in this article as critical neighbors, include the leading and following vehicles in the same lane or vehicles in different lanes in blind spot positions. For safety purposes, being aware of such neighbors can reduce the chance of accidents and increase road safety.

With the current DSRC technology, drivers can be aware of most vehicles within a 300 m range despite an obstruction between the transceivers. Hence, DSRC can possibly detect...
all critical neighbors and many additional non-critical neighbors. With VLC, on the other hand, we claim that while the number of neighbors that can be detected is far fewer than that detected by DSRC, most of them will be critical neighbors. In fact, the number of vehicles that can be detected by VLC depends on the topology of nearby vehicles, which can either emit or block light. In other words, VLC coverage scales with the topology and only includes vehicles of which the drivers should be aware.

**Simulation Setup**

To further illustrate how VLC differs from DSRC, we conducted a simulation study of an urban scenario with a vehicle arrival rate of 1 vehicle/s on a straight three-lane one-way road of length 2.4 km. With fixed transmission power, the VLC range varies with the alignment angle and relative positions of the surrounding vehicles. In the simulation, each vehicle is assumed to be equipped with two 80 W headlamp transmitters and two 30 W taillight transmitters, both with a half-power angle of 20°. The ranges of these two types of light sources are approximately 260 and 160 m with 0° alignment angle, respectively. Each of the four receivers is assumed to be placed at the same locations as the transmitters (i.e., at the two headlamps and two taillights), and an optional receiver is placed at each of the two side mirrors, as shown in Fig. 1.

To measure the usefulness of the network connectivity, we compare the number of neighbors that can be detected by different technologies with the number of critical neighbors. The alternative technology we considered is the DSRC technology with an omnidirectional RF range of 200 m. Since VLC is directional, we also compare our results with a bidirectional DSRC transceiver whose maximum gain is in the forward and backward directions with 90° horizontal beamwidth. The bidirectional RF range considered is also 200 m. The simulation time is set to 2000 s. However, the considered road topologies are a series of vehicular traffic snapshots at every 2 min interval starting from the time instance of 300 s into the simulation.

**Comparison Study of VLC and DSRC**

**Number of Neighbors**

Figure 2a shows the probability mass function (PMF) of the number of neighbors that can be detected by different technologies: VLC with four receivers, and omnidirectional and bidirectional DSRC. According to the results, it is clear that DSRC (RF) can communicate with a lot more neighbors than VLC. That is, on average, it can detect about 32 vehicles in all directions with omnidirectional DSRC, while the number neighbors reduces slightly by 1–2 neighbors with bidirectional DSRC. On the other hand, the number of neighbors that can be detected by VLC is much fewer. More specifically, if we allow loose VLC neighbor detection (using only the less accurate positioning provided by GPS), with at least one link being established between any transmitter/receiver pair, each vehicle will have approximately eight neighbors. However, in order to use the accurate relative positioning provided by VLP, we need a stricter detection rule with at least three VLC links established. In that case, the average number of neighbors is approximately five, which is only slightly greater than the average number of critical neighbors.

**Critical Neighbor Detection Rate**

In terms of detection performance, we also measured the percentage of critical neighbors that can be detected by VLC. Figure 2b shows a complementary cumulative distribution function (CCDF) at different detection rates with different technologies. By using four VLC receivers, at least 82 percent of the vehicles can detect all the critical neighbors. This ratio increases to 99.8 percent when we have an additional pair of
receivers at the two side mirrors. By analyzing our results in detail, we have discovered that the missing 0.2 percent are usually the neighbors in distant blind spots, which are at least two lanes away from the considered vehicle (e.g., the neighbor is on the side but the leftmost lane while the considered vehicle is in the rightmost lane. We claim that while these critical neighbors are of lower priority than the ones directly on the side, which could potentially cause an accident, we could possibly exploit the neighbors’ broadcast information of their local map to indirectly detect these neighbors. However, if we applied a strict VLC detection scheme, only 70–75 percent of the vehicles can detect all critical neighbors. An in-depth analysis shows that these critical neighbors that cannot be detected by the strict VLC scheme are mostly in blind spot areas, but they can typically be detected by using the loose VLC detection scheme with six receivers.

As for DSRC, omnidirectional RF can detect all critical neighbors, while bidirectional RF fails to detect a much greater number of critical neighbors because of the missing signal radiation in blind spot areas. Hence, the performance of bidirectional DSRC is similar to that of the loose VLC scheme with four receivers.

Discussion — While it seems that DSRC outperforms VLC, we note here that the presented results do not take into account the inter-node interference. With a much greater number of neighbors, it is very likely that some of the communication will be in error if one uses DSRC technology (or RF in general) because of the missing signal radiation. Hence, the performance of bidirectional DSRC is similar to that of the loose VLC scheme with four receivers.

number of neighbors when using VLC remains roughly constant $O(1)$, because of the dynamic nature of the VLC range caused by the light blocking effect. Hence, for safety purposes, VLC is a promising alternative to DSRC.

POSINGION

VLP has become an active research topic in the past few years. In indoor environments, strong signal attenuation prevents GPS from providing accurate location information, and VLP appears as an attractive alternative because lights are generally installed throughout a building for illumination. In a typical VLP system, each LED emits a modulated optical positioning signal, which can be used by the receiver to determine the absolute location of the light (by the ID information embedded in the signal) and the distance to the light. Combining the results obtained from multiple lights, the receiver can then use geometrical calculation to accurately estimate its own position with an error of tens of centimeters.

A similar configuration can be used for vehicle relative positioning [8]. In such a system, each taillight or headlight emits a high frequency sinusoid, and the receiver can then measure the phase differences of the receiving sinusoids from different lights in the same vehicle. The difference of the distances to different lights can be calculated with the phase difference. When two or more sets of distance differences are available (i.e., more than three established VLC links between the two vehicles are available), they can be used to solve a set of equations to obtain the position of the vehicle with respect to the transmitting vehicle on the 2D plane. Compared to ranging sensors used in off-the-shelf vehicle products today, such as radar and lidar, VLP is much more cost effective, and its error performance of tens of centimeters is sufficient for most safety applications.

In this section, we present the results from a series of numerical analyses to determine the error performance of a VLP system, followed by

Figure 2. Comparison of the number of vehicles in the collision domain and the critical neighbor detection rates: a) PDF of the number of neighbors detected by different technologies; b) detection rate achieved by different technologies.
important design guidelines and system parameters that can be derived from the results. Results presented in this section assume no additional attenuation caused by severe weather conditions such as rain, snow, and fog. For details on the VLC link budget model used for the analysis, please refer to the Appendix.

**SIGNAL FREQUENCY**

When using the phase difference positioning scheme, thermal noise and shot noise add a random phase to the received sinusoid, which causes the positioning error. One way to mitigate the problem is to increase the frequency of the sinusoid. As the phase difference is inversely proportional to the frequency, the random phase caused by the noise has less influence on the positioning result when using a higher signal frequency.

When the signal frequency increases to more than 1 MHz, for most high brightness LEDs the effective transmission power at that frequency starts to degrade drastically. This is due to either the phosphor relaxation time of a phosphorescent LED or the parasitic capacitance due to the large die area of a high brightness LED; both effects are present and, depending on individual diode construction, one or the other would dominate to determine the actual response time. The response time of a LED is typically on the order of hundreds of nanoseconds. To improve the effective transmission power at the operating signal frequency, a resonant driving circuit needs to be designed and placed behind the LED component [14]. However, as the frequency increases, it becomes more complex to design such a circuit. Moreover, the processing performance required for high frequency signals also increase the system cost significantly. As a result, it is crucial to determine a frequency that can offer sufficient positioning accuracy for vehicle safety.

Figure 3 shows the mean positioning errors when using different signal frequencies. The target vehicle with its lights sending the VLP signal is assumed to be 40–50 m from the receiving vehicle, and is in the same lane, in the left or right lane with respect to the receiving vehicle. One can observe that a higher signal frequency can indeed reduce the positioning error significantly. To achieve a positioning error of less than 1 m for all lights on a vehicle 50 m away (2 percent error), the signal frequency needs to be more than 20 MHz.

**TRANSMISSION OPTICAL POWER AND HALF-POWER ANGLE**

Adopting high brightness LEDs (i.e., LEDs with high transmission power) increases the SNR and also reduces the influence of the random phase caused by the noise. Figure 4 compares the positioning error performance of a headlight (i.e., locating a following vehicle) and a taillight (i.e., locating a preceding vehicle). The middle of the front/rear bumper is assumed to be at the origin, with the two headlights/taillights located at (0.1) and (0.1). With the headlight, VLP can generate accurate positioning results with mean error less than 20 cm for a vehicle up to 50 m away. On the other hand, with the taillight, the system can generate positioning results with the same level of error for a vehicle up to 40 m away. The better error performance for a following vehicle makes sense in terms of vehicle safety, as it is more likely to be within the blind spots of the driver than the preceding vehicle is.

Existing lights in vehicles are usually designed to have a very small divergence angle; the lights are intended for vehicles directly in front or behind. Figure 4c shows the positioning error performance when the half-power angle$^5$ of the headlamp is only 20°, which is typical for automotive lighting. One can observe that a triangular blind zone with very high positioning error appears in the upper left corner, corresponding to a vehicle that is very close but slightly to the side. However, this could be problematic because when the vehicles are closer to each other, a higher positioning accuracy is required to prevent collisions. To avoid this problem, the lights need to have a larger divergence angle.

It is worth mentioning that other LED lights in the vehicle, such as the turning signals and third brake light, can also be used in VLP. On the other hand, as the transmission optical power of these lights is much less than that of the headlights and taillights, it can only be used to generate accurate positioning results for vehicles that are very close. However, this can sometimes still be useful. For example, the rear-facing turning signals on the side rearview mirror (only available in certain car models) can be used to locate vehicles on the side, which is not possible with headlights and taillights.

**PROTOTYPING EFFORT**

In this section, we present the design and the results from the prototyping effort to implement a VLC system using commercially available scooter LED taillights and software defined radios (SDRs). Scooters are one of the most important transportation means in Taiwan, and in several other Asian and European countries.

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$^5$ The typical recommended safety distance between vehicles on a highway.

$^6$ The angle at which the effective transmission power is only half of the maximum power.
revolution, brake status, and turning signal status from the scooter, and sends it to a laptop. In the laptop, digital packets with the information as the payload and a footer with forward error correction (FEC) code are created, and then modulated with 4-pulse position modulation (4-PPM). The packet goes through a digital-to-analog conversion in a SDR and is passed to the VLC frontend, which changes the light intensity of the LED taillight according to the input analog signal. On the receiving end, the photodetector converts the received optical signal to an electric signal, which goes through an analog-to-digital conversion in SDR. The laptop then performs the demodulation and decode processes to obtain the scooter information in the original packet. Finally, the information is sent to a smartphone mounted on the handlebar of the scooter. The smartphone presents a warning, and the information of a preceding scooter to the driver when a collision with this scooter is possible.6

The following presents a few key design considerations of the prototype, which can also serve as design guidelines for future commercial products.

• We choose to use SDR to implement the communication system of our prototype so that we have the flexibility to easily change various physical layer designs and networking protocols. To commercialize the system, these designs can be transferred to a field programmable gate array (FPGA) or an application-specific integrated circuit (ASIC) to reduce costs.

• We only implemented a one-way link with the taillight and a photodetector on the front of the scooter. A second link with an LED headlamp and a photodetector on the back of the scooter can be added in a similar way so that the communication link between the two scooters becomes bidirectional.

• Our choice of 4-PPM as the modulation format is due to its high power efficiency [16] — with the same optical transmission power, the modulation can achieve the highest range with the same bit error rate (BER).

• We do not use a lens in front of the photodetector, resulting in a wider 90° field of view (FOV) angle. A lens is usually used to increase the received optical power, providing a higher link signal-to-noise ratio (SNR) and thus a more reliable link. However, in that case it also decreases the FOV angle. Our measurement results of two different taillights indicate that the beam angle is only about 20°7 (see the packet reception rate contour with respect to the first successful reception location in the left plot of Fig. 6); as a result, receiving vehicles on the side already have smaller received power and less reliable links, and the FOV angle of the receiver cannot be further reduced. Instead, we choose to use a photodetector with a larger receiving area (100 mm2) at the cost of a lower receiving bandwidth (2.4 MHz). Since most safety applications do not need a data rate of more than 1 Mb/s, this trade-off does not limit our system performance. However, if a higher link data rate is desirable, the taillights need to be designed with a larger beam angle so that a lens can be used.

Figure 4. Mean positioning error when using headlamps and taillights. The white dashed lines represent the lane markings: a) headlight transmitter (80 W), half-power angle = 60°, f = 40 MHz; b) taillight transmitter (30 W), half-power angle = 20°, f = 40 MHz; c) headlight transmitter (30 W), half-power angle = 20°, f = 40 MHz.

In Taiwan, they account for approximately 70 percent of registered mobile vehicles, including cars, trucks, buses, and so on. In the past 10 years, they have been responsible for more than 75 percent of deaths in traffic accidents, resulting in more than 2000 deaths annually. As a result, it is crucial to quickly develop a cost-effective solution to improve their safety, and the objective of this effort is to evaluate the feasibility of integrating VLC as part of a safety system in commercially available scooters, as well as how they perform in real-world scenarios.

SYSTEM DESIGN

Figure 5 shows the system block diagram of our prototype. On the transmitting end, the electronic control unit (ECU) connector periodically collects information such as current speed, engine

6 This prototype is demonstrated in [15], and a demo video is available at http://goo.gl/0io199.
used. Alternatively, infrared LEDs, together with photodetectors covering both the infrared and visible light wavelengths, can be used together with existing lights to boost the SNR.

- Ambient light in the environment could interfere with VLC transmission and decrease receiving performance. To collect the optical spectrum on roads, a photodetector was mounted on the front bumper of a car to record received optical signals while the car was driven in a downtown area of Taipei, in both day and night. The obtained data reveals that the ambient light has most of its power in very low frequencies: 87.8 percent of the power is below 1 kHz during the day, while 58.6 percent of the power is below 1 kHz during the night. We also discovered that streetlights and illuminated signs are strong sources of interference, but concentrated mostly at 120 Hz and its multiples. Our system uses a carrier frequency at 100 kHz, and a high-pass or bandpass filter could remove most ambient interference.

**REAL-WORLD EVALUATION**

To evaluate performance of our prototype in the real world, we carried out a series of experiments that emulate the scenario where one scooter overtakes another scooter from a different lane. The experiments were carried out on a sunny day with no rain or fog. Both scooters operated at speeds between 10 and 40 km/h. The overtaking scooter is equipped with a VLC taillight transmitter, and 20-byte packets that contain information about the current speed, brake status, and so on were continuously broadcasted from the taillight at a data rate of 10 kb/s. The overtaken scooter is equipped with a VLC receiver and has the photodetector mounted on the front. If the overtaken scooter can start receiving the packets before the other is directly in front, the safety system could either send a warning to the driver or automatically lower the speed in advance, decreasing the severity of a potential collision or even avoiding it.

Figure 6 presents the packet reception traces of one of the experiments as well as the average packet reception rate combining all experiments. In the experiments, both scooters are moving, but the figures are plotted with the receiving (overtaken) scooter at the origin, showing the relative movements and locations of the overtaking scooter. The following observations can be made from the experimental results, and these preliminary results are encouraging in that it shows evidences that:

- There is no observable difference between the error performance of scooters operating at different speeds. This is expected, as with our system parameters the Doppler shift is only 0.037 Hz when the relative speed between the two scooters is 40 km/h, and 4-PPM is not sensitive to frequency shift.
- With an unmodified off-the-shelf scooter LED taillight, our results show that the front scooter can reliably communicate with the back scooter when they are more than 10–15 m apart. Most scooters in the urban area do not travel at speeds higher than 60 km/h or 16.67 m/s. This implies that, when a sudden traffic event happens directly in front, VLC allows the driver to have as much as 0.9 s to react to the event after receiving the warning. When feasible, the data rate could be reduced to increase the range, or, equivalently, the maximum reaction time, to a higher level. Note that most literature indicates that the time required for a person to react to the warning takes about 1 s.

- Figure 6 shows that the packets started to be received by the overtaken scooter more than 1 s before the overtaking scooter moves into its projected path. This allows sufficient time for the overtaken driver to react and avoid a potential collision.

**CONCLUSION AND FUTURE WORK**

In this article, we propose the use of VLC for vehicle safety applications, creating a smart automotive lighting system that combines the functions of illumination and signaling, communications, and positioning. The system provides an all-in-one low-complexity and low-cost solution that could replace a DSRC onboard unit and ranging sensors, and we believe this is important in bootstrapping the adoption of V2V communications in commercial products. Taking advantage of the propagation property of visible light, VLC can automatically limit its communication coverage to include only the

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7 The local safety regulation for scooters specifies the minimum light intensity at 30 m only up to 20° alignment angle as the tailight is designed to be seen by vehicles directly behind. Reflector shields are commonly used behind the LEDs to limit the beam angle and increase the light intensity at locations with small alignment angles. Our results seem to match the specification.

8 On a Yamaha Cygnus-X 125 (model year 2011) scooter.
vehicles that could potentially collide with its host vehicle, and thus is more scalable in both vehicle density and rapid topology change. Several useful design guidelines are also obtained from our studies:

- The beam angle of the current automotive lights are usually very small; a larger beam angle can provide better communications and positioning performance to vehicles on the side, that is, in different lanes.
- Additional photodetectors on the side rearview mirror could significantly improve the coverage to vehicles on the side.

Finally, our real-world evaluations of the prototype have provided evidence that the proposed system could indeed improve road safety by providing advance warnings to drivers before a potential accident might occur. Our next step is to develop a lightweight medium access control (MAC) protocol that allows multiple vehicles to transmit to the same receiving vehicle with minimum interference, as well as feasibility studies for a few specific safety applications.

**APPENDIX: VLC LINK BUDGET MODEL**

In an optical link, the channel gain is given as

$$H(0) = \frac{(m+1)A}{2\pi D_d^2} \cos^m(\theta)\cos(\psi)$$

(1)

where $m$ is the order derived from a Lambertian pattern, $A$ is the physical area of the photodetector, $D_d$ is the distance between the transmitter and receiver, $\theta$ is the angle of irradiance, and $\psi$ is the angle of incidence. The Lambertian order $m$ is given by $m = \ln \frac{2}{\ln (\cos \Phi_{1/2})}$ where $\Phi_{1/2}$ is the half-power angle. The equation only applies if $\psi < \psi_c$, where $\psi_c$ denotes the width of the FOV at a receiver; otherwise, $H(0) = 0$. In most cases in our scenarios, $\theta = \psi$, and is referred as the alignment angle in the article.

The received power $P_r$ can be derived from the transmission optical power $P_t$ as

$$P_r = H(0) \cdot P_t$$

(2)

and the SNR can be obtained by

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**Figure 6. Packet reception in overtaking scenarios.**
where $\gamma$ is the detector responsivity, $\sigma^2_{\text{shot}}$ is the shot noise variance, and $\sigma^2_{\text{thermal}}$ is the thermal noise variance.

Full details of the model can be found in [17].

REFERENCES