Tran-SET
Transportation Consortium of South-Central States
Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Vehicle Sensing and Communications using LED Headlights to Enhance the Performance of Intelligent Transportation Systems: Proof of Concept, Implementation, and Applications

Project No. 18ITSOKS01

Lead University: Oklahoma State University

Final Report

August 2019

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16. Abstract

This project investigates the use of vehicle light-emitting diode (LED) headlamp devices for improving the accuracy and reliability of traffic (sensing and communication) data measurements required for developing effective intelligent transportation systems (ITS) technologies and solutions.

Vehicular communication and sensing technologies are mainly based on conventional radio frequency (RF) or laser technologies. These systems suffer from several issues such as RF interference and poor performance in scenarios where the incidence angle between the speed detector and the vehicle is rapidly varying. Introducing a new sensing technology will add diversity to these systems and enhance the reliability of the real-time data. In this project, we proposed and investigated a novel speed estimation sensing system named "Visible Light Detection and Ranging (ViLDAR)" (patent pending).

ViLDAR utilizes visible light-sensing technology to measure the variation of the vehicle's headlamp light intensity to estimate the vehicle speed. Similarly, visible light sensing technology is used for data communication purposes, where the vehicle headlamp is utilized for wireless data transmission purposes. This project outlines the ViLDAR system simulations, implementation including hardware and software components, experimental evaluation in both laboratory and outdoor environments. The experimental measurement settings of the ViLDAR experiments are detailed. Encouraging results for both sensing and communication scenarios are obtained. The outcome of this proof-of-concept study both in the laboratory and outdoor validates the merit of the proposed technology in speed estimation (sensing) and data communication. The outcomes of this project will inspire a wide and diverse range of researchers, scientists and practitioners from the ITS community to explore this new and exciting technology. This project built initial steps in exploring this new sensing and communication modality using vehicle headlamps, leaving open a wide field for exploration and novel research.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ADC	Analog to Digital Converter
ASK	Amplitude Shift Keying
DSP	Digital Signal Processing
DRL	Daytime Running Light
ITS	Intelligent Transportation System
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging
PD	Photo-Detector
RADAR	Radio Detection and Ranging
RF	Radio Frequency
USRP	Universal Software Radio Peripheral
ViLDAR	Visible Light Detection and Ranging
VLC	Visible Light Communication
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

EXECUTIVE SUMMARY

Vehicular communication and sensing technologies are mainly based on conventional radio frequency (RF) or laser technologies. These systems suffer from several issues such as RF interference and poor performance in scenarios where the incidence angle between the speed detector and the vehicle is rapidly varying. Introducing a new sensing technology will add diversity to these systems and enhance the reliability of real-time data. In Intelligent Transportation Systems (ITS), visible light communication (VLC) has emerged as a powerful candidate to enable wireless connectivity in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links.

The introduction of light emitting diodes (LED) in automotive exterior lighting systems provides opportunities to develop viable alternatives to conventional communication and sensing technologies. Most of the advanced driver-assist and autonomous vehicle technologies are based on Radio Detection and Ranging (RADAR) or Light Detection and Ranging (LiDAR) systems that use radio frequency or laser signals, respectively. While reliable and real-time information on vehicle speeds is critical for traffic operations management and autonomous vehicles safety, RADAR or LiDAR systems have some deficiencies especially in curved road scenarios where the incidence angle is rapidly changing. In this project, we proposed and investigated a novel speed estimation system called Visible Light Detection and Ranging (ViLDAR[1]) that builds upon sensing visible light variation of the vehicle headlamp. The objectives of the project were: (1) implement the ViLDAR system in a real-world setting, (2) perform laboratory and field tests in various scenarios, (3) optimize the ViLDAR system performance, and (4) test the ViLDAR system in different applications.

We used ViLDAR to determine the vehicle speed estimation and evaluate its accuracy. We further present how the algorithm design parameters and the channel noise level affect the speed estimation accuracy. For wide incidence angles, the simulation results showed that the ViLDAR outperforms RADAR/LiDAR systems in both straight and curved road scenarios. The prototype of the ViLDAR system is successfully implemented and the implementation details are provided including used hardware and developed software components. The evaluation results (laboratory and outdoor (field)) are presented. The measurement settings of the ViLDAR experiments are detailed. Finally, following the same principles, a vehicle communication prototype was designed and implemented to transmit (broadcast) vehicle ID by using vehicle headlamps which can be utilized in different vehicular communication applications, e.g., arterial travel time measurements.

Promising results are obtained in the real-world environment/setting. This project built initial steps in exploring this new sensing and communication modality using vehicle headlamps. It serves as proof-of-concept to validate our original hypothesis of using vehicle headlamp for speed estimation. Much investigation is needed to quantify its capability and limitations and improve its utility. The areas of improvement include (but not limited to) optimization (both hardware and software) and calibration (and environment adaptive) of the algorithms.

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[1] Abuella, H., S. Ekin, and M. Uysal. System and method for speed estimation, detection and ranging using visible light in vehicles. *U.S. Patent No. 16/057,239*, Feb. 15, 2019.

1. INTRODUCTION

Through the application of sensors, communications, and information technology, intelligent transportation systems (ITS) offer proven solutions and strategies for improving transportation safety, mobility, and environmental sustainability. There have been numerous developments in vehicle sensing and tracking technologies. Examples of such technologies include inductive loop detectors, magnetic detectors, magnetometers, sonic detectors, video detectors, Bluetooth and Wi-Fi MAC address signal readers, cellular, and RADAR/LiDAR systems (Radio or Light Detection And Ranging). Likewise, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies have been developed for ITS applications (i.e., radio frequency (RF) wireless communications). Some examples of ITS applications that need wireless communication or sensing technologies are: collision avoidance, V2V, V2I, dynamic traffic light sequence, payments/billing in tollways *(1-5)*, etc.

Existing vehicle sensing/tracking and communications technologies suffer from certain limitations and disadvantages that can degrade the quality of information obtained from these systems in various environments. For instance, V2V communications using an RF system can be inefficient due to the possibility of high interference, limited RF spectrum, and power usage issues. Currently, the impact of V2V and V2I communications on the amount of RF spectrum usages is low, but this is expected to significantly increase in the near future. RF bands can quickly suffer from interferences when hundreds of vehicles located in the same vicinity try to communicate simultaneously, thus degrading the quality of acquired information severely. Furthermore, privacy concerns and power consumption are well-known limitations of image-based vehicle sensing/tracking systems.

Most vehicle manufacturers use light emitting diode (LED) headlights because of their long lifetime, energy efficiency, and short rise time. In addition, the automotive industry started to equip their vehicles with daytime running lights (DRLs), particularly vehicles with LED headlights because of their power efficiency. Research results indicate that DRLs help decrease inclement-weather related crashes by up to 28% for multi-vehicle and pedestrian crashes *(6,7)*.

If the LED headlights are switched on and off fast enough (modulation), it is possible to transmit information using the LEDs without a notable effect on the visibility of objects or the human eye. Therefore, LED vehicle headlights have great potential for *sensing* and *communication* purposes in ITS applications due to: (1) availability of the LEDs (hardware) in vehicles, (2) unique properties of visible light optical propagation, (3) immunity to the electromagnetic interference, (4) operation in unlicensed bands, (5) inherent safety and security, and (6) high degree of spatial confinement that allows high reuse factor. Consequently, the idea of using visible light communication (VLC) in the V2V communication via vehicle lights has become attractive. Utilization of vehicle headlights for communication purposes requires hardware modification to the vehicles LED headlights to transmit modulated signal (information). VLC is also appealing for data transmission in airplanes and vehicular scenarios in which the use of an RF band is restricted (or banned) due to the safety regulations (e.g., industrial parks such as in oil/gas/ mining industries and military vehicle platoons).

This project investigates the use of vehicle LED headlamp devices for sensing and communication purposes for improving the accuracy and reliability of traffic data measurements required for developing effective ITS technologies and solutions. This aligns with Tran-SET vision to use innovative techniques to overcome transportation challenges in the South-Central region. The purpose of this project is to develop a new sensing and communication modality that intends to complement the current methods (e.g., RF- and imaging-based) to increase reliability of sensing and communication data. It is well-known that the reliability in ITS technologies is crucial. Inherently, applications of this work can be any ITS technology that needs wireless "sensing" and "communication".

2. OBJECTIVES

Our long-term goal is to improve the accuracy and reliability of traffic data required for developing effective visible-light-based ITS technologies and solutions. The overall objective of this project is to perform a proof-of-concept for the ViLDAR system by conducting the following tasks:

1. Implement the ViLDAR system in a real-world setting.
2. Perform laboratory and field tests in various scenarios.
3. Optimize the ViLDAR system performance.
4. Test the visible light sensing and communication systems system in different ITS applications.

The aim is to assess the performance of the visible light sensing and communication systems in a real-world test setup and investigate the impacts of both system parameters and environment. We consider utilization of vehicle's LED lights as a *complementary and/or alternative technology* to current RF- and image-based data acquisition methods for ITS applications. Alternative sensing and communication methods can turn out to be useful to offload the RF channels and enhance the performance of ITS solutions, hence improve the quality of acquired information.

3. LITERATURE REVIEW

V2V and V2I sensing and communication technologies have received much attention by ITS researchers and industry in order to improve traffic operations and safety (*8)*. Most of the wireless V2V and V2I systems use RF technologies, which are well-established systems and operate at their highest potential. Examples of these systems include RADAR and LiDAR which determine the location and speed of vehicles. The theory behind RADAR and LiDAR systems is that they measure the change in frequency or travel time of the reflected RF waves from the targeted vehicle. Both RADAR and LiDAR have limitations and issues that can make the speed estimations unreliable *(9)*. One of these issues is the narrow beam-width required for accurate speed estimation.

LED headlamps are being widely used by vehicle manufacturers because of their longer life and less power consumption. Many researchers have investigated the use of visible light technology in V2V and V2I sensing and communication *(10-12)*. A hybrid system that uses a RF-based system and visible light communication (VLC) was introduced by Ucar et al. *(13)* to perform ITS functions. Cheng et al. compared VLC and RF channel in vehicular communication *(14)*.

During the past few years, VLC studies and its applications in V2V communications have increased significantly. There are numerous studies in the literature which have utilized VLC principles in V2V communication systems (see *(11-21)*). Using a proper channel model in VLC and sensing systems is critical. Hence, visible light channel models have been examined extensively in the literature, since they were first introduced by Gfeller *(22)*. Komine and Nakagawa *(23)* introduced a performance evaluation of visible-light wireless communication that paved the foundation of the current VLC research in general. Luo et al. *(24)* presented one of the most comprehensive studies addressing channel modeling for V2V applications based on VLC technology. They used analytical methods to model a wide range of factors in such a system. They characterized the daylight beam pattern of empirically measured low and high beams of LED headlights selected based on vehicle sale numbers. On the receiving side, their model accounts for the line-of-sight (LOS) and non-line-of-sight (NLOS) components of the signal, including the implications of the road surface on NLOS reflections. Kim, Cahyadi and Chung *(25)* did experimental tests on VLC-based V2V communications under fog conditions to check the performance of VLC under different weather conditions. While, Viriyasitavat, Yu and Tsai *(26)* used a Lambertian model and compared its results with the empirical results by using an off-the-shelf scooter taillight. Using the Monte Carlo ray tracing method, Lee et al. *(27)* presented channel delay profiles for the use of VLC in automotive applications. Practical vehicular LED headlamp and street lamp that consider the lighting regulations for transportation were used to design the VLC based ITS technologies. Simulations for the VLC channel delay profile evaluation were then gathered by using a ray-tracing scheme employing the commercially available LightTools software. It should be noted that the work described in *(27)* is based on the assumption of fixed reflectance. However, the reflectance of materials in the visible light spectrum should be taken into consideration due to the wideband nature of the VLC link. Memedi and Dressler *(28)* developed a novel vehicular VLC channel model based on very accurate empirical data allowing realistic simulation of vehicular VLC in ITS scenarios. Their model is based on a number of real-world experiments and uses curve-fitting methods. They also investigated the impact of turns on a curved road on the VLC communication.

In our recently under-review publication, we have shown that vehicle LEDs can also be used for sensing purposes. We have introduced a new novel speed estimation method called ViLDAR

(Visible Light Detection and Ranging). In this method, the speed of an approaching vehicle is detected using the vehicle's LED headlight intensity information acquired by a photodetector (PD). In the proposed system, the vehicle's LED headlights do not need any modification. Both theoretical and simulation results indicate that the proposed ViLDAR method outperforms RADAR/LiDAR systems in terms of speed estimation accuracy for a wide range of incidence angles between the vehicle and PD. In addition to speed estimation, ViLDAR has potentially useful applications in the "Advanced Vehicle Safety Systems" bundle of the national ITS architecture *(15)*.

4. METHODOLOGY

In this project, we investigated the use of visible light in sensing and communication applications for vehicular and ITS applications. First, simulations (see Subsection 4.1) have been performed to analyze the parameters affecting the visible light sensing system used to estimate vehicle speed. Then, in Subsections 4.2 – 4.4, we prototyped/implemented the ViLDAR system (including hardware and software components) to evaluate its performance in laboratory and outdoor environments. Finally, in Subsections 4.4 – 4.5, we implemented a visible light communication (VLC) system that is used to transmit the vehicle ID to an infrastructure receiver (photodetector) on the side of the road.

4.1. Simulations

Simulation has been performed in MATLAB. The purpose is to analyze the performance of the system with respect to different parameters such as vehicle speed, interference, and noise power level. We have evaluated the performance of the ViLDAR system in different simulation scenarios such as foggy and clear weather as summarized in Subsection 5.1.

In addition, we also used Zemax tool to simulate the environment for the channel modeling. We first construct the simulation platform of the outdoor environment integrating the CAD models of buildings, vehicles, and any other objects within. We further specify the type of object surface materials (coating) and the types of reflections (i.e., purely diffuse, specular, and mixed reflections). The specific type of reflection is defined by scatter fraction parameter. We use Mie scattering to model clear weather. With the “Bulk scatter” method in the software, the particle refractive index, the particle radius and the particle density can be defined. Please see Figure 1.

In the second step, we use the non-sequential ray tracing feature of Zemax as used in *(29)* to calculate the detected power and path lengths from source to detector for each ray. In the third step, we import this data to MATLAB *(30)* and obtain the channel impulse responses (CIRs) for the environment under consideration.

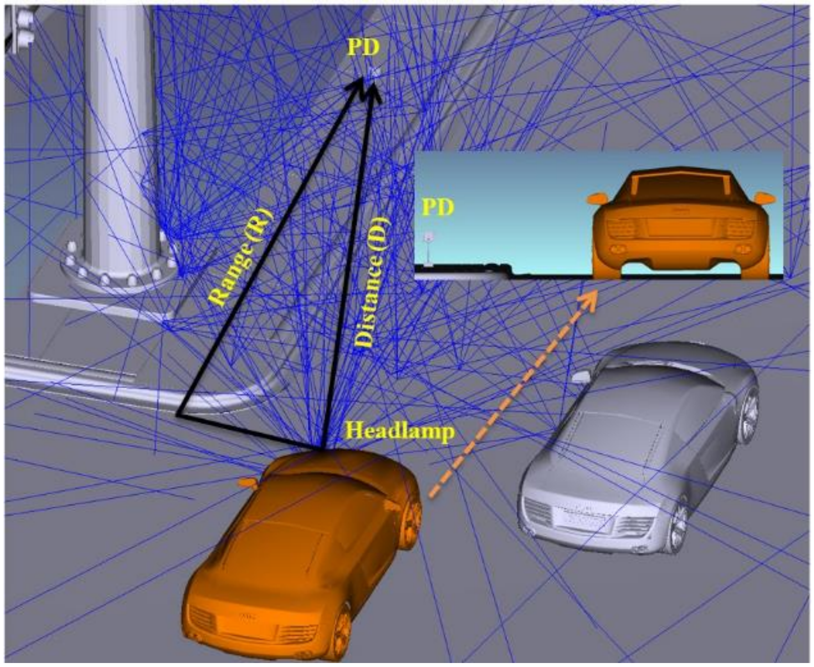

Figure 1. Transmitter and receiver closeup in the 3-D ray tracer (Zemax).

4.2. System Setup

The ViLDAR system model is illustrated in Figure 2, where θ and d are the incidence angle and the lateral distance between the vehicle and the PD, respectively. R and D are the varying longitudinal distance and the actual distance between the vehicle and the PD, respectively, at a given instant. The PD collects the measurements, then an analog to digital converter (ADC) digitizes the readings and sends the data to the digital signal processing (DSP) unit to estimate vehicle speed.

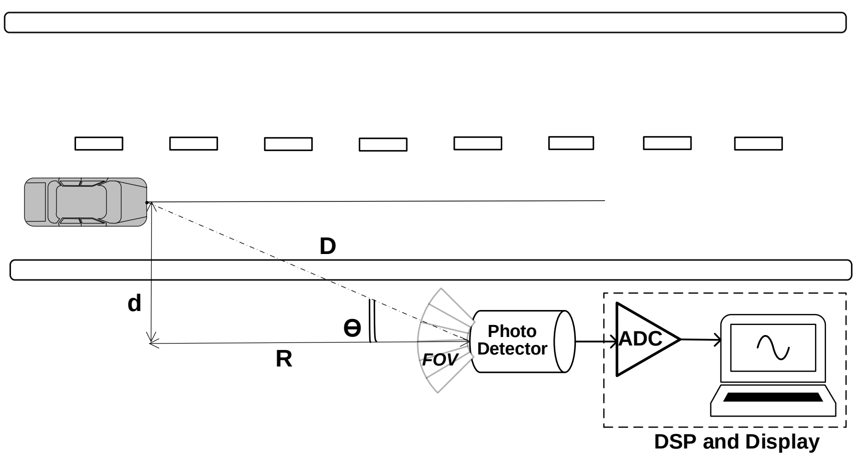

Figure 2. Model for ViLDAR system.

4.3. Speed Estimation Algorithm

The simplified model of the signal power associated with the visible light received by the PD at distance D is given by:

$$P_r = K\mathrm{D}^{-\gamma} \quad [1]$$

where D is the distance between transmitter (vehicle headlamp) and receiver (PD) in meters, K is a constant that depends on the PD settings (area, angle, and field-of-view), γ is the path-loss exponent which depends on the environmental conditions (reflectiveness of materials, humidity, etc.). Typically, the range of path-loss exponent lies between 1 and 5. As the vehicle approaches the PD the received light power increases. Notice also that for any values of K and γ, the received power will change with the distance.

Equation 1 is used to estimate the values of K and γ (referred to as the channel model parameters) and calibrate the ViLDAR system based on the prevailing environmental conditions. Measurements of the light intensity received by the PD are taken at known incremental distances (D_1, D_2, …, D_n) between the PD and light source in the range of 3 to 15 m. Note that these incremental distances are needed for testing purposes and required for implementation as part of the calibration process. Least square (LS) estimation is applied to determine the values of the channel model parameters as follows:

$$b = [A^T A]^{-1} A^T \mathrm{y} \quad [2]$$

where $A = \begin{matrix} 1 & 10\,log_{10}(D_1) \\ 1 & 10\,log_{10}(D_2) \\ . & . \\ 1 & 10\,log_{10}(D_n) \end{matrix}$, $b = \begin{matrix} K \\ \gamma \end{matrix}$ *and* $y = \begin{matrix} P_r(D_1)_{dB} \\ P_r(D_2)_{dB} \\ . \\ P_r(D_n)_{dB} \end{matrix}$.

The received power measurements are disaggregated for short time intervals (windows). Next, the raw data are filtered to reduce the measurement noise. Equation 15 in reference *(31)* (the well-known LS inverse formula) is then used to estimate the speed for each window. The reader is referred to *(31)* for additional details. Finally, the average vehicle speed estimation is calculated from the multiple window estimates.

4.4. Hardware Selection for Field Testing

We have investigated the potential hardware parts in order to build our ViLDAR platform (e.g., photodetector, light source, and processing unit for sensing and communications algorithms).

4.4.1. Photodetector

The photodetector is the most important component in the system as it impacts the sensing accuracy and dynamic range. Table 1provides a comparison of potential photodetectors that we have considered in terms of cost, speed, durability, setup time, and sensitivity.

Table 1. Comparison of different photodetector sensors.

Parameter\Type	Thorlabs PDA100A	Thorlabs PDF10A	Adafruit TSL2591	Solar Photocell
Cost	Moderate	High	Low	Low
Speed (supported sampling rate)	High	High	Low	Moderate
Durability	Moderate	Moderate	Moderate	High
Setup time	Low	Low	Moderate	High
Sensitivity	High	High	Moderate	Low

The following ranges represent “Low” and “High”:

- Cost: “Low” less than $50, “High” higher than $300.
- Speed: “Low” less than 100Hz, “High” higher than 200kHz.
- Durability is not quantitative but it was decided based on how a photodetector will relatively be affected by environment and pollution.
- Setup time is not quantitative, but it was decided based on the relative time needed to prepare the setup and if any modification is needed.
- Sensitivity: “Low” do not have any gain capability, “Moderate” have limited gain capability (3-6 dB), or “High” high gain capability (more than 20 dB).

After comparing the different options for the photodetector and considering the project’s need, we decided on Thorlabs PDA100A. High sampling rate and sensitivity were some of the important features of this sensor, as high sampling rata could be used for communication. In addition, Thorlabs PDA100A has the following features:

- Price: $370.86.
- Switchable gain detector.
- Working in visible and invisible light frequencies (320 - 1100 nm).
- High data rates can be supported: 11 MHz (bandwidth).
- Compatibility with variable lens and filters.
- Large active area (75.4 mm^2), which allows higher sensitivity.
- Plug and play (don’t need any special libraries or installation).

4.4.2. Light Source

The different light sources were chosen from commercial off-the-shelf (COTS) options as:

- Alpha TEK 2,800 Lumen multipurpose LED
  - Uses X-Lamp XM-L2 CREE LED
  - Cost: $69.99
- Lastfit Headlamp LED 3,000 Lumen (L1 9005)
  - Uses CREE Chips
  - Cost: $52.99 (for 2 LEDs)
- Adafruit 1 Watt cool white LED 90 Lumen:
  - This LED was tested but they were not efficient due to low power.
  - Cost: ~$4.00

Multiple light sources were used and tested. However, we used a real vehicle headlamp (Lastfit Headlamp LED) for a more realistic testing environment.

4.4.3. Processing Unit for Sensing

The three options were considered are: (1) Raspberry-Pi (an operating system based processing unit), (2) Arduino (a microcontroller-based system), and (3) directly using a laptop.

We have selected Raspberry-Pi as it offers the advantage of small size and the operating system features. The main specifications of Raspberry-Pi 3 are given as follows:

- System on Chip (SoC): Broadcom BCM2837
- Central Processing Unit (CPU): 4×ARM Cortex-A53, 1.2GHz
- Graphics Processing Unit (GPU): Broadcom VideoCore IV

- RAM: 1GB LPDDR2 (900 MHz)
- Networking: 10/100 Ethernet, 2.4GHz 802.11n wireless
- Bluetooth: Bluetooth 4.1 Classic, Bluetooth Low Energy
- Storage: MicroSD
- GPIO: 40-pin header, populated
- Ports: HDMI, 3.5mm analog audio-video jack, 4×USB 2.0, Ethernet, Camera Serial Interface (CSI), Display Serial Interface (DSI).

Please note the signal collected from the photodetector sensor was analog. Hence, an ADC circuit was needed to convert data from analog to digital. We have used DAQC2plate circuit from PiPlate because of its compatibility with the Raspberry-Pi. DAQC2plate can support up to eight inputs with [-12, 12] volts input range and output of 16-bit resolution.

In the case of processing unit, we choose the Rasberry-Pi due to its small size compared to a laptop and having an operating system, which gives flexibility. Since the developed sensing method does not require a lot of computational power, selection of processing unit is not critical. Any processing unit with basic capabilities would easily be able to do the job. Hence, we have not done any comparison during the selection of a processing unit.

4.4.4. Processing Unit for Communication

We have selected Universal Software Radio Peripheral (USRP) from National Instrument for the communication system because of its superiority in wireless systems prototyping and the availability of demos and examples. In addition, our team had previous experience with USRPs and LabVIEW software. In addition, a bias tee from Mini circuits (ZFBT-6GWB+) was used to combine the modulated signal and DC signal together to send to the LED for transmission.

The following RF daughterboards were used with two USRPs:

- Ettus LFRX Daughterboard 0-30 MHz used in Rx.
- Ettus LFTX Daughterboard 0-30 MHz used in Tx.

In summary, we have prepared our experimental setup by using a Thorlabs PDA100A photodetector *(32)*, a Raspberry-Pi miniature computer *(33)*, an ADC (PiPlate) circuit *(34)*, an off-the-shelf fixed power LED light source, and display unit as shown in Figure 3.

We implemented our data collection software by using Python scripting language run in PiPlate and Raspberry-Pi. DSP algorithms (Figure 4) have been implemented in both Matlab and Python.

4.4.4. Software Code

We have developed our software code as part of the implementation of the ViLDAR system. All the developed codes for sensing data collection, speed estimation, and analysis are provided in Appendices A – F.

The software codes can be described as:

- The main Bash script (Appendix A) used to initialize and organize the different measurements for different conditions and scenarios.

- The Python function (Appendix B) is used to collect the data from the ADC and record it to the dropbox file in Raspberry-Pi. It uses different libraries (ADC library, timing library, etc…).
- The Matlab script (Appendix C) and function (Appendix D) are used to analyze collected data. It estimates the vehicle speed based on the speed estimation algorithm (Subsection 4.3) and Figure 4 from *(31)*.
- This Matlab script (Appendix E) and function (Appendix F) are used to estimate the channel model parameters in the speed estimation function (Subsection 4.3).

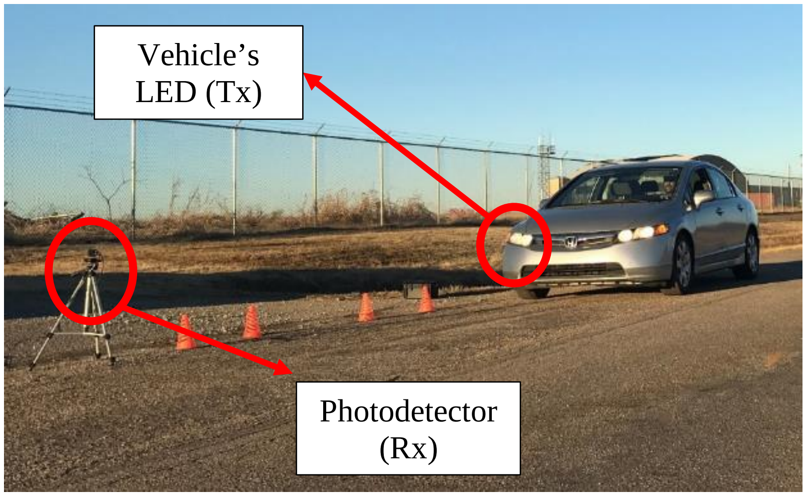

Figure 3. Outdoor setup for ViLDAR measurements.

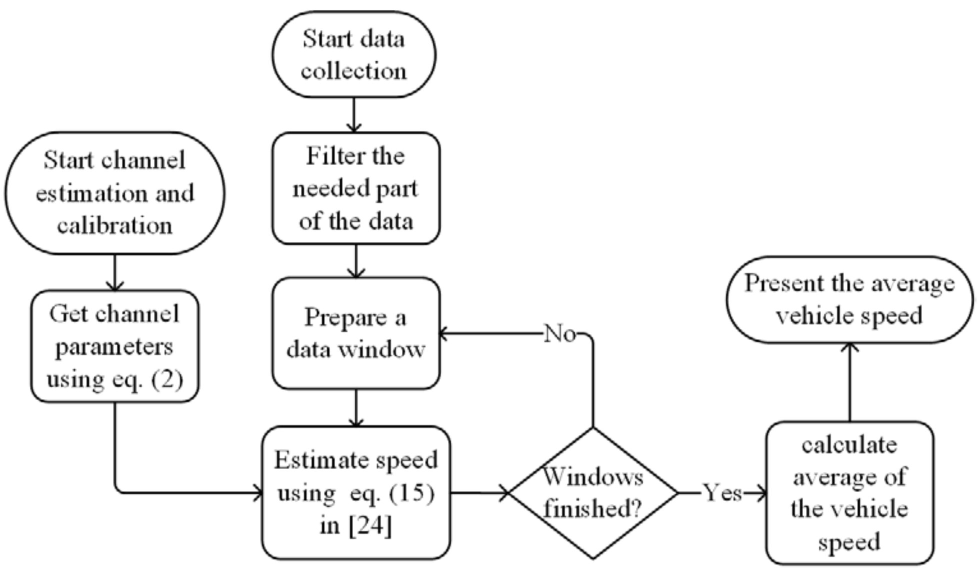

Figure 4. Algorithm used in the ViLDAR system.

4.5. Implementation of Communication System using Vehicle Headlamp

We implemented a system that can transmit a message (data) with vehicle headlamp to a roadside infrastructure using an off-the-shelf vehicle LED.

We used a software-defined radio USRP2 *(35)* and LabVIEW *(36)* to implement the algorithm used in data transmission.

Amplitude-Shift-Keying (ASK) digital modulation technique was used to transmit the data where the amplitude of the signal changes depending on the digital bit being sent. To avoid any effect of noise and interference caused by the prototype or the environment a data repetition technique was used to add diversity to the message sent. The block diagram of the visible light communication (VLC) system is given in Figure 5.

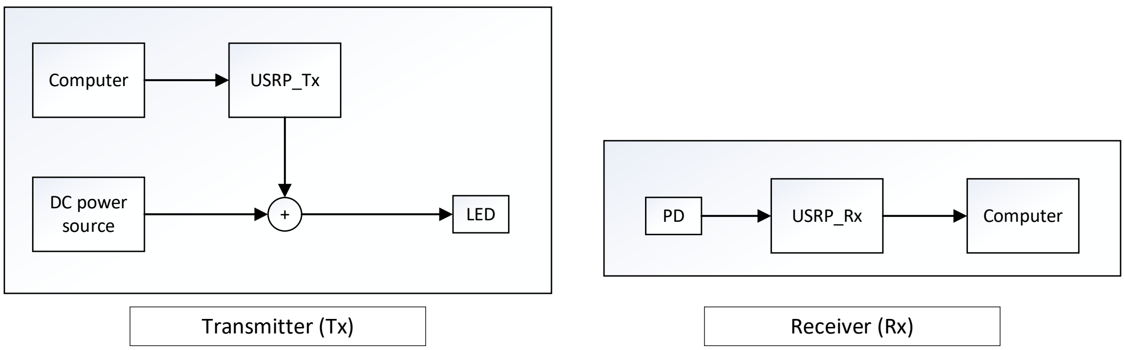

Figure 5. Block diagram for the VLC system.

An ASK lab module from LABVIEW examples was modified to be used for this application. The detail of the lab module is given in *(36)*. The important modification specific to this application are:

1. Continuous mode for transmitter (Tx) and receiver (Rx).
2. Transmitting an 8 symbol message (e.g., vehicle ID) message instead of transmitting random data.
3. Adding the repetition error correction in the Tx and Rx.
4. Building an .exe file for Tx and Rx.

The main communication system parameters used in the transmission are:

1. LED electric power = 7 watts.
2. Data rate used = 200 kbps.
3. Signal carrier frequency used = 500 kHz.
4. Message length =512 bits (The message size is 512 bits (8 symbols each have 8 bits repeated 8 times).

The screenshots of transmitter and receiver LabVIEW interfaces are given in Figures 6and 7, respectively.

In Figure 6, the transmitter controllers are shown as device IP address, carrier frequency used, gain, antenna port, message length and sampling rate (IQ rate). Moreover, the output of this software program is presented in two figures to show the baseband signal sent to the USRP (before transmitting it thought the light source) in both time domain and frequency domain (power spectrum).

In Figure 7, the receiver has a similar controller as shown in the transmitter. Moreover, the received baseband signal is shown, and the eye diagram is also shown for the received symbols sent. The eye diagram is a tool used in telecommunication in which the high-speed digital signal symbols at the receiver is displayed in a single graph where the vertical axis represents signal amplitude and horizontal axis represents the symbol time duration. It is a good measure for the noise and interference that the received signal experienced in the channel between transmitter and receiver.

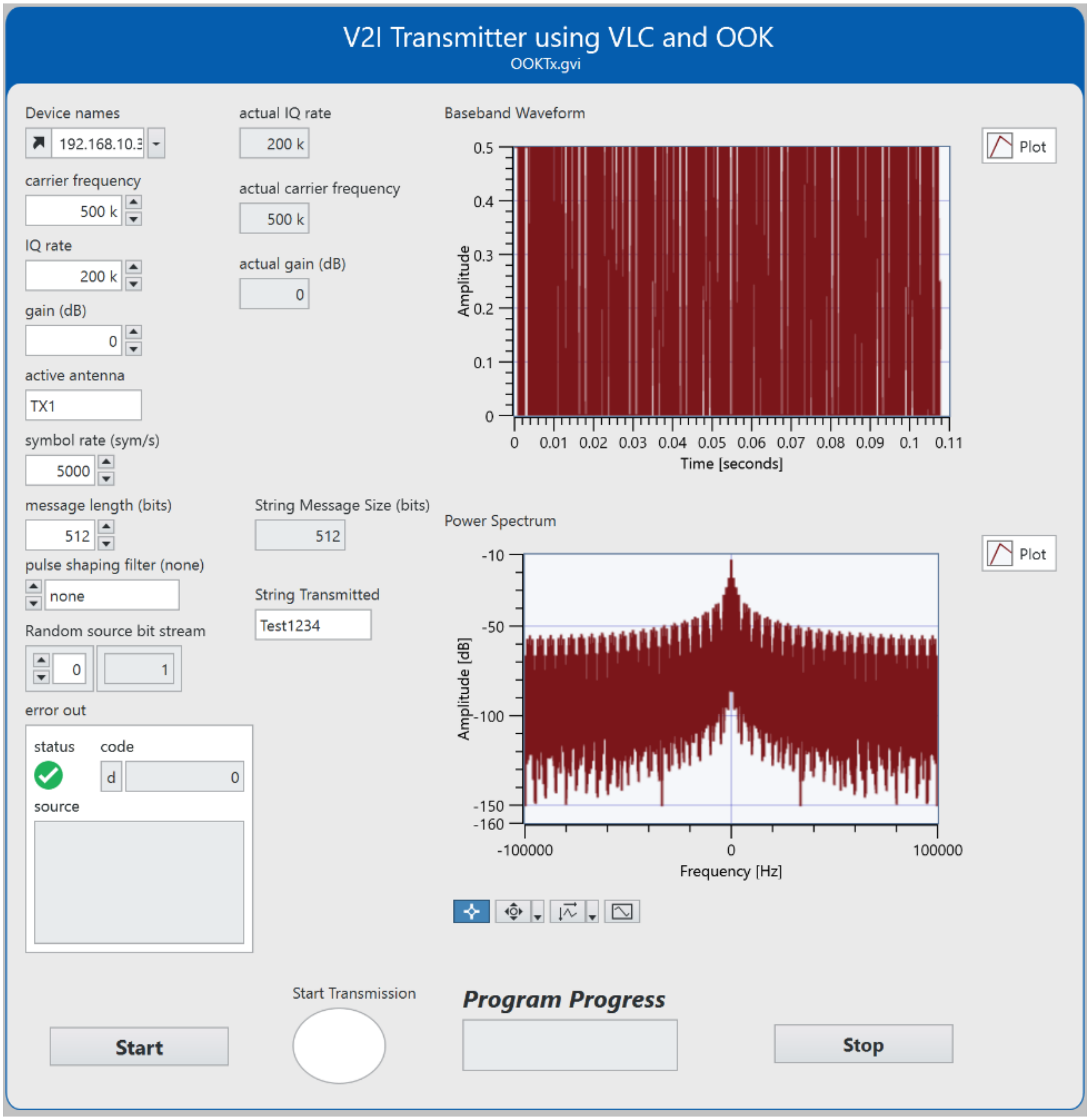

Figure 6. LABVIEW Tx user interface.

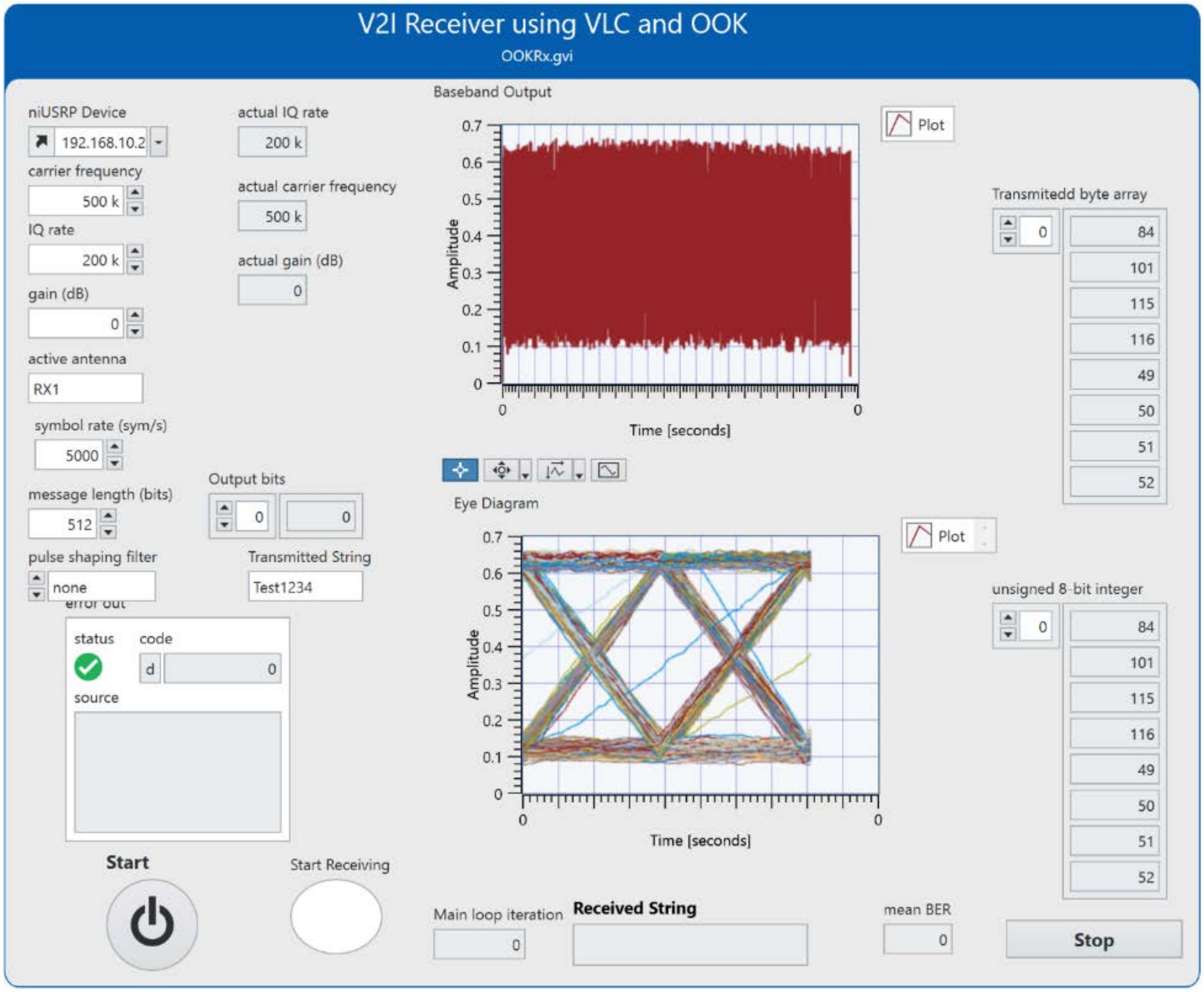

Figure 7. LABVIEW Rx user interface.

5. ANALYSIS AND FINDINGS

In this section, the analysis and results from simulations, implementation, and experimental evaluations are provided.

5.1. Findings from Simulations

Our results showed that using the received light intensity of a vehicle's headlamp, one can estimate the vehicle's speed with an accuracy of more than 90% for a wider range of incidence angle (up to 70-80% of the simulation's time). Comparison of results obtained for ViLDAR and RADAR, also reveal that RADAR detectors poorly perform in fast incidence angle changing scenarios, while promising performance can be observed for the ViLDAR system. The impact of different system parameters on speed estimation accuracy of the ViLDAR system was further investigated. It is observed that the half viewing angle of vehicle's headlamp is of crucial importance for speed estimation accuracy.

In Figure 8, the simple (Equation 1) and Lambertian *(14)* visible light channel models are compared. The Lambertian model is provided for different initial signal-to-noise-ratios (SNRs) as 30 and 40 dB to show the impact of noise. The initial point t_o is at time 0, and as the vehicle approaches the detector, new measurements are taken (i.e., distance decreases). As expected, in both models the received power increases as the vehicle approaches the detector. Furthermore, although the estimation can be performed from all the received power levels, high accuracy of speed estimation can be obtained in a certain region, which is shown as the reliable region of operation. The speed estimation problem can be interpreted as designing an estimator to obtain the slope of the received power (see Figure 8); hence, estimate the speed of the vehicle.

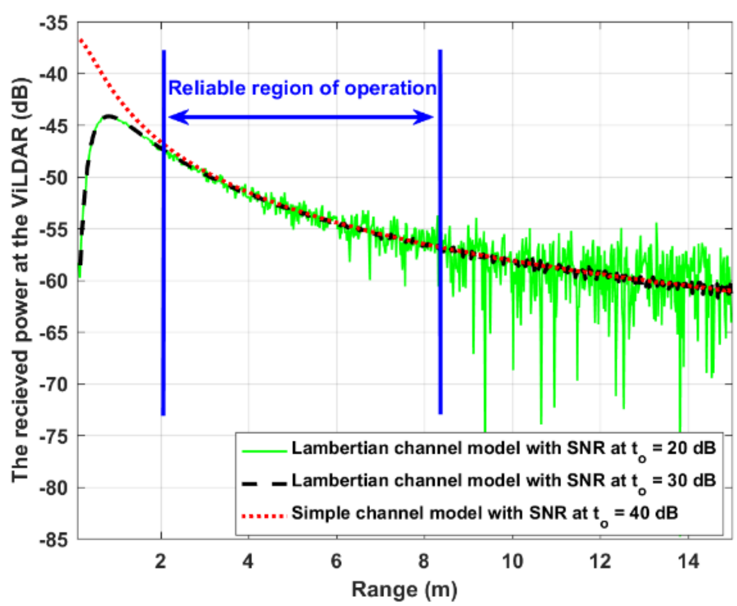

Figure 8. The power received from the vehicle under the two channel models with initial range Ro = 15 m, V = 72 km/hr, d = 0.5 m, KdB = -41.39 dB and γ = 1.673.

It is observed from Figure 9 that the path loss obtained with the Lambertian headlamp is underestimated with respect to the realistic headlamp. This is a result of the fact that the low-beam headlamp provides an asymmetrical pattern designed to offer adequate forward and lateral illumination, in addition to controlling glare by limiting light being directed toward the eyes of other road users. In other words, the light from the realistic headlamp is mainly emitted towards the road surface while the light from Lambertian headlamp is emitted towards the front. It is also observed that the path loss obtained under the foggy weather condition is larger than that one obtained under the clear weather condition, since the scattering of light from water droplets reduces the received power from the headlamp. It should be noted that the incremental trend of path loss could be observed for distances larger than 5 m. In the other words, for the distances smaller than 5 m, when the vehicle moves toward the PD, the headlamp is out of the receiver field of view and the path loss increases instead of decreases.

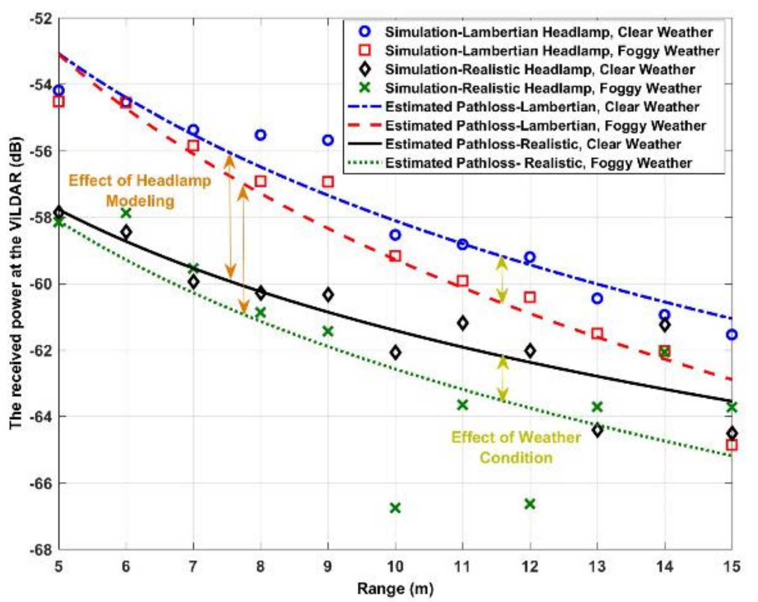

Figure 9. Channel models fitting for Lambertian and realistic headlamp model in foggy and clear weather conditions.

In the Zemax simulation, we modeled the system in different environments: clear and foggy, LED radiation patterns, and Lambertian headlamp and realistic headlamp. These different environments lead to different channel models. These channel models were tested under different noise levels for long simulations to make sure that the system is robust in these conditions. Different environments (clear and foggy) and LED radiation patterns (Lambertian headlamp and realistic headlamp) can be initialized in the ray-tracing tool Zemax stated in Subsection 4.1 where the channel parameters (models) are estimated.

In Figure 11, we present the effect of the different channel models (foggy and clear) and estimation time on the speed estimation accuracy. As expected, the performance is impacted more in foggy weather.

The proposed algorithm works at different speed levels (see Figure 10), while the performance is impacted only with the estimation duration. Moreover, as the speed of the vehicle decreases, ViLDAR needs more estimations duration (measurements samples) to keep the same speed estimation accuracy.

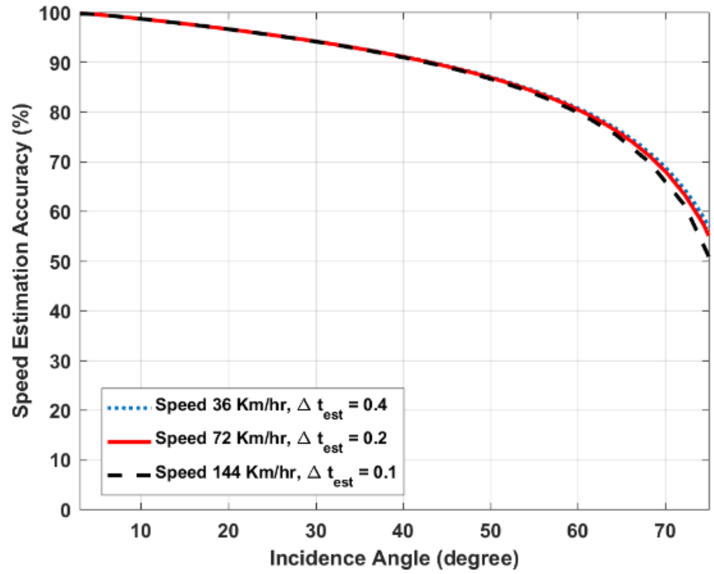

Figure 10. Speed estimation accuracy using simple LS method for different actual speed values for SNRo = 40 dB.

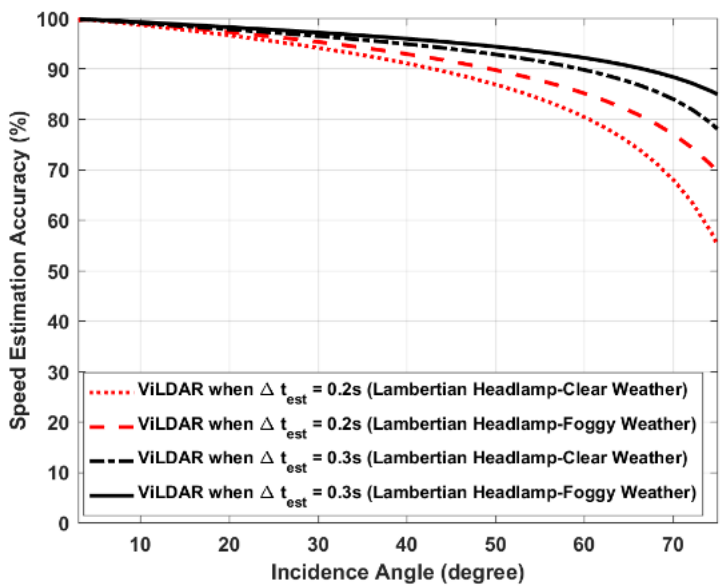

Figure 11. Speed estimation accuracy of the vehicle versus time in different weather conditions for a straight road scenario.

5.2. Findings from Implementation and Experimental Evaluations

5.2.1. ViLDAR Speed Estimation via Visible Light Sensing (VLS)

The field experiments for speed estimation were conducted on a local road east of the Stillwater regional airport, in Stillwater, Oklahoma, as shown in Figure 12. This road was chosen because of its low traffic volume and the ability to close it to traffic if needed to control the measurement environment.

Figure 12. Location for field experiments to estimate vehicle speed.

Visible light channel modeling is needed before starting an evaluation of speed estimation. Channel modeling can be considered as a calibration process. Figures 13 and 14 show channel modeling setups. Note that the vehicle used in all experiments is Honda Civic 2008.

Figure 13. Visible light channel modeling setup.

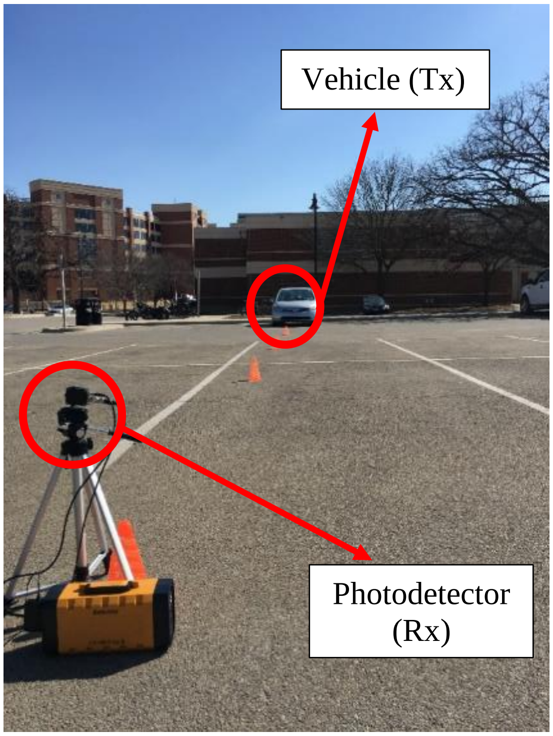

Figure 14. Visible light channel modeling setup (second set-up).

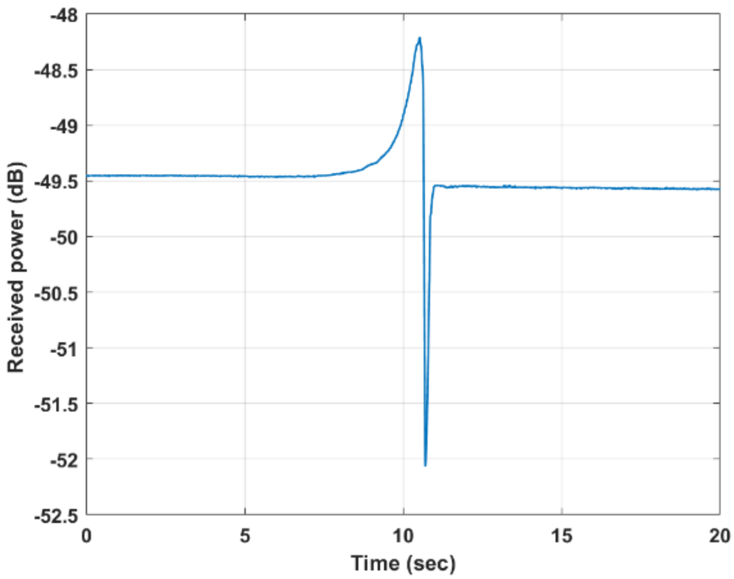

Figure 15. Visible light power measurement of approaching vehicle during day time.

We have taken measurements during the day (Figure 15) and night (Figure 16) to observe the impact of daylight. It is clear that the highest change in the received light power has been observed during the night. Higher change in the received power enables the speed estimation algorithm to capture the rate of change easier (i.e., the impact of noise and other ambient lightings would have less impact on the speed estimation accuracy). A video of our ViLDAR outdoor measurements can be found at: https://youtu.be/bJXGzErX7Qs.

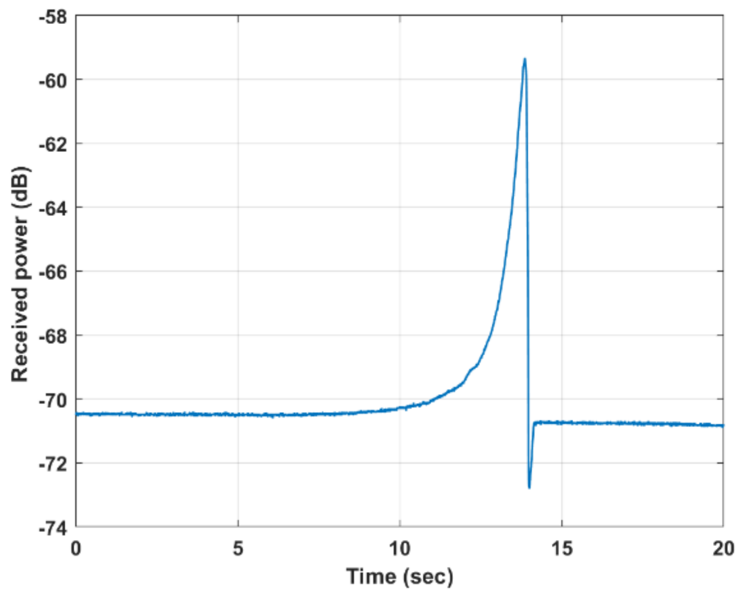

Figure 16. Visible light power measurement of approaching vehicle during night time.

After measuring the power received at different distances, the two required parameters path lost exponent γ and the constant K_{dB} can be estimated by using a curve fitting approach (see Figure 17).

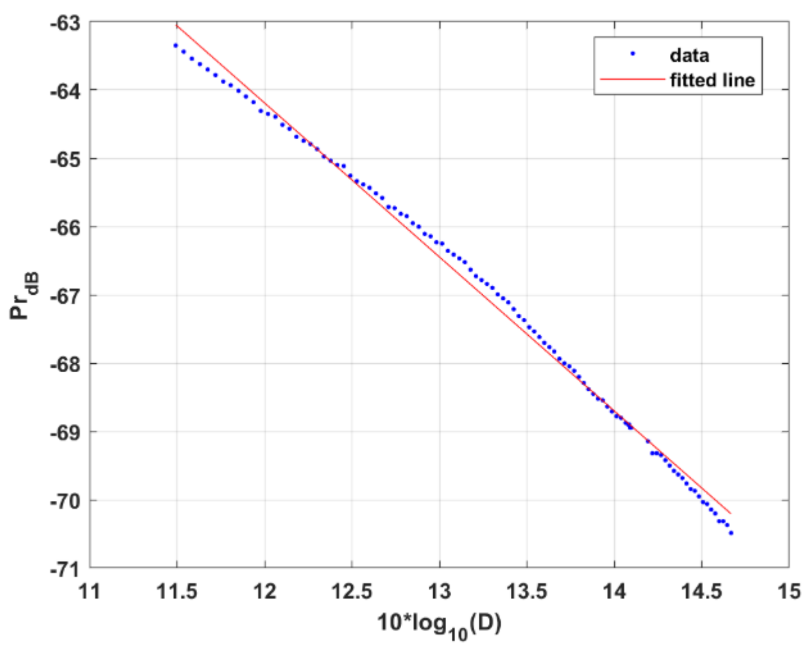

Figure 17. Visible light channel model estimation measurement.

For example, using one of the measurements and using channel information, we estimated that $\gamma = 2.33$ and $K_{dB} = -36.1$. With the estimated γ and K_{dB} on different measurements for different speeds and day and night time, the following (Table 2) average speed estimation accuracy (for 1-4 measurements at each speed level) is obtained.

Table 2. Speed estimation measurements.

	High Speed (~70mph)	Mid Speed (~50mph)	Low Speed (~30mph)
Abs. Error at Night (%)	1.17 ($K_{dB} = -36.27, \gamma = 2.35$)	2.15 ($K_{dB} = -33.66, \gamma = 2.49$)	13.1 ($K_{dB} = -37.65, \gamma = 2.16$)
Abs. Error at Day (%)	1.13 ($K_{dB} = -55.31, \gamma = 0.27$)	11.69 ($K_{dB} = -48.11, \gamma = 0.09$)	29.11 ($K_{dB} = -48.15, \gamma = 0.15$)

5.2.2. Vehicular Data Transmission via Visible Light Communication (VLC)

We have implemented a VLC system and have conducted both indoor and outdoor evaluations. Figures 18 and 19 show the VLC setups.

The VLC setup was tested in the laboratory and the vehicle ID (data) was successfully transmitted by vehicle headlamp (Tx) and received by a photodetector at a maximum distance of up to 6 m. In outdoor measurements, the vehicle travels a certain route (Figure 20) and passed by a PD at two different times. The purpose was to detect the vehicle ID by VLC setup and measure the travel time. Such scenario can be applicable in arterial travel time measurements. During the outdoor measurement, we successfully received the vehicle ID at a 3 m distance when the vehicle is static, but not in mobility. Further modification (as future directions) on the VLC software and hardware is needed to test the system when the vehicle is mobile. Synchronization between Tx and Rx and/or preamble addition in the data could improve mobile measurements.

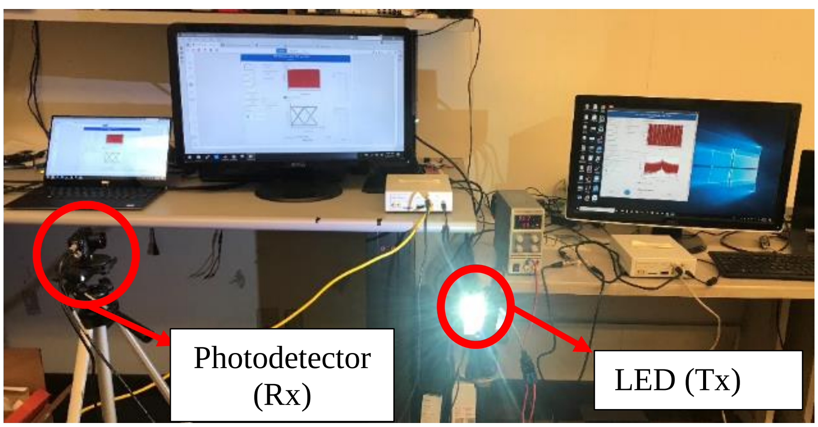

Figure 18. Indoor (laboratory) VLC setup.

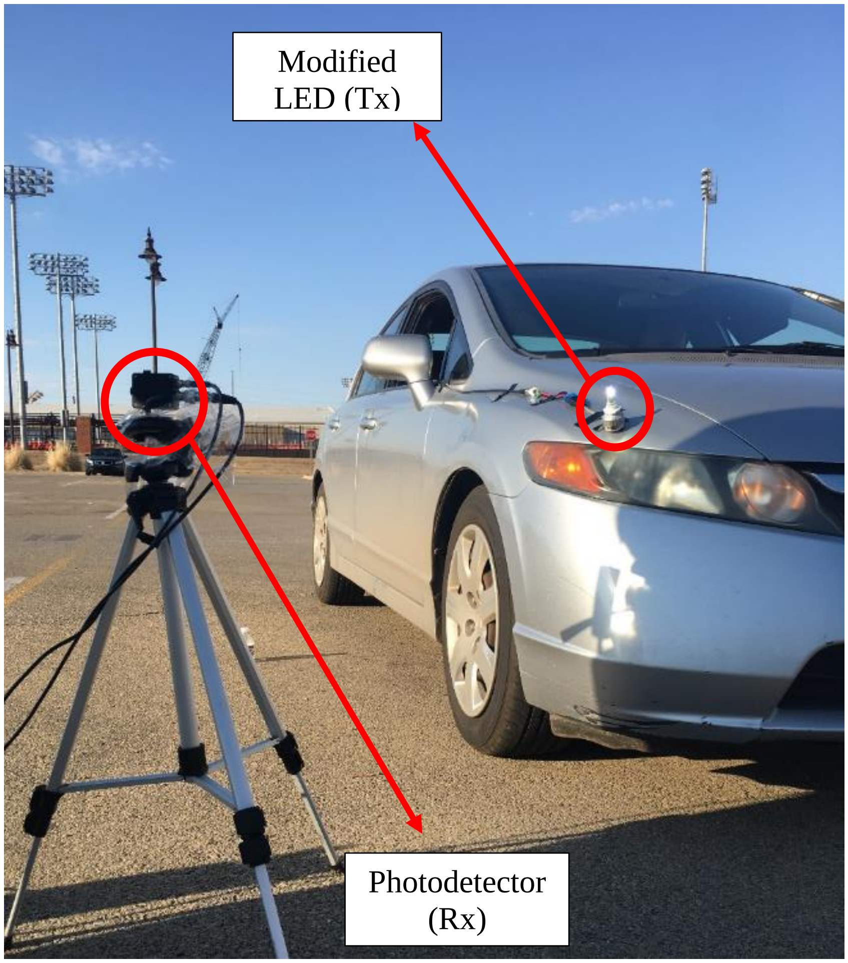

Figure 19. Outdoor (field) VLC setup.

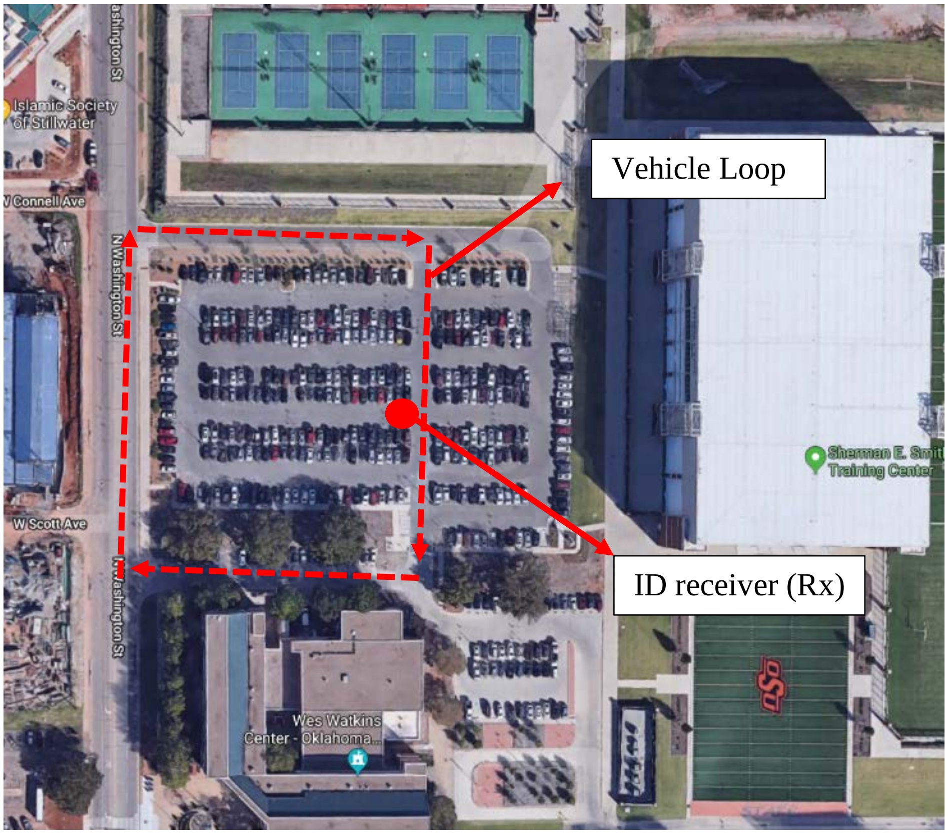

Figure 20. Vehicle loop route for VLC measurements.

6. CONCLUSIONS

In this project, the ViLDAR simulation, prototyping, implementation details including hardware and software components, and laboratory and field measurement results were presented. The main objective of the project is to conduct a proof-of-concept study for the utilization of vehicle headlamps for *sensing* (VLS: visible light sensing) purposes, particularly vehicle speed estimation. The promising results validated our hypothesis of using vehicle headlamp for speed estimation. This research will inspire new thinking about how VLS can impact ITS applications. It was observed from both day and night time measurements that sunlight can impact the received light signal-to-noise ratio, hence impact the performance of the system. One solution recommended for future studies is to use frequency modulated light signal at the transmitter (i.e., headlamp) and filter it at the receiver in order to mitigate the effect of sunlight (DC effect). Note that such change would require hardware modification to the vehicles. Another challenge that was observed was how the speed estimation parameters, such as constant K and path loss exponent γ, can change throughout measurements, hence the system needs re-calibration. Nonetheless, adaptive signal processing algorithms (such as filtering, optimization) and machine learning tools can readily be utilized to handle an adaptive calibration process.

Another objective of the project was to show how data can be transmitted using vehicle headlamps (VLC: visible light communication) for vehicular communication purposes, such as V2I, V2V, and V2X. We have successfully designed, implemented, and evaluated a VLC system using vehicle headlamps. Using this system, we showed that vehicle ID data can be transmitted using vehicle headlamps. Promising results were obtained in the laboratory and outdoor environments. One lesson learned is that synchronization between Tx and Rx and/or preamble addition in the transmitted data could improve the reliable data transmission.

Findings of this project can impact: (1) the policies for regulations on speed estimation and vehicular data transmission methods, range and usage and (2) private companies (e.g., automakers and auto part makers).

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APPENDIX A: RASPBERRY-PI DATA COLLECTION BASH SCRIPT

```
$#!/usr/bin/env bash

echo "Hello, Welcome to WCRL, We are Starting the ViLDAR - VLS script if you want one measurement enter 1 and then press enter if not press enter .. "

echo "Given that defualt acquisition runs at Fs= 400Hz for 60 seconds... and then data is saved in Dropbox folder"

echo "if you want default enter 1 and then press enter if not press enter .. ==>  "

read varname

if [ "$varname" == "1" ]; then

  echo "What is the file name? :==> "

  read File_name

  echo " Start one default acquisition ......."

  python3 /home/pi/Desktop/Test_Python/PiPlate_Scope_Function.py "$File_name" 400 24000 1 7 0

elif [ -z "$varname" ]; then

  echo "What is the number of tests needed ? :==> "

  read Num_used

  echo "What is the name of the files ? :==> "

  read File_name

  echo "How many Seconds for the files ? :==> "

  read Num_Second

  echo "What is the Fs needed (Hz)? :==> "

  read Fs_used

  Samples_used=$(($Fs_used*$Num_Second))

  ii=1

  while [ $ii -le $Num_used ]

  do

    echo " Start a $Fs_used Hz acquisition of $Num_Second seconds ..."

    Current_Test_name="$File_name$ii"

    echo "Please Press Enter to Start Iteration ($ii)..:==> "

    read Temp
```

```
    python3   /home/pi/Desktop/Test_Python/PiPlate_Scope_Function.py   "$Current_Test_name" $Fs_used $Samples_used 1 7 0
    ii=$(( $ii + 1 ))
    echo "=========================================================="
    echo "=========================================================="
    echo "Please Enter the Speed or the distace of this test :==> "
    read data_[$ii]
    echo "Is this measurement good or repeat it ? Enter 1 to repeat it !!!!!!!"
    read Repeat_Flag
    if [ "$Repeat_Flag" == "1" ]; then
     ii=$(( $ii - 1 ))
    fi
  done
  echo "=========================================================="
  echo "=================Test is finished ======================"
  echo "=========================================================="
  echo "=========================================================="
  echo "Speed or distaces or SOA ==> ${data_[*]} ..."
fi
read rand
```

APPENDIX B: RASPBERRY-PI DATA COLLECTION PYTHON FUNCTION

```
import sys
def
PiPlate_Scope_Function(Saved_File_name,fs,Number_samples,Internet_FLAG,Plate_Address,P
rint_Flag):

 import piplates.DAQC2plate as DAQC2
 import time
 import wiringpi
 import os
 import subprocess
 ################# PiPlate Parameters ####################
 Channel_No=0
 print('Using Print flag ',Print_Flag,' in PiPlate....')
 print('Using Channel number ',Channel_No,' in PiPlate....')
 #################### User Parameters #######################
Delta_time=float(1/fs)
 print('Acquisition Ts is ',Delta_time,' sec .....')
############################################################

 EndTime=Number_samples*Delta_time
 print('Acquisition time is',EndTime,' seconds ....')

 FileName_Path ='/home/pi/Desktop/Test_Python/FileName.txt'
 text_file1 = open(FileName_Path, "w+")
 text_file1.write(Saved_File_name)
 text_file1.close()
 Parameters_Path ='/home/pi/Desktop/Test_Python/Parameters.txt'
 text_file2 = open(Parameters_Path, "w+")
 text_file2.write("%s \n%s "%(fs,Number_samples))
 text_file2.close()

 Final_File_Path ='/home/pi/Desktop/Test_Python/Saved_Data/'+Saved_File_name+'.txt'
 Temp_File_Path ='/home/pi/Desktop/Test_Python/Synch_Folder/'+Saved_File_name+'.txt'
 text_file= open(Temp_File_Path, "w+")
 time.sleep(1)
 print("Data acqisition Start !!")
 ii=0
 Time=[]
 Data=[]
 Start_time=time.time();
for ii in range(Number_samples):
   Value=(DAQC2.getADC(Plate_Address,Channel_No))
   if Print_Flag:
       print('V = ',Value,'volts ....')
```

```
    Data.append(Value)
    Time.append(time.time()-Start_time)
    text_file.write("%s \n"%(Value))
    Modified_Delay=((ii+1)*Delta_time)-time.time()+ Start_time
    if Modified_Delay>=0:
      wiringpi.delayMicroseconds(int(Modified_Delay*1000000))
    if ii % fs == 0:
      text_file.flush()
      #print('One second passed.... cp ')
      #print(ii/fs)
      print('... Scope ... ',int(ii/fs),' Seconds')
      Command=str("cp "+Temp_File_Path+"
/home/pi/Desktop/Test_Python/Synch_Folder/Data"+str(int(ii/fs))+".txt")
      os.system(Command)

 text_file.flush()
 Command=str("cp "+Temp_File_Path+"
/home/pi/Desktop/Test_Python/Synch_Folder/Data"+str(int((ii/fs))+1)+".txt")  #gcp --no-
progress
 os.system(Command)
 print("Data acqisition End!!")
 text_file.close()
 text_file_last = open(Final_File_Path, 'w+')
 for jj in range(Number_samples):
     text_file_last.write("%s \t %s \n "%(Time[jj],Data[jj]))
 text_file_last.close()
 if Internet_FLAG:
   Command2=str("/home/pi/Dropbox-Uploader/dropbox_uploader.sh upload
"+Final_File_Path+"  /  ")
   os.system(Command2)
   print("Data Uploading done")
 print("Done... Press Enter to continue ... ")
if __name__ == "__main__":
    Saved_File_name = str(sys.argv[1])
    fs = int(sys.argv[2])
    Number_samples = int(sys.argv[3])
    Internet_FLAG = int(sys.argv[4])
    Plate_Address= int(sys.argv[5])
    Print_Flag=int(sys.argv[6])

PiPlate_Scope_Function(Saved_File_name,fs,Number_samples,Internet_FLAG,Plate_Address,P
rint_Flag)
```

APPENDIX C: MATLAB SCRIPT TO CALCULATE VEHICLE SPEED

```
clear
clc
close all
PLOT_FLAG=0;
Flag_Use_Full_data=0;

for Test_number=11:12
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
Estimation_Duration=0.2;  % seconds
Measurement_Duration=2; % seconds
Constant_K_dB=      -55.9631; % dB
Path_Loss_exp=      0.2252 ;
ViLDAR_distance_Inch=20; % inch
ViLDAR_distance=0.0254*ViLDAR_distance_Inch;    %should be in meters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
Data_file_Name='Speed_sun_';

Real_Speeds=dlmread([Data_file_Name,'real.txt']);   % MPH
Real_Speeds(Test_number)
Ref_speed=Real_Speeds(Test_number)*0.44704;

Data_=dlmread([Data_file_Name,num2str(Test_number),'.txt']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
data=Data_(:,2).';  % Voltage
Time=Data_(:,1);
if PLOT_FLAG
    figure(2001)
    plot(Time,data,'LineWidth',2)
    % title('Lambertian Channel Model Method 1 Speed Estimation (LS)','FontWeight','bold')
    xlabel('Time (s) ','FontWeight','bold')
    ylabel('The recieved signal (v)','FontWeight','bold')
    grid on
    hold on
end
Delta_Time=mean(Time(2:end)-Time(1:end-1));
Fs=1/Delta_Time;
%%%%%%%%%%%%%%%%%Detecting Peak%%%%%%%%%%%%%%%%%%%%
Max_Peak=max(findpeaks(data));
Max_Peak_Index_temp=find(data==Max_Peak);
Max_Peak_Index=Max_Peak_Index_temp(1);
Start_Index=Max_Peak_Index-ceil(Measurement_Duration*Fs);
End_Index=Max_Peak_Index;
```

```
Pr_used= data(Start_Index:End_Index); % to match to channel model
Time_Vector= Time(Start_Index:End_Index).'-Time(End_Index);
if PLOT_FLAG
   figure(2002)
   plot(Time_Vector,Pr_used,'g')
   hold on
   plot(Time(Max_Peak_Index),Max_Peak,'or')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
Pr_dB_Vector=10*log10((Pr_used.^2)/1e6);
Constant_K=db2pow(Constant_K_dB);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if Flag_Use_Full_data

[Vest]=Calculate_Speed_ViLDAR(Pr_dB_Vector,Time_Vector,Path_Loss_exp,Constant_K,ViL
DAR_distance,PLOT_FLAG);
else
   Estimation_Duration_Index=floor(Fs*Estimation_Duration);

[Vest_vector]=ViLDAR_Window_Speed_Estiamtion(Pr_dB_Vector,Time_Vector,Path_Loss_e
xp,Constant_K,ViLDAR_distance,PLOT_FLAG,Estimation_Duration_Index);
   Vest=mean(Vest_vector);
end
% Vest=Vest*2.23694
Vest_Vec(Test_number)=Vest*2.23694;
Error=Vest_vector*2.23694-Real_Speeds(Test_number);
% plot(Error)

Error_Test(Test_number)=100*abs(Vest_Vec(Test_number)-
Real_Speeds(Test_number))/Real_Speeds(Test_number);
End
```

APPENDIX D: MATLAB FUNCTION TO ESTIMATE VEHICLE SPEED

```
function
[Vest,Time_Index]=ViLDAR_Window_Speed_Estiamtion(Pr_dB_Vector,Time_Vector,Path_Lo
ss_exp,Constant_K,ViLDAR_distance,PLOT_FLAG,Estimation_Duration_Index)

Step=floor(Estimation_Duration_Index/10);
Iterations= floor((length(Pr_dB_Vector)-Estimation_Duration_Index)/Step);
for Window_Iteration=1:Iterations
   Start_Index=(Window_Iteration-1)*Step+1;
   End_Index=(Window_Iteration-1)*Step+Estimation_Duration_Index;
   Pr_dB_Vector_Window=Pr_dB_Vector(Start_Index:End_Index);
   Time_Vector_window=Time_Vector(Start_Index:End_Index);
      Y=sqrt((db2pow(Pr_dB_Vector_Window)/Constant_K).^(-2/Path_Loss_exp)-
ViLDAR_distance^2); % New right equation
   T=Time_Vector_window;
   A=[-1*T' , ones(size(T,2),1)];
   Vest_Do = A\Y.';
   if(Vest_Do(1)<0)
      Vest_Do(1)=abs(Vest_Do(1));
   end

   Vest(Window_Iteration)=Vest_Do(1);
   Time_Index(Window_Iteration)=mean(Time_Vector_window);
   if PLOT_FLAG==1
      figure(9999)
      Pr_est_MODEL_L=pow2db(Constant_K*((A*Vest_Do).^2+ViLDAR_distance^2).^(-
0.5*Path_Loss_exp));
      scatter(T,Pr_dB_Vector_Window)
      hold on
      plot(T,Pr_est_MODEL_L,'LineWidth',2)
      xlabel('Simulation time (sec)','FontWeight','bold')
      ylabel('The recieved Power at the ViLDAR (dB)','FontWeight','bold')
      legend('Actual Pr','Estimated Pr curve')
      grid on
      drawnow
   end
end
if PLOT_FLAG
   figure(9001)
   plot(Time_Index,Vest*2.23694,'LineWidth',2)
   xlabel('Time (s) ','FontWeight','bold')
   ylabel('VilDAR Speed Estimation (mph)','FontWeight','bold')
   grid on
   hold on
end
end
```

APPENDIX E: MATLAB SCRIPT TO ESTIMATE THE CHANNEL MODEL PARAMETERS

```
clc
clear
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
Channel_Plot_Flag=0;
Peak_Distance=0.1;  % meters
distance_Buffer=12:14;% For Sunny = 14:16; % meters
Channel_Estimation_Duration=1; % seconds
Fs=200;
Order_Poly=1;
%%%%%%%%%%%%%% Assume w=1meters and constant!!
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
Data_file_Name='Speed_sun_'; %Speed_night_ %Speed_sun_ %Speed_dusk_
Test_number=12;
Real_Speeds=dlmread([Data_file_Name,'real.txt'])   % MPH
Ref_speed=Real_Speeds(Test_number)*0.44704;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%
Data_=dlmread([Data_file_Name,num2str(Test_number),'.txt']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
data=Data_(:,2).';  % Voltage
Time=Data_(:,1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
Max_Peak=max(findpeaks(data));
Max_Peak_dB=10*log10((Max_Peak.^2)/1e6)
for Distance_Index=1:length(distance_Buffer)

[Estimated_K_dB(Distance_Index),Estimated_Gamma(Distance_Index)]=channelModel_Estima
tion_using_data(data,Time,Peak_Distance,Order_Poly,distance_Buffer(Distance_Index),Ref_spe
ed,Channel_Estimation_Duration,Fs,Channel_Plot_Flag);
end
 figure()
 plot(distance_Buffer,Estimated_K_dB)
  xlabel('Distance Buffer (m)')
    ylabel('K_{dB} estimated')
    grid on
    set(gca,'FontWeight','bold')
 figure()
 plot(distance_Buffer,Estimated_Gamma)
 xlabel('Distance Buffer (m)')
    ylabel('\gamma estimated ')
```

```
    grid on
    set(gca,'FontWeight','bold')

     figure()
 plot(Data_(:,1),10*log10((Data_(:,2).^2)/1e6))
 xlabel('Time (sec)')
    ylabel('Received power (dB) ')
    grid on
    set(gca,'FontWeight','bold')
mean(Estimated_K_dB)
mean(Estimated_Gamma)
```

APPENDIX F: MATLAB FUNCTION TO ESTIMATE THE CHANNEL MODEL PARAMETERS

```
[Estimated_K_dB,Estimated_Gamma]=Channel_fitting(Distance_Vector_dB,Pr_dB_Vector,Ord
er_Poly,Plot_Flag)

switch Order_Poly
    case 1
        Order='poly1';
    case 2
        Distance_Vector_dB=10.^(Distance_Vector_dB./10);
        Order = fittype('(c-1)*5*log10(1-(1/x^2))+b*10*log10(x)+a');
end

[f,Goodness_fit_statistics,Fitting_algorithm_information]=fit(Distance_Vector_dB.',Pr_dB_Vect
or.',Order)
if Plot_Flag
    switch Order_Poly
    case 1
    figure(9871)
    plot(f,Distance_Vector_dB,Pr_dB_Vector)
    xlabel('10*log_{10}(D)')
    ylabel('Pr_{dB}')
    grid on
    set(gca,'FontWeight','bold')
    hold on
    case 2
    figure(9871)
    plot(f,Distance_Vector_dB,Pr_dB_Vector)
    xlabel('D (m)')
    ylabel('Pr_{dB}')
    grid on
    set(gca,'FontWeight','bold')
    figure(10101)
     F_Estiamted=(f.c)*10*log10(1-
(1./Distance_Vector_dB.^2))+f.b*10*log10(Distance_Vector_dB)+f.a;
    plot(10*log10(Distance_Vector_dB),F_Estiamted)
    hold on
     plot(10*log10(Distance_Vector_dB),Pr_dB_Vector,'*r')
      xlabel('10*log_{10}(D)')
    ylabel('Pr_{dB}')
    grid on
    set(gca,'FontWeight','bold')
     hold on
    end
end
if Order_Poly == 1
```

```
   Estimated_K_dB=f.p2;
   Estimated_Gamma=f.p1*-1;
elseif Order_Poly==2
   Estimated_K_dB=f.a;
   Estimated_Gamma=f.b*-1;
   n=f.c-1
end
end
```