Developing and demonstrating Visible Light Communication system for Smart Transportation

Shraddha Vijay Govindwad

A Thesis Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

Indian Institute of Technology Hyderabad

Department of Electrical Engineering

June 2019

Declaration

I declare that this written submission represents my ideas in my own words, and where ideas or words of others have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

S. Govindwad

(Signature)

(Shraddha Vijay Govindwad)

EE17MTECH11006

(Roll No.)

Approval Sheet

This Thesis entitled Developing and demonstrating Visible Light Communication system for Smart Transportation by Shraddha Vijay Govindwad is approved for the degree of Master of Technology from IIT Hyderabad

24/06/19

(Dr. Rupesh Wandhare) Examiner
Dept. of Electrical Eng
IITH

24/6/19.

(Dr. GVV Sharma) Examiner
Dept. Electrical
IITH

24/6/19

(Dr. Abhinav Kumar) Adviser
Dept. of Electrical Eng
IITH

24/6/19.

() Chairman
Dept. of Electrical Eng
IITH

Acknowledgements

I would like to thank my guide Dr. Abhinav Kumar for his valuable guidance and help. And also Dr. Gajendranath Chaudhury, Dr. Vandana Sharma. Also I would like to thank Mr. Thummaluri Uday Reddy, Mr. Balakrishna Reddy, Mr. Pranay Agrawal and Miss. Yoghitha R.

Dedication

I dedicate this thesis to my family and teachers and friends.

Abstract

Smart Transportation System (STS) is a basic requirement of smart cities. In STS for vehicle to vehicle and vehicle to infrastructure communication a dynamic communication system is required with fast locking and ability to handle continuously changing channel conditions. Due to localised nature and unlicensed frequency band Visible Light Communication (VLC) can be a good alternative for STS. In this thesis we performed hardware experiments on VLC link for distance of 16m and got zero bit error rate and distance of 23m with BER less than 0.02. We have experimented for data rate of 2KHz. We have experimentally calculated the rise time and fall time of LED driver and receiver photo diode. The bottolneck in increasing data rate in outdoor VLC is LED driver. We proposed an algorithm for fast locking of devices with automated threshold decision. It is suitable for continuously changing channel conditions and rapid handoffs occurring in vehicular environment. The proposed algorithm is compatible with IEEE standard for VLC.

Contents

Chapter 1

Introduction

The Smart City project of government requires an efficient dealing of transportation and traffic issues. Smart Transportation System (STS) or Intelligent Transportation System is a service or application, this provides more coordinated and informed transportation, to ensure safer driving and to reduce carbon foot prints. Smart Transportation System (STS) is an energy efficient and promising system for transportation. According to World Health Organization, more than million people are killed on roads every day. It is a leading cause of death for children between 10 to 19 years of age. Efficient prevention measures like Smart Transportation System can avoid accidental injures, damages and deaths. STS will be the backbone of Smart Cities. 360 degree collusion warning is required for STS. However the deployment cost of sensors for ensuring 360 degree collusion warning will be very high. Alternatively, communication between vehicles and positioning can be used. In this system vehicles will communicate amongst themselves (Vehicle to Vehicle) and with infrastructure (Vehicle to Infrastructure) for safe and eco-friendly driving. In STS, the adjacent vehicles need to have information of location, speed, direction, acceleration of each other for safety. The location information of the vehicles can be conveyed to city central traffic control. This will be further used for routing the vehicles so as to minimise the air pollution and make efficient use of road infrastructure. The use of VLC for STS has been demonstrated on real road in day time as well as in night time at speed about 80 kmph and at distance of 20 m [1]. The VLC system has been demonstrated under fog conditions also using concentrator lens [3]. The feasibility of inter vehicle communication, using the new Li-Fi technology, for the improvement of the vehicles drivers safety has been showed using small representative toy vehicles [4]. Image sensor based VLC for automotive applications have been proposed in [6].

Visible Light Communication (VLC) is a communication system using light as carrier wave. In VLC the transmitter is LED and receiver is camera or photo diode. The communication channel is open air. This system is localised since the transmitter and receiver should be in line of sight.

The advantages of VLC system are as follows :

- License free band : The frequency band used as carrier is license free.
- Energy efficient : The LED lights used in this are energy efficient and serve purpose of both lightening and communication.
- Eco friendly : Since the transmitter (LED) lights are having long life this system is eco friendly.

- RF frequency free communication : Since the carrier wave is light, the system will have no interference to RF.
- Cost efficient : Since the transmitter (LED) is already in existing infrastructure. And photo diode circuits are cheap.
- Secure : Due to line of sight property.

1.1 Visible Light Communication for Smart Transportation System

The vehicles in the vicinity of considered vehicle constantly change with time resulting in rapid handoffs. Due to moving Tx (Transmitter) and Rx (Receiver) the channel conditions are continuously changing. For STS VLC is suitable communication system since :

- Licence-free band : The frequency band used for VLC (430 to 770 THz) is licence free.
- Already existing Infrastructure : The vehicle headlights and traffic lights can be used as transmitter. Hence the traffic lights and headlights can be used for dual purpose of lightening as well as communication. Almost all the vehicles have cameras on them that can be used as receiver.
- Scalability : VLC system works only when direct line of sight path is available.
- Interference free : Due to line of sight nature it is free from interference of the transmitters which are not in near vicinity. It is free from interference due to RF waves.
- Pedestrians : Since the receiver is equipped with camera the a warning can be issued to driver regarding any pedestrian or animal, approaching the vehicle, by using suitable image processing techniques.
- It can be used in remote areas where mobile communication facility is not available, and in RF restricted areas.
- Secure : Due to its localized nature, VLC is secure and immune to jamming and message falsification.
- Independent of upgrading mobile technologies.

Hence we decided to use VLC as a communication system for STS. The following are the challenges before VLC system for STS:

- Rapidly changing channel conditions: Since both the transmitter and receiver are moving in V2V case and one of them is moving in V2I, the channel conditions are continuously changing.
- Interference : The intensity of Sun and background lights vary temporally during day time. This results in dynamic interference to VLC link. Other light sources which are not part of the system also add to interference.

- Rapid handoffs : Since the vehicles and traffic signals which are in near vicinity or in area of contradiction with any particular vehicle are continuously changing hence rapid handoffs will occur. So the communication system should be able to do fast locking with new devices.

Thus we propose to use VLC to communicate between the vehicles and road infrastructure. In this system the adjacent vehicles transfer to each other the information like their speed, acceleration, location, direction etc. So that the vehicles get warning to avoid any collusion. The vehicles communicate with the road infrastructure (traffic light). The city has traffic control center. All the traffic lights will be connected to traffic control center with wired communication. From there traffic of city can be controlled and guided to make efficient use of roads and reduce the carbon footprints and have eco driving.
The structure of communication system for STS is as shown in Figure 1.1:

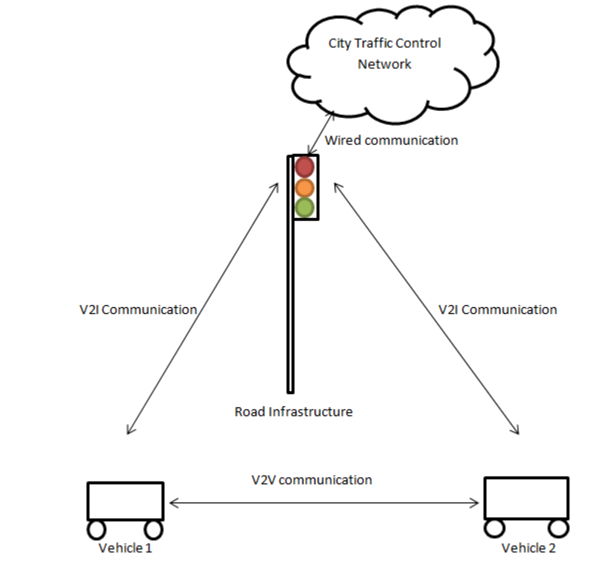

Figure 1.1: V2V and V2I communication for STS

1.1.1 Requirements of VLC for STS

- Range :
  For safe driving the driver should get warning of probable collusion before some minimum amount of time. This minimum amount of time depends on various factors, like speed of vehicle at that time, dry or wet road, drivers reaction time etc. Generally response time of drivers is 2 sec and breaking distance in worst case (wet road + 110 Kmph speed) is 97 m. So total stopping time is 4.1 sec and stopping distance is 143 m. So the minimum required range of communication is minimum 150 m.

- Data rate :
  For communication high data rate is required. Logically data rate can go upto GHzs. But because of slower switching rates of power LED drivers the data rate is getting limited.

- Threshold decision :
  The vehicles are continuously moving and the outside lightening conditions are continuously

changing due to the Sun and road lights. Hence the threshold for decision of bit 1 or 0 also needs to be adjusted continuously.

- Rapid handoffs :
  The vehicles which need to communicate, i.e. the vehicles in near vicinity of each other are continuously changing so rapid handoffs will be there. So fast locking of devices is required.

1.2 Contributions of thesis

- In this thesis we have demonstrated VLC link for distances more than 25 m and presented the variations in BER against distance. We have observed that with transmitted power of about 25 Watt at transmitter and using Si PIN photo diode at receiver (BPW34) We can communicate at about 16 m distance with zero BER.
- we have determined the properties of LED and LED driver like rise time, fall time, which mainly decide the maximum possible data rate.
- We have proposed an algorithm for automated threshold detection and for fast locking of devices using IEEE preamble structure designed for VLC.

1.3 Organization of the Thesis

The organization of the thesis is as follows:

- Chapter I is introduction with the detailed description of aim and work done.
- Chapter II has experimental results and the conclusion and presented the variations in BER against distance for transmitted power 25W.
- Chapter III has the experimentally determined LED properties like Rise time and Fall time. The analysis of bottleneck on increasing data rate in STS VLC (high power LED).
- In Chapter IV, an algorithm for fast locking of transmitter and receiver is proposed for the system to handle rapid handoffs encountered in STS.
- Chapter V summarizes the work done.

Chapter 2

Distance range at given transmitter power analysis

For safe driving the driver should get warning of probable contradiction before some minimum time and distance. And that minimum time and distance depends on road condition (wet or dry), vehicle speed, driver response time. From the literature survey it is found that in worst case (wet road, speed 110 kmph) the driver should get collusion warning at least before distance of 150 m. So the communication system used for STS should have minimum range of 150 m. In this thesis, we have performed experimented with power LED light at transmit power 25 Watt. Demonstrated communication with decent BER up to distance of 20 m and with zero BER up to distance of 16 m. This distance will increase when used with LED with reflector casing used in vehicle headlights.

2.1 Demonstration

We have demonstrated a Visible Light Communication link for a power LED similar to vehicle headlights but without the reflector casing. BER increases as the communication distance increases.
The experiment block diagram is as shown in Figure 2.1:

- The first block is Function Generator (AFG3102C). The function generator is programmable. We gave output from function generator to enable pin of LED driver according to our data sequence. (We have selected this function generator because it gives up to 100 MHz bandwidth and the output waveform is programmable, we used this to programme the output according to data to be transmitted).
- The next block is LED Driver (LM3409HV Evaluation board). We need driver because we have used power LED and function generator can not give the required power. The driver is powered by DC power supply, and the digital data input is given from function generator, according to the data input the high power (25 Watt). (We selected this because its output characteristics have matched with our requirements and it gives frequencies up to 400KHz).
- The next block is LED (BXRC-30G10K0-L-23). The LED is the transmitter. The LED transmits the data in form of light wave in open air channel. The data rate is 2kHz, so humans

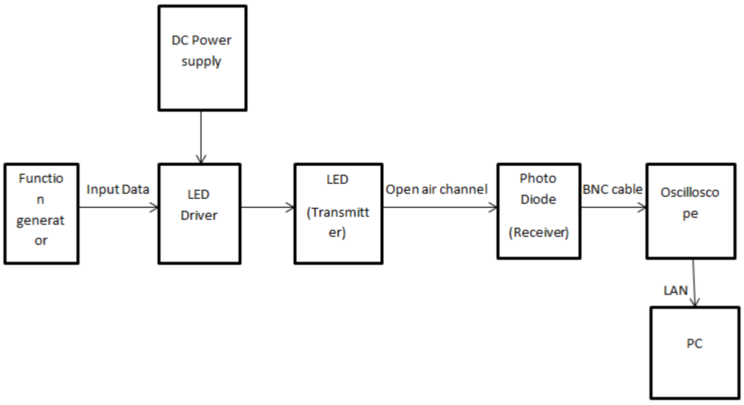

Figure 2.1: VLC link Block diagram.

can not notice the flickering since the human eye perception is 0.1 sec. (We selected this LED because it satisfies our power requirements).

- Then open air channel. (Visible Light Communication system uses open air).
- The next block Photo diode (BPW34) Si PIN photo diode is the receiver. The resistance of photo diode varies according to the intensity of light falling on it. We apply constant DC across the photo diode and one resistance in series and record the voltage across photo diode, the voltage across photo diode varies according to intensity of light falling on it. (We chose this because it satisfies our requirements and is economic).
- The voltage across photo diode is recorded by oscilloscope (Rohde and Schwarz RTM2054). (We select this oscilloscope because it gives bandwidth 100 MHz to 1 GHz and sample rate 1 Gsample/s. It is able to transfer recorded data to PC).
- The data recorded by oscilloscope is stored in PC using LAN connection.
- In PC using MATLAB programming we recover the data and calculate BER at different distances and plot it.

The experiment photo is shown Figure 2.2:

2.2 Conclusions

We observed that with transmit power 25 W and Si PIN photo diode as receiver, we can have VLC link for about 16 m with zero BER and up to distance of 20 m with BER less than 0.01. Our LED was without reflector casing of vehicle headlights, for headlights with reflector casing the distance will increase. Headlights of 70 to 100 Watt are available in market. So using the concentrating lens, the Visible Light Communication system can be used as communication system in Smart Transportation System.

Figure 2.3 presents the variations of BER against distance:

The received waveform at the receiver is in Figure 2.4.

Figure 2.2: Experiment set up.

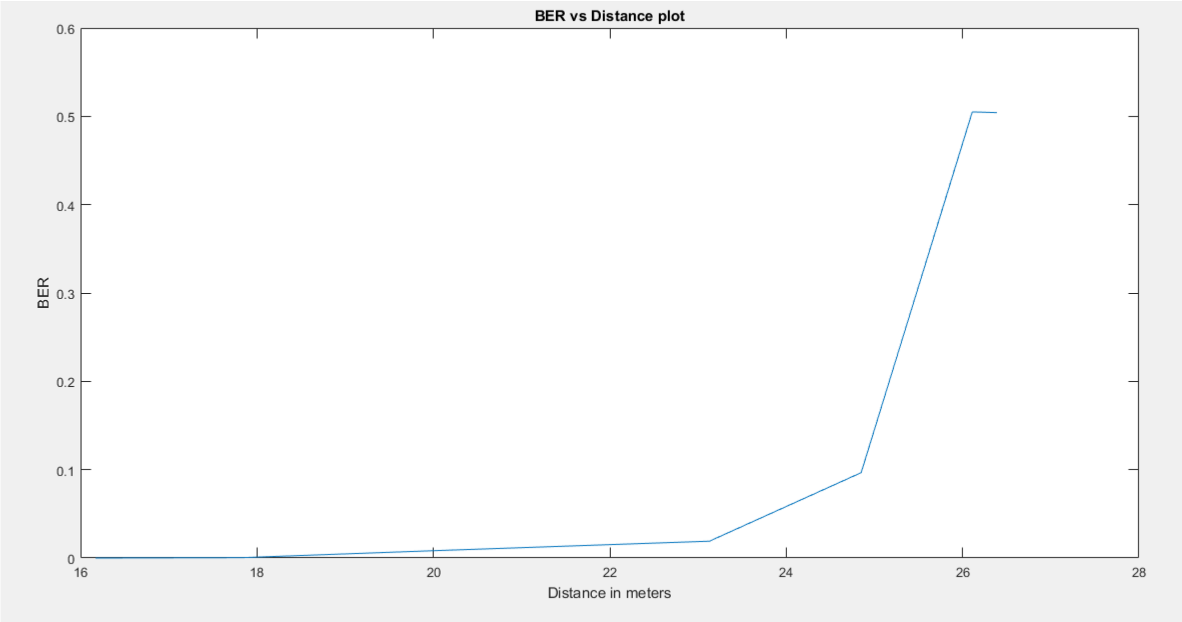

Figure 2.3: BER vs Distance plot

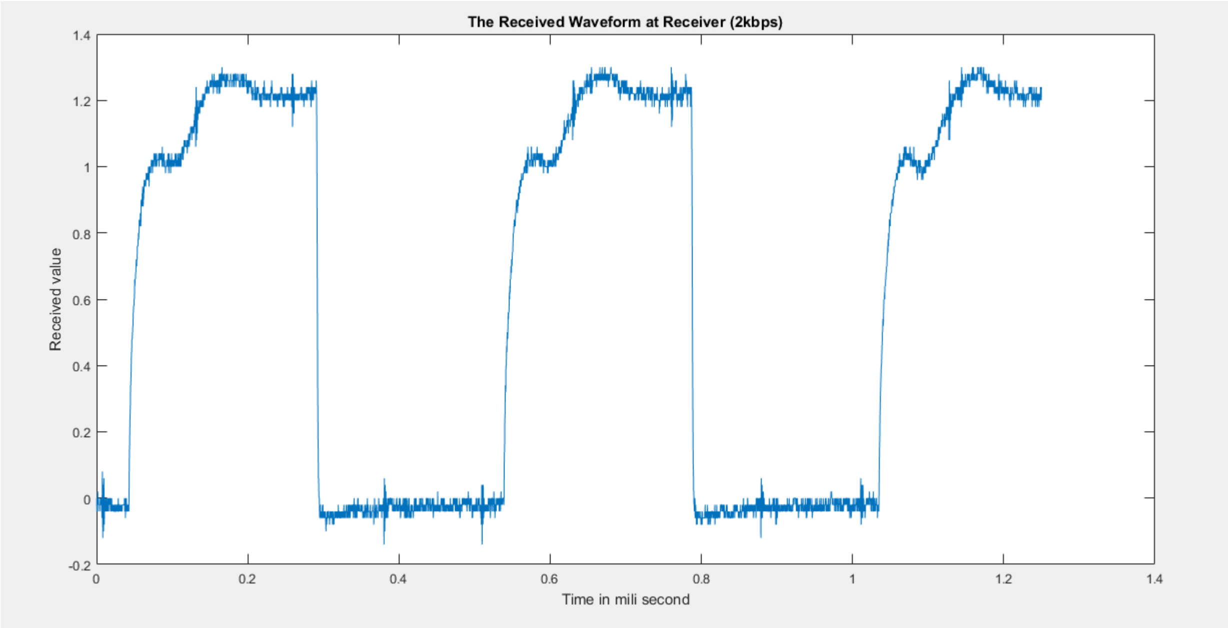

Figure 2.4: Waveform received at receiver

Chapter 3

Data rate limit analysis

High data rate is desired in communication systems. Although using smaller LEDs data rate upto 45 MBps have been demonstrated with camera receiver as receiver [5]. Ideally, the data rate of Visible Light Communication can be in GHzs because the band of frequencies in visible range is from 400 THz to 800 THz. For low power LEDs data rates up to some GHzs have been demonstrated. However for STS the headlights are power LEDs. So to drive them high current LED drivers are required. The drivers have high output current driving capacity. But they have comparatively high rise time and fall time. The fall time is more because the drivers use P-Field Effect Transistors which take more time to come out of saturation. To increase data rate of STS VLC system, fast switching current drivers are required.
In this chapter, we analysed the rise time and fall time of LED driver (LM3409HV Evaluation board).

3.1 Experimental set up

The set up is same as that of of previous experiment (BER vs Distance analysis). The only difference is that previously we recorded waveform at receiver, now waveform outputs of the LED driver are recorded.

3.2 Analysis of Rise time and Fall time

We observed that the waveform at transmitter and receiver are having almost same rise time and fall time so we conclude that the limit on data rate is from transmitter side due to LED driver.
The waveform received at output of LED driver is as shown in Figure 3.1:

Analysing the waveform which we recorded at output of LED driver we have observed that the average fall time, the time taken to go from Vcc (34 V) to zero is 150 micro sec, and the mean rise time is 230 nano sec. We notice that the mean rise time is negligible compared to mean fall time. Thus the fall time has affected the data rate.
The single waveform rise time plot is as in Figure 3.2.

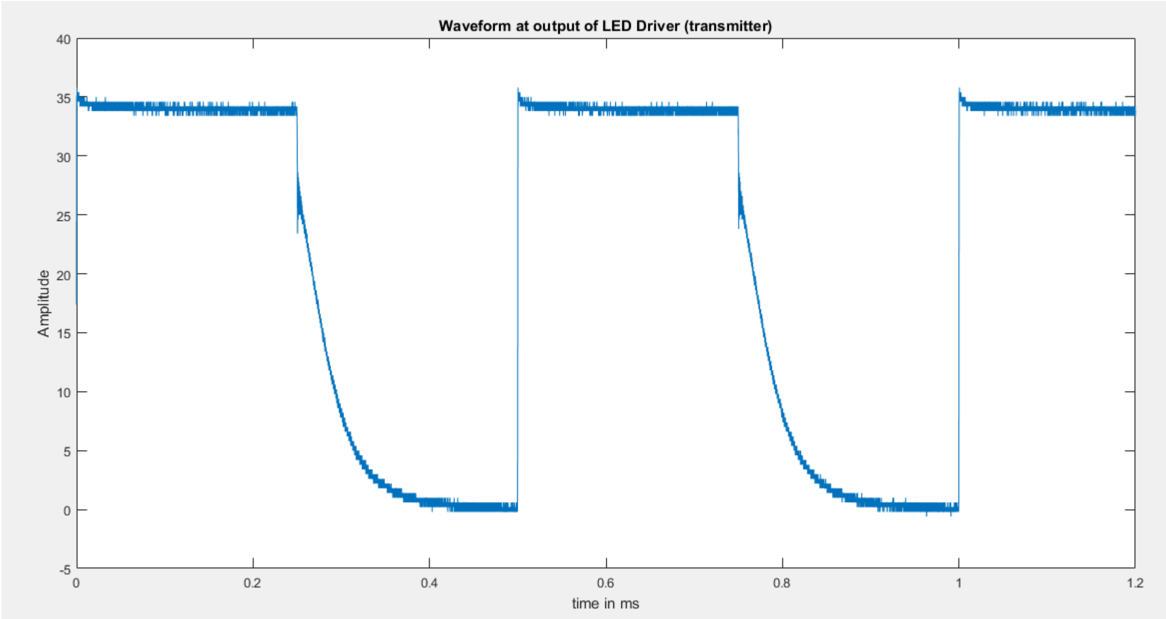

Figure 3.1: The waveform observed at LED driver output

The single waveform fall time plot is as shown in Figure 3.3.

The rise time and fall time of each cycle from 100% to 0% is as shown in Figure 3.4.
Most of the time in fall time is taken to fall from 10% to 0% of Vcc.
The detailed instantaneous voltage vs fall time and rise time graph is shown in fig 3.5.

3.3 Inference

From the observations and waveforms we observed that the limit on data rate is from LED driver fall time. It has large fall time because PFET in it takes time to come out of saturation. The problem of lower data rate can be overcome by either using MIMO or developing fast switching high current drivers.

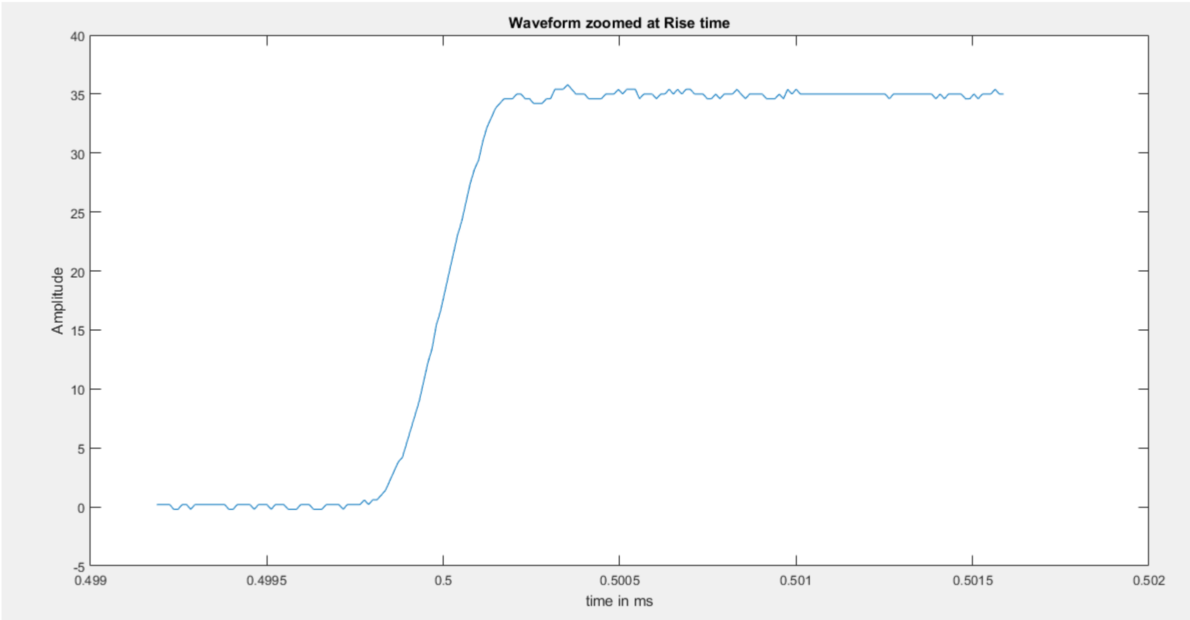

Figure 3.2: The single waveform rise time at LED driver output

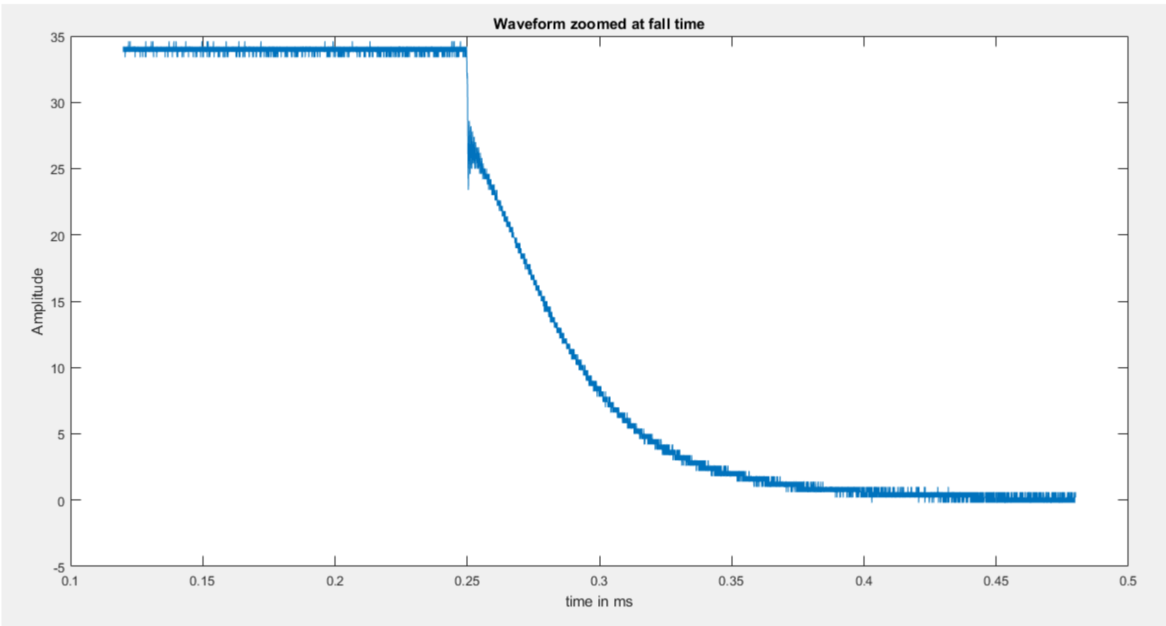

Figure 3.3: The single waveform fall time at LED driver output

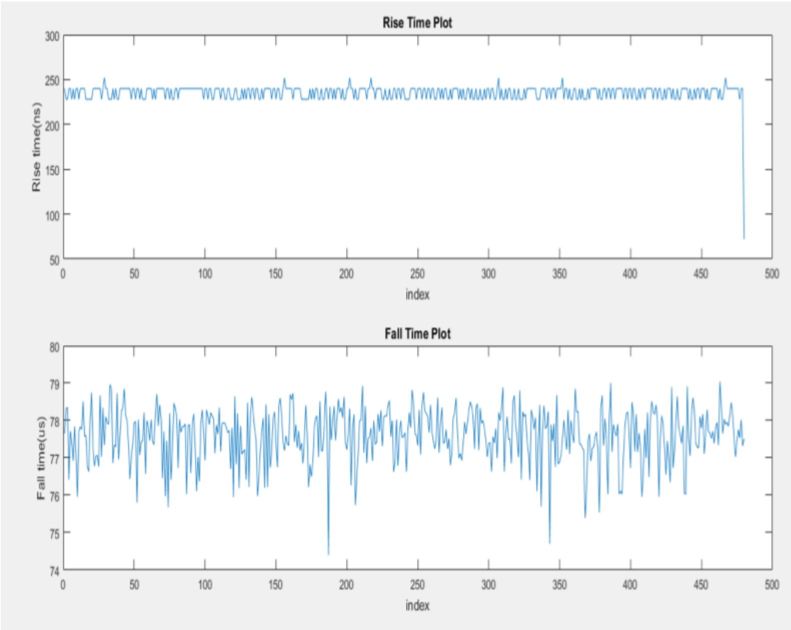

Figure 3.4: Rise time fall time plot of each cycle from 100% to 0%

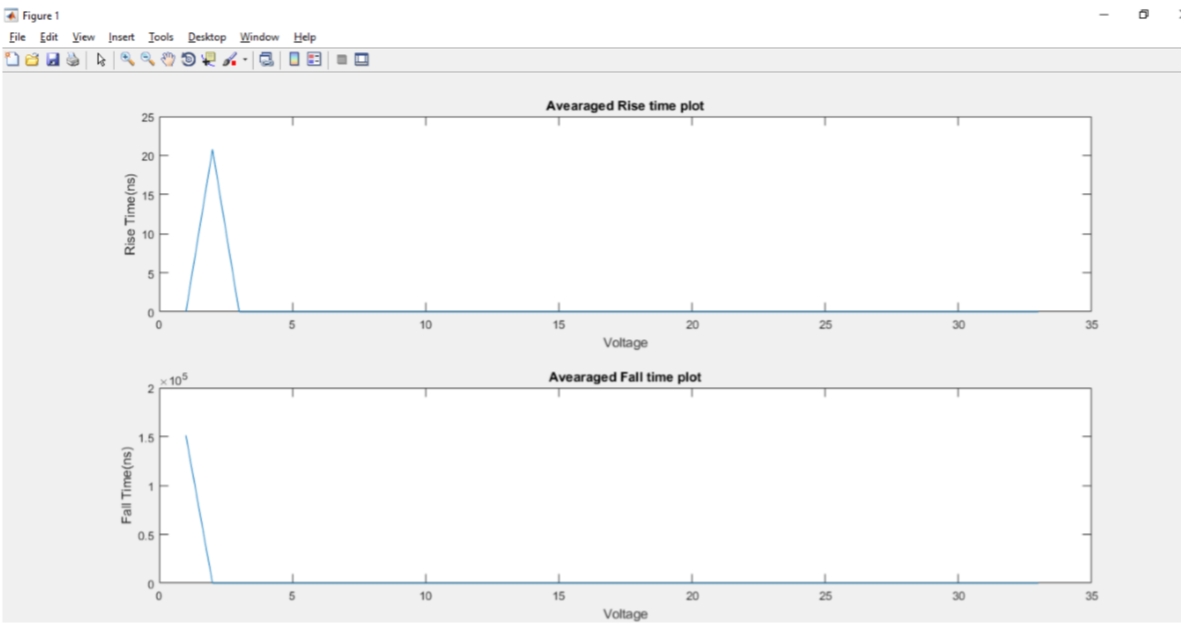

Figure 3.5: Voltage vs fall time and voltage vs rise time graph averaged over all the cycles

Chapter 4

Algorithm for Automated Thresholding and fast locking of devices

The algorithm used at receiver to decode data in any communication system should be suitable to its channel conditions. In vehicular environment, the background light is continuously changing due to Sun and other street lights. Hence, the threshold deciding bit 1 or 0 should be continuously adjusted to it. The vehicles which are near to each other are also continuously changing hence there will be frequent handoffs. So the the algorithm used for decoding at receiver should be able to handle frequent handoffs and capable of fast locking. In this thesis, we propose an algorithm to handle frequent handoffs and has automated threshold decision.

4.1 Vehicular communication requirements

The important requirements of vehicular communication are

- Threshold decision : Due to continuously changing channel conditions and varying distance between transmitter and receiver threshold should be adjusted continuously.
- Hand off : Since the desired transmitter and receiver for are continuously changing frequent hand offs should be handled.
- Range : The range of communication should be at least 150 m.

4.2 IEEE 802.15.7: Visible Light Communication standard

IEEE 802.15.7 is the IEEE standard for Visible Light Communication [29]. Flicker is disturbance in lighting system perceived by humans due to use of the same light for VLC. Humans can notice changes upto 0.1 sec in time. So the data rate should be minimum 200 Hz. Flicker can cause noticeable, negative/harmful physiological changes in humans. So it should be avoided. For energy efficiency dimming control should be provided along with the communication. IEEE 802.15.7 provides mechanisms for dimming adaptable and flicker free VLC.

IEEE 802.15.7 provides three main modulation schemes :

- OOK (On-Off Keying) modulation : In this modulation scheme the transmitter LED is simplly turned on and off according to the data i.e. on for bit 1 and off for bit 0. It has two voltage levels to one each to represent 1 and 0. The two voltage levels may not necessarily be ground and Vcc. Any two voltage levels can work as long as the receiver is able to differentiate between them.
  The data frame for OOK modulation is as shown in Figure 4.1.

Figure 4.1: IEEE 802.15.7 proposed data frame for OOK modulation.

  Each block has :

  - FLP (Fast Locking Pattern) : Contains continuous pattern of alternate "1"s and "0"s, and used for lock of new devices and handle rapid dandoffs.
  - TDP (Topology Dependant Pattern) : It is 15 bit pattern to differentiate between four different topologies i.e. 1) Visibility pattern, 2) Peer to Peer, 3) Star topology, 4)Broadcast.
  - PLH (Physical Layer Header) : To identify Physical Layer Topology.
  - DU (Data Unit) : Contains the data to be transmitted.

- VPPM (Variable Pulse Position Modulation) Modulation :
  VPPM modulation scheme supports dimming control for energy saving. The Pulse Position Modulation scheme conveys information of bit 1 or 0 by the position of high amplitude in waveform as shown in Figure 4.2.
  The term Variable here implies that the width of pulse can be varied according to the dimming requirements.
  The VPPM wave with 75% duty cycle is shown in Figure 4.3.

- CSK (Colour Shift Keying) Modulation :
  White light can be generated using equal brightness of Red, Green and Blue lights. In Colour Shift Keying modulation scheme, different (generally three i.e. Red-Green-Blue) coloured LEDs are used. The data bits are encoded in to colour combinations. For example for 8-CSK we will decide 8 combinations of different brightness of these three colours and allocate each combination to each one bit pattern (number).

In this work we have used OOK modulation scheme.

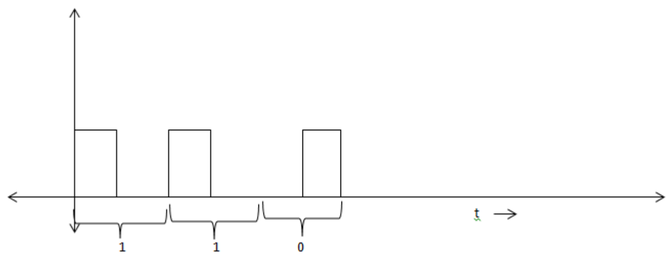

Figure 4.2: The VPPM modulated waveform (50% duty cycle)

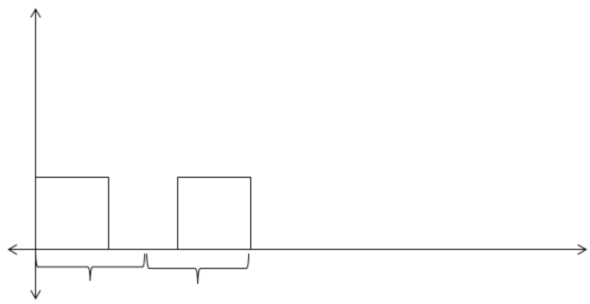

Figure 4.3: VPPM wave with 75% duty cycle.

4.3 Proposed algorithm

In this thesis, we have proposed an algorithm to decode the received data using OOK modulation scheme using the data frame structure given by IEEE 802.15.7.
In this experiment, we have transmitted preamble structure of 64 bits (1010...) and then 85 data bits (17 times bit sequence '11010'). We recorded the data at photo diode receiver at various distances and using the proposed algorithm, we estimated thresholds for each distance and got zero BER after decoding.
The Algorithm is as follows :

Algorithm :

1] Take count c = 0, e = predefined value (minimum delta value), c1 = 0, vth = 0.
2] We check the difference between current and immediate past bit.
3] If the difference is more 'e' then we increase count 'c' by one and make vth = difference between current and past and go to step [2]. Or go to step [4].
4] Increase c1 by 1. if c is more than 63 go to step [5]. Or if c is less than 63 and c1 is more than 3 then go to step 1. Else if c is less than 63 and c1 is also less than 3 then go to step [2].
5] The last bit of preamble is 0, so if (current value - past value) is greater than vth then decode it as 1, or else 0. Similarly decoded remaining data bits.

The data frame that we transmitted is as in Figure 4.4.
The transmitted data, the analog values received at receiver, decoded data and generated threshold are as shown in following Figure 4.5.
And the generated threshold vs distance graph is shown in Figure 4.6.

101010...64 times	110101101011010110101101011010110101101011010110101101011010110101101011010110101101011010110101101011010

Figure 4.4: Transmitted Data frame.

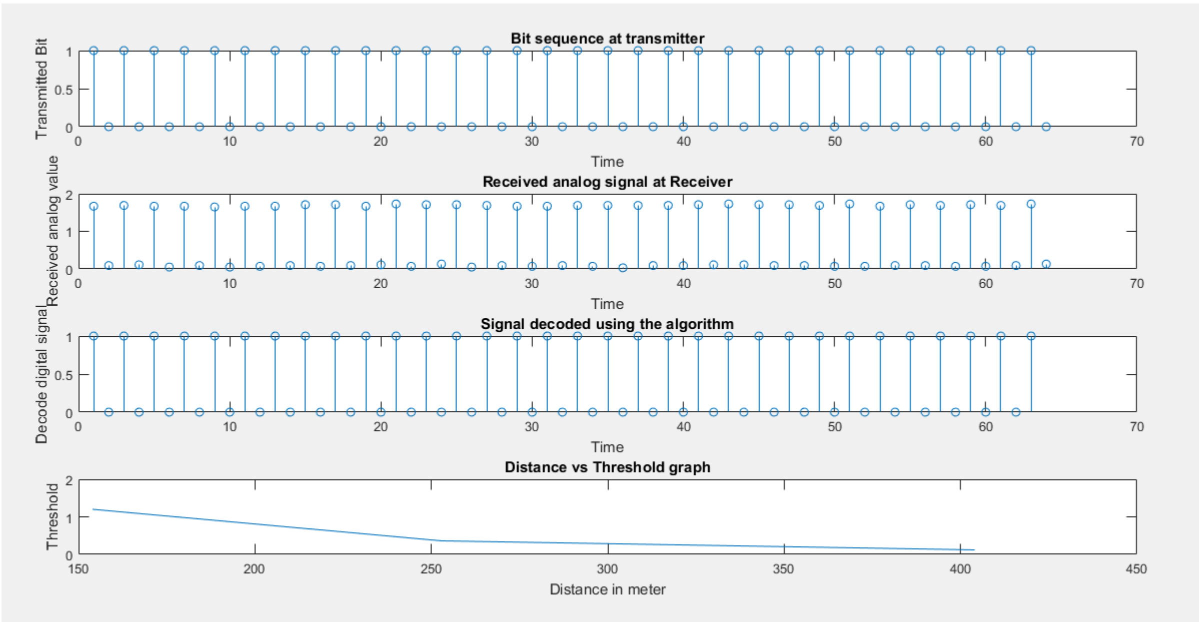

Figure 4.5: The transmitted data, received value at receiver, decoded data and generated threshold.

4.4 Results

Using this algorithm, we are able to adjust real time threshold at different distances and correctly recover transmitted data. And we are also getting real time fast locking of devices, and handle rapid handoffs. We recovered transmitted data with zero BER using this algorithm.

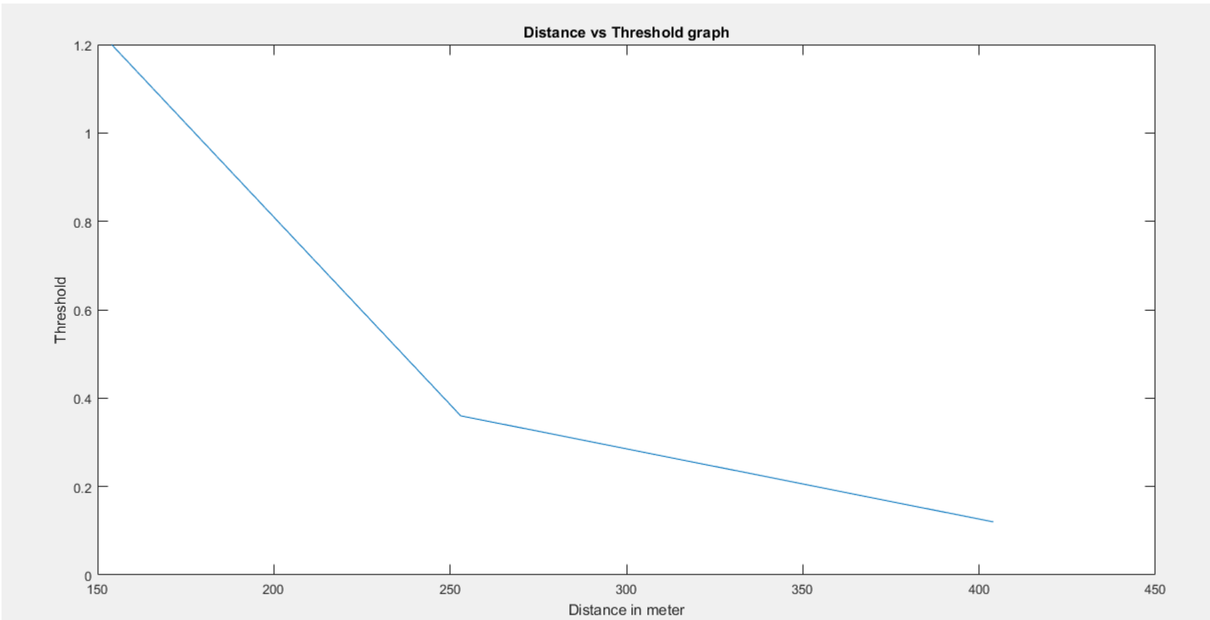

Figure 4.6: Generated threshold vs distance graph.

Chapter 5

Conclusion

In this work, we have calculated that the minimum range of communication for STS system is 150m. We demonstrated a Visible Light Communication link for Smart Transportation System, and found that with transmit power of about 25 Watt, we get communication link with BER less than 0.01 for about 20 m. With reflector casing of vehicle headlights and with the headlights of power nearly 70 Watt, the range can further increase up to 150 m. We conclude that using VLC for STS is feasible. We found that the limit on data rate in long distance VLC is because of the high current LED drivers.

We propose an algorithm for automated real time decision of threshold and fast locking of devices for VLC system for Smart Transportation System. The developed algorithm is compatible with the IEEE 802.15.7.

References

[1] K. Siddiqi, "Visible Light Communication for V2V Intelligent Transport System", *2016 International Conference on Broadband Communications for Next Generation Networks and Multimedia Applications (CoBCom)*,pp. 1-4, September 14-16, 2016, Graz, Austria(IEEE).

[2] M. Uysal, "Visible Light Communication for Vehicular Networking: Performance Study of a V2V System Using a Measured Headlamp Beam Pattern Model Performance Study of a V2V System Using a Measured Headlamp Beam Pattern Model", *IEEE Vehicular Technology Magazine* Volume: 10, Issue: 4, pp. 45-53, Dec. 2015.

[3] Y. Chung, "Experimental Demonstration of VLC-Based Vehicle-to-Vehicle Communications Under Fog Conditions", *IEEE Journal*, Volume 7, Number 6, pp. 1-10, December 2015.

[4] D. Mohammed l et al., "Digital data transmission via Visible Light Communication (VLC): Application to vehicle to vehicle communication", *Control Engineering and Information Technology (CEIT)*, pp. 1-5, 2016 4th International Conference.

[5] Y. Goto et al., "A New Automotive VLC System Using Optical Communication Image Sensor", *IEEE Photonics Journal* Volume: 8, Issue: 3, pp. 1-17, June 2016.

[6] T. Yamazato et al., "Image-sensor-based visible light communication for automotive applications", *Journal, IEEE Communications Magazine*, Volume: 52, Issue: 7, pp. 88-97, July 2014.

[7] S. Hosur, "Visible light communications: the road to standardization and commercialization (Part 1)", *IEEE Communications Magazine*, Volume: 51, Issue: 12, pp. 24-25, December 2013.

[8] J.-H. YOO1 et al., "DEMONSTRATION OF VEHICULAR VISIBLE LIGHT COMMUNICATION BASED ON LED HEADLAMP", *Ubiquitous and Future Networks (ICUFN)*, pp. 347-348, 2013 Fifth International Conference.

[9] Y. Kim1 et al., "Experimental Demonstration of LED -based Vehicle to Vehicle Communication under Atmospheric Turbulence", *Information and Communication Technology Convergence (ICTC)*, pp. 1143-1145, 2015 International Conference.

[10] I. Takai et al., "Optical Vehicle-to-Vehicle Communication System Using LED Transmitter and Camera Receiver", *IEEE Journal*, Volume 6, Number 5, pp. 1-14, October 2014.

[11] M. KINOSHITA1 at al., "Channel Fluctuation Measurement for Image Sensor Based I2V-VLC, V2I-VLC, and V2V-VLC", *Circuits and Systems (APCCAS)*, pp. 332-335, 2014 IEEE Asia Pacific Conference.

[12] Ai-Ling Chen at al., "Time Variation in Vehicle-to-Vehicle Visible Light Communication Channels", pp. 1-8, *2016 IEEE Vehicular Networking Conference (VNC).*

[13] T. Yamazato et al., "Vehicle Motion and Pixel Illumination Modeling for Image Sensor Based Visible Light Communication", *IEEE Journal, IEEE Journal on Selected Areas in Communications*, Volume: 33, Issue: 9, pp. 1793-1805, Sept. 2015.

[14] Bugra Turant,Seyhan Ucar*, Sinem Coleri Ergentand Oznur Ozkasap* "Dual Channel Visible Light Communications For Enhanced Vehicular Connectivity", *IEEE Conference, Vehicular Networking Conference (VNC)*, pp. 84-87, 2015 IEEE.

[15] Alin-Mihai Cailean and Mihai Dimian, "Current Challenges for Visible Light Communications Usage in Vehicle Applications: A Survey", *IEEE Journal, IEEE Communications Surveys and Tutorials*, Volume: 19, Issue: 4, pp. 2681-2703, Fourthquarter 2017.

[16] Peng Ji*, Hsin-Mu Tsai, Chao Wang*, "Vehicular Visible Light Communications with LED Taillight and Rolling Shutter Camera", *IEEE Conference, Vehicular Technology Conference (VTC Spring)*, pp. 1-6, 2014 IEEE 79th.

[17] Alin-Mihai Cailean 1,2, "A survey on the usage of DSRC and VLC in communication-based vehicle safety applications", *Communications and Vehicular Technology in the Benelux (SCVT)*, pp. 1-6, 2014 IEEE 21st Symposium.

[18] Shogo Kitano, Shinichiro Haruyama and Masao Nakagawa, "LED road illumination communications system", *Vehicular Technology Conference, 2003. VTC 2003-Fall*, pp. 3346-3350, 2003 IEEE 58th.

[19] Sayaka NISHIMOTO et al., "High-speed transmission of overlay coding for road-to-vehicle visible light communication using LED array and high-speed camera", *Globecom Workshops (GC Wkshps)*, pp. 1234-1238, 2012 IEEE.

[20] M. Yoshino, S. Haruyama, M. Nakagawa, "High-accuracy Positioning System using Visible LED Lights and Image Sensor", *Radio and Wireless Symposium*, pp. 439-442, 2008 IEEE.

[21] T. Yamazato et al, "Range estimation scheme for integrated I2V-VLC using a high-speed image sensor", *Communications Workshops (ICC)*,pp. 1-5, 2016 IEEE International Conference.

[22] Mohammad Y. Abualhoul et al., "Visible light inter-vehicle communication for platooning of autonomous vehicles", *Intelligent Vehicles Symposium (IV)*, pp. 508-513, 2016 IEEE.

[23] Muhammad Saadi et al., "System Demonstration for Visible Light Communication using Adaptive Threshold Detection for Low Data Rate Applications", pp. 1-3, 978-1-4673-5696-1/12/26.00 2012 IEEE.

[24] S. Rajagopal, "IEEE 802.15.7 Visible Light Communication: Modulation Schemes and Dimming Support", *IEEE Communications Magazine*, pp. 72-82, March 201272 0163-6804/12/25.00 2012 IEEE.

[25] IEEE Computer Society, "IEEE Standard for Local and metropolitan area networks Part 15.7: Short-Range Wireless Optical Communication Using Visible Light ", *IEEE Std 802.15.7*, pp. 1-309, 2011.

[26] S. Rajagopal, "IEEE 802.15.7 VLC PHY/MAC Proposal Samsung/ETRI ",*IEEE*, pp. 1-121, October, 2009.

[27] Alin-Mihai Cailean, "Novel DSP Receiver Architecture for Multi-Channel Visible Light Communications in Automotive Applications ", *IEEE SENSORS JOURNAL*, VOL. 16, NO. 10, pp. 3597-3602, MAY 15, 2016.