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# A Low-Cost NLOS Ultra-Violet V2I Identification System for Vehicular Theft Recovery

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***Abstract*— With increasing populations in urban areas, an intelligent means of vehicular identification, tracking, and communication becomes a necessity. In this paper, an optical alternative to radio frequency identification (RFID) using ultra-violet (UV) light is presented. A non-line-of-sight (NLOS) UV vehicle-to-infrastructure (V2I) system is proposed to establish proof of concept. The performance of a proto-type communication system demonstrating the use of UV lamps and on-off keying (OOK) to transmit an identification number over free space channels up to 30 m (~100 ft) is analyzed. Although a proto-type, the ultra-violet identification (UVID) system yields an effective, discrete solution towards unidentified terrestrial vehicle identification. Several applications of UVID within amber alert scenarios, recovery of stolen vehicles and vehicular networking are analyzed. Implementations in development including a low power UV LED-based transceiver adapted for car headlights capable of vehicle-to-vehicle (V2V) communication and its applications within intelligent vehicle design are discussed as well.**

***Keywords*— Communication systems, nonlinear optics, nonlinear optical devices, optical communication equipment, optics, Rayleigh channels, ultraviolet sources, vehicle safety**

## I. INTRODUCTION

Ultra-violet (UV) communications provide an interesting alternative to the constantly debated RFID technology. RFID has become an extremely effective form of identification and is used widely, but has limitations such as poor security due to the broadcast nature of its radio frequency operation, high cost of active RFID tags, and collision of RFID tags when multiple tags are energized within a given area. With the emergence of free space optical communication systems in recent years, a new alternative presents itself as a candidate for identification and communication systems. Operating outside of the visible light spectrum ranging from 300nm-700nm, communications may be achieved using the transmission and reception of UV light within the "solar-blind" or "deep UV" spectrum of 200-280nm [1]. This range of UV spectrum is referred to as solar-blind due to operation within this spectrum remaining impervious to the majority of ambient solar radiation. When compared to propagation characteristics of visible and infrared (IR) light, an interesting behavior is observed due to the higher frequency and shorter wavelength of UV light. Operating within the extremely high frequency of the solar-blind spectrum causes propagating light to scatter due to its higher photonic energy associated with its higher frequency and shorter wavelength. For relatively short range communication systems, this Rayleigh scattering ensures sufficient attenuation compared to the propagation of line-of-sight (LOS) dependent optical communication systems.

Free space optical systems operating within wavelengths outside of the solar-blind spectrum prove to be limited and unreliable due to their LOS nature. In order to communicate data, a direct visible path is required between the transmitter and receiver in LOS systems. If at any moment, a non-transparent object obstructs this LOS, due to the optical nature of the visible and IR wavelengths being used, the transmitted signal is significantly attenuated by the obstruction. Another problem with LOS systems is the difficulty of configuring and aligning such LOS-dependent free space optical systems. Because a direct path is required between transmitter and receiver, gauging the appropriate trajectory of transmission can be burdensome and unstable. Due to these two reasons, LOS-dependent free space optical systems are rendered impractical and unreliable. The use of UV communication provides an attractive solution to problems evident within visible or IR free space optical communication systems. The use of a light source within the solar-blind UV spectrum provides a distinct advantage over its visible and IR light-based counterparts, NLOS operation. Due to the nature of UV light propagation in combination with photonic Rayleigh scattering phenomenon, the performance of the proposed free space optical system becomes non-linear. This NLOS communication provides needed reliability and functionality to mobile vehicular communication systems.

In this paper, we exploit these behaviors of NLOS UV communication systems and discuss beneficial applications of such systems applied towards the automotive industry. Specifically, we first provide background information towards the performance of the on-off keying (OOK) modulation scheme used in the NLOS UV communication system presented in this paper. Mathematical expressions for the data rate, signal to noise ratio, and bit error rate of the modulation

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scheme are included and discussed in detail. Next, we review the state-of-the-art technology for constructing the presented NLOS system. Low, medium, and high noise channel models for solar-blind UV systems are measured and provide insight towards how such NLOS UV communication systems will suffer from channel noise in indoor and outdoor settings.

A prototype system for vehicular theft recovery via NLOS UV communication in presented. Solar-blind UV transmitters placed within vehicles' light sources provide a continuous, invisible transmission of each vehicle's vehicle identification number (VIN #). The transmitted identification numbers are then acquired via solar-blind UV receiver placed in desired locations. The applications and effectiveness of these UV systems towards resolving matters regarding vehicular theft and child kidnappings (amber alert scenarios) are discussed in this section as well. We also provide a glimpse of a work currently in progress, a NLOS UV communication system embedded within headlights of an automobile. This system measures distances of surrounding vehicles via an IR sensor and communicates the proximities of surrounding vehicles between vehicles via a NLOS UV system. This intra-vehicular communication not only provides an exciting glimpse towards the future of smart travel, but also has the potential to prevent collisions and save lives.

The reminder of this article is organized as follows. In Section II, we present an analysis for the signal to noise ratio (SNR) and bit error rate (BER) of the OOK UV system. We then review the state-of-the-art in Section III. The proposed UVID system is presented in Section IV. Its potential applications and future work are discussed in Sections V and VI, respectively. Section VII concludes this paper.

## II. BIT ERROR RATE ANALYSIS

Many visible light communication systems adopt the on-off keying modulation scheme. On-off keying is the simplest form of available digital modulations. In OOK, a serial bit stream is provided. A bit '1' is represented by a logic-high pulse and a bit '0' is represented by a logic-low pulse. The widths of these pulses are recorded as a function of time and are known as pulse durations, $T_p$. These pulses are then arranged in a limited time frame designated to each bit known as the bit interval, $T_b$. As long as the pulse duration is a fraction of the bit interval, the bit interval retains its integrity and may be filtered or used as a reference clock. The data rate of the bit stream is indirectly proportional to the bit interval, as [3]:

$$R_b = 1/T_b,$$

The bandwidth efficiency of the OOK system is given by the ratio of a pulse duration versus bit interval, or [3]:

$$\varepsilon_{BW} = \frac{T_p}{T_b},$$

In order to calculate the bit error rate of an on-off keying communication system, several sources of noise in addition to our desired received signal should be considered. The two main sources of noise accounted for in this OOK channel model are the noise power associated with the dark current of the detector being used, $P_{dark}$, in addition to the measured ambient background radiation and light at the detector, $P_{ambient}$. The noise power of the detector's dark current is provided by [3]:

$$P_{dark} = \frac{hcB}{n\lambda}$$

where $h$ is the Planck constant, $c$ is the speed of light, $B$ is the bandwidth of the receiver, $n$ is the quantum efficiency, and $\lambda$ is the signal wavelength.

Using the dark current and ambient noise sources mentioned, the SNR of the OOK system may be expressed as [3]:

$$SNR = \frac{Pr}{P_{ambient}\sqrt{P_{dark}+P_r}},$$

where $Pr$ represents the power of the received signal. Finally, the bit error rate (BER) of the on-off keying system is provided by [3]:

$$BER = 0.5 * erfc(SNR),$$

where $erfc(\cdot)$ is the error function.

## III. STATE-OF-THE-ART

Following the appropriate procedures in calculating the SNR and BER for an OOK communication system as shown in Section II, researchers at the University of California-Riverside have measured the BER of a similar UV communication system as a function of distance between the transmitter and receiver. Several differences to be noted when comparing the modeled OOK system to the prototype presented in this paper include a lower data rate of 5 kbps, whereas the UVID system presented in this paper operates at a data rate of 10 kbps. In addition, the UC-Riverside system used UV LED's as a light source. When light sources with limited transmission beamwidths such as UV LED's are used, the overall performance of the system relies heavily on the intersecting angle of the transmitter being used and the field of view of the photodiode used to capture the transmitted signal (as shown in Figure 1-b). This NLOS intersection between the transmitted optical beam and field of view of the receiver is what provides a distinct advantage to optical communication within the solar-blind UV spectrum, whereas optical communication systems utilizing wavelengths outside of this region are limited to line of sight (LOS) functionality.

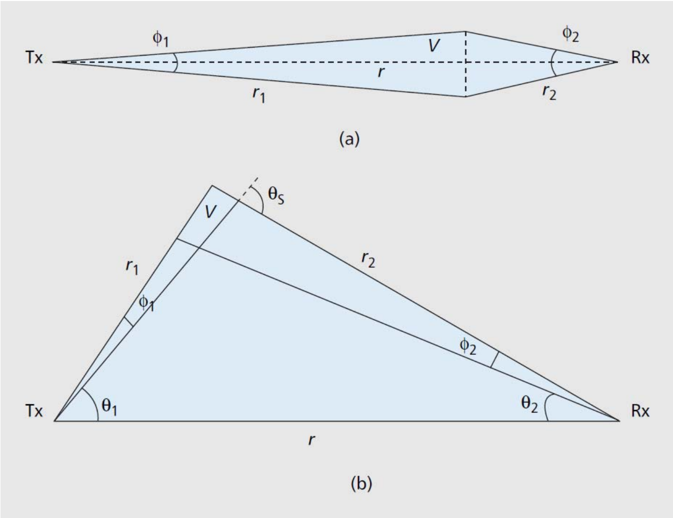

*Fig. 1 – (a) An illustration of a line-of-sight (LOS) configuration used in conventional free space optical systems. The linear behavior of these optical systems only allows communication to be established when a direct path between the two nodes is available. (b) An illustration of a Non-Line-of-Sight Configuration [4]*

Employment of NLOS optical communication systems serves a considerably more reliable and practical role in communication when compared to their LOS limited optical counterparts. Because LOS systems need to have a direct LOS between transmitter and receiver, setting up and maintaining such a system for a moveable platform is challenging. In addition, the performance of LOS optical systems within vehicular communications, such as direct short range communication (DSRC) systems, is unreliable compared to that of NLOS UV systems due to the inherent susceptibility of an object obstructing the LOS between transmitter and receiver, thus fully attenuating the propagating optical signal.

To further simplify and ensure greater reliability for the proposed UV communication system, using UV lamps as a transmission source provides a nearly omni-directional light source. This not only eliminates a great deal of time in setting up a functional optical intersection between the transmitter's beamwidth and receiver's field of view, it also ensures reliable communication between the two. Therefore, worries regarding passing objects possibly obstructing and interfering with signal reception are nearly eliminated.

The OOK UV communication system modeled and measured at UC-Riverside provides performance results in three various channel settings necessary for consideration. Because the UV communication system presented in this paper is a prototype for vehicular implementation, fluctuating channel environments need to be considered. Three such environments are presented in Figure 2.

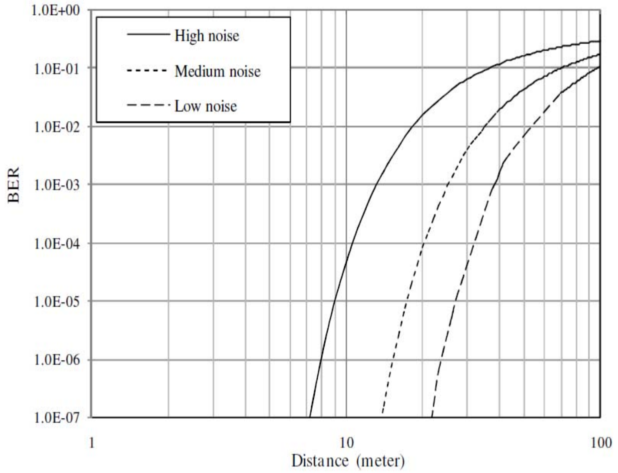

*Fig. 2 – Calculated bit error rate performance of UC-Riverside's 5 kbps OOK NLOS UV system relative to the distance between transmitter and receiver in high, medium, and low noise scenarios [5].*

The performance modeling depicted in Figure 2 provides crucial insight towards how the proposed UV communication system will perform in its vehicular applications. Transmitters of the proposed UV communication system are to transmit via the exterior of vehicles, therefore outdoor communication performance during daytime (high noise scenario) and night-time (medium-to-low noise scenarios) of the proposed UV communication system may be adequately predicted using the measurements presented in Figure 2.

## IV. ULTRA-VIOLET IDENTIFICATION SYSTEM

In this section, the operation, components, and specifications of the proposed Ultra Violet identification (UVID) system are presented. The system design is illustrated in Figure 3. For the perceived UV communication system, but more specifically, UVID system, the transmitted identification data is the Vehicle Identification Number (VIN #) of an automobile. The VIN # is stored in a 256 kb programmable integrated circuit (PIC) capable of storing the 17-character ASCII identification number. The PIC outputs the stored identification number in the form of a transistor-transistor-logic (TTL) binary serial waveform at 10 kbps. The digital bit stream is then fed into a digital-to-analog converter (DAC) which converts the binary bit stream into an analog waveform. This conversion allows for a simple amplification process to take place due to the inherent difficulty of digital signal amplification. The analog signal is then amplified significantly to meet the required turn-on voltage of 14.5 volts associated with the mercury-arc lamps used as the UV light source (USHIO G4T5).

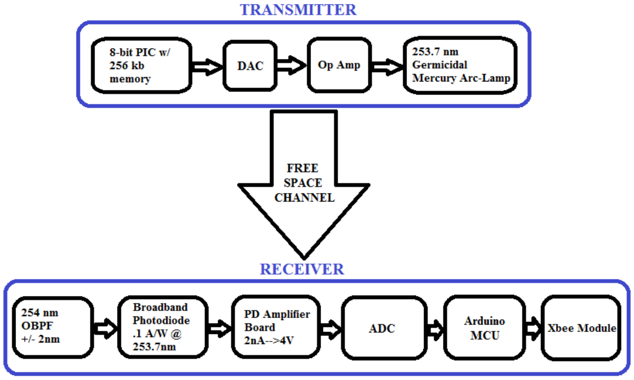

*Fig. 3 - Block Diagram of Ultra-Violet Identification System.*

Mercury-arc lamps were used to keep the cost of each transmitter under ten dollars to maintain a reasonable cost per transmitter/vehicle; considering the hypothetical implementation of the UVID system and the high number of transmitters in circulation. Mercury-arc lamps are an ideal candidate for prototyping this system due to their low cost, solar-blind transmission wavelength, and measured performance of up to 100 kbps [2]. If these systems are produced on a large scale, an efficient alternative to mercury-arc lamps is to use UV LED's due to their shorter rise and fall times. Although UV LED's are more expensive, their use would provide straightforward integration with newer vehicle headlights as the use of high-power LED's in headlights is gaining popularity.

In our experimental work, the transmitted 253.7 nm wavelength (transmission wavelength of light source) optical signal then travels through atmospheric channels with measured distances of up to 30 meters (~100 ft) from transmitter to receiver. When recovered at the receiver, several considerations need to be made to increase the signal-to-noise ratio of the receiver. Because the transmitted signal is optical in nature, most channel noise encountered on the path to the receiver will be of an optical nature as well. Pre-existing solar radiation, ambient UV light, and atmospheric turbulence are all factors in impacting the integrity of the desired signal [1].

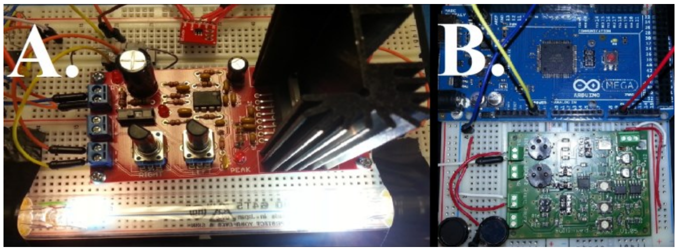

*Fig. 4 – (a) Transmitter Prototype – DAC (Top), Amplifier (Middle), UV Lamp (Bottom); (b) Receiver Prototype – OBPF & Photodiode Array (Bottom Left), Trans-impedance Photodiode Amplifier Board (Bottom Right), Arduino Microcontroller Unit (Top)*

To combat the out-of-band optical noise present, an optical band pass filter (OBPF) is placed at the front end of the receiver. The Roithner LaserTechnik OBPF (RLT-254-11-A) is centered at a frequency of 254 nm with a tolerance of +/- 2nm; nearly ideal for recovering the transmitted 253.7 nm signal. The optical signal is then collected via an array of two broadband UV photodiodes (SIC01L-18) which have a measured spectral responsivity of approximately 0.1 A/W at our 253.7 nm wavelength signal. Once the optical signal is gathered by the photodiode array, it is converted to an electrical signal and output to a specified photodiode amplifier board. The amplifier board is a trans-impedance amplifier board configured to amplify a received analog signal with a minimum of 2 nA of current to a 0 ~ 4 V signal. The signal is then fed into an analog-to-digital converter (ADC) where it is converted back to a digital serial waveform. The bit stream is then fed into an Arduino microcontroller platform where it is ultimately recovered as a VIN #.

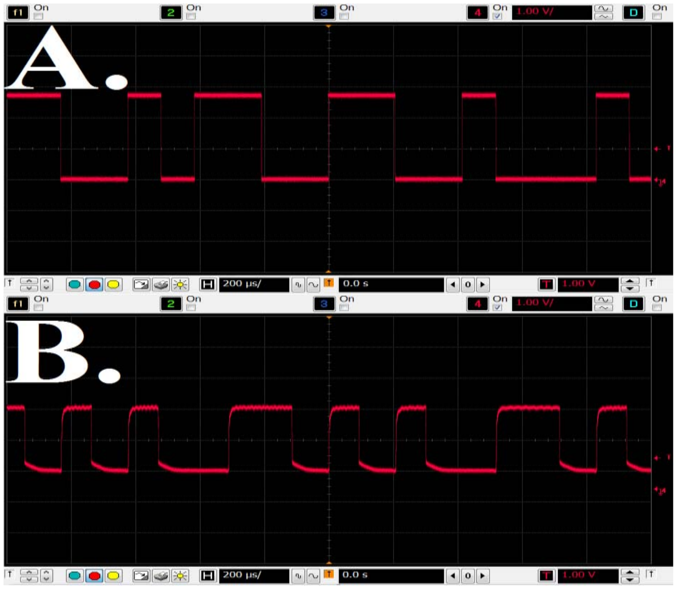

*Fig. 5 – (a) Transmitted Serial Bit Stream, (b) Recovered Serial Bit Stream*

Once the VIN # is successfully recovered at the receiver as shown in Figure 5.b., it may then be transmitted via a Xbee RF module adapted to Arduino microcontrollers through a radio frequency link to a central computer where the VIN #'s of passing vehicles associated with the recovered serial bit streams are to be recorded, compared or further processed.

## V. PROOF-OF-CONCEPT

Three parameters of interest, bit error rate (BER), distance and the channel environment, were measured during testing of the UVID prototype. Bit error rate was measured to provide insight towards how different variables influence the overall quality of the signal and how noise may impact signal quality. Measurements recorded at distances in increments of 5 meters starting from 5 meters to 30 meters were used to analyze the effect of distance on the signal integrity. These measurements were taken in three different channel environments to gain perspective on how the proposed UVID system would perform in various settings.

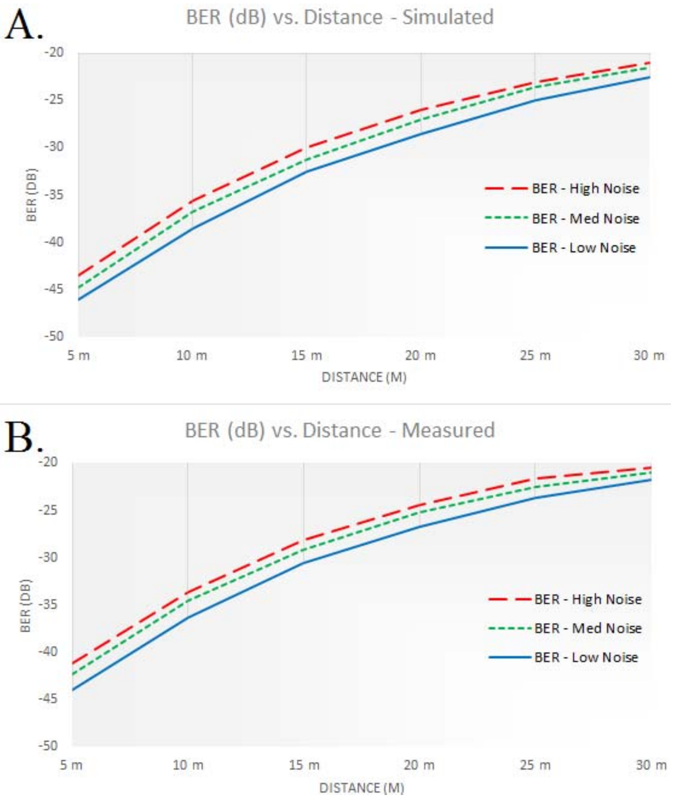

*Fig. 6 – (a) Simulated and (b) measured bit error rate (BER) as a function of distance between transmitter and receiver at a data rate of 10 kbps.*

Figures 6.a. and 6.b. show the simulated and measured bit error rate values as a function of distance in low, medium and high noise environments. Measurements for low-noise conditions were performed in a 50 meter x 50 meter auditorium with no ambient lighting to provide a baseline comparison for outdoor and higher-noise measurements. The medium and high-noise measurements were taken at outside at night-time and day-time, respectively. All measurements were made in environments with clear conditions and virtually no cloud cover.

The measured BER of each distance in every channel environment was recorded three times and then averaged. The results of the experiment are displayed in Figure 6.b.

The measured data for the UVID system is plotted in Fig. 6.b. In comparison to the hypothesized values depicted in Fig 6.a., it is shown the BER of all three tested evironments was uniformly lower across approximately all measured distances. Although the values are slightly offset, the behavior of the communication system performs as expected and provides decent bit error for an OOK communication system; ultimately providing adequate communication quality and system performance to validate the proof-of-concept behind the proposed NLOS UVID system.

## VI. APPLICATION

The proposed UVID system can have a wide variety of applications, providing solutions to problems such as vehicular theft, child abduction, or vehicle-to-vehicle networks. With each vehicle continuously and invisibly transmitting its VIN #, a targeted vehicle may be tracked as it passes each receiver station. These receiver stations are to be strategically placed on intersections, high-traffic roads, etc. If a vehicle is stolen, or a suspicious vehicle needs to be found, its location and identification number will be recorded as it passes certain locations with receivers in place. The location of each identified vehicle is then relayed to the central computer in possession of whatever legal or commercial authority is in charge of the UVID system's use. Because the VIN # is already being acquired, other desired information such as the speed of the vehicle may be transmitted along with the VIN #. This provides an appealing mobile alternative to current standards in speed detection such as radar and lidar guns currently used by traffic authorities.

Since this system uses an invisible ultra-violet light to transmit information, the functionality of the system may be independent of the use of the headlights themselves.

We hope to expand and integrate this technology to areas where lighting is already being used to serve a ubiquitous purpose. The integration of UVID systems is a plausible candidate for developing "smart" traffic systems with an optical infrastructure. Vehicle lights provide a ready light source, ultimately to be accompanied by a low-cost UVID beacon.

## VII. FUTURE WORK

A low power version of the presented UV communication system using UV LED's is currently under development. Focusing specifically on implementing a UV communication system within an automobile's headlights, the use of UV LED's as a light source allows for easier integration with many LED headlights already being used in automobiles today. In an effort to further increase the intelligence and capabilities of modern smart cars, an application of UV communication within intra-vehicular communications presents itself.

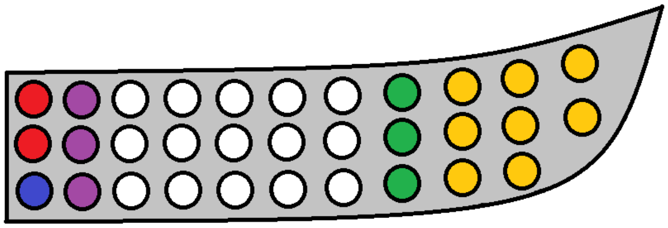

*Fig. 7 – The proposed configuration of the UV & IR embedded headlight.*

*White – standard white LED for lighting purposes, Yellow - yellow LED used for turn signal, Red – IR LED, Blue – IR photodiode, Violet – solar-blind UV LED, Green – solar-blind UV photodiode.*

Figure 7 shows the arrangement of infrared, visible and ultraviolet LED's to be used in the headlight transceiver. Within the LED configuration of the headlight displayed in Figure 7, an ample amount of distance must be present between the UV LED's and UV photodiodes in order to prevent local flooding. If the proximity between the two becomes too close, the field of view associated with the photodiodes begins to capture the UV light transmitted from the local UV LED's.

Using a long distance IR LED and photodiode in conjunction with a UV communication system consisting of a UV LED and UV photodiode, an automobile equipped with the proposed UV & IR communication system provides the capability of communicating the apparent position of automobiles in front of and behind a given vehicle. The pair of IR transmitters and receivers obtains distance measurements between objects in front of and behind a vehicle (assuming tail lights are to be equipped with a UV & IR communication system as well) and relays the information to the UV communication system. The distances between vehicles are then communicated between the vehicles within a close proximity to one another via a NLOS free space optical channel. Once shared, this information will allow the vehicles to control their respective speeds and maintain appropriate distances from one another.

This vehicle-to-vehicle communication provides a rewarding possibility towards the advancement of speed detection and regulation as well. Due to the advantage of the embedded UV communication system being a mobile communication system, traffic authorities will no longer be required to use stationary speed detection methods such as radar or lidar guns. Traffic authorities with vehicles equipped with UV communication systems will be able to read speeds of vehicles around them while their own vehicles are still in motion. Thus allowing a traffic authority to drive behind or alongside a targeted vehicle while simultaneously being capable of identifying the vehicle and acquiring its traveling velocity and other information being transmitted from vehicles equipped with UVID systems. Thus rendering radar and lidar systems currently used for speed detection obsolete.

Finally, various modulation schemes as well as channel coding and error correction techniques will be evaluated and incorporated into the proposed UVID system to make the system more robust to transmission impairments.

## VIII. CONCLUSIONS

UVID proves to be a valid and effective means of identification at a measured distance of up to 30 m (~100 ft). Utilizing the simplest digital modulation technique, OOK, the identification system uses as few components as necessary. The cost per transmitter is under ten dollars, providing substantial feasibility for its wide-spread implantation. Once deployed, this technology has the potential to greatly benefit our society. Operating outside of the visible light spectrum, the functionality of this system may be independent of standard vehicular lights, providing a possible continuous source of transmission to help recover stolen or wanted vehicles, preventing future traffic collisions, and ultimately providing a stepping stone towards smarter and safer transportation systems.

## IX. ACKNOWLEDGEMENTS

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