

Camera Based Visible Light Communication System for Underwater Applications

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Abstract— Visible light can be used to implement an underwater communication link, as an alternative for the current acoustic based communication methods. This paper presents the design and implementation of a unidirectional underwater visible light communication (VLC) system where a camera receiver is used. Specifically, data is transmitted from a submerged system to a floating body. In order to characterize the performance of this system, we first model the channel under zero water turbulence conditions for different transmission distances. Also algorithms and experimental results of detection are discussed. Our results show that, the proposed system can only achieve low data speeds compared to traditional VLC underwater systems, where photo detectors are used at the receiver. However, reasonable bit error rate performance can be achieved using the proposed VLC system design. Hence the proposed system can be developed further and can be used as a successful alternative for acoustic based under water communication systems.

Keywords — Underwater communication; visible light communication; Light emitting diode; camera receiver; bit error rate.

I. INTRODUCTION

Growing interest has been experienced among scientific community towards the development of underwater communication systems due to its wide applications. Present underwater wireless technologies are mostly based on acoustic communication means and they are subject to time varying multi-path propagation, high latency, low data speeds and high attenuation at long range communication, which possess problems in real time communications [1,2]. Even though radio frequency (RF) waves are widely used in over water applications, applicability of RF waves for communication in underwater is restricted due to high attenuation [3].

Visible light is a portion of the electromagnetic spectrum which the human eye is capable of seeing. Using visible light for underwater communication purposes has its own merits and demerits [1, 4-6]. Light wave show better directional properties than RF waves. Furthermore, data speeds achievable using visible light communication (VLC) techniques are much higher compared to acoustic transmission techniques in water. However, the demerits of visible light are the absorption and scattering loses of light waves in water [5,7,8]. Hence it can only be used for short and medium range transmission purposes.

Traditional overwater VLC systems consist of light sources and photo detectors. Data to be transmitted are encoded into multiple streams at the transmitter. The receiver detects the

received voltage level, in order to decode the data [4-6]. However, when implementing such a system in an underwater environment, decoding at the receiver using photo detectors is difficult. This is because of low received power and high cross channel interference, due to high absorption and scattering respectively of light waves in water.

In this paper, we implement a visible light communication system which has light emitting diodes (LEDs) at the transmitter and a camera at the receiver [9-11]. Since visibility does not decrease, in the way received power decreases in water with increasing transmission distances, using image based camera receivers will be beneficial compared to using photo detectors. Furthermore, if a camera is used at the receiver, cross channel interference cancellation can be done effectively through image processing when decoding data. However, the speed of data transmission is restricted due to the frame rate of the camera, which is typically in the range of 15 to 30 fps. [3,12].

Most of the camera receiver based communication system designs have been carried out for over water applications, while having a display as the transmitter [3,4,11]. Using such a display as transmitter in an underwater environment will be practically challenging and cost ineffective. However, due to the significant developments in solid state lighting technology and the high luminous flux emission possibility of LED's, they are used in our design.

Initially, design and implementation procedure of the proposed VLC system is discussed. The performance of the system is evaluated under different transmission distances. To reduce the computational time and power, simple image processing and detection algorithms are adopted. Two such used algorithms are discussed. Before transmitting actual data, at the training phase the underwater channel is modeled through channel matrix as a function of distance considering it to be a multiple input multiple output (MIMO) problem. Thereafter output detection is carried out using the obtained channel matrix by analyzing each frames of the captured video stream individually [17]. In the proposed second detection method, the properties of the cross correlation functions of the transformed signals of the training phase data frame and the arbitrary send frames are analyzed for output detection.

The rest of the paper is organized as follows: In Section II design and implementation of the proposed underwater VLC system is discussed. Section III contains details related to channel estimation and output detection. Section IV include material related to real time implementation of the system. In Section V experimental results are presented with a discussion. The paper concludes with a conclusion and followed by references.

II. DESIGN AND IMPLEMENTATION OF THE VLC SYSTEM

In this section, the design and implementation of an underwater VLC system is discussed. We analyze a scenario where unidirectional point-to-point communication happens in vertical direction from a submerged body (transmitter) to a floating body (receiver) in water [5, 7] as shown in Figure 1. The transmitter and the receiver are vertically aligned and the receiver camera was focused towards the LEDs.

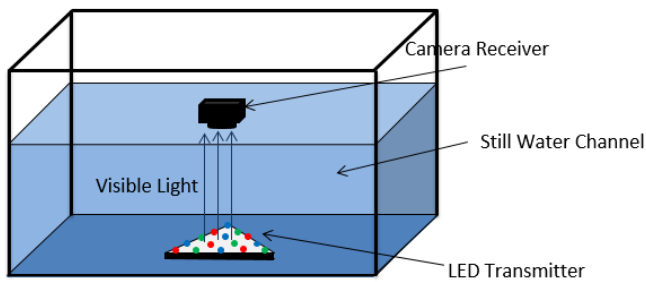


Fig. 1 VLC system model

A. Transmitter and Receiver

Any light source which exhibits reasonable switching capabilities can be used as a transmitter. In our study multiple LEDs were used at the transmitter as shown in Figure 2.

Spread angle of different LEDs (i.e. flat top LEDs, oval LEDs and power LEDs) were analyzed in order to select a LED source which produces the narrowest beam signal to minimize the cross channel interference. Experimental observation show oval and flat top LEDs have less spread angle, hence they were used in the system design. Optimal spatial separation between three LEDs (i.e., the maximum inter distance between 3 LEDs) were obtained when they are kept at the corners of an equilateral triangle. Hence triangle shaped LED array was used. Furthermore, to achieve spectral separation among adjacent transmitter sources, Red, Green and Blue colored LEDs were used. Distance between adjacent LEDs were selected based on the expected minimum transmission distance, spread angle of view of the camera and the focus distance capability of the camera [7,10,18].

A camera which has higher angle of view and high and fixed frame rate was considered as the receiver. Logitech c170 webcam which had angle of view of approximately 60° and frame rate of 30 fps was used.

B. VLC System Design

The data at the transmitter is encoded into multiple LEDs. Due to the simplicity of implementation, On-Off Keying

(OOK) modulation is used at the transmitter [7]. Intensity level of the LEDs were reduced and optimized for better performance (i.e., if intensity is high, cross interference is high, if intensity is low, visibility reduces). All LEDs have the same switching rate and were synchronized. In order to receive without any loss of data, switching rate of the LEDs should be less or equal to the frame rate of the camera. When switching rate of LEDs are made equal to the frame rate of camera, LED patterns corresponding to different switching periods will be available in different frames of the live video stream captured. Hence by analyzing a particular frame, all data sent from different LEDs corresponding to one specific switching period can be decoded. Therefore, by continuously analyzing successive frames of the video stream, output can be decoded.

To validate the discussed output detection algorithms (in Section III), a controlled experimental setup was implemented as shown in Figures 2 and 3. In this setup, minimum and maximum transmission distances were restricted to 0.2 m and 1.0 m respectively. 15 flat top LEDs were used at the transmitter arranged in a triangular array. The corner three LEDs were always kept at ON condition to detect the region of interest. Hence 12 LEDs were used for data transmission. At the transmitter, data to be transmitted is modulated into the LEDs using the Arduino platform. Moreover, the data demodulation and pattern recognition was done using MATLAB software.

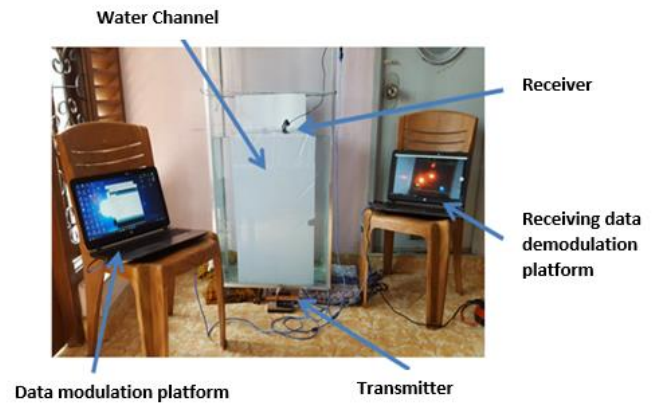


Fig. 2 Implemented VLC system.

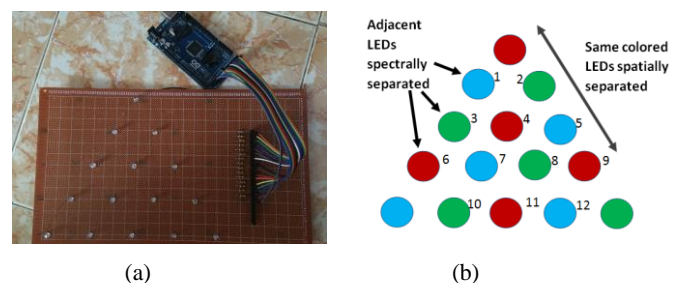


Fig. 3 (a) Transmitter of the designed VLC system (b) Graphical image of the transmitter with LEDs numbered.

III. DETECTION

In this section algorithms for output detection at the receiver, from a single frame is discussed. Output detection, will be carried out at the receiver using image processing. Two possible methods which can be used for output detection are discussed.

A. Detection Method 1

In order to detect output when an arbitrary pattern is transmitted, channel should be characterized. Therefore channel was modeled through a channel matrix, considering the system as a MIMO static system at the training phase by transmitting known LED combinations and analyzing its corresponding received frames.

The vector relationship of inputs and outputs of a multiple input multiple output (MIMO) static system is expressed as,

$$Y(i) = H * X(i) + N(i) \quad (3)$$

where X , Y are the input, output vectors containing input and output symbols respectively, H is the channel matrix and N is the vector which represents noise.

In the designed VLC system, input output relationship corresponding to one single frame can be modeled using (3). LED channels in the transmitter and each individual pixels in the captured frame can be considered as inputs and outputs respectively. Hence, the noise vector N models the background visible signature and the additive noises due to blurring at the camera end. (i.e., if r , n are the number of LEDs and number of pixels respectively, Y , H , X , N would be of size $n \times 1$, $n \times r$, $r \times 1$, and $n \times 1$ respectively.)

. All RGB images are transformed into grayscale images before they are analyzed. Also to ensure the use of unbiased data set, from each pixel value DC off set is removed and then normalized with respect to standard deviation.

As shown in Figure 4, not all pixels in the captured frames were affected by LED illuminations. Hence these redundant pixels were neglected and only the pixels in the rectangular region of interest were used for further analysis.

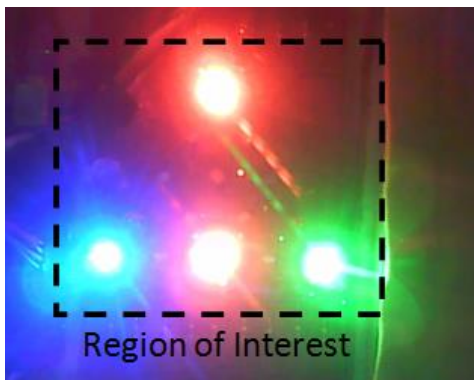


Fig. 4. A sampled captured frame and region of Interest.

If the channel matrix calculated at the training phase, remains fixed throughout the transmission (i.e., same transmission distance, zero water turbulence), then the

calculated channel matrix can be used to decode data from any received frame corresponding to an arbitrary LED pattern.

First, algorithms were developed to identify the channel matrix elements by transmitting known inputs LED patterns and analyzing the corresponding captured frames. Initially only the corner LEDs were illuminated to identify the elements in the vector N . Thereafter by illuminating one LED at a time with three corner LEDs, separate column elements of the channel matrix were identified from (4).

$$H(:, i) = Yi - N \quad (4)$$

$$Xi = [0, 0, \dots, \dots, 1, \dots, \dots, 0] \quad (5)$$

↑
ith element

Here $H(:, i)$ represent the i^{th} column of the system matrix and Xi , Yi represent the input and output vector corresponding to i^{th} LED pattern. As shown in (5), only the i^{th} element in input vector is one as only i^{th} LED was switched ON at that instance.

After the calculation of channel matrix, if any arbitrary LED pattern was transmitted, from (6) output was be decoded.

$$Xr = (H^T * H)^{-1} * H^T * (Y - N) \quad (6)$$

where Y is the given output vector constructed from the captured frame, and Xr is the calculated input vector from channel matrix. As $H^T * H$ quantity is singular, Moore-Penrose pseudo inverse is taken to find inverse of the quantity.

Thereafter a threshold on each element in the vector Xr was applied to obtain zeros and ones which represent OFF and ON conditions of each LED corresponding to the given frame.

$$Xtr(i) = \begin{cases} 1 & Xr(i) > thr \\ 0 & Xr(i) < thr \end{cases} \quad (7)$$

where, Xtr is the calculated input vector after the threshold was applied and thr is the threshold level.

When the transmission distance is increased, the dimensions of the region of interest in the captured frame will reduce and vice versa. So effectively the number of pixels which are affected by the transmitter LEDs (number of output channels) decrease with increasing transmission distance.

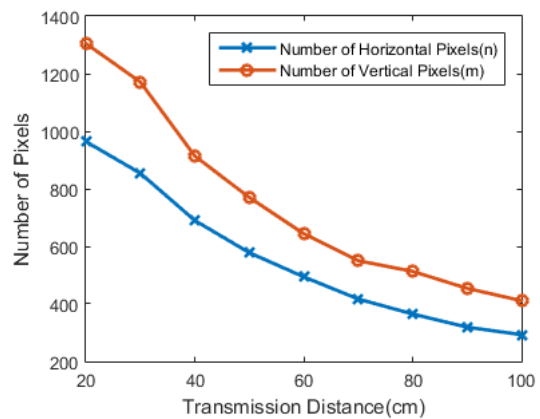


Fig. 5. Variation of number of vertical and horizontal pixel in the area of interest with varying distance

Hence channel matrix H , whose size directly depend on the size of region of interest, (i.e., size of H = size of region of interest in pixels \times number of LED channel) will have different dimensions and different values for different transmission distances. Thus one approach would be to calculate H for each possible transmission distance separately from (2), (3) and (4). However, this will result in a long training process and high storage requirement. As an alternative, resized channel matrix function, $Hr(d)$, is calculated and it was used at decoding for all transmission distances. Specifically, to calculate the resized channel matrix function, the channel matrix of three separate transmission distances were identified after resizing the region of interest of all three distance into one specific size. Hence the obtained channel matrices corresponding to all three transmission distance were of the same size. Thereafter by linear interpolation channel matrix elements are calculated as a function of distance to form the resized channel matrix function.

When decoding at varying transmission distances, based on the dimensions of the region of interest, the transmission distance was identified. Thereafter, using the channel matrix obtained from the resized channel matrix function corresponding to the identified transmission distance, the output was decoded. The flow of this procedure for detection is written in Algorithm 1.

Algorithm 1: *Detection using method 1*

Inputs: Video Stream
Channel Matrix function

Read: Video Stream
Extract frames of the video
for each frame
 Crop the region of interest
 Identify transmission distance
 Resize the region of interest to the standard size
 Obtain the resize channel matrix for the transmission distance
 Identify possible pattern corresponding to the frame, using inverting and thresholding

end
Demodulate the continuous data stream

B. Detection Method 2

When fewer number of LEDs were illuminated, detection was less erroneous. However, when a large number of LEDs were illuminated, the error performance worsened under method 1. Hence a more robust detection method is discussed which is referred to as method 2 hereafter.

In this method, at the training phase all data LEDs are illuminated individually and its corresponding received frames were obtained. Then the region of interests of those captured frames were cropped and all data frames were resized in to the standard size of $m \times n \times 3$ (i.e. three $m \times n$ size matrixes of the images corresponding to red, green and blue respectively). Then the columns of the images are unwrapped to form a $mn \times 1$ data signal. Then to ensure the use of unbiased data

signal, from each data element, DC offset was removed and then normalized with respect to standard deviation. The corresponding signals were named R_i , G_i and B_i , where $i=1,2,\dots,r$, where r is the number of LEDs in the transmitter and R, G, B represent red green and blue signals.

Thereafter whenever an arbitrary LED pattern was sent, the corresponding captured frame was also cropped, resized, unwrapped, centered and normalized to make it comparable with the obtained signals at the training phase. The corresponding signals were named Y_r , Y_g and Y_b which represent red, green and blue spectrum signals respectively. Then, if we consider the analysis of red signals only, the cross correlation was taken between Y_r with all training phase data signals R_i . And it was observed that if some j th position LEDs were kept ON in the arbitrary LED pattern, in the envelop of cross correlation function between Y_r and R_j signal, a peak is detected at the zero lag position.

This observation is illustrated through an example in Figure 6 and Figure 7. An arbitrary pattern in which first three data LEDs are ON is shown in figure 6. Figure 7 show the cross correlation functions of the arbitrary pattern signal with the 12 training signals. And it was observed, in Figure 7 subplot 1,2 and 3, a peak is observed at lag zero in the cross correlation functions envelop.



Fig. 6. An arbitrary LED pattern in which first three data LEDs are ON.

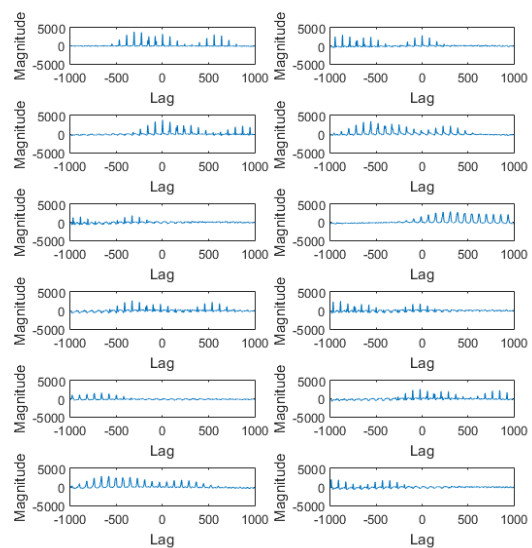


Fig. 7. Cross correlation function between the signal of the arbitrary pattern in Figure 6 and the 12 training data sets.

Hence by taking this observation into consideration, by detecting the peaks of the cross correlation functions envelop, the unknown arbitrary LED patterns were identified. By doing this procedure for all three color spectrums one by one, and merging the results, detection process was made less error-prone.

IV. REAL TIME IMPLEMENTATION

A real time data transmittable link was developed based on the system we had presented. Even though theoretically symbols can be transmitted at camera frame rate, due to the transient behavior of video capturing technique and the auto focus feature of camera, the achievable data switching were only half of the theoretical achievable data switching rates.

It is required to synchronize the transmitter and the receiver so that detection can be successfully achieved. For this purpose, a known synchronization data pattern was transmitted before any information carrying data was transmitted. This known pattern was generated by transmitting the pulse shown in Figure 8(a) by all 12 LED streams. However, as alignment was not achieved (i.e., finding the corner LED positions, rotating the frame if necessary and cropping the region of interest) before synchronization, it was not possible to detect these LED ON OFF conditions using the detection methods explained in section III. Hence an alternative procedure was used. When all LEDs were ON, high number of pixels have higher intensity and when all the LEDs were in OFF state, higher number of pixels have lower intensity irrespective of whether the transmitter and receiver was perfectly aligned or not. Hence, if the number of high intensity pixels were counted as a function of the frame number and if the rising edges were detected, synchronization can be achieved successfully up to the accuracy of $\pm 1/2$ the data switching rate of the transmitter. A detected synchronization signal at the receiver is shown in figure 8(b).

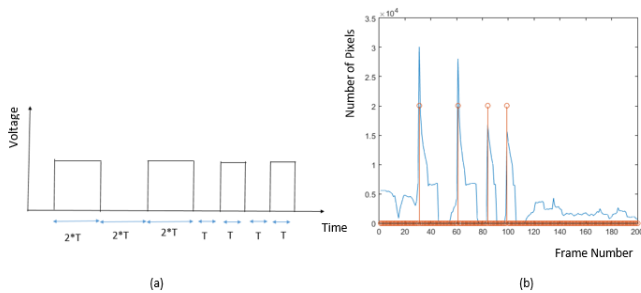


Fig. 8. (a) Transmitted synchronization Pulse (b) Detected Synchronization Pulse

V. RESULTS AND DISCUSSION

In this section, we present experimental results for the BER performance of the implemented VLC underwater system. As the first step to validate the channel matrix and detection technique discussed in detection method 1, for the transmission distance of 50cm, channel matrix was identified at the training phase. Thereafter few LED patterns were

transmitted and the corresponding frames were analyzed for validation. The corresponding results were as follows: With the given 12 LEDs, 12 bit data can be transmitted from a single frame. Also $(2^{12} - 1)$, different LED patterns can be generated and transmitted. 104 different patterns distributed equally among $(2^{12} - 1)$ all possible combinations were selected and transmitted to investigate the performance. Hence 1248 (104×12) bits were transmitted and decoded using the algorithms presented. It was realized that only 34 bits were detected in error and this corresponds to a BER of 2.72%.

Next as mentioned in Section III A, channel matrix function $(Hr(d))$ was identified using linear interpolation. For this purpose channel matrix corresponding to transmission distance of 20 cm, 50 cm and 90 cm were used. Thereafter for different transmission distances, LED patterns were fed in and using the calculated channel matrix function values corresponding to those specific distances, the demodulated outputs were analyzed to calculate the BER.

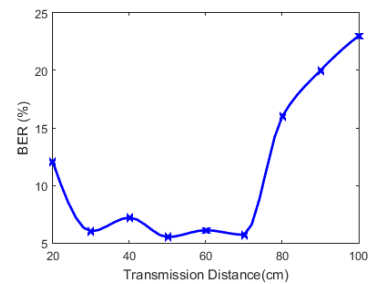


Fig. 9. Bit error rate versus distance.

Due to the increasing blurring introduced with increasing distance, the assumption of linear channel model gets de validated with increasing distance. Hence BER increases with increasing transmission distances. However, at very low transmission distance, BER was comparatively high, as the used camera was not designed to focus such very small distances.

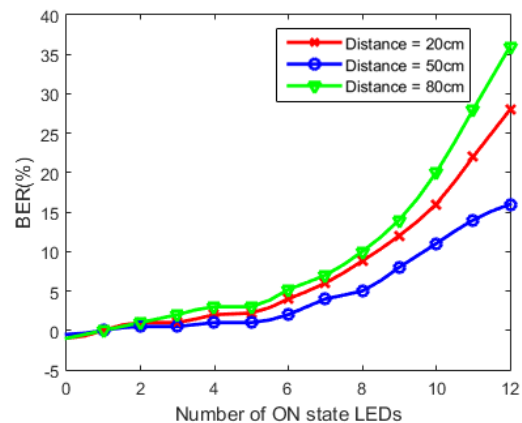


Fig. 10. Bit error rate performance versus number of ON state LEDs for different transmission distances.

When the number of ON state LEDs increases in an arbitrary pattern, the probability of incorrect detection of a

LED state increases, under detection method 1. This effect is shown in Figure 10.

This increasing BER pattern was the result of the default feature that cameras has in order to control the luminous level which it absorbs. To partly overcome this effect, detection method 2 was used for bit detection. The results plotted in Figure 11 show, BER variation has a better spread with varying number of ON state LEDs as compared to detection method 1 if detection method 2 was used.

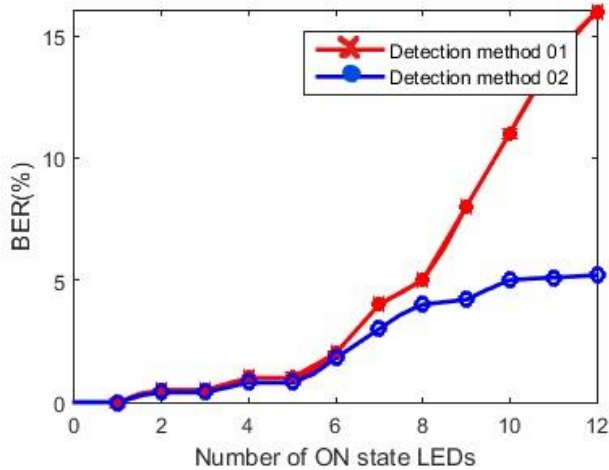


Fig. 11. Bit error rate performance versus number of ON state LEDs for demodulated using different detection methods

Results in Figures 10 and 11 show, that BER performance at a fixed transmission distance vary with the number of ON state LEDs in the encoded pattern. Hence to reduce the overall BER further for a given distance, the incoming data can be only coded into specific bit patterns where low BER performance was realized. (i.e., coded only into bit patterns where fewer number of LEDs are ON, which are the codes which have lower weights)

CONCLUSION

We present the design of a unidirectional point-to-point underwater VLC system which uses LEDs at the transmitter and a camera as the receiver. Transmitter, receiver models, algorithm for demodulation and system performance evaluated through experimental setup were discussed. The proposed VLC system can transmit at 100bps speed to a distance of 20cm to 100cm. Further by either increasing the physical dimensions of the transmitter system or by using a camera which has higher resolution and wider angle of view, transmission distance can be increased up to several meters. From our study it became evident that the implemented underwater VLC system can be used as a successful alternative for the existing underwater communication systems at short to medium distances which are based on acoustic means. Also if images noise eliminations can be done more rigorously, the same algorithms for detection can be used effectively even inside mud and ocean water to transmit and receive data successfully.

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