Link Design for Multi-hop Underwater Optical Wireless Sensor Network

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***Abstract*—This paper presents a link designed for a multi-hop underwater optical wireless communication system using green/blue Light Emitting Diodes (LEDs). The proposed system can increase the communication distance using multi-hop communication compared to single hop communication. The suggested system uses very simple and inexpensive hardware to build a cost effective solution. The established link can support a bandwidth up to 100 KHz for a communication range up to 1 meter without using any external optics and without degrading the required signal to noise ratio.**

Keywords-underwater; optical wireless; sensor network; visible light.

I. INTRODUCTION

More than two thirds of world's surface is covered by water and this area is still mostly undiscovered by human beings. One efficient and reliable communication system is the first step towards the invention of this huge underwater world. Until now, most underwater communication is based on either wired or acoustic technology. Wired technology has its limitation in terms of installation, maintenance and mobility. For short and medium range applications, wireless is the suitable solution especially underwater, where the medium is very rough and harsh. So far, acoustic methods are the dominant underwater communication system used for long range low bandwidth links, because sound propagates very well underwater compared to other waves. However, the limitation of acoustic communication is the lack of bandwidth to support high speed communications, for example, sound can propagate up to a few kilometers with a speed of 1500m/s, which is not enough for many applications. Time-varying multipath propagation and low speed of sound underwater produces a very poor and high latency communication channel, which cannot support real time data transfer such as audio/video. Moreover, the cost of acoustic components is very high and the dimensions of components are very large. All those limitations of acoustic communication have stimulated researchers to find a cheap alternative for underwater communication system capable of allowing high bandwidth for real time applications.

In this paper, a multi-hop static underwater optical wireless communication network using visible light has been proposed. Multi-hop communication is a well-known technique in free space communication for spatial reuse which was also proposed by many researchers for underwater optical wireless communications. In this process, intermediate nodes relay the information and control signals to the gateway node which ultimately stores and sends data to the base station.

The rest of the paper is organized as follows: Section II reviews the background and related work. In Section III, some of the issues related to underwater optical wireless communication are described. The system design procedure is described in Section IV, followed by performance analysis in Section V. Finally, conclusion and future work are illustrated in Section VI.

II. BACKGROUND AND RELATED WORK

Several research groups are actively investigating different aspects of underwater optical wireless communication systems, starting from channel characterization to system design. The water medium itself is a complex medium and light propagation varies in different types of water at different depths [1], so it is not an easy option to find a generic channel model for all types of water. Since underwater optical wireless is a relatively new research area, most of the work until now has focused on unidirectional single hop communication, implemented either by software or hardware, and also some groups are investigating sensor applications. Vasilescu *et al* at MIT have built an underwater sensor network using visible light but have used an optical wireless link only to upload the data from a sensor node to an Unmanned Aerial Vehicle (UAV) [2]. An unidirectional optical wireless link capable of sending data at 320Kbit/s up to a distance of 2.2m for an underwater sensor network was presented in [2]. To achieve this communication distance, a high powered LED array was used, and this link was only used to upload the sensor data from sensor node to an Autonomous Underwater Vehicle (AUV). The same group advanced their research to achieve a data rate of 1.2Mbit/s for a communication range of 30m. Recently, they reported a bi-directional communication system to achieve a communication range of 50m [3]. They used very high power LEDs and expensive optics to obtain these results.

Chancery designed and tested an FM optical wireless communication system for underwater which was capable of sending data at 10Mbps rate [4]. Later, his work was advanced by Cox, Simpson and Everett to investigate the various fundamental issues like modulation techniques, error correction, high speed communication channels, etc. [5][6][7] .

 ISBN: 978-1-61208-231-8

Anguita *et al.* are working on diffuse underwater optical wireless sensor network using a planner transceiver [8], but they are concentrating on integration of free space technology with underwater. They have achieved a 100 Kbps data rate in a communication distance of 1.8m.

Norman and the group at Woods Hole Oceanographic Research Center have reported a high bandwidth communication link of 5Mbps over a distance of 200m in clean water using a diffuse optical communication link [9]. They used both green and blue light to make the system bidirectional, and an acoustic modem to wake up the sea floor installation [10].

Amongst others, Felix reported an underwater communication system using the IrDA physical layer with 3Watt, high-power LEDs [11]. Frank proposed a laser-based communication link which achieved a data rate of 1Gbit/s over a distance of 2m in a laboratory water pipe, and predicted that up to 48m could be achieved in clear water [12]. A cost effective underwater optical modem has been proposed by Feng to achieve a communication distance up to 10 meters [13]. Sermask modeled the underwater optical wireless channel using vector radiative transfer theory to investigate the multiple scattering and polarization of light [14]. He calculated the bit error rate of On-Off-Keying modulation, and 4-level amplitude modulation with different FOV. Arnon proposed three types of communication links and analyzed the performance of each type [15]. From his analysis it is seen that the communication performance decreased rapidly when water absorption increased, but a high data rate was still possible.

III. ISSUES RELATED TO UNDERWATER OPTICAL WIRELESS SENSOR NETWORK

In this section, some of the fundamental issues related to underwater optical wireless and adopted network architecture are discussed.

A. Which spectrum range to select?

An underwater optical wireless channel suffers from both scattering and absorption, resulting in severe attenuation. Behavior of light in water depends on the water components. Sea water is primarily composed of H_2O, but it also has different salts, such as $NaCl, MgCl_2, Na_2So_4, KCl$ etc., which absorb light at specific wavelengths. Equation (1) describes the relation between attenuation and communication distance,

$$A = e^{-k(d_1 - d_2)(\frac{d_1}{d_2})^2} \quad (1)$$

where the transmitter and receiver are placed at *d1* and *d2*, and *k* is the attenuation coefficient defined as:

$$k = \alpha(\lambda) + \beta(\lambda) \quad (2)$$

Here, α is the absorption coefficient which depends on the light wavelength, and β is the scattering coefficient which mainly depends on wavelength as well as the turbidity of water. From the basics of light propagation in water, it is found that the best wavelengths which propagate in water are in the green-blue region of the visible spectrum (wavelength 400-550nm), and so two wavelengths within this range have been selected for the communication system to be described.

B. Modulation techniques

Modulation techniques play a vital role in all sorts of communication systems including optical wireless. Three major characteristics of modulation techniques are transmission efficiency, power efficiency and bandwidth efficiency. A modulation technique with high bandwidth efficiency ensures that the overall system bit rate is high; on the other hand side, power efficiency is needed for longer life time of the system when run from local finite sources. Two most common modulation schemes used in optical wireless are On-Off-Keying (OOK), and Pulse Position Modulation (PPM).

On Off Keying (OOK) is the simplest form of modulation in terms of implementation. Here, the optical power is directly modulated by varying the source current in sympathy with the data, whereas on the receiver side the detector produces a photocurrent proportional to the received photons. OOK can be either in the form of Non Return to Zero (NRZ), or Return to Zero (RZ). In this paper, NRZ-OOK signaling is used because of lower power requirements.

As mentioned, in PPM the position of the pulse is changed during a temporal cycle to represent a different bit. In this method the average power requirements are decreased compared to OOK, in compensation for an increase in bandwidth requirements. PPM can be either in two, or multi-level, depending on the requirement, where it is represented by L-PPM.

The proposed design has considered NRZ-OOK modulation techniques because of the simplicity of implementation and lower power requirement.

C. Proposed Network architecture

Two possible network architectures for underwater communication are presented in Figure 1.

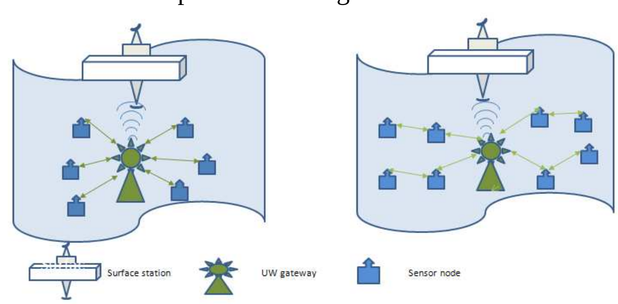

Figure 1. Underwater optical wireless network architecture

In the first scenario, a star network topology is presented, where sensor nodes send information via an optical link to a gateway station which can be located on the surface or under the water. The underwater gateway station stores information from all nodes in the cluster and sends it to the surface station periodically. Another scenerio presented on the right hand side of the above figure is based on a tree topology, where each node relays the information to the next node, and the surface station receives all node information via its nearest sensor nodes. Both these architectures have some advantages and limitations, for example, in the first case protocol development will be easier since the total communicaton system is based on one hop communication, and it will have lower power consumption because, after passing the data to gateway nodes, each node can go to the sleep state. This type of architecture has limitations in terms of distance covered. On the other hand, a tree-based multi-hop architecture has the advantage of covering a large geographical area. Multi-hop comunication needs a complex routing protocol, since each node needs to know its neighbour to forward information, especially in the mobile environment. Since the focus of this work is to build a static and directional sensor network, this problem can be easily solved by using hop-by-hop routing.

D. *Physical layer development*

The possible physical layer architectures of the network are shown in Figure 2. As seen, it can be implemented in different ways. First of all, a simplex communication is possible where each sensor node just forwards sensor information through the optical wireless link to the gateway station. In this case, the gateway node gives a command to the sensor node by using another medium, for example, in an acoustic link. So, this is not fully optical communication, but rather a hybrid communications approach. Having both optical and acoustic hardware increases the overall system complexity, especially when the cost of suitable higher bandwidth acoustic modems is high.

Another approach is presented in figure 2 (b), where both up- and downlinks are designed using the same colored LED. In this approach, a half-duplex communication can be achieved, which means a lower throughput for the system.

The implementation which is being described here utilizes a full-duplex communication model using two different colored LEDs. Compared to the half-duplex system, it has greater bandwidth efficiency at almost the same complexity. Only a pairing of a green and a blue transceiver has to be done correctly to make the system work properly.

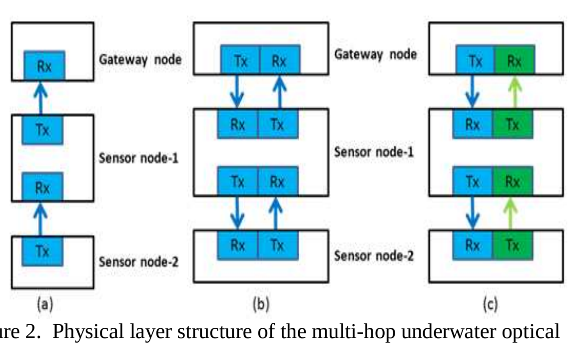

Figure 2. Physical layer structure of the multi-hop underwater optical wireless sensor network a) Simplex, b) Half-duplex, and c) Full duplex

IV. SYSTEM DESIGN

Free space optical wireless communications is dominated by infrared technology which cannot be used underwater. As discussed in the previous section, the best wavelengths suitable for underwater communication are in the green/blue part of the spectrum, so whole system is designed accordingly.

A. *Components selection*

An LED and a photodiode are the two main components which need to be selected carefully for best performance. After careful consideration, an Avago HLMP LED was selected which is available both in green and in blue. The power dissipation of this device is about 116 mW and the viewing angle is 15 degrees.

A SILONEX SLD-70BG2 photodiode was chosen for the receivers which has peak sensitivity in the green spectral region. Compared to other silicon photodiodes available in the visible spectrum range, it has less capacitance (180pF) and higher active region (9.8 sq.mm).

B. *Transmitter circuit*

To transmit a digital signal, a relatively simple digital optical wireless transmitter circuit was used with the selected LED as shown in Figure 3 to provide OOK signals.

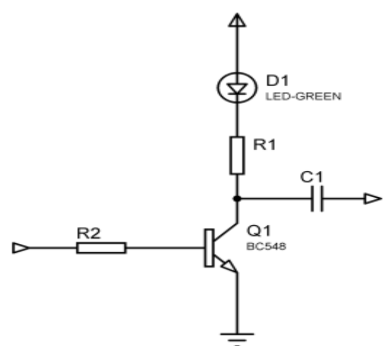

Figure 3. Digital optical wireless transmitter

C. *Receiver circuit*

The receiver can be the more complicated part of an optical wireless system design. There are a few common receiver design architectures which are mostly preferred by researchers. Amongst them, the bootstrap front end and transimpedance front end are frequently used. The target of all configurations is to increase the bandwidth and sensitivity by minimizing the photodiode's capacitance effects. For the high bandwidth applications, the bootstrap configuration is preferred, whereas for better gain, the transimpedance configuration has advantages over the bootstrap approach. After investigating both the receiver techniques, a simple form of transimpedance front end circuit using a single transistor, as shown in Figure 4, was used for the proposed system.

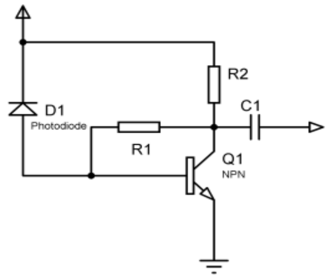

Figure 4. Modified transimpedance receiver front end

The bandwidth of the transimpedance system can be determined by the following equation,

$$f = \frac{1}{2\pi R\left(\frac{C_D}{A} + C_{bc}\right)} \qquad (3)$$

Where, R = load resistance, C_D = Device capacitance, C_{bc} = transistor base emitter capacitance and A = open loop amplifier gain.

As seen, the device capacitance is reduced in significance considerably due to the high gain, A, of the amplifier, but the base-collector capacitance effects cannot be similarly minimized.

V. PERFORMANCE ANALYSIS AND DISCUSSION

Performance analysis of the designed receiver has been done in terms of gain, bandwidth, and noise characteristics. To estimate the performance, all the experiments were carried first in air and then through water to compare the performance analysis.

A. Gain of the transceiver in air

As seen in Figure 5, the received signal decreases continuously when communication distance increases, understandably, because of the weakening optical power incident on the photodiode. Conversely, the greatest signal is achieved when the transmitter and receiver are around 1 cm apart. Overall, when the distance between transmitter and receiver is about 80 cm, the channel loss is about 48 dB. In this project, the target communication range is about 60 cm, where corresponding loss is around 45 dB.

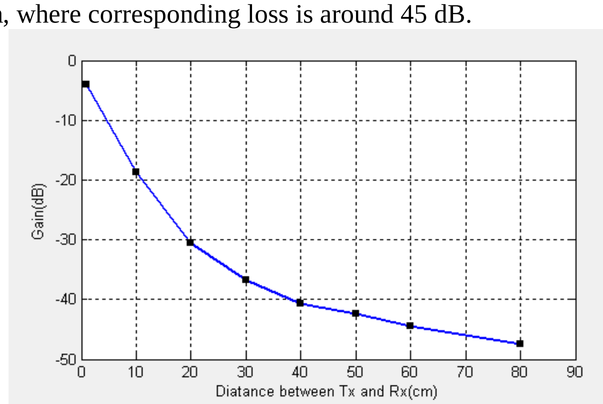

Figure 5. Link gain in different communication range

B. Bit-rate of the transceiver

The achievable bit rate of the designed transceiver has been estimated from Figure 6. With the digital transmitter, finding the achievable bandwidth of the system was undertaken using the maximum bit rate the system can convey.

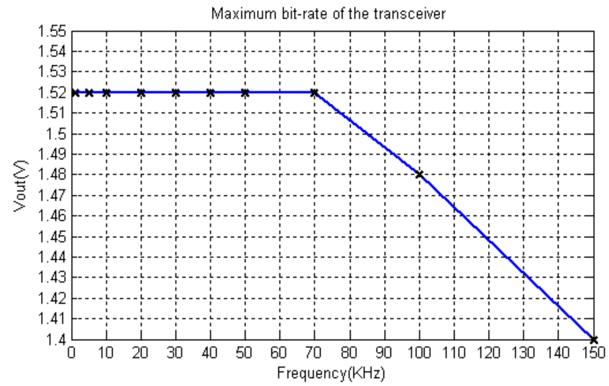

Figure 6. Maximum possible bit-rate of the transceiver

C. Noise performacne in air

Finding signal to noise ratio experimentally in an optical wireless system is challenging due to the effects of ambient light in respect of shot noise in the detector, thermal noise in the input resistances (especially the load resistor), and the masking effect of the ambient itself. Here, the average peak-peak value of the signal and noise was measured, and signal to noise ratio was calculated from the following equation:

$$SNR = 20\log\frac{(S+N)_{Pk-Pk}}{N_{Pk-PK}} \qquad (4)$$

Where $(S+N)_{Pk-Pk}$ is defined as the peak to peak amplitude of the signal with noise and N_{Pk-PK} is defined as the amplitude of the noise voltage. Noise analysis of the system has been estimated in three different scenarios: first of all, the signal to noise ratio was measured in the ideal situation where neither ambient light nor daylight was present. The same measurement was done in the presence of ambient light and in the night environment without any light sources, to find the noise characteristics.

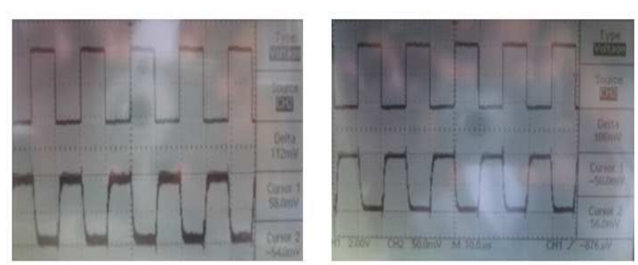

Figure 7. Signal output at the receiver with and without ambient light

Figure 7 shows the output waveform at the receiver with and without ambient light during the day time. As seen, the ambient light has a strong effect on the communication system. The average ambient noise Pk-Pk to value was measured at about 16 mV. A signal to noise ratio of 14 dB was calculated without the ambient light, and 10 dB with the ambient light.

D. *Comparison of air test with water testing*

The picture of the water test setup is shown below,

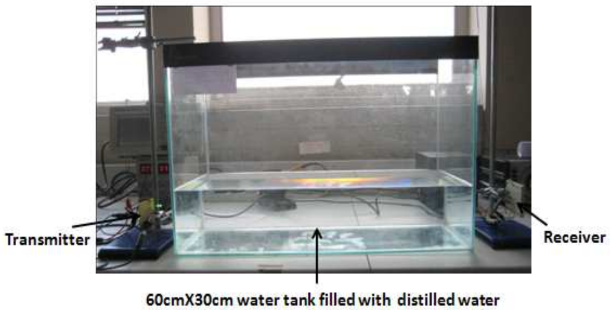

Figure 8. Water test setup

Here, transmitter and receiver are placed on either side of the tank and pointed to each other to measure the gain of the receiver. The tank was made of glass and dimension of the tank is 60cm x 30cm x 45cm. The tank was filled with 20 liters of distilled water and placed inside the experimental laboratory.

To validate the air testing gain of the link has been measured for air and through water for same distance. The output waveform at the receiver can be found in the following figure.

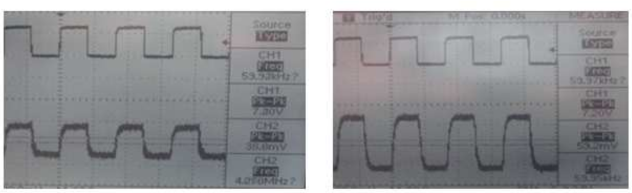

Figure 9. Comparison between output voltage at receiver (Left side through air and Right side through water tank)

As seen, the received output signal voltage was about 40mV for air and about 60mV for water testing for the same distance of 65cm and same frequency of 60 KHz. Because of the glass water tank some light might reflected back from the glass while propagating to the receiver which made for a better gain during water testing. In reality, the gain in water must be lower than the air as water is denser medium than air.

E. *Discussion in context of available underwater system*

Underwater systems developed by different research groups have different objectives, and chosen components accordingly. For example, Vasilescu *et al.* designed his transmitter with high power LEDs to obtain maximum distance [2]. The radiant power of used LED was 700mW which is much higher compare to LED used for the proposed solution (120mW). It is clear that more optical power will ensure larger distance according to Beer’s law. However, the objective of this solution is to design a cost effective system to prove the concept of multi-hop underwater communication, so comparison in terms of distance and bandwidth with other system may not justify the achieved results. The same analogy is true for other systems as well. Anguita *et al.* implemented a planar type transmitter with 12 LEDs to achieve the communication distance of 1.8m [8]. The proposed solution in this paper also works in the 1m range without using any external lenses, and can go beyond few meters if external lenses are used. The same way, other underwater systems can be discussed and compared with the proposed system.

VI. Conclusion and Future Work

An underwater optical wireless communication link has been presented for multi-hop underwater optical wireless communication. Performance analysis of the multi-hop communication system will be undertaken next. As the communication system will be in the form of an amplify-and-forward system, so the expected multi-hop communication performance will be relatively similar to a single hop system, in terms of gain. Moreover, a directional Medium Access Control (MAC) layer protocol is being developed to support the built network for real applications.

Acknowledgment

The authors would like to acknowledge the facilities and support provided by the School of Engineering, University of Warwick.

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