LightByte: Communicating Wirelessly with an Underwater Robot using Light

Robert Codd-Downey and Michael Jenkin
Department of Electrical Engineering and Computer Science, York University, Toronto, Ontario, Canada

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Abstract: Communication with and control of underwater autonomous vehicles is complicated by the nature of the water medium which absorbs radio waves over short distances and which introduces severe limitations on the bandwidth of sound-based technologies. Given the limitations of acoustic and radio frequency (RF) communication underwater, light-based communication has also been used. Light-based communication is also emerging as an effective strategy for terrestrial communication. Can the emerging Light Fidelity (Li-Fi) communication standard be exploited underwater to enable devices in close proximity to communicate by light? This paper describes the development of the LightByte Li-Fi model for underwater use and experimental evaluation of its performance both terrestrially and underwater.

1 INTRODUCTION

Very few robots are designed to operate completely autonomously. Rather their actions are controlled (or at least influenced) by commands provided to them by human operators. Leaving aside the complexity of the development of a language for human-robot communication, the actual problem of transmitting electrical information in air is a relatively simple task using modern technologies such as WIFI (IEEE, 2013), Bluetooth (IEEE, 2002), NFC(ISO, 2013) and RFID(ISO, 2008). Unfortunately such approaches find limited application in the underwater environment because the electro-magnetic spectral bands associated with these technologies are highly attenuated in the underwater domain rendering them unusable at any reasonable distance(Bogie, 1972). This is not to say that RF-based communication is not possible underwater. Radio wave attenuation in water is highly dependent upon frequency, and thus underwater communication technology is typically based on very low frequency (VLF) radio waves in the 3-30kHz range. Such signals can propagate long distances but have particularly poor bandwidth. Given the shortcomings of RF transmission underwater, other techniques are more popular. One effective approach is to use acoustic communication. Sound propagates more effectively underwater than in air. Underwater acoustic communication was developed for the US Navy during the 1940's(Quazi and Konrad, 1982) in the form of the underwater telephone. Since then the technology has matured with commercial off the shelf (COTS) acoustic underwater acoustic modems being readily available(EvoLogics, 2009). Such devices are manufactured for different depth/distance applications, but performance in the 31.2kbit/s over a 1km range are typical. Given the long ranges associated with VLF and acoustic techniques, other approaches are more appropriate over shorter distances. One interesting approach here is to utilize visible spectrum light communication. Such devices can be developed with a range of different power/distance/bandwidth tradeoffs and can be constructed using relatively inexpensive off the shelf components. Furthermore, given the commercial interest in light-based communication terrestrially, one can expect a substantive decrease in component costs as the technology is deployed in the terrestrial domain. Given this, here we consider the questions: How effective can light fidelity (Li-Fi)-based technology be underwater, and is it practical to develop "Li-Fi modems" for robot-robot and robot-human communication underwater?

Although Li-Fi can certainly be used to develop a network-based communication infrastructure, here we are particularly interested in bidirectional communication between two underwater units; an autonomous underwater device and an underwater device controlled by a human operator. Although the human could certainly be underwater themselves, we concentrate on the case in which a shore- or

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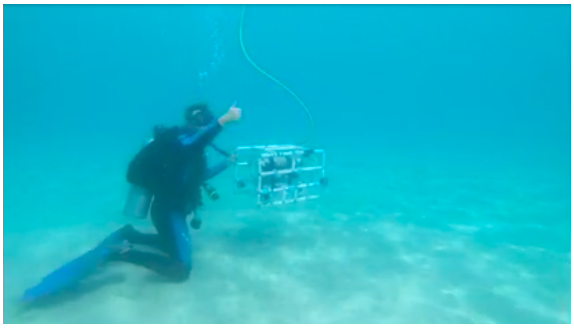


Figure 1: Unmanned underwater vehicle control. Communicating with such a device wirelessly is complicated by the nature of the aquatic medium. As a consequence wired communication is common with its inherent problems related to cable management and fouling.

boat-based operator communicates via light with a single thruster-based UUV such as the Milton platform(Codd-Downey et al., 2017) shown in Fig. 1.

2 BACKGROUND

Underwater communication has a long history and can be traced back at least to Leonardo da Vinci who observed "If you cause your ship to stop, and place the head of a long tube in the water, and place the other extremity to your ear you will hear ships at a great distance from you"(da Vinci, 2010). Of course, there have been substantive technological improvements since then. Lack of space prohibits a full review of advances in the use of sound, radio waves and light energy for communication underwater here. The interested reader is directed to(Kaushal and Kaddoum, 2016) for a recent review of the RF, acoustic and optical communication strategies underwater and their limitations.

Although RF and acoustic communication strategies have their advantages, we are particularly interested in short range, reasonably-high bandwidth communication for which optical approaches seem particularly useful. A number of such systems have been developed and deployed underwater using both laser and LED-based systems. Although high-power systems are necessary for long distance communications, for shorter distance (<10m) communication, a wide range of technologies exist that can be applied to the problem. Terrestrially, digital communication over short ranges has also received substantive attention and standard communication technologies have been developed using RF technologies including Bluetooth, WIFI and other technologies. Light-Fidelity communication (Li-Fi) (Condliffe, 2011) aims to use visible light as the communication medium for digital

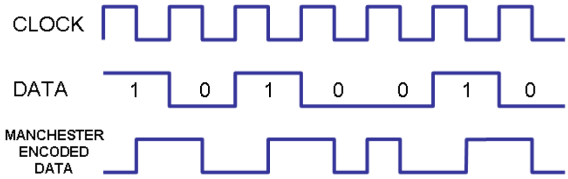


Figure 2: Manchester Encoding.

communication (See (Haas et al., 2016) for a review of the technology.) Although still in its infancy, Li-Fi has shown substantive promise, however, there have been few large-field tests of the technology.

Beyond the terrestrial domain there have also been a number of efforts to deploy Li-Fi technology underwater. For example, (Medhekar et al., 2016) looks at the transmission properties of different light sources for Li-Fi underwater and observes that LED-based communication has advantages when line of sight cannot be guaranteed. (Wang et al., 2016) demonstrates a long distance (100m) light-based communication system that utilizes optics to concentrate the emitter and a single photon avalanche diode to enhance detection.

The IEEE 802.15.7 standard for visible light communication (VLC)(Rajagopal et al., 2012) utilizes on-off keying (OOK) to encode the format of the data stream from the transmitter to the receiver. The basic idea here being that by turning a light on and off at the transmitter the receiver can decode this sequence into the transmitted message. A popular approach for this OOK process is Manchester encoding (Tanenbaum and Wetherall, 2011) (Fig. 2), which is a recommended OOK approach in the IEEE VLC standard. Essentially this approach modulates the data stream using a clock signal. One downside of this mechanism is its relatively high overhead in terms of the communication signal consuming 100% more bandwidth than a raw encoding scheme.

3 UNDERWATER LI-FI MODEM

Evaluating the potential for the use of VLC for UUV control involves developing waterproof modems that modulate an electronic signal onto the light signal and then back again to an electronic signal. Rather than developing a system that simulates this process above ground (e.g., by placing a water tank between emitter and receiver), or developing a small tank that can be suspended from the surface, we are particularly interested in testing performance under realistic conditions where human-robot interaction will happen. That is, at depths greater than 10m and under realistic turbidity and external illumination conditions.

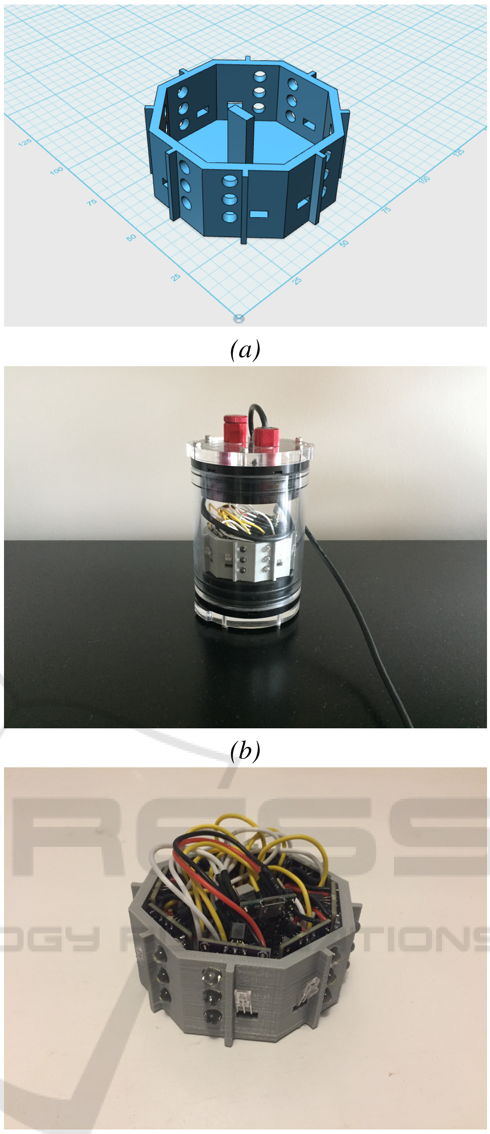
Table 1: A list of the primary components that make up each transceiver. For the purpose of brevity resistors and transistors are excluded from this list.

Primary Components	
Teensy 3.2	32bit ARM Cortex-M4 arduino-compatible micro-controller. The micro-controller has 256kb program storage space, 64kb of dynamic memory
TSL12S-LF	Eight light-to-voltage converters, combines a photodiode and transimpedance amplifier.
C503D-WAN	Twenty-four cool white LEDs with high luminous intensity (64600 mcd).
SSD1306	An I2C OLED graphical display.

The goal here is to not only identify issues related to Li-Fi generally, but also to investigate potential interactions between underwater housing construction and illumination conditions found at depth. This decision drives the basic physical design of the LightByte system shown in Fig. 3. The LightByte ”modems” are essentially small cylindrical housings with port glands for power and data (USB). Light emission and sensing is performed using emitters and sensors mounted in an octagonal 3D printed structure that is mounted inside the housing and isolates the emitters from the receivers to reduce crosstalk and also enables both emitters and receivers to cover a full 360° horizontal field. Operationally, these devices can be mounted as small external pucks on the external shell of a UUV.

Each LightByte transceiver communicates using five sets of emitters each composed of three LEDs, five light sensors that act as receivers and a small amount of electronics to drive and monitor the emitters and receiver. A small display is also included within each transceiver to enable monitoring of the state of the device when it is operating. The cost of each unit is under $200 US including the cost of the housing. Table 1 lists the components housed within each transceiver node.

Each LightByte node provides a USB connection for data transfer. For low power operations the Li-Fi LED’s can be powered from the USB bus. For higher power operations, power can be provided externally or a battery can be included inside the transceiver node.



(a) *(b)* *(c)*

Figure 3: LightByte Transceiver node. (a) 3D printed mounting rig. (b) A LightByte transceiver node in its underwater housing. (c) The electrical components of the node.

4 COMMUNICATION PROTOCOL

The IEEE 802.15.7 standard for VLC provides standards at both the data modulation and physical layers. The IEEE standard speaks to the use of VLC for local communication networks. As the goal here is for point-to-point communication we deviate from the IEEE standard at the physical layer, introducing a simple frame-based communication structure (based on UDP with components borrowed from TCP). The two transducers are identical in structure with identical communication protocols in both directions. Following the IEEE 802.15.7 standard frames are encoded using a Manchester line code. In addition to being an effective encoding scheme, this scheme has the benefit of using a constant amount of power irrespective of the data being sent and thus the flicker of the emitting LEDs cannot be perceived. This makes the emitter appear as a dim stable illuminator to any operator in the vicinity.

4.1 Physical Layer

As signals are emitted they are encoded using the Manchester coding scheme. This requires the emitter to maintain a stable clock to drive the encoding process. All of the output LED's are driven to the same level (100% of their maximum possible output (20 mA)). The complete set of LEDs use a total of 480mA in addition to the 45mA consumed by the micro-controller.

4.2 Data Link Layer

The data link layer utilizes the capabilities of the physical layer to construct a protocol for data transmission that deals with errors and regulates the flow of data in an effective manor. This is accomplished by encapsulating data into 128 byte fixed sized packets/frames with 8 byte headers that can be used to validate, sequence and identify each piece of data. Data is packed into a frame/packet as shown in Table 2. The ESC, PREAMBLE, SYNC, STX and ETX symbols are reserved. In order to avoid becoming confused by such tokens appearing in the signal itself, these symbols are reserved in the data packet and must be recoded there. Like UDP packets there is no guarantee of delivery, however unlike UDP this protocol does guarantee packet ordering. The physical layer also provides duplicate packet protection because data is only transmitted once and not relayed by subsequent nodes. Data frames are of fixed sized.

4.3 Error Detection

The Data Link Layer provides the ability to perform a certain amount of error correction. The two-byte Fletcher-16 (Fletcher, 1982) checksum facilitates the identification of transmission errors in the data stream. Frames that fail the checksum test are discarded, invalidating the current data stream. Considering that frames are sent sequentially the ID, DID and FID framing bytes can be used to identify non sequential frames and intrusive frames from another sender. Error detection helps to prevent invalid data from being propagated further up the communication stack. Thus, only validated transmitted and received data is transferred to the application layer.

Table 2: Packets are 128 bytes long. The Preamble, STX, SYNC and ETX characters are reserved in the data packet and are escaped in the data transmission using the ESC character 0x1B.

Packet/Frame Structure	
PREAMBLE (0xAA)	used to compute a signal average
SYNC (0xD5)	allows the receiver to align itself, signifies the start of a frame
ID (1-byte)	unique identifier of the sending node
DID (1-byte)	unique identifier for the current sequence of frames
FID (1-byte)	numerical identifier for the frame in sequence
CHKSUM (2-bytes)	two-byte checksum of the data in the frame (Fletcher-16)
STX (0x02)	signifies the start of data transmission
DATA (119-bytes)	user data
ETX (0x01)	signifies the end of data transmission

4.4 Data Communication

Given the ability to send bidirectional packets with checksums a variety of different lossless bidirectional communication strategies are possible. For ease of implementation a modified version of the classic ZMODEM(Forsberg, 1988) protocol is used to transmit binary data between the two transceivers.

5 EVALUATION

The bottleneck of this VLC device is the response time of the TSL12S-LF light sensor which has a response time of approximately 10μs. This equates to absolute maximum bit rate of approximately 6.25 kilobytes per second. Each data frame has an eight byte overhead, which translates to a theoretical maximum of approximately 5.8 kilobytes per second. This level of throughput is capable passing controller information akin to a wireless joystick and other low bandwidth sensors.

Figure 4: Aquatic Test. Both the transmitting and receiving nodes during an aquatic range test are shown. The emitter appears as a constant (but dim) light. Here the receiver is not transmitting.

The experiments that follow are all conducted in a similar manner, each consisting of a one-way communication between transmitter node and a receiver node as shown in Fig. 4. The transmitter is configured to send out a thousand numbered "test string" messages. The receiver is connected to a laptop where incoming packets are recorded and then analyzed to recover the packet drop percentage.

5.1 Range Test

Unlike most Li-Fi systems which operate in controlled environments where ambient light is a minimal competitor, the Li-Fi modems operate in direct competition with light from the sun and other intensive artificial sources and ambient light in the surrounding environment. Competition becomes a problem when the attenuation of light through the environmental medium (water or air) causes the brightness of the transmitter to be indistinguishable from the ambient light. In an environment with no ambient light the maximum range of transmission is based on the attenuation of light through the environmental medium (water or air) and the light sensitivity of the receiver.

The range test experiment evaluates the operational range of the device under normal and optimal ambient conditions in both terrestrial and aquatic environments. Both devices are setup in the same vertical plane with a single opposing transmitter and receiver manually aligned at 10cm, 50cm, 1m, and 5m apart. Results are given in Fig. 5 and Table 3. Rates are for 1000 packets. Note that performance in air under strong ambient illumination shows very high drop off rates at 5m but that performance in the water in the 2-3m range is quite good even under strong illumination.

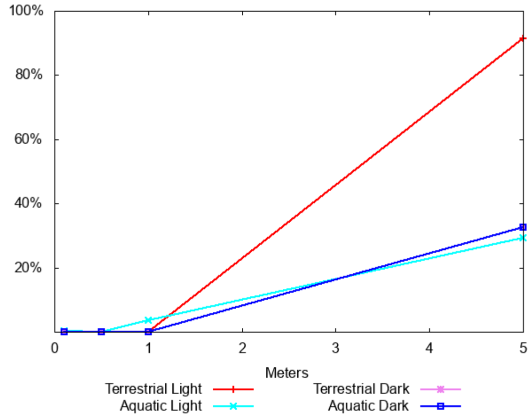


Figure 5: Range packet drop-off rates. The terrestrial dark signal is occluded by the aquatic dark signal in the above graph. Each test involved transmitting 1000 packets from the sender to the receiver. Numerical values are given in Table 4.

Table 3: Packet/Frame drop percentages in different environments and lighting conditions at various distances. Rates were estimated over 1000 packets.

	Terrestrial		Aquatic	
Offset	Light	Dark	Light	Dark
10 cm	0.01%	0.01%	0.25%	0.00%
50 cm	0.00%	0.00%	0.00%	0.00%
1 m	0.07%	0.00%	3.70%	0.00%
5 m	91.3%	32.7%	29.40%	32.65%

5.2 Radial Offset Test

Each LightByte modem consists of eight separate units arranged radially around the modem. A set of three vertically aligned transmitters and one receiver is positioned on each face of the octagonal layout. Transmitter LEDs have a viewing angle of 15° with a sharp falloff in brightness after 22.5°. Receivers have a nominal viewing angle of ±30°. These specifications suggest that at certain radial misalignments of the transmitter and receiver the communication signal will be attenuated due to the optics of the receiver and emission properties of the transmitting LED. Due to the octagonal layout of the sensor, realignment should occur every 45°. However, since the transmitter/receiver pair order is inverted every other emitter/transmitter pair, realignment with a similar transmitter/receiver pair configuration occurs every 90°.

This experiment evaluates packet/frame drop percentage as a function of the orientation alignment of the transmitter and receiver. Both devices are set up in the same vertical plane with a single opposing transmitter and receiver manually aligned 1m apart. One sensor is then rotated from 0° to 90° in increments of 5°. Results are shown in Fig. 6. As the receiver is ro-

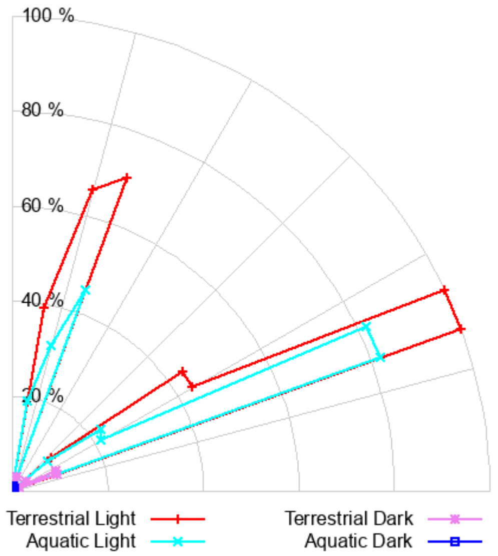


Figure 6: Radial offset packet drop-off rates. Terrestrial light test (red), terrestrial dark test (fuchsia), aquatic light test (cyan), and aquatic dark test (blue). Data was captured from 0° (horizontal) to 90° (horizontal) offsets of 5° increments.

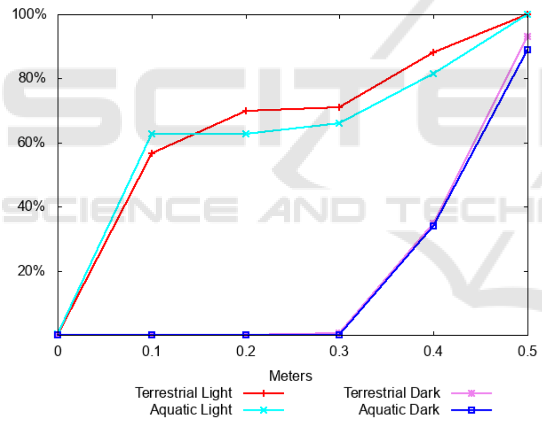


Figure 7: Vertical offset packet drop-off rates.

tated relative to the transmitter in the light throughput drops at the angles at which the sensor-receivers are misaligned. Performance in the dark is excellent at all orientations.

5.3 Planar Offset Test

Each set of three LED transmitters in the Li-Fi modem are vertically aligned along the eight walls of the 3d mount. The top and bottom LEDs are tilted 10° in opposing directions. This provides a 25° vertical viewing angle with a sharp falloff in brightness at ± 45°.

This experiment evaluates packet/frame drop percentage as a function of the vertical misalignment of the transmitter and receiver. The devices were set up 1m apart with different vertical offsets of 0cm to 50cm in increments of 10cm. Results are shown in Fig. 7 and Table 4. Performance in the light falls off quite quickly with vertical misalignment while performance in the dark is good up to approximately 30cm at 1m.

Table 4: Packet drop percentages under different environments and lighting conditions at different vertical offset distances at a range of one meter.

	Terrestrial		**Aquatic**	
Offset	Light	Dark	Light	Dark
0 cm	0.01%	0.01%	0.25%	0.00%
10 cm	56.56%	0.01%	62.8%	0.00%
20 cm	69.78%	0.01%	62.66%	0.00%
30 cm	71.11%	0.50%	65.90%	0.00%
40 cm	88.23%	34.80%	81.5%	33.90%
50 cm	100.0%	93.10%	100.0%	89.00%

6 DISCUSSION

Li-Fi-based technology can be an effective mechanism for underwater communication between a robot and a human. For reasonably short (<5m) distances and well aligned emitter-receiver pairs (±16°) good performance is obtained, even under illuminated conditions. However, as revealed by the experimental evaluation outlined above, The current LightByte hardware is not an ideal solution to the underwater wireless communication problem. As currently constructed vertical misalignment along the axis of the device can lead to substantive signal loss. That being said these experiments do outline certain application for which LightByte is well suited and other areas that can be improved upon in future versions of the hardware. For example, it would be straightforward to extend the vertical range of the device so that accurate off-axis alignment is not required.

The performance gap between high and low ambient light conditions is not surprising. Performance underwater in the light is acceptable, but performance in lower levels of ambient illumination is very good. As ambient illumination declines with depth this suggests that transmission reliability will increase alongside operational depth. Performance is also very good radially save for a few problem zones. Again this is likely to be easily addressed by increasing the density of light detectors around the device.

Even with the current prototype implementation transmission rates allow for the ability to transmit joystick-like commands from a command/control device to a nearby UUV (<5m). Excess bandwidth can be used to transmit other relevant sensor data to/from the robot. Considering the range/alignment limitations identified in the evaluation above this would require the operator and robot to remain in the same plane.

As far the writers are aware this is the first LIFI capable system designed for real world applications in the underwater domain. As such it is a prototype that demonstrates the technologies readiness to compete. Already its has demonstrated bandwidth comparable to that of commercially available acoustic modems. The range of this device is a severe limitation in comparison to acoustic modems. This limitation is explored below.

7 FUTURE WORK

The current version of both the hardware and communication protocol have a number of known limitations. The Cree C503D0-WAN LEDs have a relatively high luminous intensity in comparison to their power consumption. Using LEDs that output more lumens while sacrificing power would allow for communication at a much longer distance and would also preform much more desirably in well lit environments.

The Manchester coding scheme is very inefficient, requiring twice as much bandwidth in its encoded form than the raw data. IBM's 8b/10b coding scheme(Franaszek and Widmer, 1984) is another DC-balanced line code that has the benefit of providing additional control symbols (no decoding) that can be used to construct a frame. 8b/10b is much more complex that Manchester but only uses 25% overhead bandwidth. Switching from Manchester to 8b/10b encoding would increase overall bandwidth by 60%.

An obviously extension to this work would be construct an VLC device that has better out of plane performance and with more uniform radial sensitivity. This would allow any two devices to communicate with each other regardless of their relative orientations, provided their bodies do not occlude the light emitted from the device. We are in the process of mounting the LightByte sensor on Milton with the goal of driving the UUV underwater wirelessly from a diver in close proximity.

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