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UNDERWATER LED-BASED COMMUNICATION LINKS

by

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13. ABSTRACT (maximum 200 words)

The United States Navy and Marine Corps require more robust underwater wireless communication capabilities than current equipment can provide, as a small, but important part of future integrated and scalable sea-based networks. I suggest that a wireless alternative to short-range acoustic and radio frequency (RF) communication may be found in the visible light spectrum. This research investigates the feasibility of incorporating visible and infrared light-based links into tactical military scenarios in order to increase data rates, reduce risks to personnel and obviate the dependence on tethered communication links during underwater operations. A visible light communication (VLC) prototype was designed and tested in clear and ocean water using 100-W blue/green light emitting diodes (LED) with an array of phototransistors. The prototype achieved communication ranges in seawater of up to 6.2 meters using a data rate of 4.8 Kbps. Near-field underwater communication was also possible at a range of 0.3 meters at a data rate of 9.6 Kbps using a 10-W infrared LED. Employing a phototransistor array enabled more freedom of movement by decreasing alignment requirements between the transmitter and receiver. The results demonstrate a substantive increase in communication range and suggest that an LED-based approach could enable sending messages between submerged mobile nodes in open water.

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UNDERWATER LED-BASED COMMUNICATION LINKS

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The United States Navy and Marine Corps require more robust underwater wireless communication capabilities than current equipment can provide, as a small, but important part of future integrated and scalable sea-based networks. I suggest that a wireless alternative to short-range acoustic and radio frequency (RF) communication may be found in the visible light spectrum. This research investigates the feasibility of incorporating visible and infrared light-based links into tactical military scenarios in order to increase data rates, reduce risks to personnel and obviate the dependence on tethered communication links during underwater operations. A visible light communication (VLC) prototype was designed and tested in clear and ocean water using 100-W blue/green light emitting diodes (LED) with an array of phototransistors. The prototype achieved communication ranges in seawater of up to 6.2 meters using a data rate of 4.8 Kbps. Near-field underwater communication was also possible at a range of 0.3 meters at a data rate of 9.6 Kbps using a 10-W infrared LED. Employing a phototransistor array enabled more freedom of movement by decreasing alignment requirements between the transmitter and receiver. The results demonstrate a substantive increase in communication range and suggest that an LED-based approach could enable sending messages between submerged mobile nodes in open water.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
AECE	arctic expeditionary capabilities exercise
AM	amplitude modulated
ASCII	American Standard Code for Information Interchange
BC	before Christ
BER	bit error rate
CDFFM	MK25 MOD2 Combatant Diver Full-Face Mask
CMOS	complementary metal-oxide semiconductor
dB	decibel
DC	direct current
DOD	Department of Defense
DoN	Department of the Navy
DRS	Diver Recall System
ELF	extremely low frequency
GaN	Gallium Nitride
Gbps	gigabits per second
GCE	ground combat element
GHz	gigahertz
GPIO	general-purpose input/output
GPS	Global Positioning System
GOV	Glider Operations Center
HF	high frequency
Hz	hertz

IR	infrared
Km	kilometers
Kbps	kilobits per second
KHz	kilohertz
laser	light amplification by stimulated emission of radiation
LD	laser diode
LED	light emitting diode
LP-CRADA	limited purpose cooperative research and development agreement
MEU	Marine Expeditionary Unit
MHz	megahertz
MDSU	Mobile Diving and Salvage Unit
mm	millimeter
NAND	not-and
NPS	Naval Postgraduate School
NAVOCEANO	Naval Oceanographic Office
nm	nanometer
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
OPA	optical parametric amplifier
PAM	pulse amplitude momentum
PCB	printed circuit board
PD	photodiode
PMT	photomultiplier tubes
PPM	pulse-position modulation
QAM	quadrature amplitude modulation

RAM	random-access memory
RF	radio frequency
RGB	red, green, blue
RS-232	Recommended Standard 232
SNR	signal to noise ratio
SSB	single sideband
TTL	transistor to transistor logic
TTS	text to speech
THz	terahertz
UAWC	underwater acoustic wireless communication
UHF	ultra-high frequency
UUV	unmanned underwater vehicle
VHF	very high frequency
VLC	visible light communication
VLF	very low frequency
WWII	World War II

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I. INTRODUCTION

The time is 0200, and it is pitch black. Six dive teams are on a mission to emplace limpet mines on an enemy ship. These mines, magnetically attached to some of the most vulnerable parts of the ship, are not necessarily designed to sink it, but rather immobilize it. Each dive team has been instructed to emplace a mine on either the rudders, shafts, propellers, or hull. As briefed prior to the mission, the enemy is watching and listening. There will be no radio or acoustic communication. Each two-man dive team has a tether connecting the pair, but no way to talk wirelessly to the other five dive teams. With no reliable option to communicate other than hand-and-arm signals and line pulls, all divers are briefed on a no later than time to depart the vicinity of the intended target before the time-fused mines detonate, *hoping* at least a few of the dive teams have successfully emplaced their mines.

Unfortunately, hope is not a reliable course of action. What if they had another means of communication—an option that provides a directional, high-bandwidth capability? What if there was an opportunity to allow divers to adapt the plan and communicate changes in real-time? The visible and infrared light spectrum may offer an untethered, high bandwidth, low cost, and low risk of interception option. By applying an optical communication system to the same scenario, the dive teams may be able to communicate about mission success, whether more time is needed to complete the assignment, or to warn other dive teams of potential hazards.

A. PROBLEM

As limpet mines have been used since World War II, so too have our standard operating procedures for underwater communication. The challenges surrounding underwater communication apply to combat dive mission sets for every military branch ranging from salvage-and-repair to amphibious reconnaissance missions.

For modern littoral operations in contested environments, underwater activity plays a significant role in intelligence gathering, early warning, and stealth operations. Moreover, today’s battlespace and decision making tempo demand faster and more frequent real-time information from both fixed and mobile nodes. However, the growing number of subsurface sensors and nodes have limited means of high speed, reliable communication even at short ranges (Chen et al., 2014). Manned and unmanned subsurface missions require an improved method to pass large quantities of data rapidly between nodes and into the larger mobile network (Xing et al., 2018). In order to achieve these goals and all-domain access, I suggest that the United States Navy and Marine Corps will require improved, cost-effective underwater wireless communication technologies that operate at higher data rates than current equipment can provide.

The seaward portion of the littoral battlespace, which includes the region from the ocean to the coastline, poses unique communication challenges that are not prevalent above the surface (Department of the Navy [DON], 2017). Radio frequency signals are absorbed quickly by water, which restricts the usage of high frequency (HF), very high frequency (VHF), and ultra-high frequency (UHF) bands (Shao et al., 2015). As a result, divers and UUVs typically must surface in order to transmit data and/or receive Global Positioning System (GPS) information (Saeed et al., 2018). This places them at increased risk, decreases stealth, and hinders the timeliness of information.

Traditional underwater communication uses either tethered or acoustic means to send and receive messages (Gussen et al., 2016). While acoustic signals are efficient for low-bandwidth underwater communication over long ranges, the bandwidth and speed are constrained (Saeed et al., 2018). Conversely, tethered communication allows for high data rates at short range, but restrict freedom of movement. In these cases, underwater personnel and unmanned assets connect to boats or buoys via a cable that acts as a gateway to transfer information (Department of the Navy [DON], 2016). Due to wireless and wired communication challenges, divers rely heavily on simple hand signal and gesture communication (Chen et al., 2014).

A wireless alternative to acoustic and radio frequency (RF) communication may be found in the visible light spectrum (Saeed et al., 2018). Visible Light Communication (VLC) has the potential to support high bandwidth, short-range subsurface communication (Saeed et al., 2018). In the current research context, short-range communication include ranges up to 20 meters between sending and receiving nodes (Chen et al., 2014). Compared to RF assets, VLC offers many benefits including a wide, unlicensed bandwidth, energy-efficient transmissions, and the ability to communicate in RF-sensitive areas (Shao et al., 2015). Additionally, light offers more agile emissions control than RF and acoustic assets (Brutzman et al., 2014). This research investigates the feasibility of incorporating light-based links into tactical, military scenarios in order to increase speed, decrease cost, and improve efficiency of underwater communication.

B. RESEARCH OBJECTIVE

The purpose of this thesis is to explore a method to improve short-range underwater wireless communication through the employment of light emitting diode (LED) based VLC links. The ability to send messages, imagery, and files at the speed of light underwater could enhance command and control and diver safety during sub-surface operations. The objective is to enable a diver's message to be translated from speech to text and converted into modulated LED signals, whereupon the receiving system would detect the LED modulation, convert the signals to text, and recite the message to the intended recipient.

In this thesis, I suggest that a LED-based optical communication system could provide a significantly improved communication capability for underwater assets. In order to support this suggestion, my research objective leads to two areas of inquiry:

1. Can LED-based underwater VLC links pass message data between two underwater nodes?

2. How do environmental and technical factors affect underwater VLC?

(a) What is the relationship between power output and range in LED-based link establishment?

(b) How many LEDs and photodiodes are necessary to create an omnidirectional field of view?

C. SIGNIFICANCE

With successful high-speed underwater data transfers over greater ranges, potential applications might expand to fully integrate light-based links into tactical networks. This would increase the speed and throughput of time-critical combat information between divers and with their headquarters element on the surface. I suggest four example tactical scenarios in which this technology could be beneficial, the first of which is empirically tested.

1. Diver to Diver

In this scenario, Diver A seeks to send a message to pass information to Diver B. Because divers are inherently mobile, achieving physical alignment between sending and receiving systems is difficult. The proposed solution includes a transmitting LED-based communication system with a relatively narrow beam width and a receiving communication system with a wide field of view. This would enable Diver A to aim in the general direction of the Diver B, and transmit the message. The receiving system would then demodulate the light impulses, convert text to speech, and recite the message to Diver B. Because a dive pair typically remains within line of sight of each other, a line of sight (LOS) communication system ranging up to 15 meters could be sufficient (DON, 2016). At night or in water with poor visibility, divers can be connected via a buddy line that restricts their separation to three meters (DON, 2016).

2. Diver to UUV

The Diver-to-Unmanned Underwater Vehicle (UUV) scenario is similar to the previous case. However, upon the UUV's receipt of the message, the text would not need to be converted to speech. The message could instruct a UUV to reposition or alter depth. This also opens the possibility to relay LED-based messages through a network of UUVs. The high bandwidth may be able to support transmitting files and images, in addition to text.

3. UUV to UUV

An UUV-to-UUV scenario could represent just one link inside a network of UUVs. Depending on the platform's capabilities, the generated messages could originate from a human source or be created autonomously by the system. With high bandwidth communication, UUVs could effectively exchange collected sensor data, the status of the

UUV, and relative positioning data. Without requiring a voice component, the fast data rates would enable receiving UUVs to respond rapidly to positioning and alignment directions, target acquisition, and collection requirements. UUVs in a transmitting mode would be able to send large amounts of data quickly, such as files and images. Multiple linked UUVs may also be able to act as communication relays to extend the ranges of optical communication.

4. Diver to Headquarters

In a diver-to-headquarters scenario, the diver would have access to existing operational networks through a nearby surface gateway node. With access to a communication node such as a buoy, LED-based messages from a diver could be received underwater and retransmitted above the surface to other operational units via conventional radio or satellite communication links. Additionally, this increases command and control capabilities by providing above-water commanders with real-time updates of underwater missions.

D. SCOPE

Current underwater communication ranges are limited by range, bandwidth, power, cost, and/or mobility. My exploratory focus is on improving the attainable communication range, while increasing mobility and bandwidth. I define a minimum effective VLC-type communication range to be 3 meters, in order to exceed the maximum tethered range for dive pairs.

For purposes of generating a proof of concept, I explore the visible and infrared light spectrums. While the use of light amplification by stimulated emission of radiation (laser) is considered in my literature review, the scope of experimentation is constrained to LEDs. Although a portion of testing includes the use of the infrared, non-visible light spectrum, stealth is not a criterion.

This research will focus on establishing a communication link between two submerged nodes to prove feasibility of VLC networking. In this case, the confirmation of message receipt will be heard through the speaker on the receiving end of the link. A full duplex form of this concept would require two transmitting systems and two receiving systems, with one of each available to nodes on either end of the link. To simplify the development of a prototype, only one transmitter and one receiver system are constructed.

At this exploratory stage, the subsurface applications of interest involve mobile underwater and surface communication nodes. The underwater nodes represent divers, UUVs, or nodes mounted on surface platforms such as buoys or small craft. The latter would serve as a gateway to transmit underwater communication to surface-based assets. This research will incorporate diver to surface communication linkage to a limited degree, but the priority is on enhancing diver-to-diver communication. Additionally, while there is potential for file, image, and video transfer, the data transmitted in experimentation will be limited to text messages.

E. ORGANIZATION

This thesis is organized in five chapters. Chapter II begins with an operational context, followed by relevant research as they relate to the three focus areas of littoral operations in contested environments, the underwater environment, and optical communication. Chapter III describes the methods for selecting hardware and software components, constructing a VLC transmitter and receiver, as well as designing and conducting the experiments. The results are analyzed in Chapter IV as they correspond to the research questions laid out in this chapter. Finally, Chapter V summarizes the conclusions regarding the proof of concept, and the theoretical and practical significance of the research. It is followed by a discussion of the limitations and suggestions for future work.

II. THEORETICAL AND PRACTICAL FRAMEWORK

This literature review addresses the intersection of three domains: the underwater environment, military diving operations, and optical communications. Regarding underwater characteristics, both military and civilian researchers have conducted comprehensive studies for numerous applications to include oceanic mapping, wildlife research, weather conditions, communication effects, and underwater warfare tactics. The second domain involves military diving in the context of contested littoral operations. The United States Navy and Marine Corps' diving tactics and procedures are clearly articulated in technical manuals and joint doctrine, and they have a critical role in modern littoral operations. The third domain, optical communication, has grown in interest over the last two decades. Most experimental and practical applications have consisted of enclosed or free space information transfer. Some researchers have studied the possibility of using various types of optical communication in underwater settings. While each of the focus areas shown in Figure 1 has been studied independently, this literature review brings them together to explore the feasibility of using underwater optical communication between military combat divers and/or unmanned underwater vehicles.

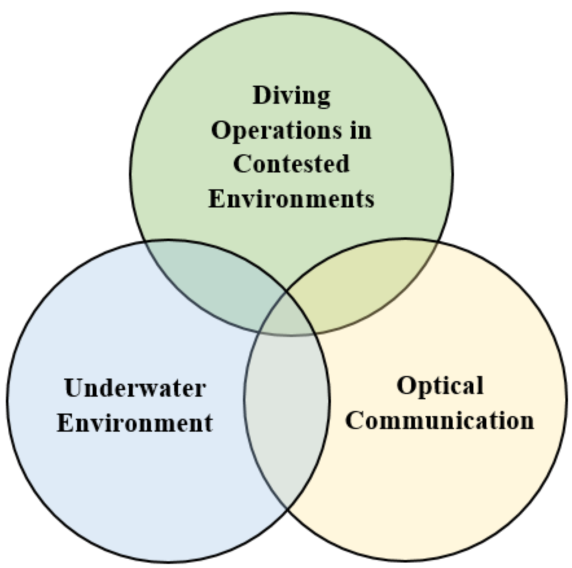

Figure 1. Focus Areas

A. DIVING OPERATIONS IN CONTESTED LITTORAL ENVIRONMENTS

Military subsurface and diving operations have ramifications at the strategic, operational, and tactical levels of war. This section focuses on the tactical element within littoral operations in contested environments. Additional research is presented regarding the history of military diving, applicable mission sets, and contemporary communication procedures.

1. Strategic Level

The strategic level of war involves national and military strategy (United States Marine Corps [USMC], 1997). This global outlook requires an integrated view of how components work together to achieve desired end states. With more than 70% of the earth's surface covered with water, the underwater environment makes up a large portion of the comprehensive operating environment (Zhang et al., 2013). The littoral regions, defined as "the area from the open ocean to the shore," encompass a large range of environmental factors affecting the implementation of strategic assets (Joint Chiefs of Staff [JCS], 2014, p. GL-6).

A singular, integrated battlespace relies, in part, on subsurface components and their ability to contribute to or access information from other domains. However, communicating between the surface and subsurface poses unique challenges. As a result, underwater nodes, such as submarines, often must surface to communicate with aerial, land, and ship-based assets (Saeed et al., 2018). In other cases, a surface gateway is required to relay the information to and from underwater nodes (Saeed et al., 2018). These processes impose restrictions on timeliness and efficiency.

2. Operational Level

The United States Sea Services, consisting of the United States Marine Corps (USMC), Navy, and Coast Guard (2015), operate jointly to allow friendly freedom of movement on the seas and prevent others from having the operational advantage. To further develop maritime power projection and enhance sea-based capabilities, the United States Navy and Marine Corps have identified a need to refocus research and development efforts on topics surrounding increased presence and gaining control within contested littoral environments (DON, 2017). Specifically, the Marine Corps defines a goal of creating "a modular, scalable, and integrated naval network of sea-based and land-based sensors, shooters, and sustainers that provides the capabilities, capacities, and persistent yet mobile forward presence necessary to effectively respond to crises, address larger contingencies, and deter aggression in contested littorals" (DoN, 2017, p. 9). The naval mission sets include protecting the homeland and maritime commons, deterring conflict and aggression, responding to crises, and providing humanitarian assistance and disaster response (USMC et al., 2015).

Military decision-makers levy increased information requirements to gain and maintain battlespace awareness when operating in contested surface and subsurface environments (DON, 2017). However, due to the characteristics of water, traditional RF communication is not effective subsurface (Gussen et al., 2016). This makes the underwater environment the most disjointed domain in the littoral region (Gussen et al., 2016). Submerged assets are typically unable to contribute to the common operational picture, provide real-time intelligence, and match the bandwidth of terrestrial communication systems. Where the littoral region transitions between land and sea, it is necessary to implement capabilities that can reintegrate the less-connected underwater environment (DON, 2017).

To support the integration at the operational level, research has been conducted on the potential for hybrid spectrum networks (Xing et al., 2018). These networks highlight future capabilities to tie optical links into existing RF and acoustic communication (Saeed et al., 2018). As seen in Figure 2, proposed hybrid networks include the use of surface gateways to transmit information above and below the surface (Xing et al., 2018). Optical communication has the potential to supplement RF and acoustic capabilities. Additionally, RF and acoustic links may be able to transmit low-bandwidth, orientation and control data to aid the precision and connectivity of directional optical links through the air and underwater (Xing et al., 2018). This has the potential to enable communication in an otherwise degraded or contested environment.

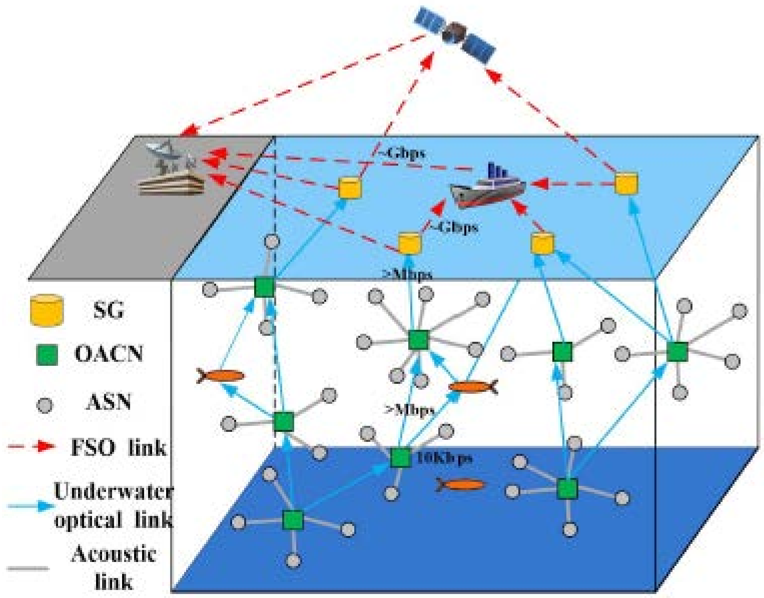

Figure 2. Potential Integrated Network Using Optical and Acoustic Communication. Source: Xing et al. (2018).

3. Tactical Level

The following three vignettes illustrate a spectrum of potential tactical applications that optical communication might support. They inform the research framework and highlight some of the potential advantages of VLC, such as high throughput, operations security, power efficiency, and mobility.

a. Salvage and Diving Mission

Mobile Diving and Salvage Units (MDSU) are regularly tasked to remove underwater hazards and repair port facilities in order to maintain port accessibility (Yingling, 2019). In September 2019, MDSU-1 was instructed to remove an abandoned sunken vessel that had been impeding access to the main fishing boat launching point in an Alaskan harbor for ten years (Yingling, 2019). This salvage and diving operation, in addition to other sunken tugboats in the area, required site surveys using pictures and recorded data to gauge the equipment and personnel required for removal (Yingling, 2019). To minimize operational risk, additional communication regarding the vessel's fuel tanks and oil within the hydraulic lines was relayed prior to cutting the vessel into removable sections. These sections, seen in Figure 3, were then brought ashore for disposal (Yingling, 2019). While this salvage and removal mission supported the Arctic Expeditionary Capabilities Exercise (AECE) 2019, the tactics and procedures used provided realistic training for future cold-water operations in contested littoral environments (Yingling, 2019). Although the coordinating information may have been communicated via umbilical cords connecting divers to the surface during this mission, the divers' flashlights had potential to be used for both communication and illumination. In order to minimize the physical tethers that can cause entanglement, a wireless, light-based communication system would have benefitted the divers by enabling them to pass the same information to other divers as well as to the surface without physical limitations to mobility (DON, 2016).

Figure 3. Salvage and Removal Operation. Source: Yingling (2019).

b. Weather Data and Sensing Platforms

The Naval Oceanographic Office (NAVOCEANO) is responsible for the Glider Operations Center (GOV) that collects and provides oceanographic data to warfighters (Mensi et al., 2014). Currently, the GOV maintains a fleet of more than 100 Navy Gliders including the Littoral Battlespace Sensing UUV pictured in Figure 4 (Mensi et al., 2014). The gliders, which are autonomous underwater data collection platforms, communicate using iridium global satellite phone systems near the 1600 megahertz (MHz) frequency range with a power output of approximately 1.1 Watts (Mensi et al., 2014). These systems collect and report data on the UUV's health as well as the ocean's salinity, temperature, and optical properties (Mensi et al., 2014). However, the reports can only be transmitted when the UUV surfaces (Mensi et al. 2014). LED-based optical communication could potentially provide a cost effective, power efficient, and real-time link to transfer of sensor data while remaining submerged. The high bandwidth would allow larger quantities of data to be transmitted to an underwater optical receiver collection point such as a buoy, while the UUV continues gliding through the water at the appropriate depth.

Figure 4. Littoral Battlespace Sensing—Unmanned Underwater Vehicles (LBS UUV). Source: Mensi et al. (2014).

c. *Marine Corps Reconnaissance Mission*

A Marine ground reconnaissance unit assigned to the ground combat element (GCE) of a forward-deployed Marine Expeditionary Unit (MEU) has been tasked with conducting an amphibious reconnaissance to collect information regarding the enemy's activities and capabilities prior to deploying the amphibious landing force. Additionally, the combat divers observe any oceanic features that may affect small boat, landing craft, or amphibious assault vehicle approaches. In two-person dive teams, Marines conduct a covert underwater mission outfitted with MK 25 MOD 2 Combatant Diver Full-Face Mask

(CDFFM) seen in Figure 5 (Marine Corps System Command [MCSC], 2018). Although this system is equipped with ultrasonic radio systems, the divers rely primarily on towlines and hand-and-arm signals to communicate rather than transmit acoustically to prevent compromising their tactical positions (DON, 2016). However, infrared communication could potentially enable the divers to exchange information more efficiently, while still offering a low risk of intercept or detection.

Figure 5. MK 25 MOD 2 CDFFM in Training Environment. Source: Marine Corps System Command (2018).

4. Diving Operations

Military diving plays a unique role in the mission sets involved in littoral operations. The history of tactical diving has greatly influenced the evolution and development of current standard operating procedures, equipment, and communication methods.

a. History of Military Diving

Military diving began as early as 332 BC when Alexander the Great instructed divers to remove obstacles and wreckage in the harbor of present-day Lebanon after the port had been blockaded (DON, 2016). From the origins through early 1900s, diving equipment and safety procedures were rudimentary. As observed in Figure 6, divers experimented with a breathing device made of leather attached to a tube running to the surface (DON, 2016). These divers wore minimal clothing and protective equipment (DON, 2016). Additionally, a safety rope was secured around the diver's waist in order for surface observers to hoist divers to the surface in case of emergency (DON, 2016). With the advancement of breathing apparatuses, portable air supplies, and lightweight diving equipment between 1916 and 1927, researchers were able to experiment with underwater communication via cables and button-operated regulatory valves (DON, 2016).

Figure 6. An Early Underwater Breathing Device Using Leather Bag. Source: Department of the Navy (2016).

WWII was a turning point for tactical diving. On 7 December 1941, Navy dive teams were deployed to salvage ships damaged in the raid on Pearl Harbor (Naval History and Heritage Command, 2017). Of the six sunken battleships, Navy divers were able to return four to the fleet (Naval History and Heritage Command, 2017). During the aftermath of Pearl Harbor, Navy divers conducted 4,000 dives and spent over 16,000 hours submerged (Naval History and Heritage Command, 2017). With the divers' value to the fleet highlighted, the Navy renewed its focus on the dive program and established a new combat diving and salvage school in 1942 (Naval History and Heritage Command, 2017).

The dive mission sets throughout WWII included intelligence gathering and obstacle removal in foreign waters (Naval History and Heritage Command, 2017).

Since WWII, more time and research have been invested into the improvement of diving equipment. By 1976, the Navy incorporated the MK1 MOD 0 mixed-gas diving system that included improvements such as a full face mask and a communication cable (DON, 2016). The communication cable ran through an umbilical cord from the diver to the surface (DON, 2016). By 1990, the diving equipment was upgraded to the MK 21 MOD 1 that made the helmet significantly lighter, but did not drastically change any communication capabilities (DON, 2016).

b. Current Diving Mission Sets

From WWII through today, the mission sets have become more diverse to include recovery of downed aircraft, underwater vessel inspections and repairs, countermine operations, and research of unmanned underwater systems (DON, 2016). However, more traditional diving assignments such as obstacle clearing and reconnaissance missions have continue to be employed in global operations (Naval History and Heritage Command, 2017).

c. Contemporary Communication Procedures

Communication is an integral component for safe diving practices. The environment and mission set can alter the necessary communication procedures. The daytime, nighttime, and cold-water missions each have specific guidelines laid out by the Department of the Navy (2016) in terms of physical and through-water communication requirements. Physical communication between divers includes hand and arm signals, writing slates, and line-pulls (DON, 2016). Through-water communication traditionally includes acoustic signals (DON, 2016).

Hand signals and line pulls require extensive memorization. Figure 7 shows approximately a third of the standard hand and arm signals (DON, 2016). These signals act as brevity codes to relay messages to other divers or the surface (DON, 2016). When visibility or darkness hinders the use of hand signals, divers are instructed to utilize flashlights to convey information, as displayed in Figure 8 (DON, 2016).

	Meaning/Signal	Comment
	**COME HERE** Hand to chest, repeated.	
	**ME or WATCH ME** Finger to chest, repeated.	
	**OVER, UNDER, or AROUND** Fingers together and arm moving in and over, under, or around movement.	Diver signals intention to move over, under, or around an object.
	**LEVEL OFF or HOW DEEP?** Fingers and thumb spread out and hand moving back and forth in a level position.	
	**GO THAT WAY** Fist clenched with thumb pointing up, down, right, or left.	Indicates which direction to swim.
	**WHICH DIRECTION?** Fingers clenched, thumb and hand rotating right and left.	
	**EAR TROUBLE** Diver pointing to either ear.	Divers should ascend a few feet. If problem continues, both divers must surface.
	**I'M COLD** Both arms crossed over chest.	
	**TAKE IT EASY OR SLOW DOWN** Hand extended, palm down, in short up-and-down motion.	
	**YOU LEAD, I'LL FOLLOW** Index fingers extended, one hand forward of the other.	

Figure 7. Examples of Standard SCUBA Hand Signals. Source: DON (2016).

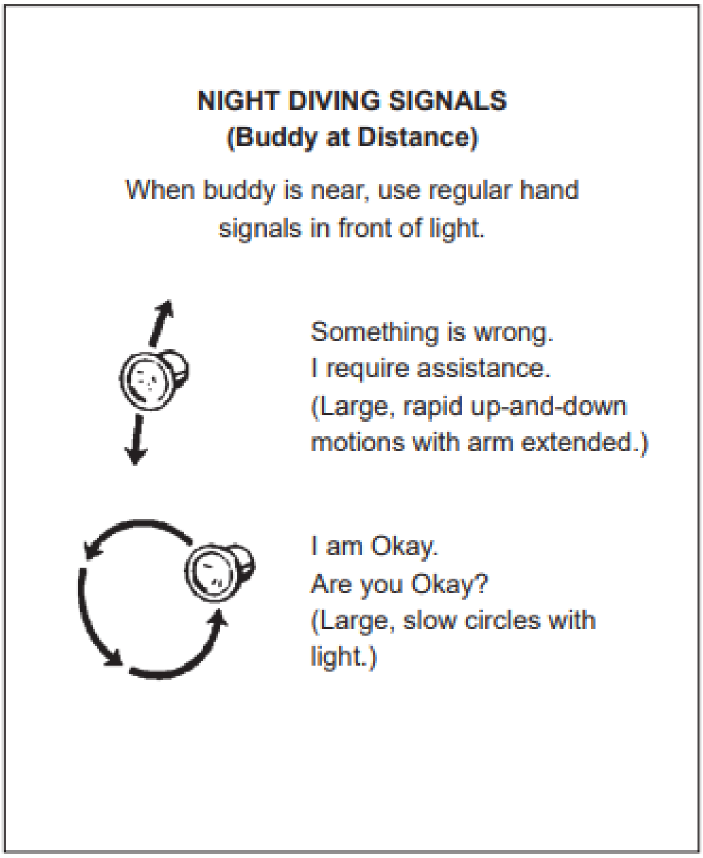

Figure 8. Night Diving Signals. Source: DON (2016)

Similar to hand signals, line pulls are memorized sequences used to convey information. The signals shown in Figure 9 can be used by the diver to communicate with the surface, or vice versa. Divers can also use the buddy line connecting a dive pair to communicate with the other diver. Line pulls require intentional, distinct tugs in order to reliably convey a message (DON, 2016). All slack must be removed in the line before beginning the line pull sequence (DON, 2016).

Another form of underwater communication involves acrylic writing slates. Divers use grease or graphite pencils to scribe messages and/or record information while submerged (DON, 2016). However, writing underwater takes time and significant dexterity compared to hand and line pull signals.

From Tender to Diver		Searching Signals (Without Circling Line)	
1 Pull	"Are you all right?" When diver is descending, one pull means "Stop."	7 Pulls	"Go on (or off) searching signals."
2 Pulls	"Going Down." During ascent, two pulls mean "You have come up too far; go back down until we stop you."	1 Pull	"Stop and search where you are."
3 Pulls	"Stand by to come up."	2 Pulls	"Move directly away from the tender if given slack; move toward the tender if strain is taken on the life line."
4 Pulls	"Come up."	3 Pulls	"Face your umbilical, take a strain, move right."
2-1 Pulls	"I understand" or "Talk to me."	4 Pulls	"Face your umbilical, take a strain, move left."
3-2 Pulls	"Ventilate."		
4-3 Pulls	"Circulate."		
From Diver to Tender		**Searching Signals (With Circling Line)**	
1 Pull	"I am all right." When descending, one pull means "Stop" or "I am on the bottom."	7 Pulls	"Go on (or off) searching signals."
2 Pulls	"Lower" or "Give me slack."	1 Pull	"Stop and search where you are."
3 Pulls	"Take up my slack."	2 Pulls	"Move away from the weight."
4 Pulls	"Haul me up."	3 Pulls	"Face the weight and go right."
2-1 Pulls	"I understand" or "Talk to me."	4 Pulls	"Face the weight and go left."
3-2 Pulls	"More air."		
4-3 Pulls	"Less air."		
Special Signals From the Diver		**Emergency Signals From the Diver**	
1-2-3 Pulls	"Send me a square mark."	2-2-2 Pulls	"I am fouled and need the assistance of another diver."
5 Pulls	"Send me a line."	3-3-3 Pulls	"I am fouled but can clear myself."
2-1-2 Pulls	"Send me a slate."	4-4-4 Pulls	"Haul me up immediately."
ALL EMERGENCY SIGNALS SHALL BE ANSWERED AS GIVEN EXCEPT 4-4-4			

Figure 9. Standard Line-Pull Signals. Source: DON (2016)

Acoustic communication is used in a variety of forms. Some of the most common diver acoustic systems include battery-powered beacons, the Diver Recall System (DRS), and the CDFFM (DON, 2016). The beacons are sonar devices that transmit high-frequency acoustic pings and can be effective up to 1,000 yards in a passive mode (DON, 2016). Divers can wear these location-tracking systems, or the beacons can be attached to devices such as buoys to fix positions in the water (DON, 2016). The DRS is an acoustic, one-way underwater speaker that can be used by dive supervisors to send messages to divers (DON, 2016). The diver does not need an acoustic receiving system to hear the message from DRS (DON, 2016). Additionally, there are Amplitude Modulated (AM) and Single Sideband (SSB) acoustic technologies that can be used to communicate between submerged divers.

However, these systems require special transmitting and receiving equipment (DON, 2016).

The CDFFM, also known as the MK 25 MOD 2 Underwater Breathing Apparatus, is equipped with acoustic systems (Marine Corps System Command, 2018). The mask has an underwater voice capability that can be used to communicate between dive pairs or to the surface. The system has two channel frequencies operating at 25 KHz and a secure DOD frequency (Marine Corps System Command, 2018). The CDFFM is currently a program of record for the Marine Corps, but the system is not widely used due to unreliability of communication and design of the mouthpiece system (S. Uziel, personal communication, July 8, 2019).

B. UNDERWATER ENVIRONMENT

1. Physical Properties

Ninety-eight percent of the Earth's water is represented in oceans, and large portions of these areas remain unexplored (Luo et al., 2018). Of the explored water regions, the physical characteristics greatly vary and frequently change. These characteristics include but are not limited to temperature, salinity, water turbidity, depth, noise and pollution (Gussen et al., 2016). They influence wildlife survivability, maritime interests, and military operations (Gussen et al., 2016).

2. Underwater Communication

The underwater environment poses many unique challenges for reliable communication. Underwater communication is traditionally classified as either wired or wireless. Wired, or tethered, communication allows for high-speed data rates and uninterrupted traffic between nodes (Saeed et al., 2018). However, the wire limits depth, range, and freedom of movement for the underwater nodes (DON, 2016). Additionally, wired communication makes it difficult to add new nodes or conduct network discovery. As a result, wireless communication provides a more promising alternative for future tactical and operational underwater environments. In this section, I review underwater acoustic, RF, and optical wireless communication.

Specific factors affecting all forms of underwater wireless communication include power consumption, fluid movement, and variable conditions (Misra et al., 2012). Underwater acoustic, RF, and optical communication each introduce power considerations that limit submerged time (Misra et al., 2012). Without the ability to easily recharge or refuel, power consumption is an issue for transmitting and receiving communication systems (Domingo, 2011). Additionally, ocean currents cause nodes to move constantly. This requires nodes to expend energy to remain in place, and complicates speed and range positioning algorithms for self-propelled, mobile nodes (Saeed et al., 2018). Other challenges include changing environmental conditions. The aquatic properties can change depending on the time of the day in a given location and greatly vary between bodies of water (Gussen et al., 2016). As a result, it can be difficult to create a communication system that operates effectively in all water, all of the time. These environmental considerations affect the ability to transmit underwater messages.

3. Effect on Acoustic Communication

Acoustic transmissions, also referred to as Underwater Acoustic Wireless Communication (UAWC), are the most frequently used means of underwater wireless communication (Gussen et al., 2016). A major benefit of UAWC is the long-range communication capability. While only a relatively low data rate can be achieved, transmissions can span over 10 kilometers (km) underwater (Wu et al., 2017). Research has demonstrated data rates of 7 Kbps and 60 Kbps over ranges of 13 km and 3 km, respectively (Saeed et al., 2018). However, while acoustic communication operates over long ranges, they degrade from scattering, attenuation, low bandwidth, high delay, and noise interference (Saeed et al., 2018).

Water depth also affects how sound travels (DON, 2016). Shallow water can create reflections, echoes, and dead spots that can interrupt acoustic communication (DON, 2016). For divers, this can make it difficult to locate the direction of sounds or potential dangers (DON, 2016). At frequencies less than 100 Hz, acoustic communication is affected by noise from earthquakes, ocean and atmospheric turbulence, storms, underwater volcanic eruptions, and distant shipping traffic (Saeed et al., 2018). At frequencies greater than 100

Hz, acoustic transmissions are affected by noise from sea states and wind, thermal noise, and marine animal sounds (Saeed et al., 2018). These factors render acoustic underwater communication more useful for long range, beyond line of sight, low data requirements.

4. Effect on RF Communication

Unlike air and land domains, RF waves do not propagate well underwater due to the high-energy absorption properties of water (Domingo, 2011). Seawater is highly conductive, which affects the propagation of electromagnetic waves (Gussen et al., 2016). Although RF waves do not broadcast as well as acoustic waves underwater, research has demonstrated that RF can be a viable means of communication (Gussen et al., 2016). Extremely and very-low frequencies (ELF and VLF), from 3 Hz to 30 KHz, can support reliable communication but only at low data rates (Gussen et al., 2016). Equipment needed for communication at these frequencies are very large, expensive, and require high power (Gussen et al., 2016). Positioning underwater nodes can be difficult without access to GPS. GPS operates in the 1.5GHz band, which does not transmit through water (Domingo, 2011). As a result, underwater nodes must use algorithms to compute relative positioning or surface to access GPS signals (Saeed et al., 2018).

Additionally, salinity causes attenuation in seawater to be greater than fresh water. (Gussen et al., 2016). Table 1 shows RF propagation ranges in meters for frequencies between 10 Hz and 10 MHz in salt water and fresh water with a signal attenuation of 50 dB (Gussen et al., 2016). This illustrates that frequencies in the MHz and higher range only propagate ranges of less than one meter in seawater (Gussen et al., 2016).

Table 1. Radio Frequency Propagation Ranges (Meters) in Seawater and Freshwater. Adapted from Gussen et al. (2016).

	Frequency						
	10 Hz	100 Hz	1 KHz	10 KHz	100 KHz	1 MHz	10 MHz
Seawater	440 m	140 m	44 m	14 m	1.4 m	0.44 m	0.044 m
Fresh Water	29 km	9.2 km	2.9 km	920 m	92 m	29 m	2.9 m

5. Effect on Optical Communication

The visible light spectrum ranges from 400 to 800 Terahertz (THz) for high-speed data communication (Haas, 2018). These frequencies have potential for underwater wireless communication at ranges up to 20 meters (Chen et al., 2014). Compared to RF and acoustic methods, optical communication has demonstrated the ability to achieve higher data rates over short ranges using less power (Saeed et al., 2018). While water is a conductor for RF propagation, it is a dielectric for optical wave propagation (Gussen et al., 2016). As a result, underwater light-based communication can reach larger data rates than RF communication over short to medium ranges (Gussen et al., 2016). Table 2 provides a comparison between underwater RF, optical, and acoustic communication capabilities and limitations (Gussen et al., 2016).

Table 2. Comparison of Underwater Mediums. Source: Gussen et al. (2016).

	Technology		
Main issues	**RF**	**Optical**	**Acoustics**
Key water property	Salinity	Water turbidity	Water depth
Water types	Fresh water × Seawater	• Main Jerlov water types: Clearest water, Intermediate water, Murkiest water • From [14], [18]: Pure seawater, Clear ocean water, Coastal ocean water, Turbid harbor and estuary water	Shallow water × Deep water
Drawbacks and/or requirements	High attenuation over short distances	• Line of sight link • Receiver direction tracking • Subject to marine fouling	• Doppler estimation and compensation • Latency in communication • Existence of shadow zones
Main characteristics	Can cross water/air surface (boundary)	Achieve higher data rates	Propagates over longer distances
Reliable communication distance	Few meters	Tens of meters	Kilometers
Achievable data rates	1 to 10 Mbps (@1 − 2 m, [91]) 50 to 100 bps (@200 m, [91])	1 Gbps (@2 m, [10]) 1 Mbps (@25 m, [89])	1.5 to 50 kbps (@0.5 km, [92]) 0.6 to 3.0 kbps (@28 − 120 km, [93])
Dependence of the speed propagation	Frequency, water conductivity (salinity and temperature)	Frequency, water turbidity (chlorophyll concentration, salt ions, etc.)	Temperature, salinity, water depth

Additionally, the speed of light is nearly five orders of magnitude faster than the speed of sound in liquids (Gussen et al., 2016). Because of the high speeds, Doppler spread effects are insignificant in optical wireless communication (Gussen et al., 2016). However, optical communication requires line of sight between receiver and transmitter and are greatly affected by water characteristics. Bodies of water are classified into one of three Jerlov water types: clear, intermediate, and murky (Gussen et al., 2016). Table 3 provides examples of water regions associated with each Jerlov category.

Table 3. Jerlov Water Type Examples. Adapted from Gussen et al. (2016)

Jerlov Water Type	**Body of Water**
Clear	Mid-Pacific Ocean, Mid-Atlantic Ocean
Intermediate	Northern Pacific Ocean
Murky	North Sea and Eastern Atlantic Ocean

Within each category, water types are further categorized as types I through III for ocean waters and IC through 10C for coastal waters (Sticklus et al., 2019). The lowest attenuation coefficient associated with each water type determines the optimal wavelength for optical communication (Sticklus et al., 2019). Figure 10 demonstrates that the wavelength range of 450 to 575 nanometers (nm) is ideal for underwater optical communication in most water types (Sticklus et al., 2019). The ideal transmitting frequency shifts from blue light at approximately 450nm for clear ocean water, to green light at about 550nm in more turbid coastal waters (Sticklus et al., 2019). These characteristics of water affect data rates and ranges.

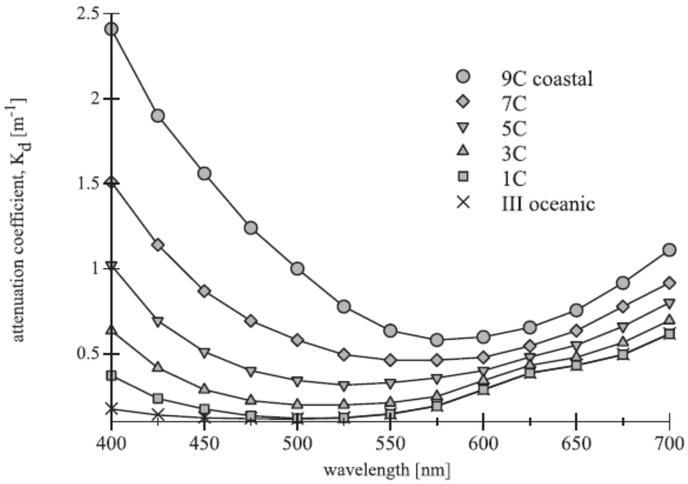

Figure 10. Plot of Attenuation Coefficients for Jerlov Water Types vs. Visible Light Wavelengths. Source: Sticklus et al. (2019).

C. OPTICAL COMMUNICATION

Within the last decade, several underwater optical communication experiments have been conducted with varying degrees of success based on the system specifications and environmental characteristics. The communication systems are composed of at least one transmitter and receiver. The transmitter can be characterized in terms of type, color, power output, and number of light sources. The receiver can be described by size, type, sensitivity, and number of sensors. Additionally, the environmental factors differ based on water type, depth, ambient light, turbidity, and salinity (Saeed et al., 2018). These variables affect the achieved data rates and ranges in each experiment. Many aspects of the following prior research informed the design of my prototype, in terms of hardware, software, and experiment design.

1. System Hardware Design

At a minimum, the hardware of a VLC system includes a computing component, light source, receiver, and power source. While some VLC systems use additional hardware, the following are the fundamental elements considered in my research.

a. Computer Options

The variety of experiments largely falls into two categories: using small, portable computing components, or using a standalone laptop. For submerged and/or mobile experiments, small computers such as Arduino, Beaglebone, and Raspberry Pi have been used (Klaver & Zuniga, 2015).

In VLC experimentation in which laptops were used, the system design did not require the computing system to be waterproofed. Wu et al. (2017) established their VLC communication system by setting up the transmitter and receiver against the outside of a glass water tank. Han et al. (2018) and Cossu (2018) established their systems with the transmitter and receiver submerged, and an underwater cable connecting to the above-water signal generator and data recovery circuits.

b. Light Sources

When deciding on the appropriate light source for an underwater VLC system, the type, color, shape, quantity, and purpose must be assessed. Both LED and laser diode (LD) are types of light sources that can be used for optical communication (Ndjiongue & Ferreira, 2018). Lasers allow for higher baud rates, but are highly susceptible to underwater refraction due to narrow beam width (Saeed et al., 2018). Lasers also typically require Pointing, Acquisition, and Tracking (PAT) capabilities to maintain or establish communication links (Oubei et al., 2018). Although lasers possess a higher modulation bandwidth, LEDs provide a lower cost and longer lifespan (Xu et al., 2016).

LEDs are different than incandescent light bulbs. A wire is not required to heat up when the bulb turns on and cool off when it is turned off (Klaver & Zuniga, 2015). LEDs offer a much faster process that directly releases photons (Klaver & Zuniga, 2015). This allows the light to be modulated rapidly and accurately to transmit data (Klaver & Zuniga, 2015). Due to lower thermal resistance, LEDs have a higher optical power and greater efficiency than lasers (Xu et al., 2016). Additionally, underwater assets could use LEDs for both underwater illumination and communication (Xu et al., 2016). While most LEDs have a relatively narrow beam width, the field of view is significantly wider than the beam width for a LD (Wu et al., 2017). A wider beam width helps align the transmitter and receiver, and decreases the required level of precision (Wu et al., 2017). Relative comparisons for LED and LD beam widths and communication ranges are illustrated in Figure 11.

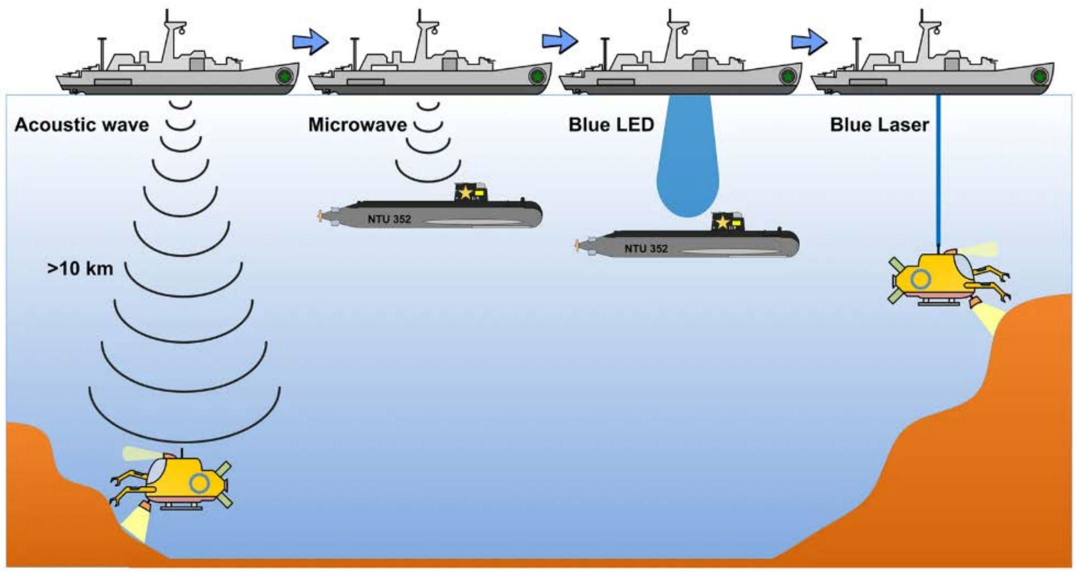

Figure 11. Visual Comparison of Underwater Communication Ranges. Source: Wu et al. (2017).

The majority of the reviewed underwater experiments used blue-green colored LEDs or LDs operating with wavelengths ranging from 450 to 550 nm, as this range demonstrates the lowest attenuation coefficient in most water types (Wu et al., 2017). The difference between experiments that incorporated LDs or LEDs into their system was based on their intended purpose. Wu et al. (2017) chose to use a 450 nm blue Gallium Nitride (GaN) LD instead of a LED for the increased modulation bandwidth and potential communication range. In this case, the researchers were focused on maximizing the data rate and less concerned about cost or complexity (Wu et al., 2017).

For most experiments that used LEDs, the objective was to develop or simulate a low cost, low power consumption, and/or ease of use system. Chen et al. (2014) selected a high-powered LED to be used inside of an existing diving flashlight. Han et al. (2018) chose LEDs due to their larger divergence area, making it more feasible to achieve a semi-omnidirectional communication system using multiple LEDs. In these experiments, the equipment selected and system design were often simpler than laser-based options.

The shape of the LED is an important consideration because it corresponds to the shape and size of the beam width. Akram et al. (2017) experimented with the difference between flat, rounded, and power LEDs. Through observations, Akram et al. (2017) determined oval and flat LEDs had less spread angle compared to power LED.

In addition to experiments using a single LED, there are many studies in which an array of LEDs was applied. The arrays vary in arrangement and number of LEDs. In the transmitter shown in Figures 12 and 13, Han et al. (2018) arranged seven blue LEDs (470 nm) evenly on a circular printed circuit board (PCB). Figure 12 shows the size and shape of the aluminum PCB with the left image providing the front view, and the right image depicting the bisected side view (Han et al., 2018). Their prototyped freeform lens was placed on each LED and widened the divergence angle up to 150 degrees (Han et al., 2018). Each LED operated independently, but synchronously (Han et al., 2018).

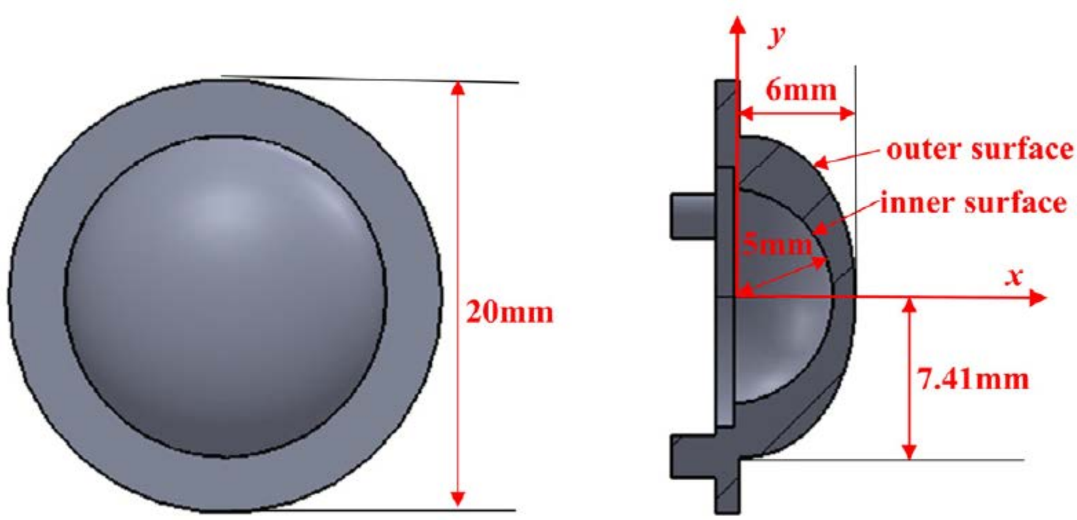

Figure 12. Quasi-omnidirectional Transmitter. Source: Han et al. (2018).

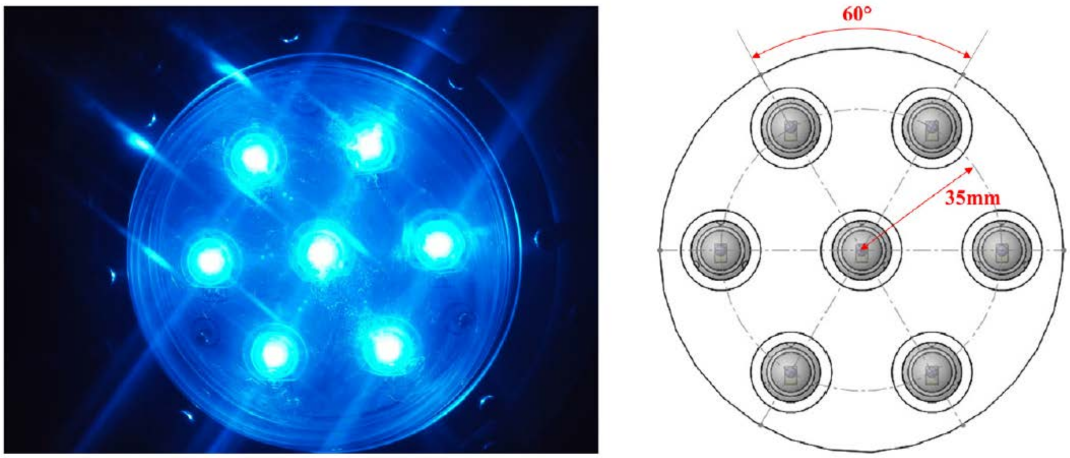

Figure 13. Arrangement of Blue LED Array. Source: Han et al. (2018)

Klaver and Zuniga (2015) also investigated the ability to provide omni-directional coverage using LEDs. While each LED had a narrow beam width of 18 degrees, they were able to use 20 LEDs evenly spaced on a circular board to achieve a 360 degree field of view as seen in Figure 14 (Klaver & Zuniga, 2015). While this experiment was geared toward improving city infrastructure such as car headlights, stoplights, and billboards, the concept may still apply underwater (Klaver & Zuniga, 2015). Since this experiment was conducted through free space and not through water, white LEDs were selected because a large portion of current urban infrastructure is already using LEDs for lighting and energy efficiencies (Klaver & Zuniga, 2015).

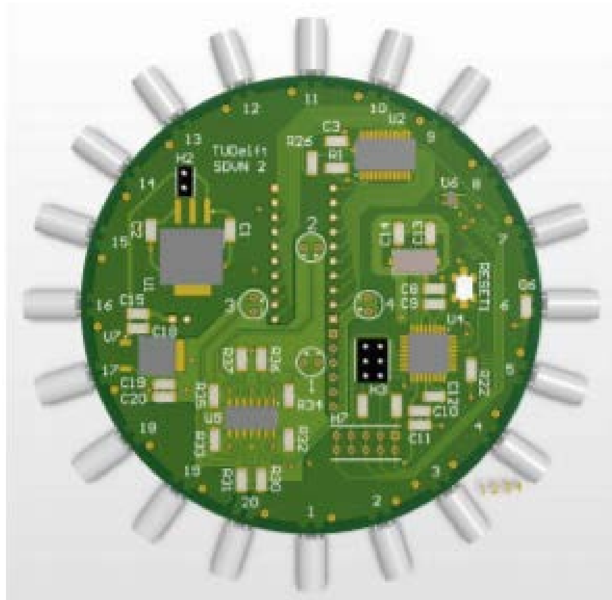

Figure 14. VLC Transmitter with 20 LEDs in Array. Source: Klaver and Zuniga (2015).

The use of infrared (IR) LEDs is also an interesting area of research for underwater communication. Gao and Guo (2010) developed fish-like microrobots that communicated using the 940nm wavelength in the IR spectrum. Using IR LEDs with a carrier frequency of 38 KHz, multiple microrobots were instructed to swim in various directions (Gao & Guo, 2010). Although the maximum communication range achieved was not offered, it appeared as though the fish-like microrobots stayed within one meter of the transmitter (Gao & Guo, 2010).

The significance of these studies is not only the successful implementation of blue and green LEDs, but also the methods used to broaden the field of view. For my experiment design, I required a light source that provided a large enough beam width to reduce aiming precision requirements, but narrow enough to minimize detection or interception. To simplify the schematics, I chose not to implement a transmitter LED array as Klaver and Zuniga (2015) and Han et al. (2018) did. Instead, I looked for a single LED with a wide enough emitting angle for my purposes, similar to Chen et al. (2014). Additionally, the success of IR LED-based communication, albeit at short ranges, was the reason I decided to include IR in my experimental design.

c. Light Receivers

Light receivers vary in type, shape, sensitivity, and arrangement. The type of receiver can be a camera, photomultiplier tube, photodiode, phototransistor, or LED (Klaver & Zuniga, 2015). Both Chen et al. (2014) and Han et al. (2018) used photomultiplier tubes (PMT) as their receiver. While the PMT offered increased sensitivity and quick response times, it required voltage stability to avoid current changes (Chen et al., 2014). A complementary metal-oxide semiconductor (CMOS) camera was also used as a light receiver (Akram et al., 2017). In another experiment, Chow et al. (2015) successfully implemented a mobile phone camera as the receiver. While cameras have high pixel counts, they often have a low frame rate, which affects achievable data rates (Akram et al., 2017). Another receiver option is to use the same LEDs as used in the transmitter. Light impulses transmitted to an LED that is off can generate a small current (Klaver & Zuniga, 2015). In systems where this is used, one LED can serve as the transmitter and receiver, but not at the same time (Klaver & Zuniga, 2015).

Photodiode and phototransistors are other options that are very sensitive to light and relatively inexpensive (Schweber, 2018). Rus (2010), Cossu et al. (2018), and Wu et al. (2017) used a variety of photodiodes (PD). Klaver and Zuniga (2015) chose the PD for “higher sensitivity, the less complex circuitry required, and the ability to provide full duplex communication” (p. 236). By using the PDs in an array, they were able to receive signals from a larger field of view (Klaver & Zuniga, 2015). PDs create a current flow when absorbing light (Schweber, 2018). Phototransistors act similarly to conventional transistors that are activated by photons pinging the device (Schweber, 2018). Although PDs can be more sensitive than phototransistors, PDs require more complicated schematics due to very low output signal levels (Schweber, 2018).

The significance of this research is in the successful implementation of PD and the use of an array of receivers. While there are many types of light receivers, I chose cost-effective equipment with the least complicated schematics. My prototype will implement the idea of a receiver array from Klaver and Zuniga (2015). However, while none of the aforementioned studies used phototransistors, I will implement them in my experimental design to compare results with others that used photodiodes.

2. Modulation Techniques

For underwater VLC, a variety of modulation techniques have been used (Ndjiongue & Ferreira, 2018). Optical power and bandwidth efficiency are the primary considerations to select a modulation type (Ndjiongue & Ferreira, 2018). For LEDs and LDs the modulated bandwidth is related to the output power (Han et al., 2018). For a high-powered LED and LD, the modulation bandwidths are typically 10 MHz and 100 MHz, respectively (Han et al., 2018).

Some of the most common techniques are binary schemes and Orthogonal Frequency Division Multiplexing (OFDM) variations (Ndjiongue & Ferreira, 2018). Binary schemes include On-Off Keying (OOK) and Pulse-Position Modulation (PPM) (Ndjiongue & Ferreira, 2018). Chen et al. (2014) chose PPM for “relatively low average power and high peak power, high SNR ratio, and high safety” (p.262). PPM requires synchronization between transmit and receiving systems (Chen et al., 2014). On-Off Keying (OOK) is a form of amplitude modulation, and it is much simpler than frequency modulation techniques (Klaver & Zuniga, 2015). Klaver and Zuniga (2015) and Han et al. (2018) both chose to implement OOK for simplicity, good average performance, and less-expensive hardware components.

There has been significant research conducted to increase the modulation bandwidth by implementing more complicated modulation techniques such as quadrature amplitude modulation (QAM), OFDM, and pulse amplitude momentum (PAM) (Han et al., 2018). Wu et al. (2017) used a 16-QAM OFDM scheme and achieved data rates in the Gbps. However, unstable communication links would drastically increase the bit error rate (BER) and require extensive positioning and tracking algorithms to maintain link establishment (Han et al., 2018).

For the reasons selected by Klaver and Zuniga (2015) and Han et al. (2019), I chose to implement OOK as the form of modulation in my prototype. Although other modulation schemes have achieved higher modulation bandwidths, the simplicity of OOK meets the needs of my experiment.

3. Experiment Designs and Results

Prior underwater VLC experimentation has occurred in a variety of settings. Because the environmental factors have a significant effect on the achievable data rates and range, it is worth highlighting these considerations. The experiment settings included simulated environments, lab testing, clear water, and seawater. In the discussion that follows, I will note particular experiments that informed my own research design.

Table 4 gives a spectrum of results and parameters used in comparable experimentation. While some research was conducted in simulated and clear water environments, four of the experiments were conducted in seawater. Of those, the maximum communication range achieved was 10.2 meters (Wu et al., 2017). However, in the tests completed by Wu et al. (2017), a LD was used as the light source in a temperature controlled water tank with a perfectly aligned photodiode receiver (Wu et al., 2017). Of experiments that used a single LED in ocean water, Rus (2010) achieved a range of 2 meters. Furthermore, Cossu et al. (2018) was able to achieve a greater range of 10 meters in seawater using an array of seven blue LEDs and an avalanche PD.

Table 4. Comparison of VLC Experimentation

	Purpose	Tx Light Source	Tx Light Color	Modulation	Rx Source	Max Range	Max Data Rate	Experiment Parameters	Additional Information
(Akram et al., 2017)	Subsurface to Surface VLC	Array of 15 LEDs in triangle formation	Red, Blue, and Green	OOK	Camera with 30 fps	1m	100 bps	Clear water	Data rates suffered from difficulties distinguishing individiual LEDs at greater distances
(Klaver & Zuniga, 2015)	Free Space Optical VLC	Array of 20 LEDs	White	OOK	Array of PDs	1m	1 Kbps	Free Space	Not for underwater use. Tx provides 360 degree coverage
(Rus, 2010)	Short Range Underwater VLC	Single 5W LED	Blue (470nm) and Green (530nm)	DPIM	Single cost-effective PD	2m	1.2 Mbps	Ocean Water	Tested at depth of 4m and visibility of 3m. Blue and Green LEDs were tested
(Rus, 2010)	Long Range Underwater VLC	Array of 6 5W LEDs in circular arrangement	Blue (470nm)	DPIM	Avalanche PD	8m	600 Kbps	Ocean Water	Test conducted at depth of 4m and visibility at 3m
(Han et al., 2018)	Semi-omni directional underwater VLC	Array of 7 LEDs in circular arrangement	Blue	OOK	Single PMT	8m	19 Mbps	Clear Water	Developed freeform lens to broaded divergence angle up to 150 degrees
(Cossu et al., 2018)	Ethernet-based Underwater VLC	Array of 7 LEDs	Blue (470nm)	Manchester-coded	Avalanche PD	10m	10 Mbps	Ocean Water	Tested at depth of 1m. Transmitted videos and images
(Wu et al., 2017)	High-speed UVLC	Single LD	Blue (450nm)	16-QAM OFDM	p-i-n PD	10.2m	7.2 Gbps at 6.8m	Saltwater in tank	Achieved 12.4 Gbps at 1.7m in clear water
(Chen et al., 2014)	Diver Communications	Single 10W LED	Blue-Green	PPM	Single PMT	20m	300 Kbps	Simulated with Matlab	Includes voice compression algorithms

Achievable data rates varied due to equipment selection, communication range, power, and environmental factors. For experiments that included the use of LEDs and photodiodes, the maximum data rates ranged from 1 Kbps (Klaver & Zuniga, 2015) to 10 Mbps (Cossu et al., 2018). For the purposes of my prototype, the most comparable experiment considerations are from Klaver and Zuniga (2015). Although their experiment was not conducted underwater, the use of LEDs, array of photodiodes, and OOK modulation most closely match my selected design parameters.

Although Han et al. (2018) conducted experimentation in clear water, their testing set-up otherwise resembled my requirements. Figure 15 is representative of a tank in which a transmitter and receiver are submerged and spaced eight meters apart (Han et al., 2018). At a depth of 2 meters, the system achieved a baud rate of 19 Mbps at night in clear water (Han et al., 2018). Additionally, the transmitter achieved a divergence angle of 150 degrees (Han et al., 2018).

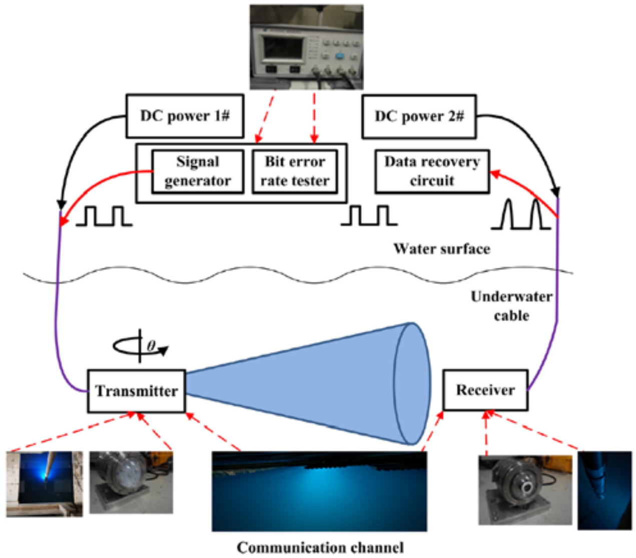

Figure 15. Experiment Design with Transmitter and Receiver Submerged. Source: Han et al. (2018)

While some research used LEDs and others used photodiodes, none of the experiments considered the use of a single LED with an array of phototransistors to achieve a cost effective, high bandwidth, and short-range VLC link in ocean water. Additionally, the use of 100 Watt LEDs, similar to bright diving flashlights, was not previously considered. I sought to address this gap when designing my methodology and VLC prototype.

III. METHODOLOGY

A. PHASE 0: DESIGN

Phase 0 involves the design of the prototype's hardware and software components. In order to select the proper equipment, I compared viable options to ensure the right attributes were selected for experimentation. Because current VLC technology on the market is proprietary, I was unable to alter any existing system to fit my research purposes.

1. Select Hardware

As stated previously, existing VLC systems on the market could not be altered to the degree required for my research. I needed a system that would allow for tests with multiple light sources, adjustable data rates, and alterable schematics for incorporating an array of sensors. Decisions regarding hardware selection were based on prior research, familiarity, availability, and cost. Some of the hardware selections were based on successful results in studies and experimentation outlined in my literature review. If not found in prior research, I selected hardware I was familiar with or was readily available. I determined that the required hardware components included two computing systems, at least one light source, at least one light receiver, and two power sources.

a. Computer Selection

An ideal underwater communication system would typically use small and powerful computers, such as a Raspberry Pi 3, to send and receive messages while submerged. The Raspberry Pi 3 is a highly capable computer with 1 gigabyte of random-access memory (RAM) and 40 general-purpose input/output (GPIO) pins that fits on a board size of 85mm x 56mm (Raspberry Pi Foundation, n.d.). However, for ease of testing and data collection, I chose a traditional laptop to be used in the transmitting system. The keyboard and display allow the user to send messages from the command line and alter the transmitting baud rate. While this laptop remained above water, a cable connected it to the submerged transmitting system. In a fully capable VLC system, the transmitting and receiving nodes could each be operated with a Raspberry Pi as long as a method is in place to input text while submerged. This could be achieved by programming pre-set command buttons, using speech to text technology, or implementing graphical user interfaces.

The prototyped receiving system used a Raspberry Pi 3, shown in Figure 16, that was selected based on availability, familiarity, size, and capabilities. The compact size allows the computer to fit inside the waterproof container. The keyboard and display are not a requirement in this receiving system. Instead, the system vocalized the received message through the speaker system after converting text to speech.

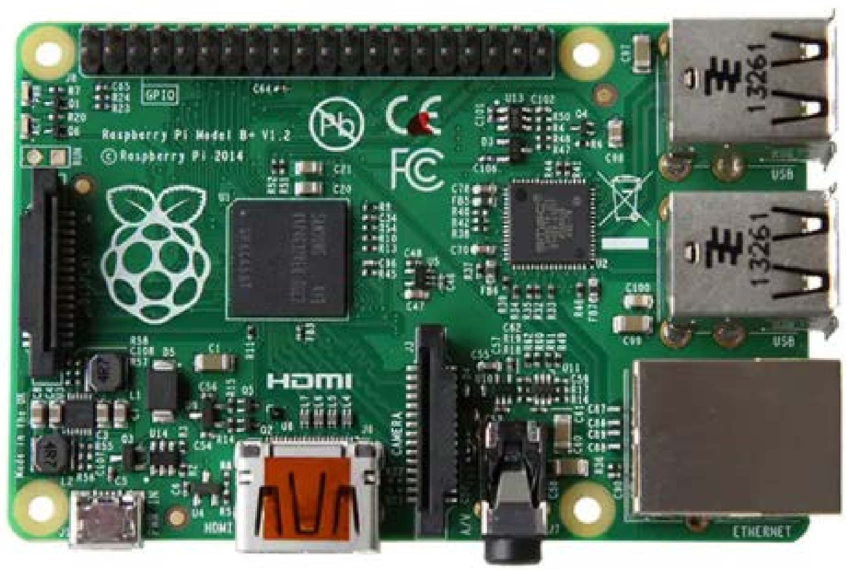

Figure 16. Raspberry Pi 3. Source: Raspberry Pi Foundation (n.d.).

b. Light Source

As discussed in Chapter II, LEDs have the potential to outperform lasers in the underwater environment in terms of power and cost efficiencies (Xu et al., 2016). Specifically, blue and green-colored LEDs have proven to be the most effective visible light wavelength in terms of effective underwater ranges (Sticklus et al., 2019). As an optical consideration for stealth in covert operations, I also wanted to test effectiveness of infrared LEDs in addition to the visible spectrum. Different strength, shape, and colored LEDs were considered and tested.

Initial tests using a red, green, and blue (RGB) LED from sensor kit made by Elegoo were conducted to determine the best modulation format. This LED was effective in proving capable data rates using either Morse Code or Recommended Standard 232 (RS-232) at a very close range of less than one centimeter.

Once the modulation format was selected, we purchased royal blue, green, and infrared 10-Watt LEDs for lab testing. The royal blue LED operates in the 440–445 nm wavelength, the green LED operates in the 520–525 nm wavelength, and the infrared LED operates at 940 nm wavelength as seen in Table 5 (Chanzon, n.d.). All three LED types are advertised to have a 120–140 degree emitting angle and have an estimated lifespan of 50,000 hours (Chanzon, n.d.).

Table 5. 10W LEDs Characteristics. Adapted from Chanzon (n.d.).

Power	**Color**	**Color Temp. Wavelength**	**Forward Voltage**	**Forward Current**	**Luminous Flux**
10W	Green	520-525nm	8-10V	840-1000mA	600-800 LM
	Royal Blue	440-445nm	9-11V	840-1000mA	90-100 LM
	IR	940nm	4.5-5.5V	840-1000mA	n/a

Due to the wide emitting angle, the prototype did not need as many LEDs in an array as previously believed. Using just one LED, we were able to turn the transmitter more than 70 degrees away from the receiver and still transmit the message. The ability to rotate the transmitter more than 70 degrees laterally to the left and right equated to nearly 150-degree emitting angle. With the transmitter and receiver aimed toward one another, the VLC prototype was able to communicate up to 11 meters apart through the air.

Following initial bench tests and the development of a LED driver, we purchased 100 Watt LEDs in the same colors—royal blue, green, and infrared, as displayed in Table 6. With higher-powered LEDs, we aimed to increase the communication range between transmitter and receiver. The blue and green 100 Watt LEDs were selected for follow-on experimentation. An example of this light source is displayed in Figure 17. Because the IR

100 Watt LED produced significant heat, we opted to use the IR 10 Watt LED instead (Chanzon, n.d.).

Table 6. 100W LED Characteristics. Adapted from Chanzon (n.d.).

Power	**Color**	**Color Temp. Wavelength**	**Forward Voltage**	**Forward Current**	**Luminous Flux**
100W	Green	520-525nm	30-34V	2800-3500mA	7000-8000 LM
	Royal Blue	440-445nm	30-34V	2800-3500mA	3000-4000 LM
	IR	940nm	20-22V	2800-3500mA	n/a

Figure 17. 100W LED Chip. Source: Chanzon (n.d.).

c. Light Receiver

In conjunction with the RGB LED found in the Elegoo Sensor Kit, we used a small phototransistor that came with it to complete the initial tests for the Raspberry Pi 3 modulation test. While the test confirmed basic functionality, the LED and phototransistor could only be spaced a few millimeters apart to send messages. The phototransistor in the kit had very low sensitivity and was too small for use in follow-on testing.

Next, we purchased 5mm IR and ambient light phototransistors. We chose phototransistors over more sensitive photodiodes due to their higher output signal (Schweber, 2018). Because a photodiode's output signal is very low, the schematics become more complicated (Schweber, 2018). The phototransistor allows for a more simplified configuration that still serves the purpose for the prototype.

While royal blue and green LEDs operate at 445nm and 525nm respectively, the phototransistor covers a larger range of wavelengths. While the phototransistor has peak sensitivity at 570nm, it still recognizes the light pulses throughout the blue, green, and infrared wavelength range.

We selected phototransistors with a rounded top rather than a flat top. The curved glass on the transistor is an optical lens that focuses the light directly on the sensor. This allows for increased sensitivity compared to the flat top transistor.

d. Power Source

The initial power source for the laptop and Raspberry Pi 3 allowed the systems to be plugged into the wall outlet. However, transitioning to underwater tests would require a portable and chargeable battery that would fit into the waterproof container. We obtained sufficiently small, but powerful batteries.

From Figure 18, the yellow battery was used in the receiving system. However, in order to use the DC-DC converter with the Raspberry Pi 3, we had to adjust the voltage from 7.4 Volts to 5 Volts. The other is a 12-Volt battery used within the transmitter. Although not depicted in Figure 18, we also used a step-up DC-DC converter insider the transmitter to achieve the 48 Volts needed to power the 100-Watt LED.

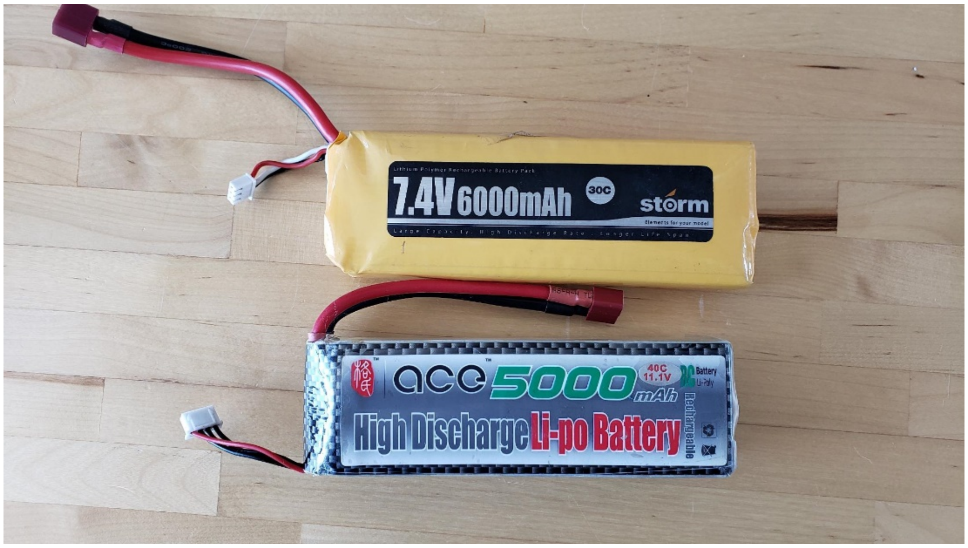

Figure 18. Transmitter and Receiver Batteries

e. Speaker

In order to test the ability to read the text message aloud to a diver, an audio device needed to be included in the receiving system. An ideal system may include an audio device inserted into a diver's ear, but for proof-of-concept, we opted for a battery-powered speaker that would remain above the water. The speaker, seen in Figure 19, was connected via an audio cable to the waterproofed box. This confirmed that the light-based message was received properly and understandable.

Figure 19. Speaker for Audio Output

Step 1 was complete upon selecting and function testing all necessary components for testing the basic concept. Through various iterations of testing, some components were modified to meet required specifications.

2. Develop Code

In order to have complete control and edit-ability of the VLC system, it was critical to develop code to operate with the selected hardware. Because testing the system was an iterative process, having the freedom to manipulate the code was essential to test functionality at each phase. The transmitting code had to convert text into pulses of light. The receiving code needed to receive light pulses as input, convert to text, and subsequently vocalize the message via text-to-speech software. Within the overarching function of the code, there were many sub-functions that needed to create in order to enable communication.

To develop the code for the optical communication system, we designed two initial prototypes using Morse Code and RS-232 to translate text messages into light pulses.

a. Morse Code

For the Morse Code version, we created a Python library that equated individual characters to a series of long and short light bursts. The receiving system timed the length of each light burst in order to convert the light to text messages. To initiate or end message transmissions, specific combinations of initial and final characters were sent. To test the code, we used a sensor kit from Elegoo that included a white LED and phototransistor. In this preliminary testing, the LED and phototransistor were nearly touching on a circuit board. The Morse Code chart in Figure 20 demonstrates how characters are translated to dots and dashes (Phillips, n.d.).

Prosign		Morse
<AA>	New line	.-.-
<AR>	End of message	.-.-.
<AS>	Wait	.-...
<BK>	Break	-...-.-
<BT>	New paragraph	-...-
<CL>	Going off the air ("clear")	-.-..-..
<CT>	Start copying	-.-.-
<DO>	Change to wabun code	-..---
<KN>	Invite a specific station to transmit	-.--.
<SK>	End of transmission	...-.-
<SN>	Understood (also VE)	...-.
<SOS>	Distress message	...---...

Letter	Morse
A	.-
B	-...
C	-.-.
D	-..
E	.
F	..-.
G	--.
H	....
I	..
J	.---
K	-.-
L	.-..
M	--

Letter	Morse
N	-.
O	---
P	.--.
Q	--.-
R	.-.
S	...
T	-
U	..-
V	...-
W	.--
X	-..-
Y	-.--
Z	--..

Digit	Morse
0	-----
1	.----
2	..---
3	...--
4	....-
5	.....
6	-....
7	--...
8	---..
9	----.

Figure 20. International Morse Code. Source: Phillips (n.d.).

To convert the Morse Code to light pulses, each dot and dash represented specific amounts of time in which the LED was illuminated. Spaces between letters and words converted to separate time periods where no light is transmitted. In order to recognize a new message being sent, we wrote code to amend the original message with starting and ending symbols. The beginning of each message includes <CT> or Start Copying, and the end has <AR> or End of Message that can be seen in Figure 20 and the following example:

Intended message: CT HELLO WORLD AR

Morse Code: -.-.- …. . .-.. .-.. --- .-- --- .-. .-.. -.. .-.-.

Using Morse Code as the conversion from text to light meant each letter would vary in transmit time. Some alphanumeric characters, such as <E> or <T> required just one pulse of light, whereas others such as <0> through <9>, required five pulses.

Initial tests with Morse Code resulted in successful transmission and receipt up to data rates of 400 bps. As we increased the data rate, more errors occurred. If an error occurred during the initial or final characters of the message, the prototype could not translate the message. If an error occurred within the text message, individual letters or words would be altered in the converted message.

b. RS-232

Each computer operating system includes a communication port library with Recommended Standard 232 (RS-232) protocol (Buchanan, 2000). This protocol converts American Standard Code for Information Interchange (ASCII) characters to the RS-232 data stream with a specified baud rate (Buchanan, 2000). The prototyped transmitting system uses the existing library, specifies the baud rate, and sends the entered text to the assigned communication port. The LED driver attached to this port amplifies the current and modulates the light.

RS-232 protocol has parity check in each sending byte, but no error correction (Buchanan, 2000). In order to drop corrupted messages, we added a parity check on the receiving side. In future experimentation, a short confirmation message indicating message failure can be added when developing two-way communication.

c. Text to Speech Software

The purpose of Text to Speech (TTS) software in this prototype was to convert the received light impulses to audio so that a combat diver could hear the message upon receipt. Although this prototype used a speaker box as a proof-of-concept, an ideal version of the system would vocalize the message through an ear bud or underwater headset. This hands-free approach prevents the diver from having to stop performing a task in order to read a message from a display screen. For applications of the system without a human end user such as an unmanned underwater vehicle, the TTS software could be disabled.

While there are advanced TTS software available, most require internet connection to have access to a wider database of pronunciations and voice inflections. The TTS we chose is more rudimentary but could be downloaded onto the Raspberry Pi 3 for offline access. With the intent of the prototyped system to operate underwater between two isolated nodes, internet connection will not be available. While future iterations of the system may connect into existing networks, this proof-of-concept required self-sustainability to translate text to speech. The selection software, known as eSpeak, was a free, downloadable option. Although the software's voice sounds robotic, it sufficed for our purposes.

d. Observations

Initially, I chose Morse Code as the modulation type because it appeared to be the most efficient method to send messages. The more common letters would require fewer pulses of light, thus making the total message transmit time shorter. However, the varying length of time for each character made translation difficult. In order to recognize the end of a character and the beginning of a new character, a rest-time needed to be implemented, slowing the overall data rate. These factors affected the leading edge of the signal. To reduce errors, it is necessary to have a clean, nearly vertical leading edge of a signal. However, the observed leading edge of the signal using the LED and photodiode from Elegoo kit was rounded, making it difficult to accurately translate the light signals to text at the desired baud rates. The curved, rather than straight, edge indicated that either the initial LED was not bright enough or photodiode was not sensitive enough for the purposes of this research. For these reasons, subsequent prototypes used higher power LEDs and more sensitive receivers. Additionally, RS-232 was chosen as the modulation type for its faster achievable baud rates and ease of use. As RS-232 libraries already existed on the computer's operating system, it was relatively simple to implement. Phase 0 was complete upon selecting RS-232 as the protocol for the VLC system and eSpeak as the TTS software.

B. PHASE 1: BUILD SYSTEM

Once all necessary components and software were on hand, the next step was to assemble the underwater VLC system. We built multiple versions of transmitters and receivers from scratch before settling on the arrangement that went into the waterproof boxes.

1. Build Transmitter

The transmitter receives the RS-232 protocol from the laptop's communication port. The pair of T1P41C and T1P42C transistors are used as a push pull cascade. The rapid current switching between power wire wound resistors amplifies the current required to power the 100-Watt LED in conjunction with the +48 Volt step up DC-DC converter. Figure 21 also depicts multiple types of transistors. The transistors labeled T1, T2, and T3 represent NPN bipolar junction transistors. The transistor labeled T4 is a PNP bipolar junction transistor. These elements work together to form the LED driver required to power the bright, 100-Watt LED.

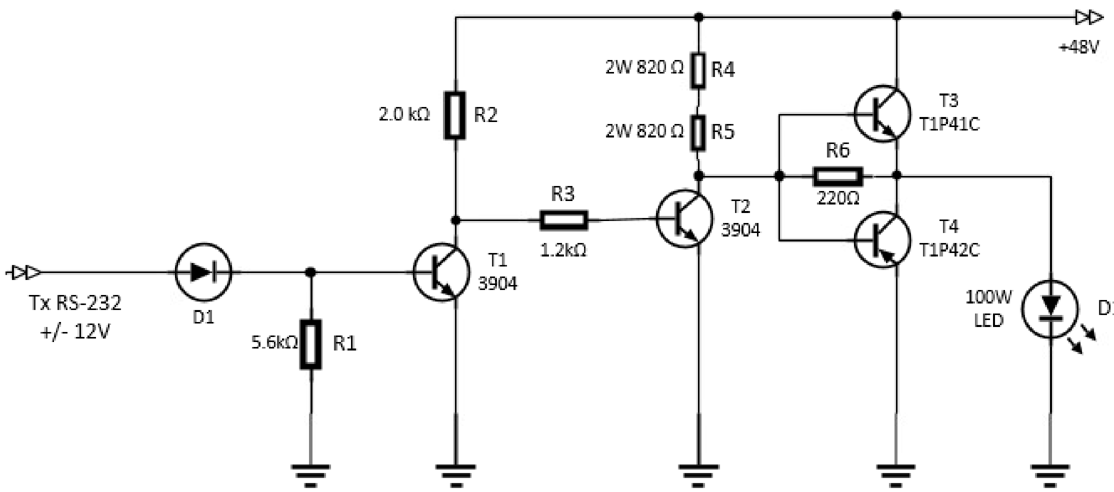

Figure 21. 100-Watt LED Transmitter Prototype Schematic

2. Build Receiver

The receiver was constructed to capture transmitted light pulses, convert to ASCII symbols, and recite the text message using TTS software. As represented in Figure 22, an array of seven phototransistors (T1 through T7) is used to capture the RS-232 light pulses. R1, C1, and R2 work together to convert the input to sharp positive and negative spikes. Next, the signal is sent to the LM358N operational amplifier. LM358N has a pair of amplifiers and is composed of eight pins. Positive signal spikes are sent through pin 5, and negative signal spikes are sent through pin 2. The signals at pin 1 and 7 are amplified, positive impulses. From LM358N, the signals are routed to the CD4011BE component. This piece is made up of four NAND logic gates and has 14 pins. The NAND logic gates allow the impulses to be converted to TTL level RS-232 data representing ASCII symbols. The text is subsequently sent to the TTS software and heard through the speaker system. The LED on the receiver schematics diagram is added for visual confirmation of message receipt in experimentation.

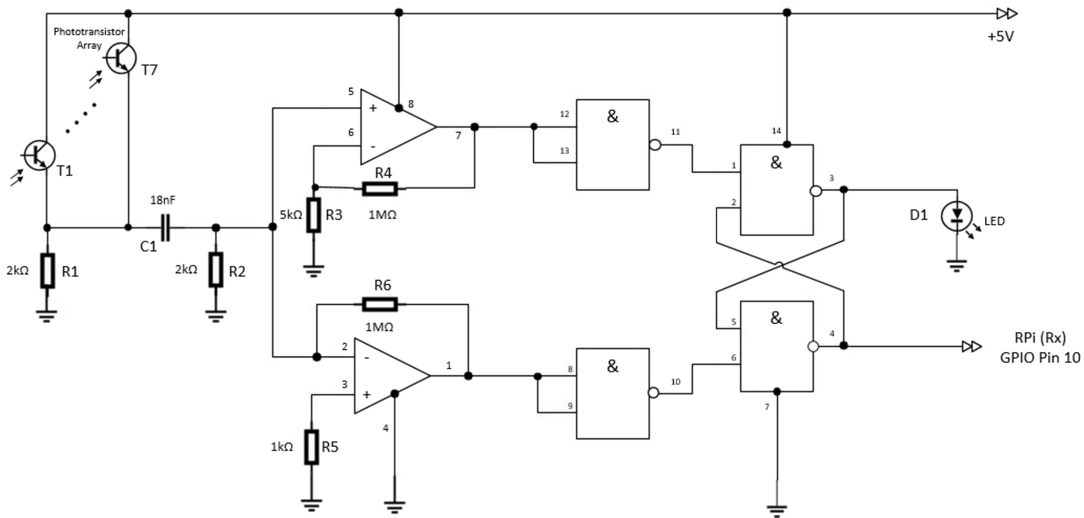

Figure 22. Phototransistor Array Receiver Prototype Schematic

3. Determine Ambient Light Threshold

We designed the system to amplify the signals to rise above the noise level. In this case, the noise is also known as ambient light. Through trial and error, the ambient light threshold was set at 1.5 Volts.

C. PHASE 2: LAB TESTING

Before waterproofing the VLC system, it was imperative to conduct bench tests in the lab. This was an iterative process that allowed us to control external variables, record data, analyze immediately, and make necessary adjustments prior to submerging in water.

To set up for initial lab testing, we placed the transmitting white light LED and phototransistor one meter apart. Both ends were angled toward each other and on an even plane. We first used a 9600 baud rate to establish communication by repetitively sending the character <1>. Upon receipt of the signal, the light message was translated to text, and the eSpeak software vocalized the text through the attached speaker system. Next, we tested 57600 baud rate using the same equipment and range. In both tests, we also used a flashlight to test the communication system’s ability to filter out bright ambient light.

Using an operational amplifier, we observed results for though-the-air lab tests. Figure 23 depicts a 9600 baud rate which corresponds to approximately 0.125 seconds per bit of data. Figure 24 depicts a 57600 baud rate which corresponds to about 0.025 seconds per bit of data. Both tests involved repetitive sending of the character <1>. The yellow line is a signal immediately after differentiator capacitor, and the cyan line is a transistor to transistor logic (TTL) RS-232 signal going to Raspberry Pi 3 serial port. The input signal was very weak at about 50 millivolts, but the optical parametric amplifier (OPA) amplifies the signal to the TTL level. Next, the digital gate microchip enables the sharp signal fronts. The sharper the signal front, the fewer errors in decoding signal. As seen in Figure 23, the impulses at the 9600 baud rate have very sharp fronts and decay curves. The speed increase at 57600 baud rate causes the fronts and decay curves shown in Figure 24 to be less sharp. However, using the bright flashlight near the phototransistor did not have any effect on receipt of the message. This verified that the system's design was insensitive to background light variations.

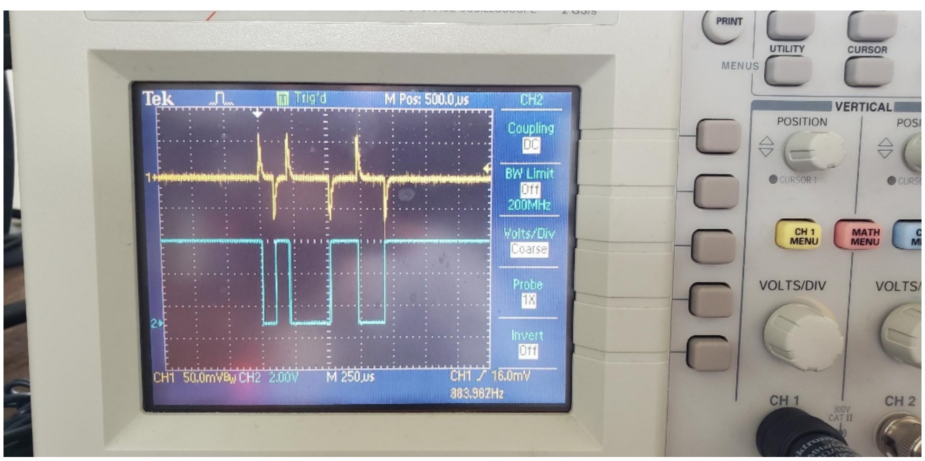

Figure 23. 9600 Baud Rate

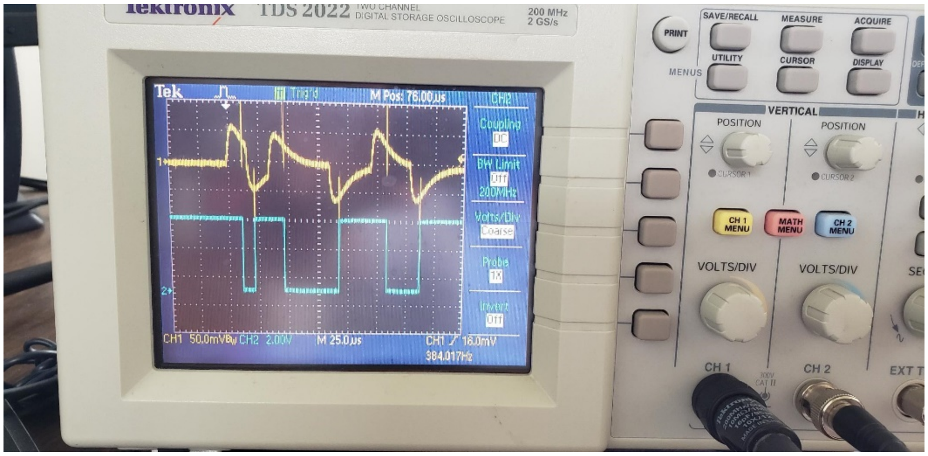

Figure 24. 57600 Baud Rate

D. PHASE 3: DISCOVERY EXPERIMENT

Aligning the transmitting and receiving system in the lab environment was much easier than aligning them underwater. In the lab, both systems can be set on tables or tripods and maintain constant communication. In the underwater environment, numerous external variables entered the equation. Between the sun reflections, water currents, and self-propelling forces, it was difficult to establish and maintain a narrow beam communication link. Prior to this phase, the transmitting system used one LED and the receiving system used one phototransistor. As a result, the receiver only received messages within a narrow 15-degree field of view. Additionally, the receiver and transmitter needed to be at a near-even height. While this prototype worked in a stationary context, it would not support the mobility required for divers. To enable a wider field of view and allow for variation in divers' presentation, we decided to develop an array of phototransistors.

1. Develop Phototransistor Array

We began developing a phototransistor array by sketching an arced prototype with overlapping field of views, as seen in Figure 25. Each phototransistor had an approximately 15-degree field of view. By overlapping the coverage areas of seven phototransistors, we sought to achieve nearly a 75-degree field of view.

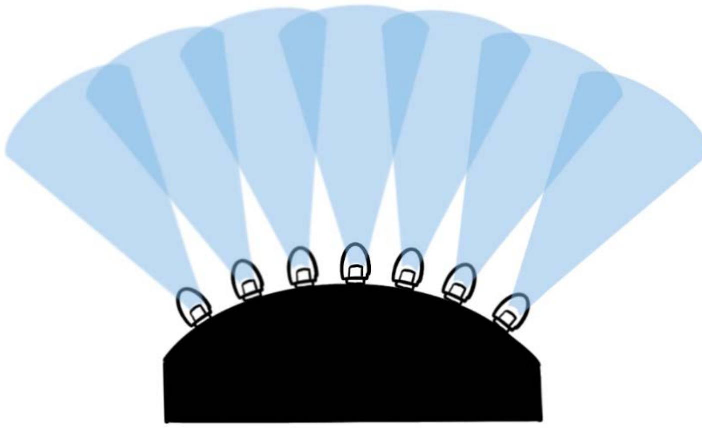

Figure 25. Drawing of Developed Phototransistor Array

From the initial concept, we used a 3D printer to design the arc for the phototransistor array. Because the arc needed to be fastened to the waterproof container and close to the clear, plastic window facing in the container, we designed a platform to attach the arc to the container. The 3D printed platform needed to fit inside the waterproof container and have two holes that aligned with the container's openings for screw fastenings. Additionally, we needed to have the ability to interchange 3D printed arcs to test different fields of view.

The final 3D printed platform had a right triangle base that fit into the corner of the waterproof container, as seen in Figure 26. This allowed the battery to fit within the container diagonally, and not obstruct the field of view of the phototransistor array. Two pegs were added to the top of the platform's schematics. These pegs fit into two openings on the arc prototypes and allowed multiple arc variations to be tested without repetitive 3D printing of the platform. The seven phototransistors were manually arranged and attached to a flexible circuit board. The board was subsequently attached to the 3D printed arc, as visible in Figure 27. The complete waterproofed transmitter and receiver systems are shown in Figure 28.

Figure 26. 3D Printed Platform for Arced Phototransistor Array

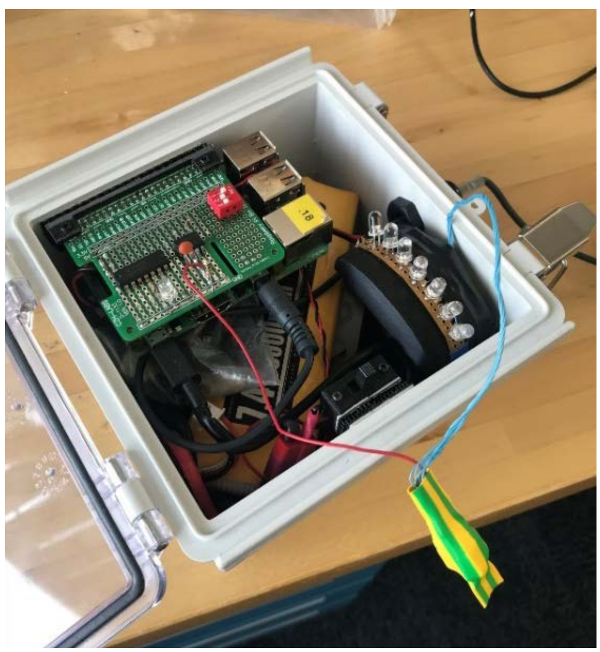

Figure 27. Inside VLC Receiver

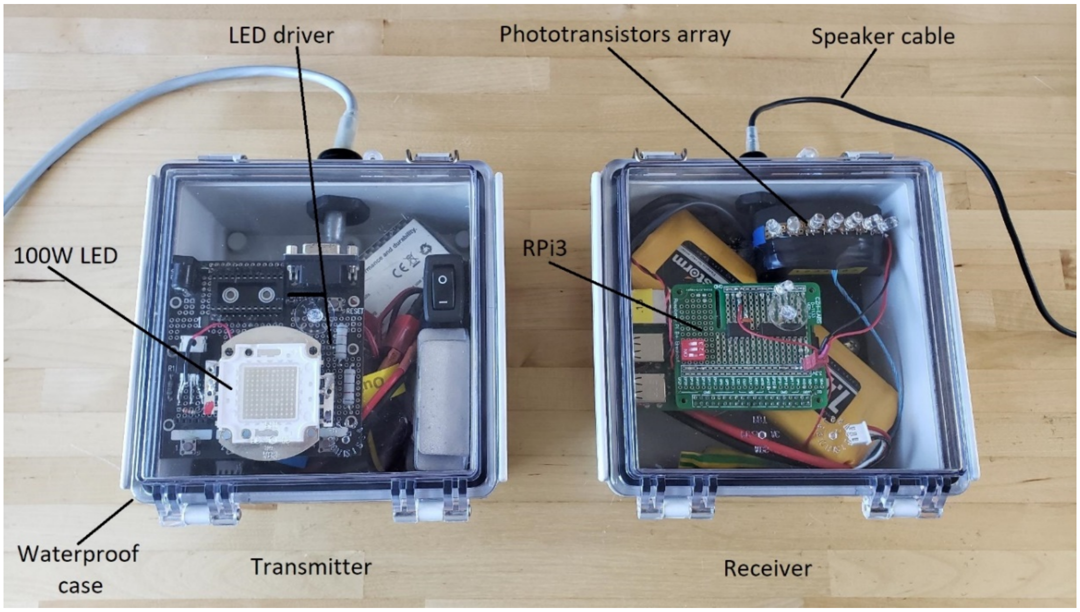

Figure 28. Waterproofed VLC Transmitter and Receiver Systems

As we prepared to conduct clear water testing, it was discovered that quickly waving our arms in front of the receiver registered as an on / off bit. Since sunlight reflects differently in water, it was necessary to re-configure the setup to be less sensitive to changes in ambient light. To prevent interference, we wrapped black tape around sides of individual phototransistors in the receiver.

2. Conduct Clear Water Test

The clear water test was designed to test functionality in ideal water conditions before further tests in the ocean.

a. Actions

Prior to submerging the transmitter and receiver, we added a lubricant around the container's seals to ensure water would not enter the system. We placed the transmitter in the water and watched for bubbles rising to the surface. This would signal water was entering the container. While no bubbles rose to the surface, the transmitter was not heavy enough to sink to the bottom of the pool. To combat the buoyancy of the system, we attached heavy metal weights to the base of the containers with Velcro.

In this test, we used the blue and green 100-Watt LEDs in the Halligan Hall clear water tank at Naval Postgraduate School. The tank measured 4 meters by 6 meters, with a diagonal range of 7.2 meters. The water was 2 meters deep and at room temperature. In this experiment, I tested the blue and green LEDs at 4800 bps and 9600 bps. The receiver and transmitter were lowered to the tank floor and aimed toward each other along the 4 meter edge of the pool. For the second test, I moved the receiver to the opposite corner of the pool to test the range of 7.2 meters.

b. Observations

The clear water tests demonstrated that the prototype VLC system was able send messages, receive them, and recite the message legibly through a speaker. At ranges of 4 and 7.2 meters, initial testing messages were successfully transmitted and received. To gather more data, additional tests were observed at the maximum available tank range of 7.2 meters. These results are found in Table 7. Using a baud rate of 4800 symbols per second, we transmitted a message with 1000 characters. Because each character represents eight bits, the total message size was 8,000 bits. The flash sequence length took 1.67 seconds to transmit the message. On the receiving end, the 1000 character message took 67 seconds to recite aloud. This corresponds to approximately 40 seconds of speech to 1 second of flash sequence.

Next, the baud rate was increased to 9600 symbols per second. Using a longer paragraph of 1500 characters, or 12,000 bits, the message was transmitted via a flash sequence of 1.25 seconds. The recitation of the message took 88 seconds. At this data rate, about 70 seconds of speech can be transmitted in 1 second of light flashes. While these observations were captured using the 100-Watt blue LED, the green LED was able to achieve the same range of 7.2 meters at 4800 and 9600-baud rates. Images of the transmitter using the green LED are shown in Figure 29.

Table 7. Clear Water Observations at Range of 7.2 meters

	4800 baud rate	**9600 baud rate**
Message size	1000 characters (8,000 bits)	1500 characters (12,000 bits)
Flash length	1.67 seconds	1.25 seconds
Message reading	67 seconds	88 seconds
Ratio of flash/character	1 sec / 600 characters	1 sec / 1200 characters
Ratio of flash/speech	~1 sec / 40 sec	~1 sec / 70 sec

With the systems submerged, we experimented rotating the transmitter and receiver away from each other to test the fields of view. The transmitter was able to be turned more than 50 degrees to the left and right to send messages to the stationary receiver. With a stationary transmitter, the receiver was only able to be turned approximately 30 degrees in either direction and still receive messages. While these tests revealed the limits in lateral movements, relative depth differences affected communication. The phototransistor array within the receiver needed to be closely aligned with the plane of the transmitter to enable communication. Depth alignment could be guaranteed when the transmitter and receiver were placed on the tank floor.

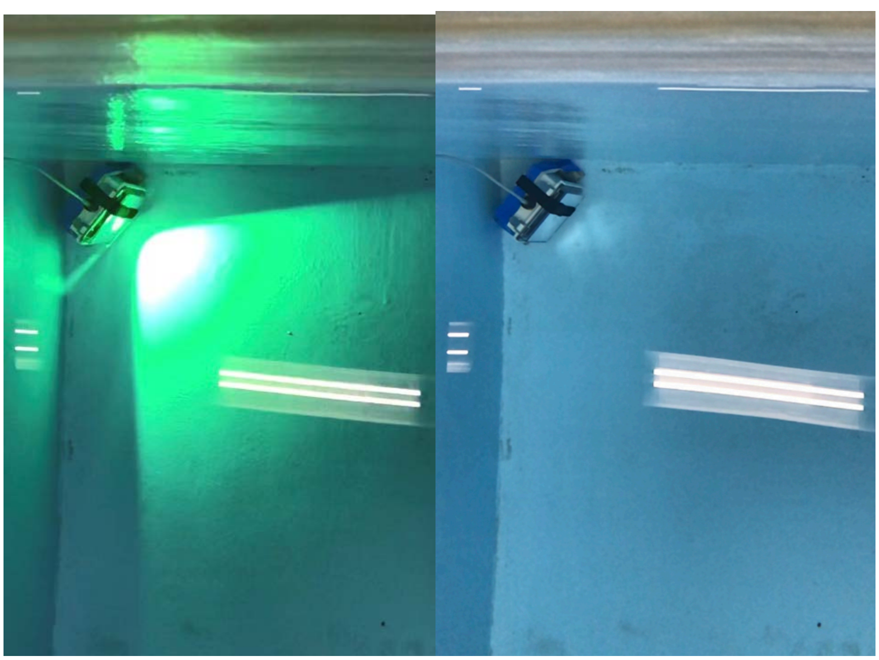

Figure 29. VLC Transmitter Operating in Clear Water

3. Design Modifications

While the aforementioned phototransistor array increased the lateral field of view, it had little impact in the ability to communicate at varying depths. We sought to improve the vertical field of view by implementing new hardware into the receiving system. Redesigning the system with a directional sensor or new phototransistor array would theoretically decrease the alignment requirements of the previous array used in the clear water tests.

a. Dragonfly Directional Sensor

To increase the vertical field of view, we expanded our original idea from designing an array with multiple phototransistors to bending the light to reach a single phototransistor. We began looking for optics that could filter a wide angle into a narrow beam. The Dragonfly Directional Sensor, originally developed to detect incoming missiles for United States Army Helicopters, advertised a 140 degree field of view (Geary et al., 2013). The Dragonfly optic taper, seen in Figure 30, was designed and produced by Schott North America, and consisted of an array of more than 2.8 million optical fibers (Geary et al., 2013). Because it was designed to recognize bright lights against a dark background, we believed it may be possible to integrate into our prototype (Geary et al., 2013).

After completing a limited purpose cooperative research and development agreement (LP-CRADA), we experimented with the Dragonfly optic. By applying this taper in front of a single phototransistor, we hoped to achieve a greater field of view than with the previously-designed phototransistor arrays.

Upon implementation, we found that the taper focused incoming light to less than a 1 mm diameter. Additionally, the observation angle was not as wide as expected. In lab tests, we achieved an angle of 40 degrees. While this taper might be more effective with other light receiving sensors or in different configurations, it did not achieve a wide enough observation angle for our purposes.

Typical Taper Specifications	
Glass Type	SCHOTT 24 Glass
Element Size (µm)	6, 10, 18, 25
Numerical Aperture – small end	1.0
Stray Light Control (EMA)	Available with or without EMA
Coefficient of thermal expansion (x 10 exp -7 / °C)	68

Figure 30. SCHOTT Dragonfly Directional Sensor. Source: Geary et al. (2013)

b. *Second Phototransistor Array*

After being unable to achieve a sufficiently wide field of view, we returned to the original phototransistor array idea. While the first array successfully received messages in ranges greater than 7 meters, the field of view was vertically constrained. Additionally, manually soldering seven photodiodes onto a flexible circuit board added complexity and risked human error. We addressed these limitations by developing a new array using different phototransistors.

For the new receiver array, we selected phototransistors with a wider field of view. The phototransistors (APTD3216P3C-P22), seen in Figure 31, have flat tops that act as strong lenses to focus the incoming light. From initial lab tests, the new phototransistor has a receiving angle of 60 degrees. To achieve a near 180-degree field of view, we used an array of three phototransistors.

Figure 31. Array of Three Flat Phototransistors Attached to Arced Platform

The new phototransistor array successfully increased the receiving angles. In lab tests, we received data within 120 degrees horizontally and 90 degrees vertically. Compared to the previous ambient light phototransistor, the new phototransistor has more than 3 times the vertical field of view. However, it is half as sensitive and reduced the communication range to 4 meters in through-the-air testing. Upon attempts to amplify the signal, the receiver became too sensitive to ambient light.

To compare and contrast the original and new phototransistor arrays, we implemented both arrays into the VLC receiver prototype. With the addition of a manual switch, future experiments could change between Array 1 and Array 2. Phase 3 was complete upon finalizing the second phototransistor array.

E. PHASE 4: ADVANCED FIELD TESTING

Experiments conducted in clear water generated results in ideal conditions. In order to test the feasibility of using light links in the operational environment, it was necessary to test the prototype in seawater. The experiments conducted in this phase tested the achievable baud rates, fields of view, and ranges for six combinations of transmitter and receiver variables. Using three different colored LEDs and two separate phototransistor arrays, I designed tests to isolate individual variables.

1. Select Location

The location for advanced field-testing was primarily based on access and water depth. With close proximity to the Monterey Bay, the body of water met our requirements. However, because the prototype used a laptop and speaker, it was not feasible to have two divers test the system in the open ocean. To more easily emplace experimental controls, we used a pier with access to relatively deep water. This allowed the transmitter and receiver to be lowered into the water while keeping the non-waterproof equipment dry. Additionally, the pier provided a stable platform to take measurements on depth and range. The experiment was conducted on a sunny afternoon as indicated by Figure 32. The water was clear, and wildlife such as fish, kelp, and sea lions were visible from the surface.

Figure 32. View from Monterey Bay Coast Guard Pier

2. Preparing Equipment

The transmitting and receiving system were each enclosed in a waterproof container with a cable connecting the system to the above-water laptop and speaker, respectively. While the cable was long enough to lower the system into the water from the pier, it did not adequately provide the ability to point and aim the systems. To mitigate this issue, each system was fastened to a 2 inch diameter, 10 foot long PVC pipe with Velcro. As shown in Figure 33, the cables were run along the side of each pipe. Additionally, tape measures were attached to each pipe to measure the depth of each system. Because the transmitter and receiver were inherently buoyant, a 3.5-pound metal weight was attached to the base of each system, similar to the clear water experiment. A tape measure was positioned to capture the communication range between the transmitter and receiver, once submerged in the water.

Figure 33. VLC Transmitter and Receiver Attached to PVC Pipes

3. Determine Testing Categories

With three light sources and two receiver arrays acting as variables, there were six possible combinations. These six variations, seen in Table 8, were the testing categories. Figure 34 shows the receiver and transmitter prototypes before testing. By capturing specific data with each variable combination, we could more accurately determine the most successful VLC system within our parameters.

Table 8. Seawater Testing Categories

Transmitter	Receiver
Blue 100W LED	Array of 7 Phototransistors
Blue 100W LED	Array of 3 Phototransistors
Green 100W LED	Array of 7 Phototransistors
Green 100W LED	Array of 3 Phototransistors
Infrared 10W LED	Array of 7 Phototransistors
Infrared 10W LED	Array of 3 Phototransistors

Figure 34. Receiver (left) and Transmitter (right) Prototype

Using each variation, we conducted three tests to capture the maximum data rates and communication ranges under different alignments. The vertical alignment was based on depth, and horizontal alignment was based on pointing angle from center. Communication was deemed effective if the message was read aloud coherently. The message length, unless otherwise stated, was standard amongst all tests using 43 characters including spaces. This translated to 43 bytes or 344 bits of data.

a. Test 1: Vertical and Horizontal Alignment

The set up for the first test involved vertical and horizontal alignment. In this scenario, the transmitter and receiver were at an even depth and aimed towards each other. Two data points were captured in this test including the maximum communication ranges using baud rates of 4800 and 9600. An example of this test can be seen in Figure 35.

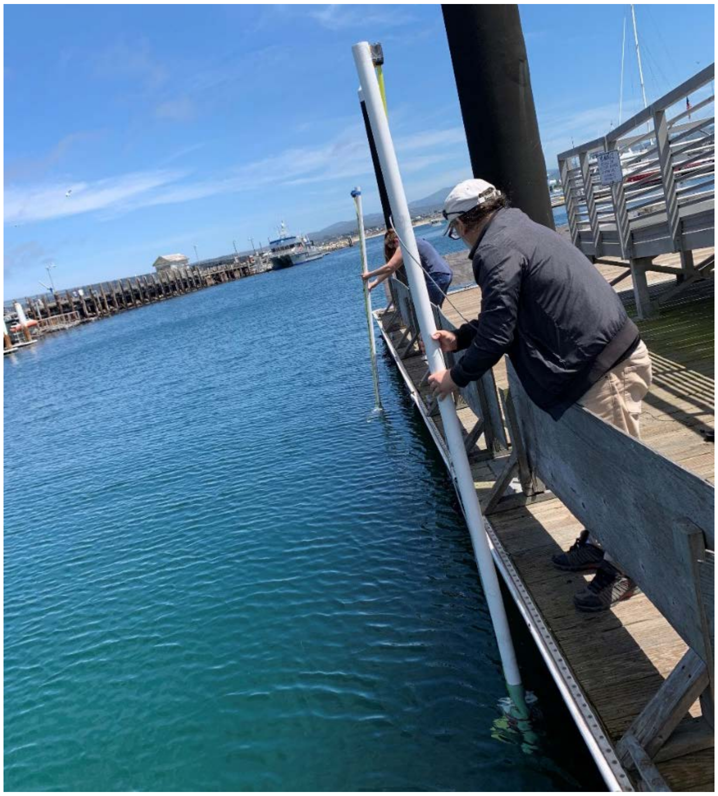

Figure 35. Maximum Communication Range Test

b. Test 2: Vertically Aligned, Horizontally Misaligned

For the second test, the transmitter and receiver maintained the same depth but the horizontal alignment was skewed. In this iteration, the baud rate was set at 4800 and the communication range was 2 meters. This test captured the maximum angle of deviation from center in which communication was still possible. First, while the receiver remained aimed at center, the transmitter was rotated away from center in five-degree increments until communication was no longer possible. This angle, multiplied by two, provided the transmission angle. Next, while the transmitter was aimed at center, the receiver was rotated away in five-degree increments until communication was no longer possible. An example of this is shown in Figure 36. By doubling this angle, we determined the receiver's field of view.

Figure 36. Testing Skewed Lateral Alignment

c. *Test 3: Vertically Misaligned, Horizontally Aligned*

In the third test, the transmitter and receiver were aligned horizontally, but at varying depths. Similar to the second test, the baud rate remained at 4800 and the devices will had a horizontal range of 2 meters. First, the transmitter was lowered in six-inch increments while the receiver remained in place, until communication was no longer possible. The same movement was conducted using the receiver while the transmitter was stationary. Figure 37 depicts the transmitter slowly being lowered to test vertical alignment deviations. This set of tests captured the allowable height deviations between transmitter and receivers.

Figure 37. Vertical Alignment Deviation Tests

4. Observations

The observations from the ocean experiments are shown in Table 9. For ease of identification, Array 1 refers to the original, seven-phototransistor array and Array 2 refers to the newer, three-phototransistor array. As noted in Table 9, Array 2 became ineffective during testing. Upon switching from Array 1 to Array 2 during experimentation with the green LED, Array 2 became overly sensitive to ambient light and failed to receive light pulses even at close ranges above the water. As a result, Array 2 was not used for testing with green and IR LEDs.

Comparing results from the blue and green LEDs using Array 1, the blue LED was able to achieve slightly farther communication ranges. However, the deviation angles and depths were identical for both colors when the transmitter and receiver were spaced two meters apart. With the limited results from Array 2, a comparison of tests with the blue LED indicates slightly longer communication ranges for Array 1 and marginally wider deviation angles for Array 2. The differences in these arrays are not as drastic as the initial results from lab tests.

Seawater tests using the 10W IR LED were successful at very close ranges. Using one-tenth of the power as the 100W blue and green LEDs, the IR tests achieved a communication range of 0.3 meters. Very little vertical or horizontal deviation was possible to reliably receive the transmitted message. This was likely the result of the lower powered LEDs, wavelength propagation in water, and the reduced sensitivity for IR frequencies in the phototransistors. The phototransistors used were more sensitive for blue and green wavelengths as they are closer to the sensor’s 570 nm peak wavelength. The results of these tests were collected using tape measures and visual observations. The measurements may be subject to human error in estimations.

Table 9. Seawater Observations

	Blue LED / Array 1	Blue LED / Array 2	Green LED / Array 1	Green LED / Array 2*	IR LED / Array 1	IR LED / Array 2*	Notes
Test 1: Vertically and Horizontally Aligned							
Max range (4800 baud rate)	6.2m	6.0m	5.6m		0.3m		Depth: 2ft
Max range (9600 baud rate)	4.3m	4.0m	4.2m		0.3m		
Test 2: Vertically Aligned, Horizontally Misaligned							
Max deviation angle (Tx)	~35°	~40°	~35°		<5°		Baud Rate: 4800
Max deviation angle (Rx)	~20°	~25°	~20°		<5°		
Test 3: Vertically Misaligned, Horizontally Aligned							
Max depth deviation (Tx)	2.5ft	2.5ft	2.5ft		<6”		Baud Rate: 4800
Max depth deviation (Rx)	1.5ft	1.75ft	1.5ft		<6”		

*During testing, Array 2 became ineffective. As a result, only Array 1 was used for the Green and IR LEDs

IV. ANALYSIS

This chapter analyzes the results of Chapter III in the context of the research questions and assesses the feasibility of establishing an underwater LED-based VLC link based on technical and environmental factors.

The primary research objective was to develop an underwater LED-based VLC link to pass message data between submerged nodes. In the parameters of our experiment, we defined a successful transfer of information as the correct narration of the intended message through the outputting speaker. Additionally, in the context of diver-to-diver communication, we determined a nominal improvement in the communication range to be greater than three meters. Furthermore, the LED-based VLC link needed to enable mobility through minimizing the requirement for precision alignment between underwater nodes. These three criteria help determine the practicability for employment in a tactical scenario.

A. IMPACT OF TECHNICAL FACTORS

The technical factors include the light spectrum, power output, and fields of view.

1. Light Spectrum

The 100-Watt blue and green LED tests were successful in meeting the aforementioned requirements. Using a data rate of 4.8 Kbps, blue and green LED transmitters were able to transfer information to the receiver at maximum ranges of 6.2 and 5.6 meters, respectively. Assuming an average word length of five letters, this data rate corresponds to approximately 120 words sent in a one-second sequence of light pulses. At a higher data rate of 9.6 Kbps, the blue and green LEDs transferred data at ranges of 4.3 and 4.2 meters, respectively. While the achievable communication range was shortened, the doubled data rate corresponds to approximately 240 words transmitted in the same one-second sequence of light pulses. These speeds are appropriate for file transfers and text messages.

The 10-Watt infrared LED was not successful in reaching a communication range of three meters at either the 4.8 or 9.6 Kbps data rate. With a limited range of approximately

12 inches, the infrared LED was only useable for near-touch communication. Moreover, the tests involving horizontal and vertical deviations displayed a very small range of working angles. Although these results did not meet the criterion for success, it is noteworthy that the infrared LED was able to communicate even at short ranges. With one-tenth the power of the 100-Watt blue and green LEDs and phototransistors designed to detect blue and green light, there is significant room for improvement in the development of a functioning infrared communication system.

While LED-based optical communication systems have the potential to operate at data rates exceeding one megabit per second, the data rates observed in this thesis are not conducive for video or image transfer. Many high-resolution images consist of 300 pixels per inch. A high-quality image measuring four by six inches equates to 2,160,000 pixels. A data rate of 9.6 Kbps can transfer 1200 bytes or 400 RGB pixels per second. Consequently, it would take nearly 90 minutes of light pulses to transfer the image. While not tested in this research, a data rate of 1 Mbps would allow the same image to be transferred in approximately 50 seconds.

2. Power Output

To answer the research question 2a, our initial expectation was that higher-powered LEDs would achieve further communication ranges than comparable experiments using less powerful LEDs. As many experiments noted in the literature review used LEDs less than 10-Watts, we aimed to exceed their underwater ranges by using brighter, 100-Watt LEDs. However, the observed ranges in our experiments were similar to other experiments shown in Table 4. Despite the bright light source, we attribute these results to the limited sensitivity in our phototransistor array. In theory, a more efficient and less detectable system would employ less powerful LEDs and more sensitive light receivers to achieve the same communication ranges.

3. Fields of View

The experiments using blue and green LEDs displayed the ability to communicate when the transmitter and receiver were misaligned. Although our ocean testing did not consist of two divers using the prototype, the experiments modeled mobile nodes. With the transmitter and receiver each attached to the base of a pipe, the system proved able to communicate while in motion. The water caused a natural sway as the receiver's PVC pipe was walked away from the transmitter. Additionally, the results from Table 9 displayed the ability to communicate at significant angles of deviation. This simulated divers communicating with imperfect alignment of up to approximately 40 degrees away from center.

The developed phototransistor arrays in the VLC receiver were designed to receive light messages from a wide angle. In Array 1, seven phototransistors achieved a 70-degree field of view. Array 2, with three phototransistors, achieved an 80-degree field of view. The phototransistors used in Array 1 had a much narrower field of view than those used in Array 2. As a result, Array 1 required a larger quantity to achieve a similar angle. To answer research question 2(b), an omnidirectional field of view for Array 1 and 2 would require 36 and 14 phototransistors, respectively.

B. IMPACT OF ENVIRONMENTAL FACTORS

Various environmental factors impacted the use of underwater VLC. These factors include ambient light, the intrinsic fluidity of water, and the optical wavelength propagation underwater.

1. Ambient Light

While the system worked as expected in indoor lab environments, sunlight played a noteworthy factor in our ocean water experimentation. Prior to submerging the VLC system into the water, direct sunlight blinded the receiver. The receiver array of phototransistors could not differentiate between the ambient sunlight and the transmitter's LED light pulses. To mitigate this, the receiver array functionality was tested in the shade before lowering the system into the water.

Once in the water, ambient light appeared to have a less significant effect on the system. If sunlight hindered the system's ability to receive messages underwater, data transfers at deeper and darker depths would likely have longer communication ranges. However, identical communication ranges were observed at two feet and five feet depths.

The implication for divers is that their communication ranges should not differ significantly within two meters of the water surface due to the effect of ambient light. As many dive missions exceed two meters depth, ambient light will have even lesser effects. Pointing the system towards the sun may degrade the ability to receive LED-based light pulses.

2. Propagation in Water

Ocean and coastal water affect the propagation of optical communication (Sticklus et al., 2019). In ocean water, blue light (450 nm) travelled the furthest (Sticklus et al., 2019). In coastal waters, green light (550 nm) exceeded the ranges of blue light (Sticklus et al., 2019). Infrared wavelengths have among the shortest propagation ranges (Sticklus et al., 2019).

From our experimentation, I found similar results. In the clear, ocean water of the Monterey Bay, blue light traveled approximately nine percent further than green light using a data rate of 4.8 Kbps and Array 1. Additionally, the blue light travelled two percent further using a data rate of 9.6 Kbps and Array 1. While the difference in range is relatively small, blue light LEDs appear to be the preferred choice to maximize ocean communication range. As expected, infrared wavelengths travelled the shortest range at an observed range of 0.3 meters.

The implication for divers is that LEDs can propagate sufficiently to be useful in coastal waters. However, the achievable communication range differs by only 0.6 meters between the color wavelengths in ocean water. An ideal system might incorporate both blue and green LEDs, and would allow the diver to select the LED color based on the mission's body of water.

3. Ocean Fluidity

The underwater environment causes constant motion and can make it difficult to align submerged transmitting and receiving nodes. However, there is a balance between using a highly direction communication system for emissions control and using an omnidirectional system for ease of use. The tested prototype is comprised of a single light emitter with an array of light receivers. It provided directional transmission, and allowed for semi-omnidirectional message receipt. While the observations in Table 9 demonstrate the ability to communicate when the nodes are skewed at angles up to 40 degrees, there is room for improvement in the design. A transmitter with a narrower beam width and an array with a wider field of view would increase emissions control and ease of use simultaneously.

The implication for divers is that LED-based VLC must compensate for ocean currents with a sufficient field of view. Compared to acoustic systems, LEDs offer a more directional transmitter. However, the wider beam width of the LED makes alignment easier. Compared to hand signals and acrylic writing slates, the receiving diver does not have to make eye contact to receive the message. The current prototype's phototransistor array allows for nearly an 80-degree field of view. Theoretically, if the field of view was expanded to 360-degree coverage, the second diver could receive messages from any direction.

C. PRACTICAL CONSIDERATIONS

In summary, LED-based VLC links appear to be feasible for communicating data between submerged, mobile nodes. Further practical considerations are addressed with respect to range, mobility, bandwidth, and cost.

1. Range

LED-based VLC shows promise to help divers communicate at up to 6.2 meters of separation. Although dependent on water conditions and line of sight, divers using blue and green LEDs would be able to send messages to other nodes at greater ranges than currently possible. Additionally, IR nearfield communication might be helpful when a diver must transmit to a buoy near the surface. Although a close range of 0.3 meters is required, the diver would not have to surface to send a message and could maintain stealth. This concept has the potential for broader implementation into relayed and hybrid networks. Although the light-based links provide short range communication, a network of submerged optical communication nodes can increase the total communication range.

2. Mobility

The schematics and emplacement of dozens of phototransistors can complicate the design and practicality of the system. For divers, the implication is that the multi-phototransistor array must not interfere with mobility or the performance of operations while still providing wide coverage. In theory, an omnidirectional array would be beneficial to surround the diver's body in order to receive from multiple angles. To achieve 360-degree coverage, the receiver array would need to expand outside of our waterproof box prototype. A phototransistor array attached to multiple places on a diver's wetsuit or fixed to belt around the diver's waist may be viable options to attain the desired coverage. Alignment between the transmitter and receiver must be maintained while the message is transmitting. At the data rates achieved, paragraph-long messages will require nodes to maintain alignment for less than one second.

Additionally, the ability to hear received light messages provided additional efficiency. While the prototype read the received messages aloud via an above-water speaker, this concept could be applied to a vocalize messages through a submerged diver's headset. This allows the diver to continue working while receiving messages instead of stopping operations to view a graphical user interface. Future implications could allow the transmitting diver to use speech-to-text software to scribe messages.

3. Bandwidth

Due to the large modulation bandwidth, optical communication has the potential to increase the speed and throughput of underwater communication. Compared to acoustic communication, LED-based links can provide greater throughput. For the purposes of our experimentation, we capped the maximum baud rate at 9.6 Kbps to maximize communication range. Compared to low data rate acoustic systems that provide data rates less than 1 Kbps, our VLC prototype offered greater throughput. However, data rates greater than 1 Mbps are required to effectively transfer images and video content.

The implication of the data rates tested in this thesis is that divers could transmit text messages rapidly. While hand-and-arm signals provide a finite number of potential messages, these directional transmissions provide more robust possibilities with low probabilities of interception. This allows divers the flexibility to elaborate on issues, change plans, and improvise if necessary.

4. Cost

Throughout the previous chapters, I allude to the potential inexpensive aspects of LED-based communication. Upon completion of prototype development and experimentation, the cost of each component was assessed to calculate an estimated cost of the proposed underwater VLC system. Table 10 depicts the price for each piece of hardware to total an estimated cost of $290. However, the calculation in Table 10 accounts for the use of two Raspberry Pi computers instead of the one laptop and one Raspberry Pi used in experimentation. While the proof-of-concept speaker system would not be utilized in a fully underwater system, it represents the potential costs associated with incorporating audio components. While this proof-of-concept is not ready for production or tactical use, the LED-based prototype is significantly less expensive than laser-based alternatives. While a high-powered laser can exceed $1,000, the 100-Watt blue LED cost only $54.

Table 10. VLC Prototype Component Cost

Component	**Estimated Cost**
2 x Raspberry Pi 3	$70.00
1 x 100-Watt LED	$54.00
2 x Batteries	$100.00
7 x Phototransistors	$1.00
2 x Waterproof Case	$30.00
Small Speaker	$25.00
General Electronic Components	$10.00
TOTAL	**$290.00**

While underwater VLC shows promise, additional research is needed to increase bandwidth and range. By using more focused LEDs, more sensitive light receivers, and alternate approaches to receiver array development, LED-based VLC systems have the potential to improve tactical underwater communication.

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V. CONCLUSION

This chapter includes the practical and theoretical significance of the developed VLC prototype as it applies to a tactical implementation in littoral operations. Additionally, I discuss the limitations of this research as well as potential areas for future work.

A. SUMMARY

This thesis explored a means to improve short-range underwater wireless communication through the employment of LED-based visible and infrared light links. While focusing on the communication between two divers, the prototype could enable a diver-to-UUV or a diver-to-surface communication option with a lower probability of detection or interception than acoustic methods.

Based on my research and experimentation, I conclude that our blue and green LED-based prototype offers a viable optical communication solution to meet the aforementioned goals. By conducting clear and ocean water tests, this technology demonstrated the potential to be employed in diver-to-diver scenarios with communication ranges reaching 6.2 and 4.3 meters at data rates of 4.8 and 9.6 Kbps, respectively. These ranges can enable divers to coordinate tasks, communicate changes, and convey complications within line of sight. The directionality and rapid transmission of light pulses provides a low risk of detection and interception. While acoustic communication provides a longer range, the LED-based prototype offers increased throughput. Additionally, it provides increased mobility for otherwise-tethered communication. Employing a phototransistor array enables more freedom of movement by decreasing alignment requirements between the transmitter and receiver. The beam width of the LED is wider than a laser, and further decreases the required orientation precision.

Near-field underwater communication is also possible using a 10-Watt infrared LED at a range of 0.3 meters with a data rate of 9.6 Kbps. At this range, divers could transmit critical data to another diver or to a surface buoy in support of covert operations where other methods are impractical, such as in shallow water or at night when VLC might be detectable from the surface.

The implications of these results can be applied to additional underwater node types and the inclusion of optical links into hybrid networks. Scenarios involving the combination of divers, UUVs, and headquarter units may each benefit from the use of LED-based underwater communication links. Specific applications include UUV-to-UUV links supporting underwater swarm research and submerged communication relays. The potential for hybrid networks using RF, acoustic, and optical links includes increased redundancy and the ability to maximize the strengths of each wireless medium.

The results demonstrate that a high-bandwidth, directional LED-based approach could extend the range of communication between submerged mobile nodes in open water.

B. LIMITATIONS

The observations and results of this thesis had environmental and technical limitations of note.

1. Environmental Limitations

In clear water experimentation, tests were conducted in an indoor, room-temperature tank with the overhead fluorescent lights illuminated. The transmitter and receiver rested on the floor of the tank and were not in motion during testing. The achieved clear water communication range of 7.2 meters was the maximum range of the tank and did not constitute the maximum capable range of the communication link.

For seawater experimentation, tests were conducted dockside on a sunny day in the Monterey Bay. The transmitter and receiver were submerged, and the laptop, speaker, and human operators remained on the dock. Because the entire system was not waterproof, the prototype was not tested with real divers. With limited exceptions, experiments were conducted at a depth of two feet into the water. The human operator approximated the observed deviation angles for the transmitter and receiver misalignment tests.

2. Technical Limitations

The tested VLC prototype only operates as a one-way means of transmission. The method of inputting a message required access to the command line on the laptop. A graphical user interface was not developed to input data while submerged. The prototype must be removed from the water to change the LED color, switch between receiver array types, and adjust the baud rate. The means to make these changes required the waterproof containers to be opened. Tests with the 10-Watt infrared LED used the same 570 nm phototransistors as the 100-Watt blue and green LEDs. Infrared phototransistors were not used.

C. FUTURE WORK

Once individual LED-based VLC links are established, a next step would be to integrate the optical links into hybrid tactical networks. By incorporating optical platforms into RF and acoustic networks, each of the three mediums might work together to optimize the benefits of each wireless technology. In order to extend the current research and integrate into hybrid networks, I suggest the following areas for future research:

- With ambient light having a noted effect on outdoor experimentation, conduct experiments during the day and night to evaluate and mitigate the impact.

- Experiment with photodiodes instead of phototransistors in the receiver array. This may allow for increased sensitivity and longer communication ranges.

- Conduct additional experimentation with the dragonfly taper. The idea of capturing light from a wide angle and focusing the light onto a single photodiode or phototransistor has the potential to simplify the receiver schematics.

- Develop a half-duplex or full-duplex solution to enable two-way communication. This would enable the message sender to obtain confirmation of message receipt from the receiver.

- Develop a graphical user interface for ease of use while divers are submerged.

- Develop a full-face mask in which divers can implement a speech-to-text capability.

- Conduct experimentation using the infrared LED and an array of infrared photodiodes or phototransistors for nighttime or covert operations.

- Design a hybrid optical-RF network experiment. By using an LED-based transmitter, a diver could send a message to an optical receiver on a buoy. The buoy would then demodulate the light, and relay the message through the air with RF waves.

- Design a hybrid optical-acoustic network experiment. Long-range acoustic pings could aid in the positioning and alignment of short-range, high-bandwidth optical communication links.

APPENDIX A. TRANSMITTER CODE

```
#!/usr/bin/python

# VLC Transmitter by Eugene Bourakov @ NPS, 2020
import serial, time
#initialization and open the port

#possible timeout values:
#    1. None: wait forever, block call
#    2. 0: non-blocking mode, return immediately
#    3. x, x is bigger than 0, float allowed, timeout block call

ser = serial.Serial()
ser.port = “COM1”
#ser.port = “/dev/ttyUSB0”
#ser.port = “/dev/ttyUSB7”
#ser.port = “/dev/ttyS2”
ser.baudrate = 2400
ser.bytesize = serial.EIGHTBITS #number of bits per bytes
ser.parity = serial.PARITY_NONE #set parity check: no parity
ser.stopbits = serial.STOPBITS_ONE #number of stop bits
#ser.timeout = None          #block read
ser.timeout = 0            #non-block read
#ser.timeout = 2              #timeout block read
ser.xonxoff = False     #disable software flow control
ser.rtscts = False     #disable hardware (RTS/CTS) flow control
ser.dsrdtr = False       #disable hardware (DSR/DTR) flow control
#ser.writeTimeout = 2     #timeout for write

print(“Set sending baudrate (1 - 2400, 2 - 4800, 3 - 9600, 4 - 19200)”)
br = input(“Baud rate: “)
ser.baudrate = 2400 * pow(2,int(br)-1)

doCycle = int(input(“Cyclic test? (1/0)”))
doTest = 0
if(doCycle) :
  singlebyte = input(“Send single byte? (1/0)”)
  print(“Single byte “ + singlebyte)
```

```
  if(singlebyte == “1”) :
     doTest = 1

print(ser.baudrate)

import signal

def keyboardInterruptHandler(signal, frame):
  print(“KeyboardInterrupt (ID: {}) has been caught. Cleaning up...”.format(signal))
  exit(0)

signal.signal(signal.SIGINT, keyboardInterruptHandler)

try:
ser.open()
except IOError:
  print(“error open serial port: “ + str(e))
  exit()

if ser.isOpen():
ser.close()
ser.open()
ser.isOpen()

print(“Port opened.”)

try:
ser.flushInput()
ser.flushOutput()

ser.write(“Ready\n”.encode())
print(“write data: Ready”)

time.sleep(0.5)  #give the serial port some time to receive  data

text=“     Attention! This is a light link test.”

while True:
text=“Attention! This is a light link test.”
if(doCycle == 0) :
```

```
 text=input("Enter text: ")
delay = 5
text += "\n"
if(doTest) :
text="1\n"
delay = 0.05
ser.write(text.encode())
time.sleep(delay)

except:
print("error communicating...: ")

else:
print("cannot open serial port ")
```

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APPENDIX B. RECEIVER CODE

```
#!/usr/bin/python

# VLC Receiver by Eugene Bourakov @ NPS, 2020
import serial, time
import subprocess
from gpiozero import Button

button22 = Button(22)
button23 = Button(23)
b1 = 0
b2 = 0
if button22.is_pressed:
  b1 = 1
if button23.is_pressed:
  b2 = 1
br = 2400 * pow(2,(b1 + b2*2))
print(br)
#initialization and open the port

#possible timeout values:
#    1. None: wait forever, block call
#    2. 0: non-blocking mode, return immediately
#    3. x, x is bigger than 0, float allowed, timeout block call

ser = serial.Serial()
#ser.port = “/dev/ttyUSB0”
#ser.port = “/dev/ttyUSB7”
ser.port = “/dev/ttyS0”
ser.baudrate = br
ser.bytesize = serial.EIGHTBITS #number of bits per bytes
ser.parity = serial.PARITY_NONE #set parity check: no parity
ser.stopbits = serial.STOPBITS_ONE #number of stop bits
#ser.timeout = None          #block read
ser.timeout = 0            #non-block read
#ser.timeout = 2              #timeout block read
ser.xonxoff = False     #disable software flow control
ser.rtscts = False     #disable hardware (RTS/CTS) flow control
```

```
ser.dsrdtr = False       #disable hardware (DSR/DTR) flow control
#ser.writeTimeout = 2     #timeout for write

try:
  ser.open()
except IOError:
  print("error open serial port: ")
  exit()

class ReadLine:
  def __init__(self, s):
      self.buf = bytearray()
      self.s = s

  def readline(self):
      i = self.buf.find(b"\n")
      if i >= 0:
          r = self.buf [:i+1]
          self.buf = self.buf [i+1:]
          return r
      while True:
          i = max(1, min(2048, self.s.in_waiting))
          data = self.s.read(i)
          i = data.find(b"\n")
          if i >= 0:
              r = self.buf + data [:i+1]
              self.buf [0:] = data [i+1:]
              return r
          else:
              self.buf.extend(data)

rl = ReadLine(ser)

if ser.isOpen():

  try:
      print("Ready")
      subprocess.call(["espeak," "-v," "en-us+m1," "-a200," "-s150," "-p45," "Ready to get
messages over the light link!"])
      cnt = 0
```

```
    while True:
      cnt += 1
      try:
        rxtext = rl.readline().decode("utf-8")
        print(str(cnt) + "  " + rxtext)
        subprocess.call(["espeak," "-v," "en-us+m1," "-a200," "-s150," "-p45," rxtext])

      except Exception:
        print("decoding error")
        pass

  except Exception:
    print("error communicating...: ")

else:
  print("cannot open serial port ")
```

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