NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

THE RAPID DEPLOYMENT OF LIGHT FIDELITY NETWORKING ON U.S. NAVY SHIPS

by

Stephanie Robinson

June 2020

Thesis Advisor:	Donald P. Brutzman
Co-Advisor:	Weilian Su

Approved for public release. Distribution is unlimited.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2020	**3. REPORT TYPE AND DATES COVERED** Master’s thesis

4. TITLE AND SUBTITLE THE RAPID DEPLOYMENT OF LIGHT FIDELITY NETWORKING ON U.S. NAVY SHIPS	**5. FUNDING NUMBERS** RFMMD; RFNA3
6. AUTHOR(S) Stephanie Robinson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) NAVWAR, San Diego, CA; NIWC, San Diego, CA	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Navy ships can utilize light fidelity networking technology to improve throughput and security. Current wireless communication technology is not suitable for deployed shipboard network environments because of the security risks that emissions create in operational environments. Light fidelity can mitigate risks while providing new channels for unclassified communication. Many factors pertain to the usability and effectiveness of shipboard design with this technology. There is demonstrated capability that the technology can be installed across all ship classes relatively quickly at an optimal cost. This thesis makes recommendations for installation and future requirements necessary to deploy on a shipboard network.

14. SUBJECT TERMS light fidelity, LiFi, shipboard communications, powerline communications, PLC, Power over Ethernet, PoE, ship networking, visible light communication, VLC	**15. NUMBER OF PAGES** 101
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THE RAPID DEPLOYMENT OF LIGHT FIDELITY NETWORKING ON U.S. NAVY SHIPS

Stephanie Robinson
Lieutenant, United States Navy
BS, Florida State University, 2013
BA, Florida State University, 2013

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN NETWORK OPERATIONS AND TECHNOLOGY

from the

NAVAL POSTGRADUATE SCHOOL
June 2020

Approved by: Donald P. Brutzman
Advisor

Weilian Su
Co-Advisor

Dan C. Boger
Chair, Department of Information Sciences

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Navy ships can utilize light fidelity networking technology to improve throughput and security. Current wireless communication technology is not suitable for deployed shipboard network environments because of the security risks that emissions create in operational environments. Light fidelity can mitigate risks while providing new channels for unclassified communication. Many factors pertain to the usability and effectiveness of shipboard design with this technology. There is demonstrated capability that the technology can be installed across all ship classes relatively quickly at an optimal cost. This thesis makes recommendations for installation and future requirements necessary to deploy on a shipboard network.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AO	Authorizing Official
AP	Access Point
ASIC	Application Specific Integrated Circuit
BPL	Broadband over Power Lines
C2C24	Combat to Compile in 24 Hours
CANES	Consolidation Afloat Network Enterprise System
CAP-WAP	Control And Provisioning of Wireless Access Points
CRADA	Cooperative Research Development Agreement
DC	Direct Current
DHCP	Dynamic Host Configuration Protocol
DODIN APL	Department of Defense Information Network Authorized Product List
EMCON	Emissions Control
EMI	Electromagnetic Interference
FOV	Field of View
Gbps	gigabits per second
Ghz	Gigahertz
GRE	Generic Routing Encapsulation
Hz	Hertz
IATO	Interim Authority to Operate
IATT	Interim Authorization to Test
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
JCIDS	Joint Capabilities and Development System
kbps	kilobits per second
LAN	Local Area Network
LED	light emitting diode
LiFi	Light Fidelity
LPD/LPI	Low Probability of Detection/Low Probability of Interception
OPSEC	Operational Security

OWC	Optical Wireless Communications
mbps	megabits per second
Nm	nanometer
NAVSEA	Naval Sea Systems Command
NOC	Network Operations Center
NOW	Network Optional Warfare
PPBE	Planning, Programming, Budgeting, and Execution
PC-LED	Phosphate Converted LED
PLC	Power Line Communications
PoE	Power over Ethernet
QoS	Quality of Service
QR	Quick Response
RGB-LED	Red Blue Green Light Emitting Diode
RF	Radio Frequency
RONJA	Reasonable Optical Near Joint Access
RMF	Risk Management Framework
STA	Station
SECNAV	Secretary of the Navy
SNMP	Secure Network Management Protocol
SOP	Standard Operating Procedure
SSID	Service set identifier
STIG	Security Technical Implementation Guides
TEMPEST	Telecommunications Electronics Materials Protected from Emanating Spurious Transmissions
UNB	Ultra Narrowband
UP-VLC	Ultra Parallel Visible Light Communication
VOIP	Voice over Internet Protocol
VLAN	Virtual Local Area Network
VLC	Visible Light Communication
WAP	Wireless Access Point
WBAN	Wireless Body Area Network
WiFi	Wireless Fidelity

ACKNOWLEDGMENTS

I am indebted to many for their help in the completion of this thesis. First and foremost, my thesis advisors, Dr. Don Brutzman and Dr. Weilian Su, for your expertise and guidance. To Captain Yokoyama and Dr. Michael August from Naval Information Warfare Center (NIWC), Pacific, for your generous research grant (document number N6600119WX00874 and NPS Job Order Number RFNA3) and time assisting my thesis development. To Captain Good for your invaluable knowledge and perspective from the surface warfare community. I also thank LT Dimitri Paspalaris for his collaboration and testing results that contributed to portions of this thesis.

This work was also funded in part by NAVWAR, NPS Job Order Number RFMMD.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. PROBLEM STATEMENT

The use of mobile devices for communications has evolved but shipboard networks are still based on desktop computers and applications. This prevents sailors deployed on ships from improving their work output and quality of life because ship networks do not support mobile devices. However, WiFi solutions are impractical because radio frequency (RF) emissions from WiFi access points pose serious security risks during deployments afloat. Emissions from traditional wireless communications reveal potentially sensitive information like ship location that harms operational security (OPSEC). Naval ships operate in environments that are increasingly contested spaces and ship networks are vulnerable to interception and other electronic warfare attacks from adversaries.

B. PURPOSE STATEMENT

LiFi's benefits of increased network speed and bandwidth, reliability, low latency, and security offer Navy tactical units a redundant communications infrastructure to current RF-dependent capabilities that aid operational success in information contested scenarios. LiFi capability on ships completely avoids attacks based on electromagnetic-vulnerabilities. LiFi also provides redundancy as an alternate networking path in case of a denied or degraded communication environment by creating a possible zero emission communications infrastructure. LiFi can facilitate the use of tablets or smart phones for time-consuming tasks like log-taking and preventative maintenance that are critical for warfighting readiness, reducing the record-keeping burden on sailors. Most of ship network traffic is unclassified or for official use only, so separating this traffic from classified traffic can also improve network efficiencies and provide more secure communications that can be segregated to support damage control, maintenance and other critical ship activities.

C. MOTIVATION FOR STUDY

The fleet currently does not have an enterprise solution for internal wireless networks that can meet security requirements while maintaining usability (Bennett, 2016).

Due to the length and refit requirements, adding cable or fiber is a major alteration that can take months or years. Alternatively for cabling changes aboard Navy ships, LiFi can use existing infrastructure and provide operational benefit at a lower cost. Standardization of light communications is essential for long-term stability, avoiding replacement contracts, and building contractor competitiveness in the acquisition process. Implementing LiFi across the fleet can enable sailors to fully utilize mobilize devices to accomplish their jobs. LiFi is a C4I capability that supports several SECNAV and National Defense Strategy policies: create a more resilient force, leverage academia and industry, balance performance and affordability, and maintain a competitive edge in a contested operational environment (Mattis, 2018). LiFi is a technology that addresses the urgency in protecting military networks.

D. RESEARCH QUESTIONS

1. Can LiFi communications reduce electromagnetic emissions to nearly zero or low enough to solve the security problems inherent in wireless communications?
2. What is the optimal configurating and usage of LED light emitters to ensure bandwidth requirements for applications are met?
3. How effective is LiFi communications in low-light settings and using infrared?
4. How effective is LiFi communications traversing the network through transformers and breakers and can any problems in the circuits be overcome?
5. How can industry products in a rapidly maturing standards arena be best adapted for rapid prototype shipboard deployment?
6. What are the best technical, procedural, and contracting metrics that need to be applied to rapidly initiate fleet WiFi rollout?

E. SCOPE OF RESEARCH

This thesis focuses on LiFi installation in a shipboard environment on U.S. Navy surface vessels on unclassified networks. The study also focuses on LiFi technology from PureLifi. Discussion of shipboard LiFi integration is limited to Ethernet cables and 120 V and 60 Hz power line systems.

F. ORGANIZATION OF THESIS

Chapter II discusses related work regarding Power over Ethernet (PoE), Powerline Communications (PLC), and other optical and networking research that has been proposed for Navy use. Chapter Three examines the component technologies of LiFi in greater detail and analyze applicability for shipboard use. Chapter Four proposes a strategy for deploying LiFi relatively quickly across the fleet. Chapter Five presents conclusions and recommendations for future work regarding light communications in tactical and operational environments.

THIS PAGE INTENTIONALLY LEFT BLANK

II. RELATED WORK

A. INTRODUCTION

Research proposing and testing LiFi networking architectures encompass several different communications mediums and is a specific example of Visible Light Communication (VLC). VLC has historical roots in the nineteenth century but technological advancements like LED lightbulbs have made VLC a viable option for computer communications in environments with RF limitations. Power Line Communications (PLC) and Power over Ethernet (PoE) are the most commonly proposed backhaul connections for VLC systems and have evolved over time to support greater data throughput. The benefits of LiFi are closely related to the objectives of Network Optional Warfare (NOW) more flexible operations at the tactical level while improving emissions security (EMCON). Previous thesis work has studied optical signaling applications for the Navy and the execution of the Navy's new concept of streamlining application upgrades for afloat networks called Combat to Compile in 24 Hours (C2C24).

B. POWER LINE COMMUNICATIONS (PLC)

1. Background

The use of powerlines for communications dates back to the 1920s and 1930s when utility companies developed ways to transmit information for remote metering and load balancing of the electric grids on the same cables producing power (Galli, Scaglione, & Wang, 2011). Development from the 1950s to the 1980s of ultra-narrowband (UNB) PLC provided unidirectional communication at ultralow frequencies with relatively low data rates of 100bps (Gorshe, Raghavan, Starr, & Galli, 2014). The development of Broadband over Power Line (BPL) in the 1990s increased the bandwidth capability of industrial systems and supported bidirectional communication on low voltage power lines. This created opportunities for "Smart Grid" technologies and as a backbone for networks carrying optical communication (Galli et al., 2011). BPL is able to support data rates up to 200 mbps in the 1.5–30 MHz frequency band (Venkatesulu, Hemasundar, Sreeja, Divya., Kumar, & Bhogendranadh, 2014). Current PLC technologies operate at frequencies up to

100Mhz and data rates as high as 500 mbps (Gorshe et al., 2014). Three widely used commercial products include Netgear's Powerline 2000, TP-link AV200 Powerline starter kit, and D-link Powerline AV2000.

Studies and research experiments have demonstrated varying degrees of success and applicability of using PLC for transmitting data. The use of PLC aboard Navy ships has been proposed in earlier research. Akkinikawe and Butler Perry proposed replacing existing fiber, Ethernet and wireless communications infrastructure with BPL utilizing the Shipboard Power System (SPS) (2009). Electronic power operates at 60Hz and 400Hz on a navy ship, which theoretically opens higher frequencies for communication (2009). Another study exploring shipboard use explored PLC channel capacity on a cruise ship: the study found low data error rates at lower frequencies, but interference from generators, transformers, and other emission sources hindered data transmission (Barmada, Bellanti, Raugi, & Tucci, 2010). Toshiko Komine and Masao Nakagawa are among the first researchers to propose a wiring solution for using existing power lines in office buildings as the backbone for local area networks (LANs) (2003). Figure 1 shows an example configuration for an office LAN using powerlines from their paper. Integrating PLC supporting 100 mbps bandwidth with LED light emitters provided high data rates to a room without requiring additional wire installation (Komine & Nakagawa, 2003). PLC has also been proposed for non-conventional applications like vehicular DC powerlines, but frequency constraints limit the achievable data rates (Granado, 2011). Network management applications have also been developed for PLC systems to improve network performance, including automating spectrum reuse and avoiding collisions (Atya, Sundaresan, Krishnamurthy, Khojastepour, & Rangarajan, 2015).

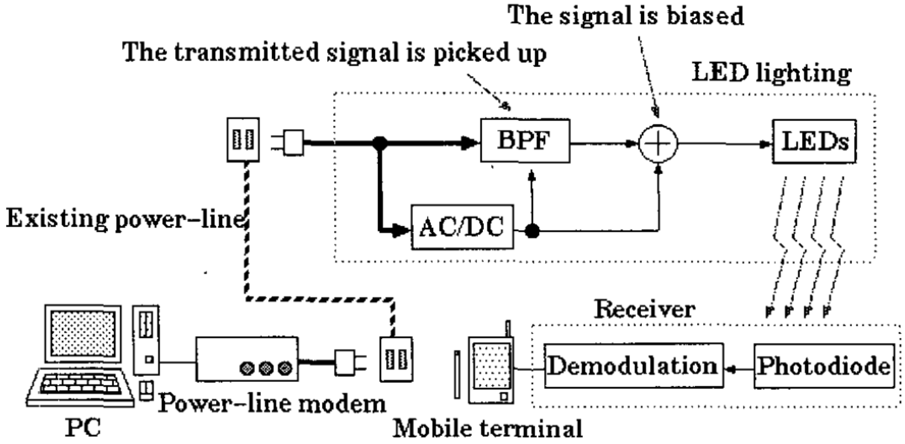


Figure 1. PLC connection in an office environment between a personal computer and a mobile phone. The plug is acting as the access point for the computer and the LED provides data for the phone. Source: Komine and Nakagawa (2003).

2. Current Applications

Several commercially viable PLC applications have been developed since the 1990s. The European Committee for Electrotechnical Standardization was the first organization to issue a standard for communications over low voltage power. Separate frequency bands were allocated for home use, alarm and security systems, and all other applications (Gorshe et al., 2014). Standards for home broadband networks like the HomePlug1.0 and the newer HomePlug AV 2.0 convert any electrical outlet into an access point (Papaioannou & Pavlidou, 2009). Several studies mention using PLC in indoor networking for connecting internet of things (IoT) devices, computer LANs, home automation, and access points that can mimic the performance of cellular networks (Gorshe et al., 2014; Ma, Lampe, & Hranilovic, 2013; Yousuf & El-Shafei, 2007). PLC is also used extensively in vehicle communications systems (Galli & Logvinov, 2008) Another study proposed using PLC as the backbone for a remote healthcare network that incorporated sensors and video links (Xi, Tao, & Fang, 2007). PLC has also been used for remote monitoring of appliances and meters, especially in the energy sector (Majumder & Caffery, 2004).

C. POWER OVER ETHERNET (POE)

A primary precursor to Ethernet was the development of the Aloha network, developed in Hawaii by Norman Abramson in 1970 (Walrend & Parekh, 2017). Several device nodes across the Hawaiian Islands were designed to send data packets to a single mainframe computer in Honolulu on frequency and receive an acknowledgement on a second frequency. The main problem with this network was that it created collisions between data packets when multiple packets were sent simultaneously as each node did not see data transmissions occurring between other nodes and the mainframe computer. A wired version of Ethernet was developed in the mid-1970s with multiple devices sharing the same Ethernet cable. This simple network had useful properties:

1) Carrier sensing: devices wait for the communication channel to be unused before transmitting data
2) Collison detection: devices stop transmitting data after a collision and wait a random amount of time before re-sending (Walrend & Parekh, 2017)

Hubs and switches were developed in the 1980s and improved the scalability of Ethernet networks. The first hub Ethernet network was called StarLAN: data travelled to a hub and then its signal was broadcasted to every device connected to a port in the hub (Walrend & Parekh, 2017). Switches refined this idea to allow specific data packets to travel to specific ports so that every device did not receive the data if it was not the intended recipient (Walrend &Parekh, 2017). Figure 2 illustrates an example of an Ethernet network connecting hubs and switches in a star topology.

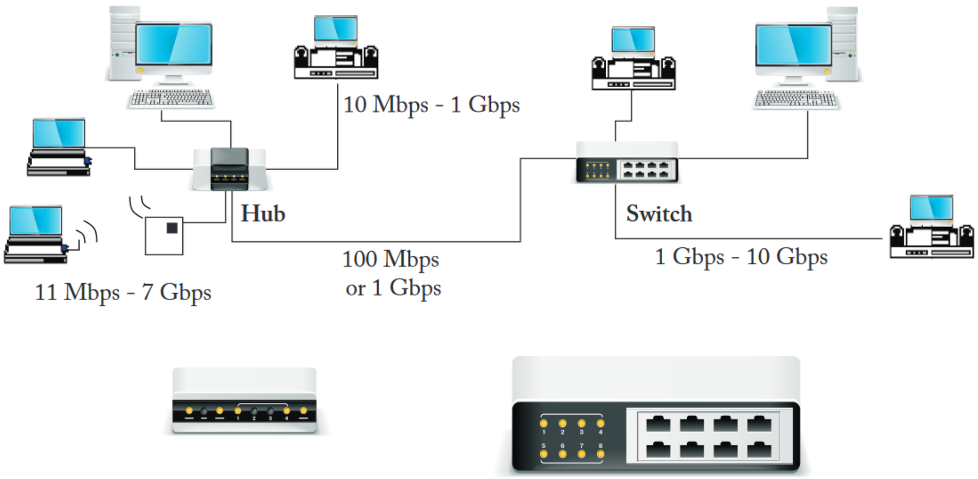


Figure 2. Example of an Ethernet network domain using Ethernet to connect a switch and hub in a star topology. Source: Walrend and Parekh (2017).

Power over Ethernet (PoE) emerged as a technology in 2003 that added further flexibility to Ethernet networks (Mendelson, 2004). An enabled switch was able to provide power in addition to data over an Ethernet cable to any connected device. This allows a network implementer to connect networked machines and add access points without having to build a separate power outlet and accompanying powerlines to a space. PoE supports technologies like Voice over IP (VOIP), video cameras, routers, small switches for devices sharing an uplink, intercom, access control systems, sensors, and LED lights (Chowdhury, Hossan, Islam, & Jang, 2018). Research has explored Ethernet as a backhaul for small cell networks where there is a high density of internet connected devices being used in indoor environments (Ni, Liu, Collings, & Wang, 2013). Figure 3 illustrates a wireless LAN configuration using a PoE switch.

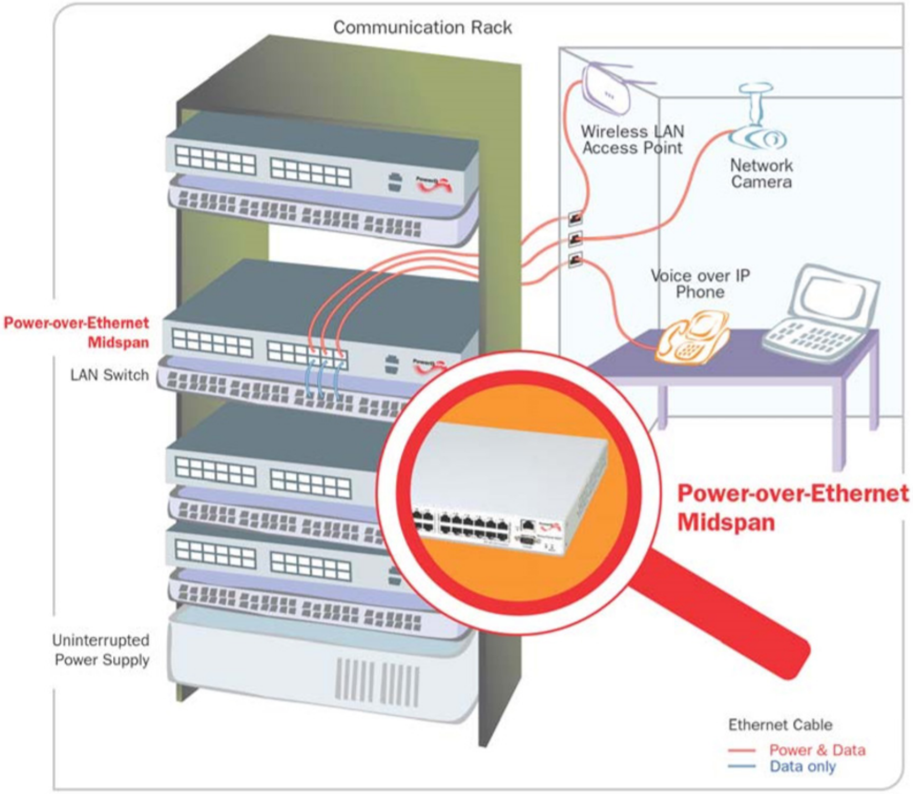


Figure 3. Example of a PoE enabled switch using Ethernet connection to connect devices in a separate space. Source: Mendelson (2004).

D. LIFI DEVELOPMENT AND APPLICATIONS

1. Visible Light Communications (VLC)

The development of LiFi for communication networks stems from earlier research exploring the feasibility of Visible Light Communication (VLC). As shown in Figure 4, visible light refers to the segment of the electromagnetic spectrum within the frequency range of 790THz-430Thz and wavelength of 380 to 750 nanometers (nm) (Rajbhandari et al., 2017).

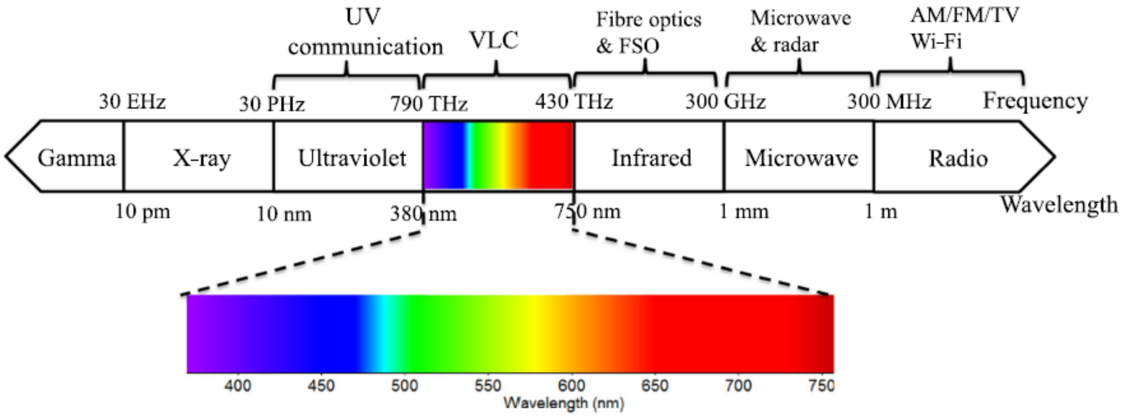


Figure 4. The VLC frequency bands within the Electromagnetic Spectrum.
Source: Rajbhandari et al. (2017).

The first transmission of voice communication over light occurred in 1880 with Alexander Graham Bell's photophone in 1880 (Mims, 1984). However, most of the communication development in the twentieth century was dominated by using radio waves for short and long-distance communication. The invention of the laser in the 1960s expanded the utility of free space communications (FSO). High efficiency gallium arsenide infrared lighting devices were also invented in the 1960s, a precursor to LED bulbs that are now the primary device used for data modulation and transmission for VLC systems (Mims, 1984). However, the technology was generally only reliable over short distances until the invention of fiber optic communication in the 1970s (Mims, 1984). IBM began developing optical wireless communication (OWC) devices in 1979 (Rajbhandari et al., 2017). OWC is an umbrella terms that encompasses several applications for using light for wireless connection instead of RF; examples of areas that are incorporating OWC technology are show in Figure 5.

Figure 5. Examples of industries incorporating OWC technology. Source: Chowdhury, Hossan, Islam, Jang (2018).

The development of light emitting diode (LED) lightbulbs has created greater interest in using VLC for more complex communications networks. The block diagram in Figure 6 gives examples of different networks and end device configurations, including utilizing cloud technology, optical fiber, and cellular broadband for core and backhaul networking and LED and laser drivers for wireless channels. In 1999, researchers used LED-enables traffic lights to broadcast audio signals (Rajbhandari et al., 2017). Dr. Masao Nakagawa from Keio University in Japan was the first to propose the idea of using white LED for wireless communication in interior spaces and demonstrate that high data rates were possible with distributed LEDs in a single interior space (Komine, Nakagawa 2004). The UK also sponsored the European Union Home Gigabit Access Project (OMEGA) project for integrating VLC using PLC while also developing a variant called Ultra Parallel Visible Light Communication (UP-VLC) that demonstrated a 3 gigabit per second link in

2013 (Rajbhandari et al., 2017). In 2001, RONJA (Reasonable Optical Near Joint Access) sent data over a one kilometer distance at a transmission speed of 10 mbps using visible light (Karunatilaka, Zafar, Kalavally, & Parthiban, 2015). The first standard proposed for VLC, IEEE 802.15.7, was introduced in 2011 but was never formally adopted by industry (Rajbhandari et al., 2017). The newest standard currently in development is IEEE 802.11bb, designed to encompass all light communications and expected to be accepted during 2020–2021.

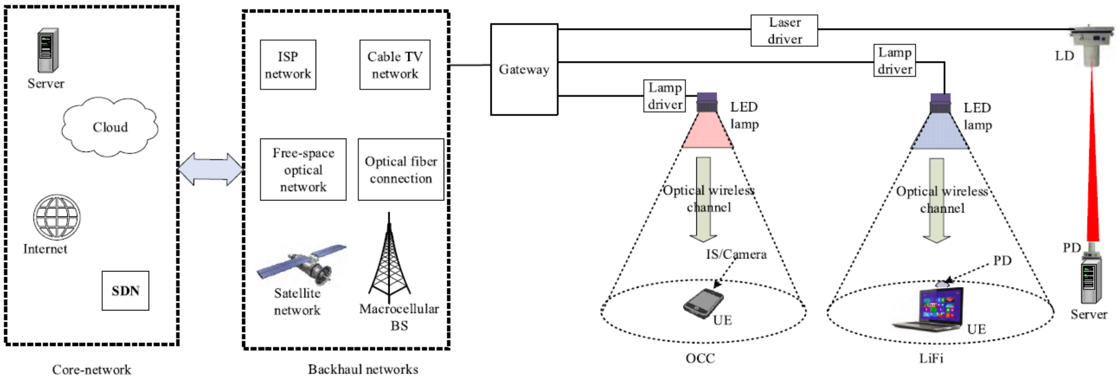


Figure 6. VLC link between network, backhaul link transporting data, gateway router, and LED transmitter. Using lasers for communications is another application of OWC. Source: Chowdhury et al. (2018).

2. Development of LiFi

The term LiFi was coined by Professor Harald Haas from the University of Edinburgh in 2011 to describe wireless networking using VLC (Haas, Yin, Wang, & Chen, 2016). Light can be used to transmit data from an access point similarly to how Wi-Fi uses radio frequency to transmit data: light signals are transmitted to an LED lightbulb that imperceptibly switches on and off to send data to a receiver (Haas, Chen, & O’Brien, 2017). In 2012, Hass demonstrated data transmission using two smart phones with the display screens acting as a transmitter and cameras acting as receivers that supported video streaming (Haas, Ying, Wang 2016). Navy ships have already upgraded their lighting systems, making this an efficient option that doesn’t require purchasing expensive and specialized equipment. Proposed applications for Li-Fi applications include personal area networks, “smart” transportation systems, underwater vehicles, environments prone to electromagnetic interference (EMI) or risk to ordinance with radio frequency, and positioning systems (Burchardt, Serafimovski, Tsonev, Videv, & Haas, 2014; Delgado, Quintana, I., Rufo, Rabadan, Quintana, C., Perez-Jimenez, 2010; Haas, 2018). One company pioneering Li-Fi technology is PureLiFi, which has developed an Application-Specific Integrated Circuit (ASIC) supporting full duplex communications, multiple users on a single access point, high data rates, and common network management protocol (PureLifi, n.d.). Cited concerns for the system are range limitations and possible interference from external emissions (Chowdhury et al., 2018). Li-Fi also has potential to integrate into cloud computing architecture as local nodes to reduce bandwidth burdens on networks.

While PureLifi is at the forefront of LiFi development, it is not the only company investing in the commercialization of this technology. Other companies of interest include Vlncomm, Oledcomm, Signify and Velmenni. Signify has two systems, Firefly SecureLink and TruLifi (Firefly LiFi, 2018). SecureLink advertises data rates exceeding 1 gbps for both outdoor and indoor applications. NIWC San Diego has tested the performance connectivity of Firefly LiFi access points between devices. The results are Distribution D but the reference is listed for DOD personnel and contractors (Wolfe, 2018). TruLifi offers two devices (Signify, 2019). TruLifi 6002 advertises 150 mbps for uplink and downlink connections, uses advanced encryption, and can work with lights dimmed or off. TruLifi 6013 is a point-to-point system advertising 250 mbps for uplink and downlink but uses RGB LED lighting instead of white light. VLncomm’s products are Lumistick2, a USB device, Lumilamp for office desk use, and the Luminex LED panel (VLNComm, n.d.). Lumistick 2 advertises 108 mbps downlink speed and 53 mbps uplink speed. Oledcomm’s LiFi Max system uses a PoE connection and includes an access point disk for ceiling installation similar in appearance to a smoke alarm and a USB dongle (LiFiMAX®, 2019). LiFi Max advertises a 100 mbps downlink and supports up to16 users per access point. Oledcomm has also developed a LiFi enabled desk lamp with a downlink up to 23 mpbs. Lightbee offers an LED panel called LightDim that can be remotely controlled and reduces energy consumption up to 50% (Lightbee Corporation, n.d.). category 6 focuses on LiFi enabled LED using proprietary signaling algorithms for indoor location services and downloading information from an LED using cell phone apps (Wired, n.d.). PureLifi was chosen as the LiFi example for this thesis based on providing all components required in a VLC system, ability to be used with other LED panels, ease of setup, and potential for mobile applications.

3. Current and Potential Applications

A LiFi network creates an opportunity for many interesting applications that can be used in an operational environment. One application is network partitioning. As shown in Figure 7, the blue, green, and red-light diodes that create the white light emitting from an LED can support distinct data streams. This adds additional layers of security by controlling what information can be seen in each space or controlling which users can connect to which access points (Haas, 2017). LiFi enabled devices can be configured to communicate with certain access points and not others using IP and MAC address filtering, allowing security to be enforced at the hardware level (N. Serafimovksi, personal correspondence, October 22, 2019).

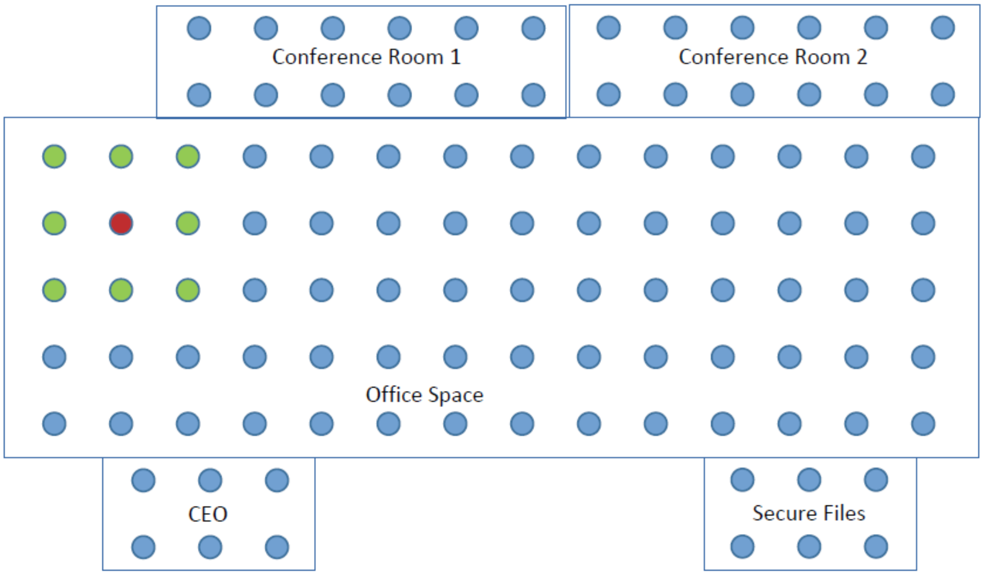


Figure 7. Network partitioning application possible with VLC system where red, blue, and green LED colors can stream different data. Source: Haas (2017).

LiFi access points can support emerging location detection technology: the LED might detect the general area a sailor is based on a signal from an article of clothing or another device connected to a person as part of a wireless body area network (WBAN) (Chowdhury et al., 2018).

PureLifi has collaborated with Babcock Industries in the UK during a six month trial of network sensors on the HMS Sutherland frigate (Babcock International, 2019). Data sensors were installed throughout the engineering spaces to provide real time system information to the crew, but also receiving real-time data from maintenance centers ashore to quickly diagnose problems (Babcock International, 2019). Babcock is also utilizing LiFi technology for biometric access control, smart sensors, and augmented reality (PureLiFi, 2019).

Underwater communications, including docking for submarine vehicles, is more effective with light than RF due to significant transmission differences through water. Areas sensitive to electromagnetic radiation, like monitoring weapons systems, car-to-car communication, and hospital settings (Burchardt et al., 2014). There is also interest in using

LiFi for disaster relief operations to create mobile networks when cellular networks become unavailable (LiFi, a lifesaving technology in disaster operations).

E. NETWORK OPTIONAL WARFARE (NOW)

Rapid technological change in the 1990s created more military interest in how to utilize networks and information for operational success. Network-centric warfare became a popular concept: by creating networks linking geographically dispersed units, military forces gain a military competitive advantage and revolutionize the way war is conducted by eliminating information gaps and decreasing time delays that hampered operations. However, this concept created unintended problems: forces were less flexible, dependent on the constant information flow and unable to make decisions without it, and less skilled at emissions control (EMCON) techniques making units vulnerable to detection (Brutzman, 2014). A new concept proposed to address such challenges is Network Optional Warfare (NOW), which refers to using communications technology that can provide low probability of detection and interception (LPD/LPI), operate under varying EMCON conditions, and data compression that can support more fluid operations (Brutzman et al., 2014). NOW seeks to recreate traditional naval operational strengths: independent operations, ability to evade detection from the enemy, and create tactical surprise (Brutzman et al., 2014).

1. Combat to Compile in 24 Hours (C2C24)

Li-Fi can integrate well with the Navy's Combat to Compile in 24 Hours (C2C24) concept for high speed and flexible communications. Rear Admiral Danelle Barrett, USN proposed C2C24 in 2018 in response to a need to build a more flexible communications architecture for sailors that allow for the deployment of application upgrades before and during deployment; the goal is new software that can be sent to a ship in 24 hours rather than months or years of development (CHIPS Magazine, 2018).

C2C24 seeks to create a web-services environment versus dependence on reaching back to servers ashore using data compression and standardized data formats that increase the speed, accuracy, and sharing of data: "efficient XML" data packets can also be designed to work in low bandwidth environments. A ship in the future is expected to download new applications as needed rather than wait for maintenance periods. The Consolidated Afloat Network Enterprise Architecture (CANES) provides a common network architecture across the fleet that makes it easier to maintain the same level of security; this means that hardware does not have to be analyzed and certified for every new software upgrade because the infrastructure has already met requirements. This shifted focus to providing capability to operators bolsters the usability of networks without sacrificing security. Thesis work by LT Shaurice Miller, USN explored processes and requirements for streamlining testing requirements for C2C24 and integrating XML into Risk Management Framework (RMF) requirements (Miller, 2019).

LiFi is a possible extension to this "tactical cloud." Linking computers, tablets, and cell phones to line of sight Li-Fi access points using a network backbone to route standardized data can provide mobility and security to end users (CHIPS Magazine, 2018). Access points can be strategically placed in high traffic areas and ship spaces where maintenance and other work critical for ship readiness is done that are currently not well connected to current shipboard communications infrastructure to maximize efficiency without adding substantial costs.

2. Optical Signaling

Dependence on constant data exchange from RF systems hampers operational stealth capability and the loss of skills operating in radio silence environments limits the ability to conduct covert operations or complete the mission in RF-denied situations. Optical signaling has a long history dating back to the use of semaphore and flashing light, and there is interest in developing modern equivalents to improve network performance on the tactical edge (Lucas, 2013). Prior NPS thesis research has proposed using QR codes "digital semaphores" for alternate line-of-sight communications where RF communications are contested, unavailable, or unsuitable (Richter, 2013). Additional operational testing is needed to test in realistic environments where motion can affect the feasibility of optical communications, including shipboard environments and ship-to-ship communications in high sea state. "Agile EMCON" provides a way for ships communications to have low probability of detection (LPI) that provides flexibility and autonomy at the tactical level of maritime operations.

F. APPLICATION AND FEASIBILITY OF LIGHT FIDELITY (LIFI) AND POWER LINE COMMUNICATIONS (PLC) ON U.S. NAVY SHIPS

LT Dmitri Paspalaris's Naval Postgraduate School thesis tested the performance of the Netgear Powerline 2000, TP-link AV200 Powerline starter kit, and D-link Powerline AV2000. (Paspalaris, 2019). Data was sent between two computers using chat and data transfer applications to simulate typical network traffic on a Navy ship. These modems have advertised bandwidth performance of 2gbps, but in had average data rates between 165 and 187 mbps during laboratory tests (Paspalaris, 2019). Distance, infrastructure construction, network configuration, and the number of users are factors that impact observed PLC performance. The PLC products were also tested integrated with Vlcomm's Luminex LiFi product and navy shipboard LED lighting in separate scenarios and in one combined system. Transmit and receive data rates between 1.3 and 8.9 mbps in a system integrating commercial LiFi, shipboard LED lights, and ship power cables. Overall, Netgear Powerline 2000 was considered to be the best product for PLC implementation. The thesis also measured electromagnetic radiation emissions from powerline cables used on navy ships and compared the results with commercially used power cable. The average emission for cables with an electric load but no communications signal was 1e-8 watts, which is relatively low and harder to detect through a metal ship hull. Emissions of cable with communications signals were measured from 0.15, 0.3, and 1-meter distances and had relatively low emissions. The Netgear product had the lowest emission and shipboard cable performed better than the commercial cable.

G. SUMMARY

Advancements in network communication have made light-based communications more feasible and increased commercial interest in developing technology and applications. Laboratory research and real-world test beds have demonstrated high bandwidth capability in a variety of non-traditional networking environments. PoE and PLC can provide the backbone network connectivity for LiFi and support higher data requirements from expanding IoT applications. LiFi complements other wireless technologies and concepts for delivering greater network flexibility at the tactical edge where it is most needed.

III. LIFI COMPONENTS FOR SHIPBOARD USE

A. INTRODUCTION

PureLifi’s LiFi-XC is their latest LiFi product that includes an LED luminaire in addition to an access point and USB receiver. Multiple LiFi devices can be used to create a full coverage unclassified wireless network in indoor spaces. These optical wireless networks provide increased network speed, bandwidth, and security, reliable operations in a tactical environment. LiFi-XC is a step toward creating a zero-emission communication infrastructure. Several types of LED are possible for communication, and modulation techniques are used to improve LED performance. This chapter discusses advantages and disadvantages of using LiFi and using PoE and PLC for a network backbone. IEEE standards are another important aspect of ensuring technology can be installed on Navy ships.

B. LIFI XC PURELIFI TECHNOLOGY

1. Physical Components and Software

Figure 8 illustrates the components of a LiFi network supported by PureLifi. The components PureLifi provides are the access points (AP), USB station dongles (STA) and LED light luminaires (PureLifi, n.d.). The equipment is built according to open standards, so customers are not locked in to a product. The access points and USB dongles can theoretically be used with LED lights from other manufacturers. The access switch, gateway router, and auto configuration server are shipboard provided equipment. The switch provides power and data to each individual access point using PLC or PoE awhile connecting that network segment to external networks via the gateway router. Each access point communicates with a station dongle that is within its range (PureLifi, 2017a). The autoconfiguration server (ACS) automatically assigns IP addresses to the access points and connecting devices (PureLifi, 2017b).

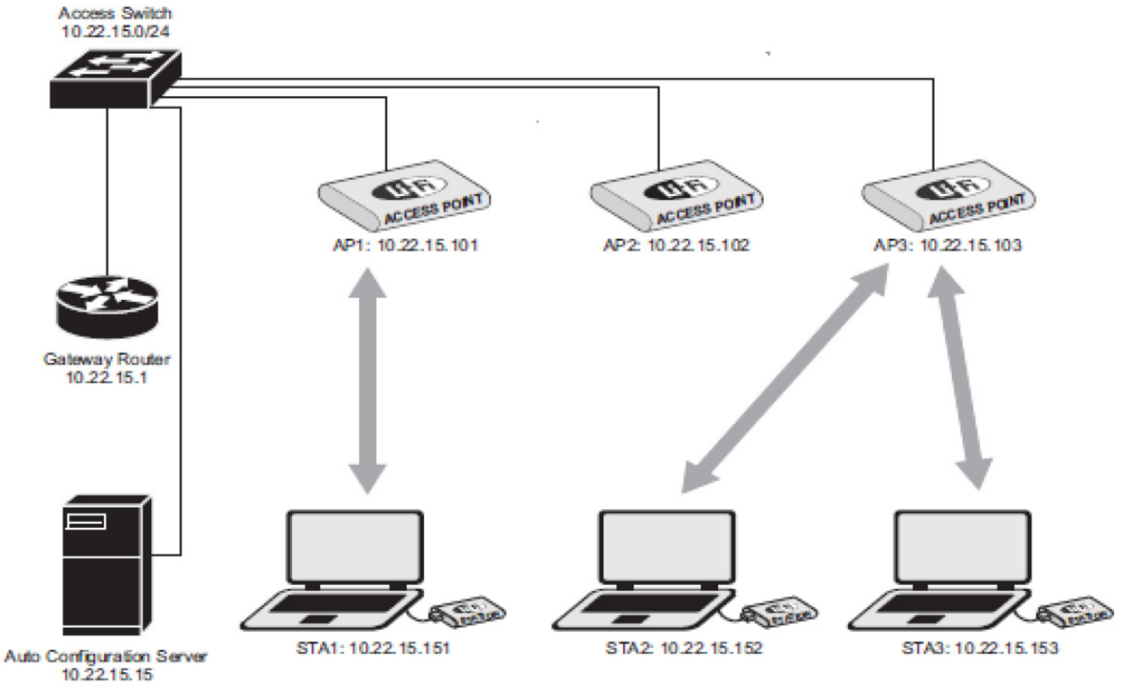


Figure 8. LiFi deployment of a small LAN; the access switch provides connectivity to access points and gateway router provides connection to external network. Source: PureLifi (2017a).

a. Access Point (AP):

The LiFi-XC access point in Figure 9 uses open source openWRT 15.05 Linux kernel version 3.18.98 as the embedded operating system that provides routing and security functionality to the device (PureLifi, n.d.). The AP supports multiple users on a single access point (PureLifi, 2017a). The AP can be powered by a PoE+ network access switch or a main power supply unit with CAT5 or CAT6 cable. CAT6 operates with the same standards as CAT5 cable but offers better protection from crosstalk and produces less noise (“Category 6 cable,” n.d.). The hardware is compliant with the IEEE802.3at standard for PoE. (PureLifi, n.d.) Each access point supports one SSID but up to eight separate devices.

Figure 9. PureLifi access point connected to Ethernet and luminair during an initial test out of the box

b. STA dongle

The USB dongle shown in Figure 10 is manufactured in USA and supports Windows, Linux, MacOS operating systems (PureLifi, n.d.). The dongle requires a Windows 7 or above operating system if running on a Windows machine, and runs Linux version kernel 2.6.32 (PureLifi, 2017c).

Figure 10. LiFi-XC USB dongle

c. LED luminaire

The luminaire in Figure 11 is from an initial set up of two LED lights and access points at NIWC San Diego. The field of view (FOV) for the downlink is 66 degrees, and the infrared uplink is 60 degrees (PureLifi n.d.). The relationship between the LED's height and coverage area at that given height can be calculated with the following equation:

$r=h*\tan(0.5*FOV)$

where r equals the cell radius, h equals the distance between the LED and the station dongle, and FOV is the field of view. Table 1 gives an example of the cell diameter at various heights, although actual cell diameter can vary.

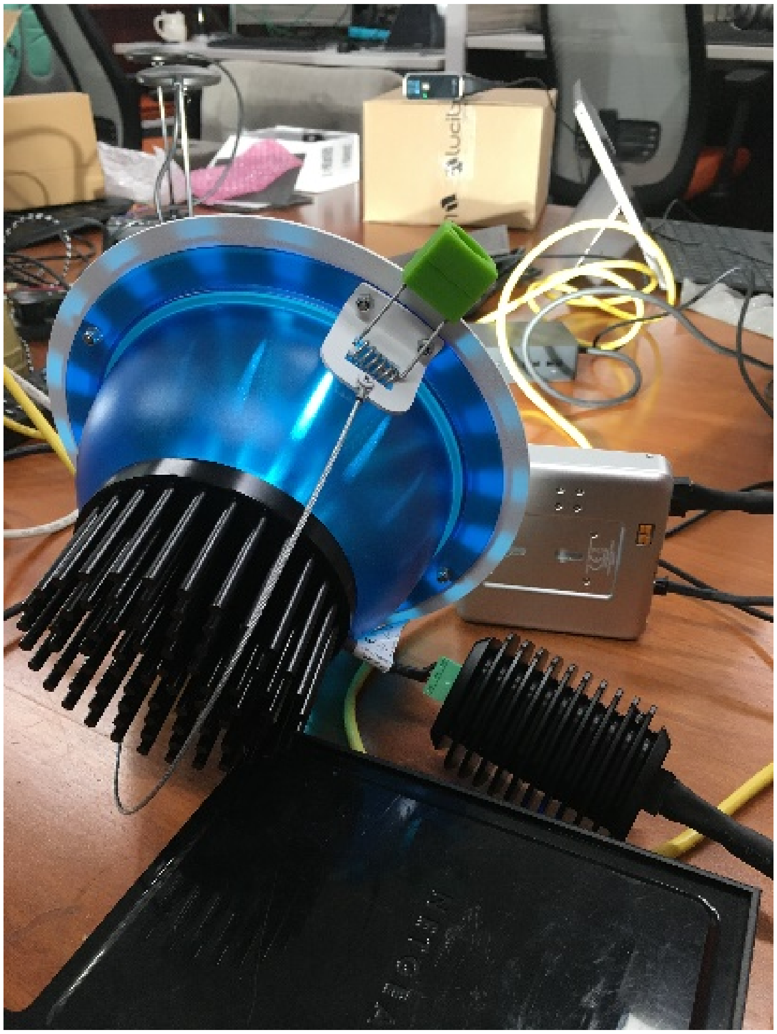
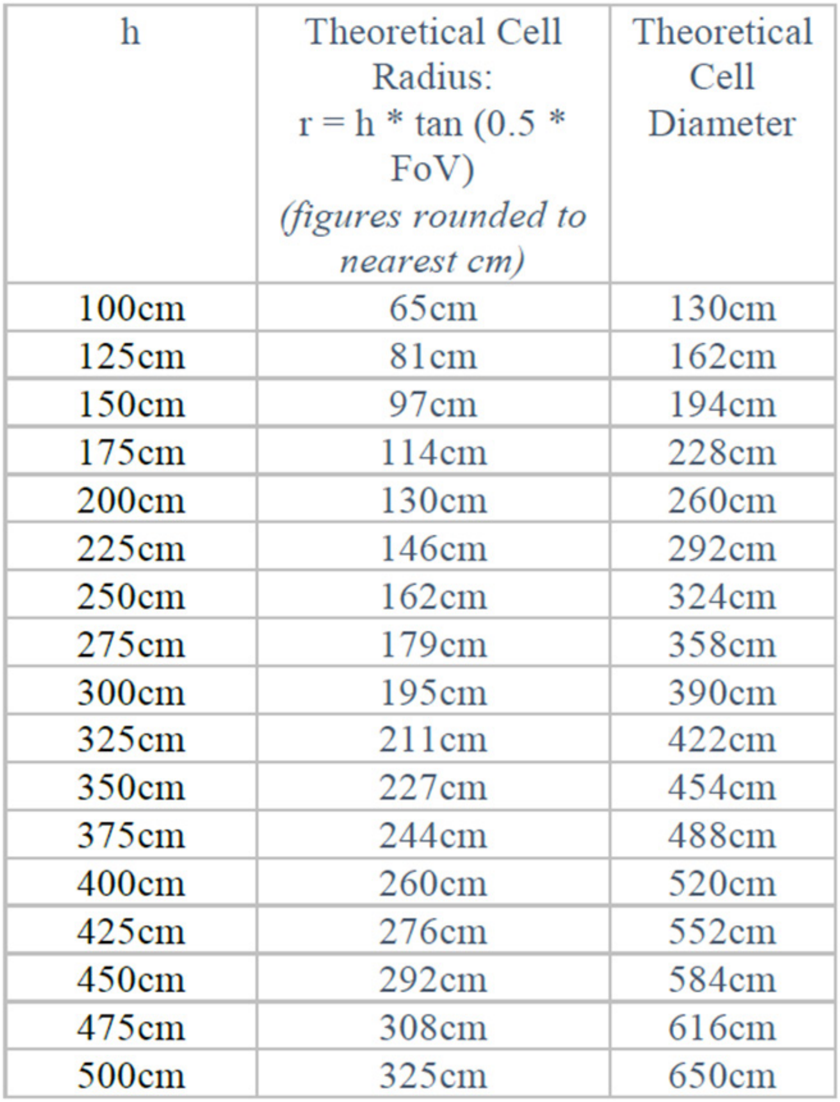


Figure 11. Lucibell II Luminaire during an initial test

Table 1. Theoretical cell radius at different installation heights Source: PureLifi (n.d.).



h	Theoretical Cell Radius: r = h * tan (0.5 * FoV) *(figures rounded to nearest cm)*	Theoretical Cell Diameter
100cm	65cm	130cm
125cm	81cm	162cm
150cm	97cm	194cm
175cm	114cm	228cm
200cm	130cm	260cm
225cm	146cm	292cm
250cm	162cm	324cm
275cm	179cm	358cm
300cm	195cm	390cm
325cm	211cm	422cm
350cm	227cm	454cm
375cm	244cm	488cm
400cm	260cm	520cm
425cm	276cm	552cm
450cm	292cm	584cm
475cm	308cm	616cm
500cm	325cm	650cm

The Optimal range between the AP and the STA is between 1 and 5 meters but peak data ranges are advertised as 1–2-meter distance. The light output is 1930 lm, which exceeds the requirements for an LED’s ability to support data transmission. Light intensity is also adjustable, so increasing the luminaire’s output may improve the signal at distances greater than 5m. The luminaire also maintains data throughput when dimmed: for a a 20–28 watt light, the power can be cut to 15% of normal intensity without experiencing noticeable performance degradation. This helps conserve power and deal with possible power fluctuations in a network.

In a test done at NIWC San Diego between two Windows computers and using an Ethernet cable to provide data input source, each machine recording a speed test of 33mpbs, which is close to the advertised range of 45 mbps. The two station dongles used were approximately 1–2 meters from the LED access point.

(1) Virtual Management

Virtual Management is the PureLifi Linux virtual machine used to run ACS, the configuration server. The ACS has a static IP address and automatically assigns IP addresses to access points and connected devices. Individual lamps can be remotely monitored: settings, power, and brightness can all be changed using the VM module.

(2) Network Protocols

- OpenSSL 1.0.2n security protocol
- 802.1x WPA2 for access point security
- IEEE 802.1q for multiple VLANs
- Currently developing compatibility with IPsec protocol
- 2048 RSA TLSv1 (encryption), CCMP wireless link encryption
- TR-069, SNMPv2 and SNMPv3
- DHCP server required to allocate IP addresses to access point and USB station dongle (PureLifi, n.d.)
- Interference avoidance algorithm to minimize co-channel interference

2. Advertised Limitations and Constraints of PureLifi Equipment

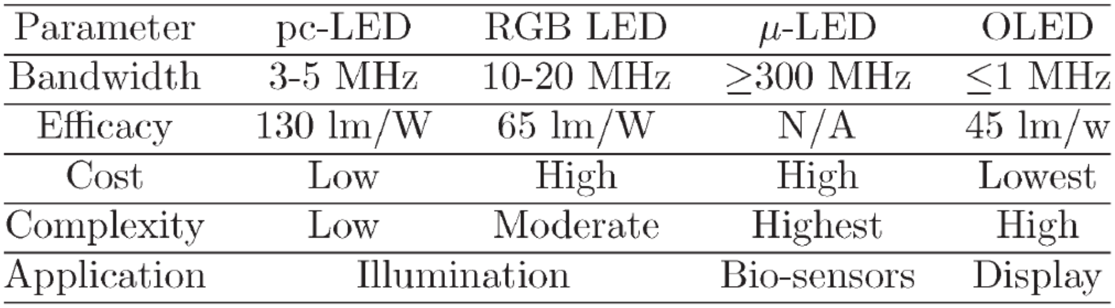
LiFi-XC currently does not support the Control and Provisioning of Wireless Access Points (CAP-WAP) and Generic Routing Encapsulation (GRE) protocols (PureLifi, n.d.). CAP-WAP is used to control wireless access points from a central access controller and GRE is used to create Virtual Private Networks (VPN). Only one SSID can connect to an access point at a time. LiFi-XC is interoperable with WPA2 Personal (PSK) and WPA2 Enterprise encryption standards. Each ship must obtain a RADIUS enabled server to enable these security protocols on the LiFi network (PureLifi, n.d.).

C. LIGHTING AND CANDIDATE DESIGN

1. LED Types and Characteristics

LEDs have many benefits for use as access points: they have a long life expectancy, high humidity tolerance, relatively highly efficient power consumption, and do not generate a high amount of heat from the bulb (Komine, Nakagawa 2004).

Figure 12 shows a comparison of LED types currently used for different applications. The LED types most suited for high speed communications are Phosphor Converted LED (PC-LED) and Red, Blue, Green LED (RGB LED). The main difference between them is the way in which they generate white light (Karunatilaka et al., 2015). In a PC-LED lightbulb, a blue gallium nitride chip generates yellow phosphor that creates white light by converting some of the blue into red and green. The most efficient type of PC-LED radiates cool white light and generates less heat (Karunatilaka et al., 2015). In a multi-chip LED, the bulb has individual red, blue, and green chips that produce white light (Karunatilaka et al., 2015).



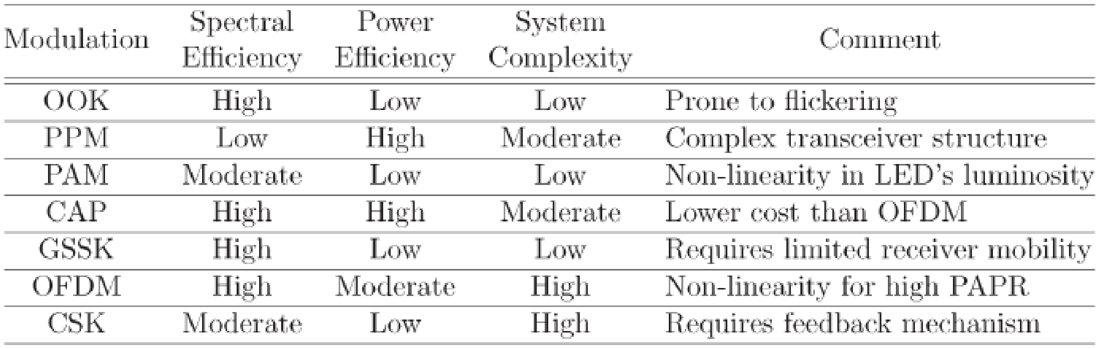
Parameter	pc-LED	RGB LED	μ-LED	OLED
Bandwidth	3-5 MHz	10-20 MHz	$\geq$300 MHz	$\leq$1 MHz
Efficacy	130 lm/W	65 lm/W	N/A	45 lm/w
Cost	Low	High	High	Lowest
Complexity	Low	Moderate	Highest	High
Application	Illumination		Bio-sensors	Display

Figure 12. Comparison of LED types. OLED is used more for screens and white light is more common than RGB light. Source: Karunatilaka et al. (2015).

Standard LED that use blue and yellow to produce white light are the most efficient to use for the purposes of VLC systems: RGB LED lights are less cost effective and are more difficult to maintain, and organic LED bulbs provide relatively low bandwidth that negates the benefit of its relatively low cost (Rajbhandri, 2017). Larger LEDs have higher bandwidth, but micro LEDs (μ-LED) in laboratory settings have achieved data rates of 11mpbs (Haas, Wang, O'Brien, 2017). The luminescence of an LED bulb required to maintain a sufficiently high signal to noise ratio (SNR) to support high data rates depends on the height of a room, but LEDs used in office and public spaces tend to have higher luminescence than those commonly installed in home setting. (Haas et al., 2017).

2. Modulation

Modulation is critical for enabling multiple users to use the same access point simultaneously as well as optimizing the efficiency of a communication channel (Haas et al., 2017). Figure 13 provides a general overview of different modulation schemes and a comparison of the strengths and weaknesses of each. Spectral efficiency refers to how much bandwidth is utilized within a communication channel: the greater the spectral efficiency the greater the possible data rate (Haas et al., 2017). Power efficiency refers to how much power is required to propagate the modulated signal. System complexity refers to how much signal processing and additional power is required (Haas et al., 2017).



Modulation	Spectral Efficiency	Power Efficiency	System Complexity	Comment
OOK	High	Low	Low	Prone to flickering
PPM	Low	High	Moderate	Complex transceiver structure
PAM	Moderate	Low	Low	Non-linearity in LED's luminosity
CAP	High	High	Moderate	Lower cost than OFDM
GSSK	High	Low	Low	Requires limited receiver mobility
OFDM	High	Moderate	High	Non-linearity for high PAPR
CSK	Moderate	Low	High	Requires feedback mechanism

Figure 13. Comparison and description of modulation types. Source: Karunatilaka et al. (2015).

- **On-Off Keying (OOK)**

OOK is one of the simplest modulation methods where the LED turns on and off rapidly producing 0 and 1 bits that can carry data (Karunatilaka et al., 2015). OOK is not as efficient as other modulation schemes, particularly compared to OFDM (Haas et al., 2017).

- **Pulse Position Modulation (PPM)**

A pulse with a certain amount of data bits is transmitted within a certain time slot. The average power requirement for PPM is lower than OOK, but it is less bandwidth efficient than other modulation techniques (Karunatilaka et al., 2015)

- **Pulse Amplitude Modulation (PAM)**

PAM is similar to PPM, but the amplitude of the signal is modulated. This signal may be more sensitive to the changes in color of an LED based on power and other factors driving light emission from the LED (Karunatilaka et al., 2015). The main issue with pulse modulation techniques is that they support lower data rates compared to OFDM (Haas, class notes).

- **Carrierless Amplitude Phase Modulation (CAP)**

Transmits orthogonal signals like OFDM but is easier to implement (Karunatilaka et al., 2015)

- **Generalized Space Shift Keying (GSSK)**

This modulation technique produces higher spectral efficiency than conventional OOK and PPM techniques (Karunatilaka et al., 2015). Its algorithm techniques are less complicated than PAM but works much better with fixed receivers compared to mobile devices.

- **Orthogonal Frequency Division Multiplex (OFDM)**

This modulation technique facilitates high data rates in VLC systems through transmitting multiple signals transmitted simultaneously and using spectrum efficiently

(Song, 2015). OFDM is one of the most commonly used approaches used in VLC network testing and supports high data rates in systems with multiple users (Haas et al., 2017). It is also considered very efficient in maximizing bandwidth usage in a communications channel (Haas et al., 2017). It is more resilient compared to other modulation schemes at higher modulation speeds with less interference and is already used as part of the WiFi standard IEEE 802.11 (Tsonev, Chun, Rajbhandri, McKendry, Videv, Gu, Haji, Watson, Kelly, Faulkner, Dawson, Haas, O'Brien, 2014).

- **Color shift keying (CSK)**

Information is sent as pulses of different colors of light depending on the distribution of red, blue, and green lights the LED uses to create white light. (Haas et al. 2017). However, CSK cannot be used in a VLC system using PC-LEDs and implementation of CSK is more complex than other modulation types. An "optional feedback loop from the receiver can be implemented for color calibration and avoiding interference from other light sources" (Karunatilaka et al., 2015).

The specific type of modulation used is not something the end user is concerned about because modulation schemes are incorporated into the device by manufacturers, but the important takeaway is that modulation that can support multipath propagation is required for a LiFi network. OFDM is the modulation type recommended by light communication standards in development.

D. LIFI ATTOCELL NETWORKS

Figure 14 illustrates an optical network utilizing LiFi access points for the optical access point connected to a PoE or PLC backhaul connection that provides power to the system (Haas et al., 2017). The LED modulates faster than the human eye can detect to create the access point for uplink connection while using infrared (IR) for the downlink connection from the access point to the user equipment (Haas et al. 2017). Infrared is ideal for the uplink because the difference in wavelength from visible light allows bidirectional communication and light emissions from the user device might otherwise degrade usability (Haas et al. 2017). Each access point creates its own high-bandwidth "attocell" that, when deployed with multiple other attocells, creates a network that can support multiple user devices at the same time in the same space. Also important is to support handover between attocells without the user detecting any connection lapse (Haas et al., 2017). The number of access points used in a space combined with the signal reflections created by the space has an impact on possible bandwidth capacity through a combination of line of sight (LOS) and non-LOS signal paths (Haas et al., 2017). The placement of access points and the field of view (FOV) of each access point also impacts networks performance (Haas et al., 2017).

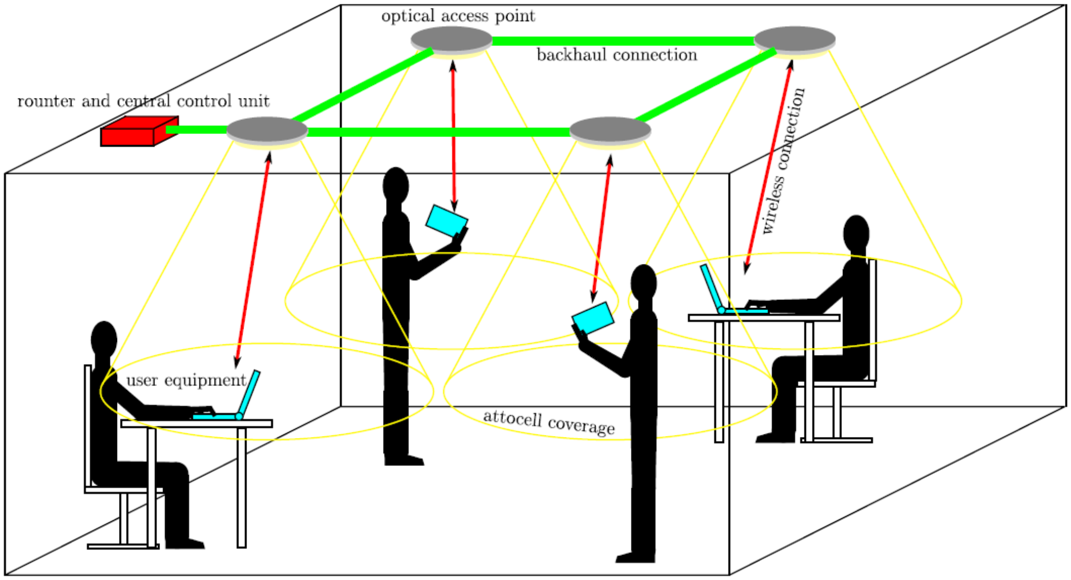


Figure 14. Implementation of a LiFi attocell network. Each optical access point creates its own attocell. Multiple attocells connected to a wired backbone provide coverage that can support mobile devices. Source: Haas et al. (2017).

An important component of a LiFi network is handover. Handover refers to a mobile device changing access point without losing connectivity. There are two types of access point handover. Soft handover is when a mobile device stays connected to an access point before connecting to another access point (Haas et al., 2017). Hard handover is when a device disconnects before connecting to another access point (Haas et al., 2017). Soft handover generally provides better service than hard handover and is the default for most LiFi devices, including PureLifi (Haas et al., 2017).

E. LIFI APPLICABILITY FOR SHIPBOARD ENVIRONMENT

1. Advantages in Using LiFi

LiFi networks have many benefits over networks using radio frequency that are useful in a shipboard operational environment. Using LiFi is an efficient use of resources because the LED provides a dual role of providing light for a space as well as an access point for communicating data (Tsonev et al., 2014). This can help reduce the power burden of adding new equipment on the ship power supply. LiFi access points radiate in a specific direction which limits radiation to a small area and avoids signal spillover between spaces (Haas et al. 2017). Using the VLC spectrum is cost effective because it does not have license restrictions like other frequency bands (Yin and Hass 2018). VLC is also safe to use in electromagnetically sensitive areas, where RF cannot be used, it does not interfere with other communication systems, and has higher physical security compared to RF because a VLC signal cannot penetrate walls between spaces (Yin and Haas 2018). Interference between spaces is less of an issue compared to RF networks because a VLC signal does not penetrate through walls (Tsonev et al. 2014).

a. Handover Capability

The system offers sub-second handover time when roaming between LiFi cells. There is no seamless cell to cell handover mechanism, hence, the LiFi-XC system works in the same way as other MAC802.11 systems (e.g., Wi-Fi), in that, each time the user moves away from one cell to another, the full association process with the AP in the new cell needs to be performed, although this process is not noticeable to the user (PureLifi, n.d.). The system can handle eight seconds of disconnect between a station and access point before the device must manually connect. This is noticeable to the user.

b. Security

LiFi stations have both hardware and software security. The uplink connection from one device cannot be detected by another device even if they are near each other; only the downlink is shared. This encryption is much more difficult to break than with RF and decreases the insider threat risk. LiFi also provides the option of not having to store information on devices themselves, which eliminates the security risk from having vulnerable data at rest. (N. Serafimovski, personal correspondence, October 22, 2019).

c. Reliability

With regards to sudden power loss, a LiFi-XC access point takes approximately two minutes to reboot after power is restored but will automatically reconnect without any manual configuration required by user (N. Serafimovksi, personal correspondence, October 22, 2019).

In a laboratory test setting, the luminaire reacted well to blockage by solid objects: the link instantly reestablished after blockage was removed.

2. Trident Warrior Testing

NIWC and John Hopkins University collaborated on an experimental installation of a LiFi access point on a ship during the Navy's Trident Warrior exercise in 2018 using Ethernet as the network backbone. (Meenecke & Holzinger, 2018). The goal of the experiment was to test the interoperability of a COTS-based LiFi access point with other shipboard hardware and software. Applications were installed on the network to mimic likely shipboard usage, including video streaming, voice, and chat. Due to the results being For Official Use Only (FOUO), additional information regarding this experiment can be found in the referenced report.

3. Power Line Communications (PLC) as a Network Backbone

One main advantage for using PLC is the relatively low cost because additional network cables and wiring are not required (Song, 2015). Adding Ethernet cables to a large amphibious naval vessel for LiFi access points costs approximately $50,000 (Paspalaris, 2019). However, shipboard networks are complex systems. Powerlines may discontinue between spaces, signals have to pass through transformers, and emissions from other devices connected to the powerline can affect the data signal (Barmada et al., 2010). Load variations within a PLC system can also affect data transmission rates (Barmada et al., 2010).

a. Drawbacks of PLC

While research shows PLC can operate as a backbone for visible light communications, there are several factors that make standardized implementation difficult relative to power over Ethernet.

1) Emissions: Emissions are much harder to control with a PLC system. Implementation certification requires surveying emissions signatures, but signatures do not remain static: any device added to a PLC network can change this signature. PLC also requires a lot of power, and creating classified enclaves are be difficult. (Majumder & Caffery J, 2004). See (Paspalaris, 2019) for further investigation.

2) Design: The distance of a receiver from a noise source may impact SNR and increase data error rate (Yousuf & El-Shafei, 2007).

3) Reliability: The equipment connected to PLC systems often vary widely in age, making performance more difficult to predict. Communications signals also do not travel well through breakers and require redesigning breaker boards to create a better signal pathway (Gorshe et al., 2014).

4) Noise and Interference: Noise refers to the additional electromagnetic activity distinct from the signals being transmitted across the wire and can distort the signal, reducing the signal quality and increasing attenuation. Types of noise include:

   - colored background noise coming from low power sources
   - narrow band noise from radio signals, and
   - impulsive noise from switches or lighting in a network (Song, Ding, Yang, F., Yang, H., Yu, Zhang, 2015).

   Impulsive noise is particularly detrimental because it can garble data during high rates of data transmission (Yousuf & El-Shafei, 2007). Attenuation along the length of a powerline can also amplify noise effects (Yousuf & El-Shafei, 2007).

5) System Stability: Any system connected to a PLC network has to account for frequent changes, like dynamic power fluctuations and circuits turning on and off (Gorshe et al., 2014). It is more difficult to make changes to individual components connected on a PLC system without potentially affecting the system. Continuity between spaces are a potential issue as not all cables travel through all spaces of a ship and through solid partitions like watertight doors and compartments.

6) Security Issues: With PLC, any electrical outlet turns into a potential access point for data. This creates additional vectors for attacking or improperly accessing the network. There is a potential for hidden backchannels and an insider threat being able to listen in on the cable with a cell phone or sensor relatively easily. A solution to this problem is adding port security to outlets and ensuring all cables used for network traffic are encrypted with a VPN.

7) Operational flexibility: It is not feasible to create a classified enclave using PLC. This presents an issue as technology advances and classified communications with LiFi become authorized.

Although PLC presents multiple challenges for integration with LiFi, it still remains a viable option in cases where PoE installation is not possible. More research is needed to assess the viability of using PLC as the backbone in a shipboard environment and test for possible mitigations.

4. Power over Ethernet (PoE) as Network Backbone

Using PoE as the network backbone for LiFi has several benefits (Mendelson, 2004):

- Cost savings: LiFi-XC can use CAT5 or CAT6 Ethernet cables if already installed

- Mobility: can be used wherever there is Ethernet and allows for easier deployment of ceiling access points where power cables are not always available. The only requirement to power a LiFi device is a RJ45 connection to shielded Ethernet cable, making it possible to have moveable end devices
- Reliability: connected to a central uninterrupted power supply (UPS)
- Control: compatible with network management protocols like SNMP that monitor system performance, and node and link statuses
- Security: ports can be turned off when not in use
- Flexibility: Can carry both classified and unclassified network traffic if a ship might want to incorporate SIPR LiFi enclaves in the future. PoE also provides greater network topology configurations compared to using PLC

a. Potential Issues and Constraints with PoE

PoE is gradually being implemented across Navy platforms. Using PoE in a shipboard environment requires the installation of PoE+ enabled switches in spaces outfitted with LiFi access points. Switches and LiFi equipment must be tested to ensure space, weight, and power fit within the requirements are for the specific ship and area of installation. Heat loads and cooling capability are another potential concern. (Jason Childs, personal correspondence, 2019)

5. Other Considerations for LiFi Implementation

There are characteristics inherent to a LiFi network that must be considered and mitigated for a successful network deployment. One issue is co-channel interference (CCI) which is a byproduct of multiple access points being deployed in the same space; communication links operating on the same channel interfere with each other (Haas et al., 2017). This phenomenon is illustrated in Figure 15. The interference decreases the throughput of the network. This can be mitigated by employing centralized control for operating the individual access points and using different modulation schemes on overlapping access points (Haas et al., 2017). Each attocell must also be configured to support multiple users on the same access point (Haas et al., 2017). Another solution is to configure the access points in a space so they do not overlap and create potential interference. However, they cannot be placed too distant from each other with no overlap because that can degrade handover capability between devices. LiFi systems are also susceptible to shadowing: if there is any blockage between the access point and the user device, the system will not function (PureLifi, n.d.). Placement of LiFi access points to minimize overlap that causes co-channel interference is critical to optimize system performance, which varies between spaces and be based on the height and area of the space.

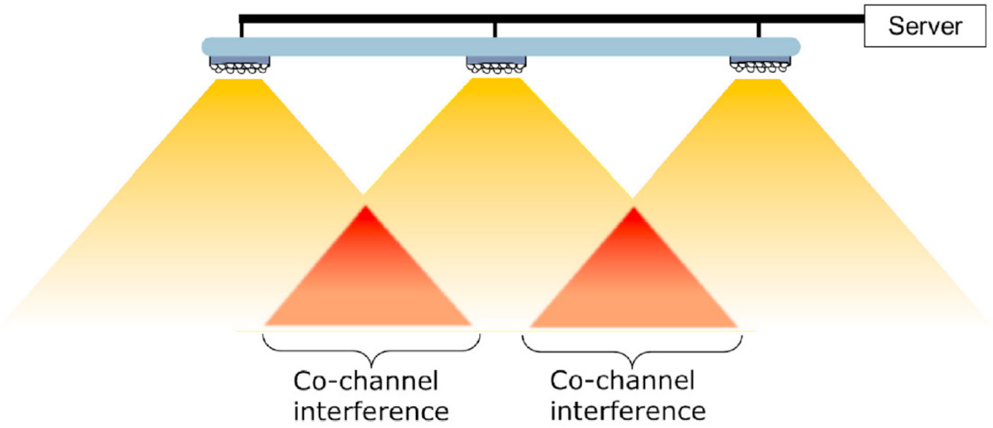


Figure 15. Co-Channel Interference (CCI) between LiFi attocells: minimizing the overlap of each LED's field of view (FOV) improves overall network performance. Source: Haas et al. (2017).

a. *Interoperability between Led and Poe*

One advantage of Ethernet is it is easier to replace PoE dedicated equipment without impacting other network and power systems on a ship. LiFi needs CAT5 or CAT6 cable which is what Navy shipboard networks already use. PureLifi is based on adopted Ethernet and wireless standards and is interoperable with other commercial networking equipment. Based on using these recognized standards, PureLifi equipment is compatible with any LED, but additional research may be necessary to ensure the certification requirements of the LED light were still met.

b. Routing Loop Hazards

A routing loop occurs when there is a mismatch between the routing algorithm that determines the best path to move data traffic and the actual topology ("Routing loop problem," 2019). As seen in Figure 16, Node A thinks the best path to send traffic is through B, while Node B thinks the optimal traffic path is via node A. Node B continues to resend packets from A back to A, creating a loop until the routers are updated and made aware of the broken link.

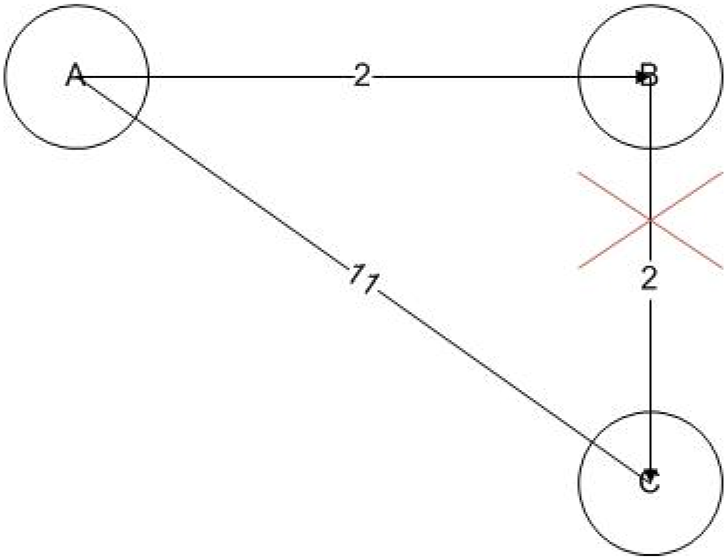


Figure 16. Routing loop between nodes A and B. Both nodes are trying to pass traffic to C, but data is trapped between nodes A and B because each router thinks the other is the shortest path. Source: "Routing loop problem" (2019).

Routing loops degrade networks and can be insidiously difficult to debug. Great care with network topology design must always be taken to ensure that routing loops never occur. During deployment, a ship with a routing loop can cause other ships sharing the same satellite communications to lose all connectivity, forcing the nearest NOC to intervene and reestablish the networks. In the case of LiFi, the routers are not the culprits as the wireless network can be configured to avoid this problem and complex routing algorithm are not applicable to this scenario.

Because LiFi devices operate at the network edge, a possible problem is if they connect to the wireless and wired networks simultaneously. Hardware configuration of PCs, laptops, tablets, and phones must prevent this possibility. One solution is to implement a software configuration setting to prevent the loop, but software solutions are usually not effective long term and may create more troubleshooting burden for ITs to fix continual network problems. Another solution is to disallow connecting LiFi devices to the non-wireless shipboard network, presumably by physically blocking or disabling multiple connection ports.

c. TEMPEST

TEMPEST is a requirement for all systems carrying sensitive information that emit electromagnetic radiation (Goodman, 2019). Radiation from information systems or cabling can be used to gain signal information and eavesdrop on communications by using directional antennas (Goodman, 2019). The NSA Tempest Endorsement Program oversees certifying government equipment meets TEMPEST requirements. Power cables used on navy ships have relatively low emissions, especially at longer distances, and the metal hull inhibits signals, but is still a concern that can be monitored if PLC is used to transmit data from LiFi transmitters and receivers.

F. CURRENT STANDARDS

The IEEE consists of industry, contractors, and users to develop technology standards to ensure interoperability of systems. It is an important step in the successful commercialization and mass adoption of technology. Below are some of the standards most pertinent to the technologies described in this thesis that have already been accepted by the IEEE and others that are in the process of formal adoption.

- IEEE 802.3 Standard for Ethernet

IEEE 802.3 describes the physical layer datalink layer requirements for Ethernet LANs and MANs (Institute of Electrical and Electronic Engineers, 2018a). This standard supports data rates from 1 Mb/s to 400 Gb/s over coaxial, twisted pair or fiber optic cables used for both half-duplex and full-duplex communications. Important datalink layer specifications included in the standard are common media access control (MAC) management information base (MIB) specifications, and CSMA/CD. The standard also gives power requirements for network devices which is important for ensuring the system can shut off safely during power failures. IEEE 802.3bt, cb, and cd are amendments to this standard for compatibility with higher power requirements needed in PoE systems (IEEE, 2019a).

- IEEE 802.15.7-2018 Short Range Optical Wireless Communications

This standard defines the physical layer and medium access control layer for short-range optical wireless communications (OWC) using wavelengths between 10 000 nm and 190 nm (IEEE, 2019b). The standard supports data rates needed for audio, video, and link mobility. Devices built on this standard are compatible with various light infrastructures. The standard also manages degradation due to noise and interference from external sources and adheres to eye safety regulations for maximum illumination power allowed. It also works for integration between camera lenses and transmitting devices with their own lenses and image sensors.

- IEEE P802.15.13 Standard for Multi-Gigabit Per Second Optical Wireless Communications (OWC) with Ranges up to 200 Meters

This is one proposed standard defining a physical and media access control layer using light wavelengths from 10 000 nm to 190 nm for line of sight (LOS) optical wireless communications up to 200 meters (IEEE, 2018b). The standard supports data rates up to 10gbps. It is designed for “point to point and point to multi point communications in both non-coordinated and coordinated topologies.” The standard allows devices to adapt to different channel conditions and maintaining connectivity while moving within the range of a single coordinator or moving between coordinators.

- IEEE P802.11bb amendment for Light Communications of the Wireless LAN Medium Access Control (MAC) and Physical Layer specifications

While IEEE802.15.13 is still a valid proposal according to IEEE, this newer proposed standard for light communications is being pursued more aggressively. The IEEE 802.11 Light Communication Task Group was formed from the IEEE802.11 Wireless Communication Working Group to create standard for light communication to support a more rapid commercialization of the technology (IEEE, 2018b). The standard is based on the IEEE802.11 wireless networking standard (IEEE, 2016). The goals of the task group are to designate uplink and downlink operations within 380nm to 5,000nm, achieve at least 10 mbps throughput for a single data link, and have at least one mode of operation that achieves single-link throughput of 5 gpbs when measured at an access point. The standard also ensures interoperability among solid state light sources regardless of different modulation bandwidths. All major chip makers and several vendors, including PureLiFi, are members of the standards development working group and have agreed to manufacture according to this standard

- ITU G.9991 Proposed standard for High-speed Indoor Visible Light Communications Transceiver

This is similar to the proposed IEEE802.11bb but was developed by ITU, the technology standards organization for the United Nations. The standard describes system architecture, physical layer and data link layer specifications for visible light for transmit and receiver devices on high speed networks. The standard also includes measures for security and system interoperability (*High-speed indoor visible light communication transceiver – System architecture, physical layer and data link layer specification: Recommendation ITU-T G.9991*, 2019).

- IEEE 1901. Standard for BPL networks

The original standard defines BPL services for frequencies below 100 MHz. used for all BPL applications including first-mile/last-mile connection to broadband services and LANs, Smart Energy applications, transportation platforms and vehicles (IEEE, 2010). The standard seeks to ensure power is used efficiently and BPL devices can coexist and operate with each other in a PLC network while maintaining required bandwidth and

Quality of Service (QoS). Security is also addressed to maintain privacy of communications between users and make BPL usable for security sensitive applications. The amendment IEEE 1901.a Standard for PLC for IoT applications revises IEEE1901 to incorporate changes so BPL can be used for Internet of Things applications (IoT) using OFDM (“IEEE, 2019c). This standard defines modes for operations in various frequency bands. IoT can be used for wired communications with any physical medium including electric power lines and coaxial cables.

- MIL-DTL-24643/59A

This standard delineates requirements for lighting specifications for shipboard use that an LED luminaire has to meet before being installed on a ship.

G. SUMMARY

LiFi-XC is a potential COTS product that works after installation after minimal configuration and is relatively easy to use. LiFi equipment that incorporates LED light sources is more secure and power efficient compared to RF devices and Trident Warrior testing shows LiFi equipment can operate in rigorous operational environments. Additional testing is needed to determine whether PoE or PLC is the best backbone to support LiFi devices on ships. The development and acceptance of PoE, PLC, and Light Communications IEEE standards will increase commercial investment in LiFi technology and improve vendor competitiveness.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. STRATEGY FOR NAVY LIFI DEPLOYMENT

A. INTRODUCTION

This chapter discusses important information for successful implementation of LiFi onboard navy ships from the perspective of a Program Manager or Commanding Officer. The IEEE standardization process is an important first step before IT can become commercially feasible. LiFi must meet security guidelines described in the Risk Management Framework process to receive an Authority to Operate (ATO) letter. Possible options for deployment are using PLC or PoE as the network backbone and using existing CANES wireless infrastructure to minimize work and cost. There are also challenges in acquiring advanced technology that must be considered during contract development.

B. IEEE STANDARDIZATION PROCESS

IEEE is one of several standards development organizations (SDO) that develop and maintain standards for technology and engineering applications (IEEE, n.d-a.). The IEEE standard development process is overseen by several committees that establish rules for developing requirements to ensure a standard is fair and a satisfactory consensus amongst all the individuals and organizations that have a stake in the new standard is met. The goal is to create agreement on minimum technology requirements necessary to create a viable commercial product that can be manufactured and sold globally. There are six steps in the IEEE Standard Development Life cycle shown in Figure 17.

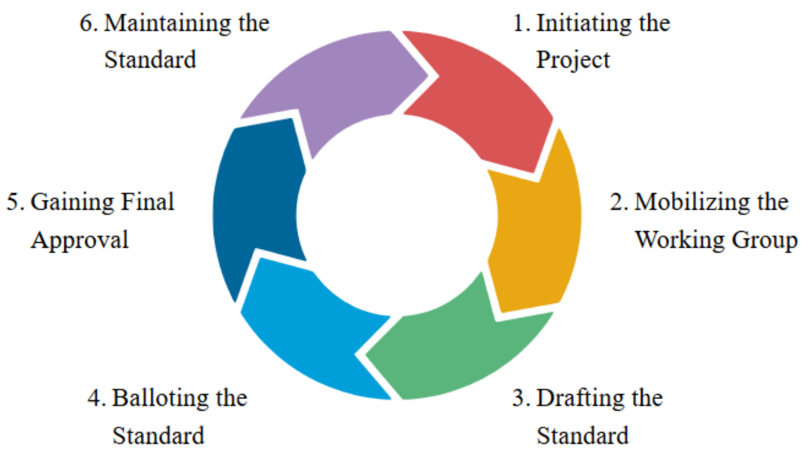


Figure 17. Six stages of the IEEE Standard Development Life cycle. Source: IEEE (n.d.).

1) Initiating the Project. A Project Authorization Request (PAR) must be submitted to the New Standard Committee (NESCOM) that states the reason behind creating a new standard and the plan for creating a new standard. The PAR also must designate a standards committee related to the proposed technology standard to oversee the project.

2) Mobilizing the Working Group. A working group is formed after the PAR is accepted. The Working Group chairperson plans meetings and is the technical point of contact for the project. The Working Group is open to individuals with technical expertise related to the project. Working Group meeting information is publicly available on the IEEE website.

3) Drafting the standard. IEEE's editorial staff assists the Working Group in writing the draft, providing templates and editing assistance so the draft can be voted on.

4) Balloting the Standard. When a draft is considered stable, IEEE members vote to approve or disapprove the standard. A draft requires 75% of voters to approve with at least a 70% member participation rate.

5) Gaining Final Approval. The Standards Review Committee (RevCom) recommends approval or disapproval to the IEEE SA Standards Board. If the

Standards Board approves the draft, the draft undergoes final editing and is then published and distributed. The new standard is also added to the IEEE Electronic Library (IEL).

6) Maintaining the standard. Amendment requests can be sent to IEEE at any time for corrections. Technical changes have to be approved through the balloting process. Standards must either be revised or withdrawn after ten years. A ballot must receive 75% approval to withdraw a standard.

Figure 18 is a more detailed view of the standardization process. A new standard must be published within four years of project authorization. All of these standardization processes are highly beneficial towards meeting the Navy’s needs for procuring stable equipment that interoperates satisfactorily over the course of long ship life cycles.

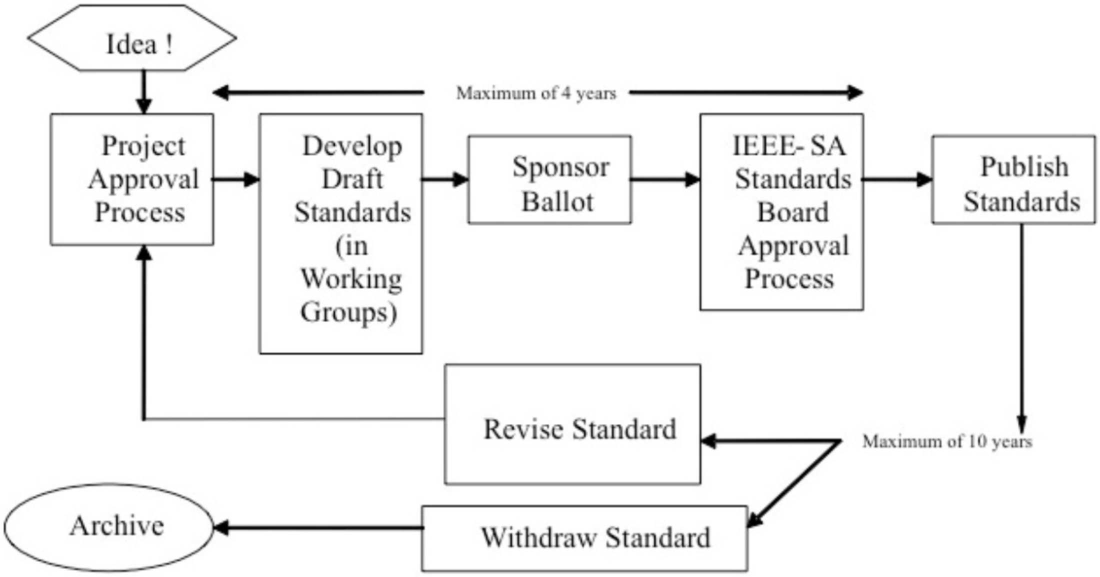


Figure 18. Flowchart of a standard development process from proposal to superseded by an updated standard. Working groups must meet time deadlines for publishing and revising standards. Source: IEEE (n.d-b).

C. IMPLEMENTATION PLAN FOR RAPID DEPLOYMENT TO FLEET

1. Suggested Configuration and Installation

Figure 19 shows two block diagrams for configuring a LiFi luminaire, access point, and Power over Ethernet switches with a fixed access point and a temporary access point that is used as a mobile kit for use in spaces that do not normally require internet connectivity but can be set up to perform maintenance. Additional CAT5 or CAT6 Ethernet cable is needed to connect the LiFi access point to the PoE switch and then to the existing shipboard Ethernet backbone for ships that do not have PoE enabled switches. Figure 20 is an example of a PoE compatible switch for extending Ethernet connectivity to LiFi access points. This distance is minimal and can be done at a reasonable cost and without requiring a major maintenance period. Existing cable is used for the connection from the network access drop through to the gateway router that connects the ship LAN to the Network Operations Center (NOC) ashore. Creating Virtual Private Network (VPN) capability increases the security and any VPN technology can be used that is listed on the Department of Defense Information Network Approved Access List (DODIN APL).

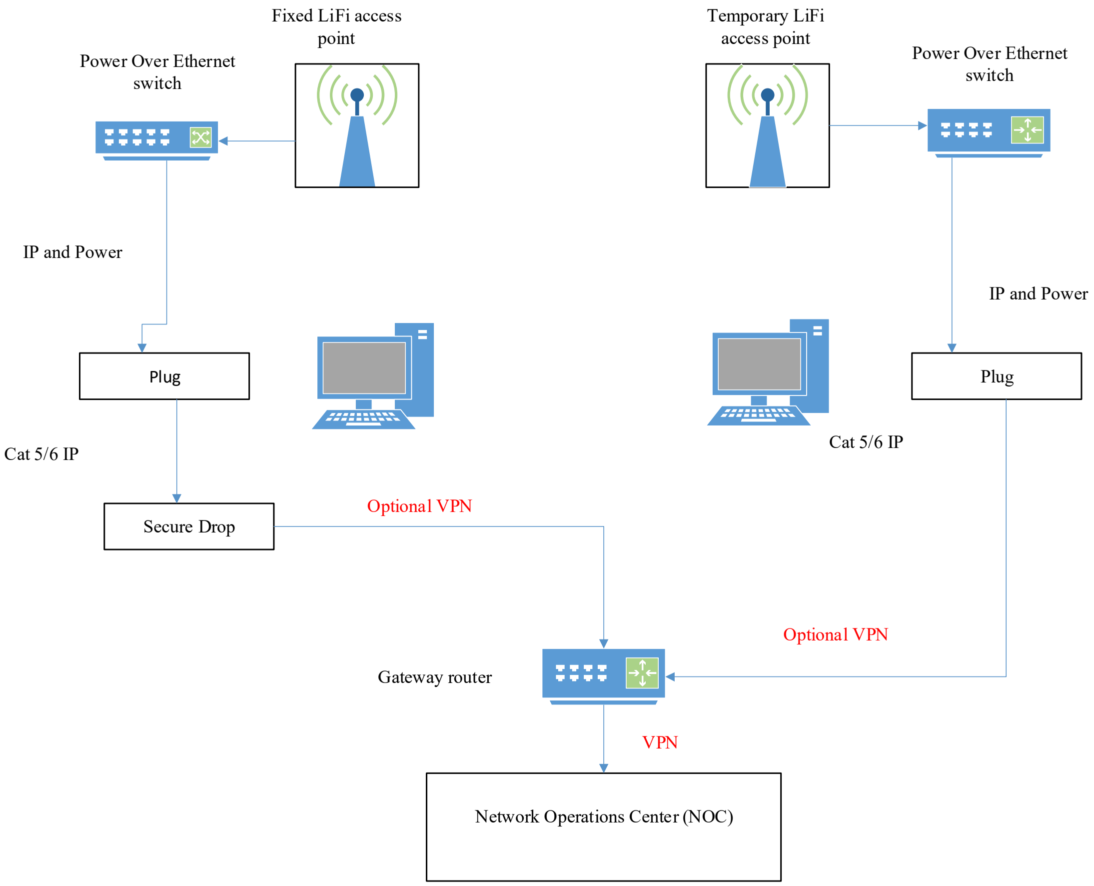


Figure 19. Theoretical Network Diagram for a Fixed LiFi access point and Mobile LiFi access point using Power over Ethernet

Figure 20. CISCO SF350-24P 24-port PoE Managed Switch. PoE switches are also made with 4, 8, 20, and 24 port varieties to accommodate smaller spaces with more restrictive space or power requirements or a larger area like crew berthing or mess spaces. Source: "Cisco SG110D 110 Series 8-Port Unmanaged Network Switch," n.d.

Figure 21 shows a similar configuration but using Power Line Communications for routing. In addition to adding smaller switches for each LiFi configured space, a ship needs at least one master switch per network enclave. Each LiFi AP must also be connected to an UPS to provide backup power long enough to safely power down the system components. UPS are typically required to work for at least 5–10 minutes to prevent damage in case of power outage. Commanding officers need to consider incorporating the process of LiFi restoral in a Standard Operating Procedure (SOP) in emergency situations. During a power casualty, sound powered phones are the primary communication method and LiFi restoration priority is after vital communication systems.

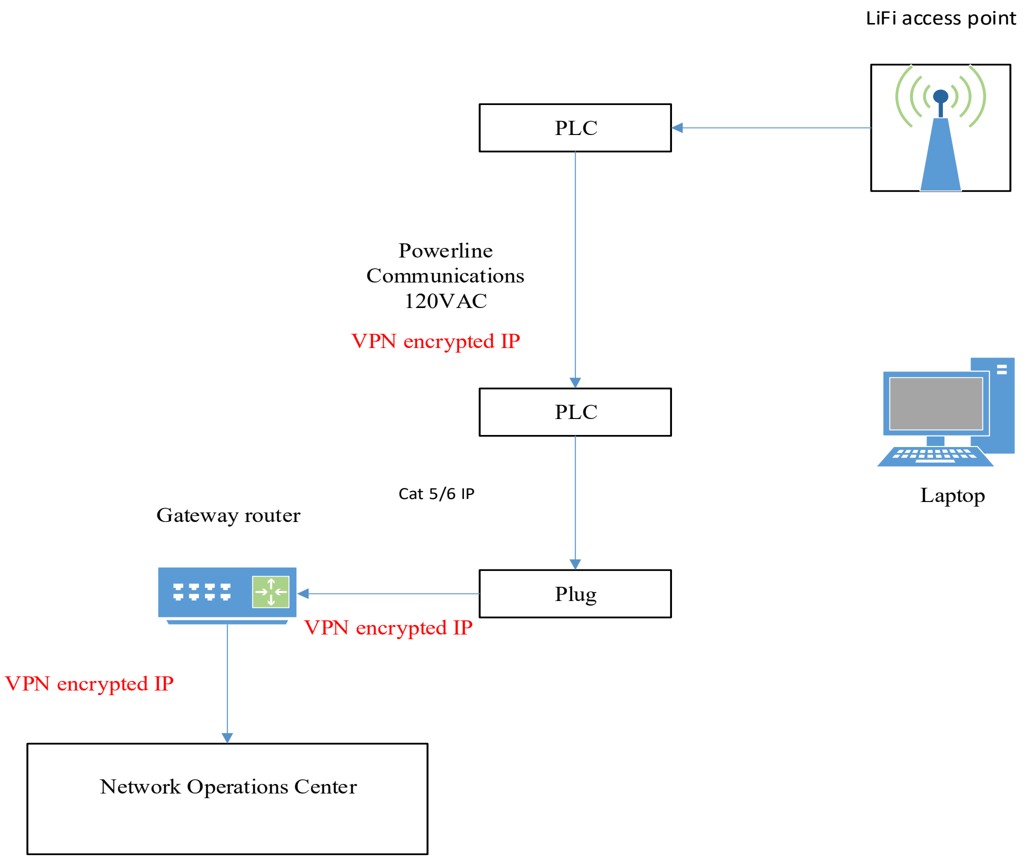


Figure 21. Theoretical Network Diagram for a Fixed LiFi access point using Power Line Communications

A site survey for each ship class is the first step in developing an installation plan. The survey recommends the optimal locations for installing necessary switches and LiFi equipment in terms of performance and for mounting feasibility. Using the DDG 1000 Zumwalt class ship for an initial operational test bed to test performance and durability before implementing across the fleet creates a baseline configuration that can be replicated across the fleet and reveal any technical deficiencies or training requirements. However, the LiFi-XC product is intended for a quick and seamless installation and designed for users of variable technical knowledge and ability.

Table 2 lists the theoretical cell diameter given a ceiling height. The ceiling heights were chosen to show the range of most ceiling heights on a ship and assumes the device is located three feet from the ceiling light. Figure 22 illustrates this relationship between ceiling height and footprint of the LiFi signal. Relatively small increases in height results in increasingly large signal footprints, so fewer lights are needed in spaces with higher ceiling height versus lower heights found in smaller compartments. A site survey has to consider the optimal distance between access points based on the dimensions of each space that both maximizes data coverage and minimizes co-channel interference. The requirements for each space must be considered. Some spaces may not need full coverage. Some spaces may not need a fixed access point and users can use a portable LiFi kit because they are only used during maintenance checks or sporadically for another reason. Users must also be aware of the distance between a device and access point as the signal degrades when there is less than a foot or two of distance between them.

Table 2. Theoretical Cell Diameter assuming an individual access point is placed at a certain ceiling height. These heights cover the most likely range of shipboard space ceiling heights that are within the range of LiFi-XC equipment.

Approximate Ceiling Height (ft)	Theoretical Cell Radius (ft)	Theoretical Cell Diameter (ft)	Theoretical Cell Area (square ft)
6	1.9	3.8	11.3
9	3.85	7.7	46.5
12	5.85	11.7	107.5
15	7.75	15.5	188.6
18	9.7	19.4	295.5

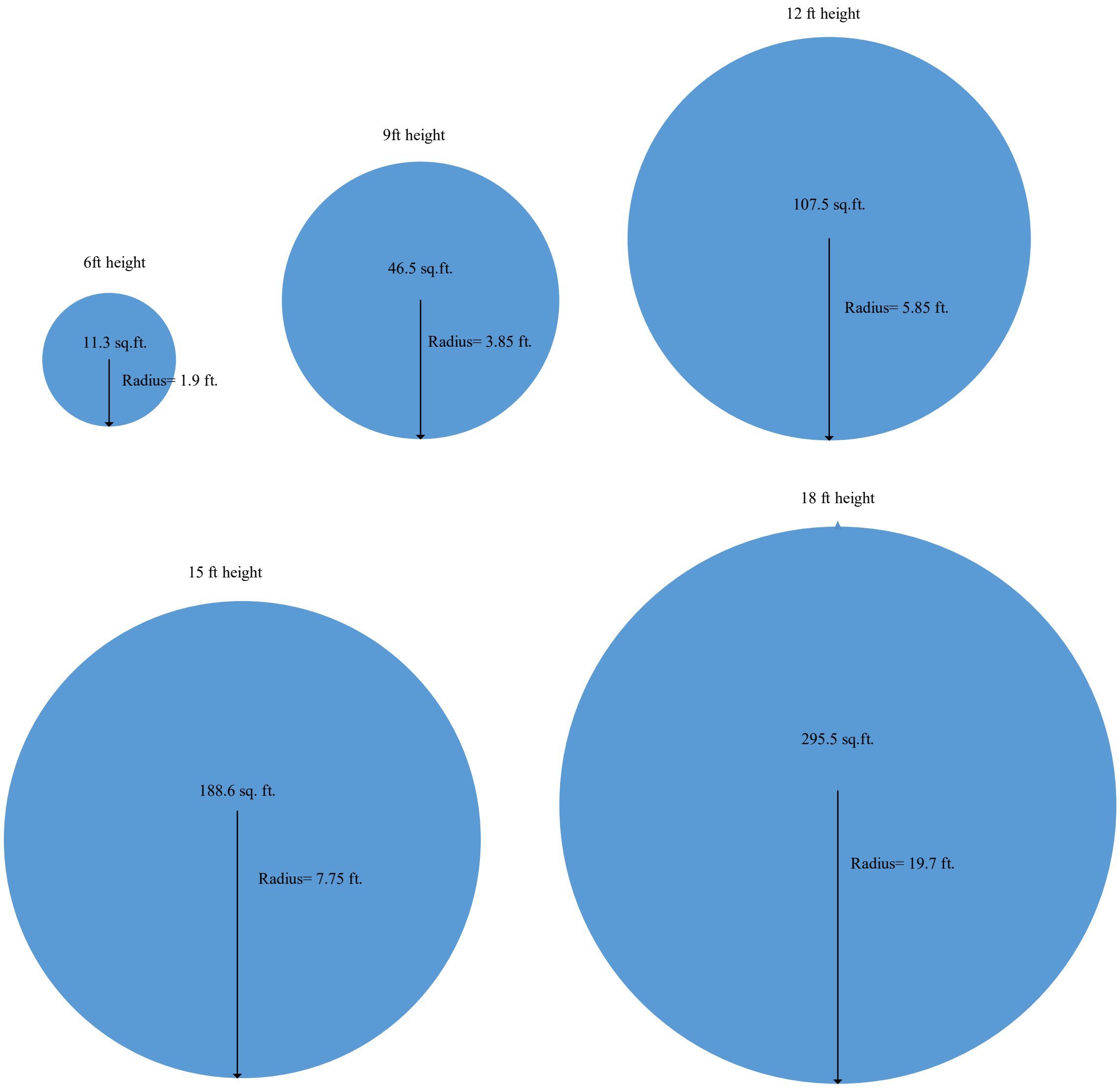


Figure 22. Visual representation and comparison of theoretical cell radius and area for various ceiling heights. Numbers above each circle represent the height of the access point from the LiFi receiver (or the expected height of the receiving computer). Numbers within represent the estimated area of the light footprint. The radius is represented by the arrow in each light footprint.

2. CANES Wireless Access Point (WAP) Conversion

A starting point for determining the number of LiFi devices needed for a ship is to convert Wireless Access Points (WAP) already approved as part of the CANES shipboard network infrastructure. Table 3 lists the recommended number of access points for each ship class based on a suitability survey for WAP installation. Since LiFi uses WiFi standards, the existing infrastructure can theoretically support multiple LiFi access points.

Table 3. List of Wireless Access Points across all ship classes approved for CANES. This includes ships under construction. Adapted from Bacani, R, email to author, November 20, 2019.

Ship Class	**Variant**	**Platforms**	**Number of WAPs per ship**
CG	Mark 41	CG-52- through G-73	18
CVN	Nimitz	CVN-68	46
CVN	Nimitz	CVN-69	39
CVN	Nimitz	CVN-70	45
CVN	Nimitz	CVN-71	36
CVN	Nimitz	CVN-74	34
CVN	Nimitz	CVN-75	36
CVN	Nimitz	CVN-76	32
CVN	Nimitz	CVN-77	45
CVN	Nimitz	CVN-78	44
DDG	Flight I	DDG-51 to DDG-71	10
DDG	Flight II	DDG-72 to DDG-78	12
DDG	Flight IIA 5/54 Variant	DDG-79 to DDG-80	10
DDG	Flight IIA 5/62 Variant	DDG-81 to DDG-84	12
DDG	Flight IIA 5/62 Variant - CIWS	DDG-85 to DDG-112	11
DDG	Zumwalt	1000	165
LCC	Amphibious Command	LCC-19	23
LCC	Amphibious Command	LCC-20	21
LCS	Freedom Class	LCS-1 through LCS-9 (odd number)	7

Ship Class	**Variant**	**Platforms**	**Number of WAPs per ship**
LCS	Independence Class	LCS-2 through LCS-20 (even number)	9
LHA	Flight 0	LHA-6, LHA-7	22
LHD	Wasp	LHD-1 through LHD-7	22
LHD	Wasp	LHD-8	19
LPD	San Antonio	LPD-17 to LPD-28	26
LSD	Whidbey Island	LSD-41 through LSD-48	16
LSD	Harpers Ferry	LSD-42to LSD-49	16

While using wireless access points is a starting point to quickly deliver LiFi capability to a ship, a wireless survey specifically for LiFi technology is necessary to address the number of LiFi access points required to fully support the needs of the force. More LiFi access points are required to match the utility of WiFi as WiFi can provide coverage area for multiple spaces while the signal from each LiFi access point is confined to its individual space.

A two-device LiFi-XC starter kit currently costs $2420. Based on this amount, the cost of procuring LiFi-XC for the 2178 access points listed in Table 3 is $2,635,380. This doesn’t consider discounts provided for bulk orders or additional shipping costs and taxes. One option is to have an initial contract just for installing and testing 165 access points on the DDG 1000 Zumwalt class vessel which costs $199,950 for parts. This does not include additional costs for labor, additional or unexpected outfitting requirements to adapt equipment to the unique shipboard environment, or training. An initial contract for DDG 1000 provides a template to build an accurate cost implementation estimate for the rest of the fleet. Further savings are likely when purchasing in bulk and as LiFi equipment becomes more of a commodity.

3. Shipboard Use Cases

LiFi implementation focused on the most commonly used ship spaces balances the need for additional bandwidth resources with cost. Areas include state rooms, office spaces, passageways, and crew dining areas.

a. State Room

Assuming a state room size of 77 square feet and ceiling height of 8 feet, one LiFi device provides coverage over a desk or bunk area and provide enough additional bandwidth for use by one to three people. Using four LiFi access points in a state room provides full coverage for the space. An estimate for the minimum number of lights required in a typical stateroom is given in Table 3. An example of a LiFi deployment in a small stateroom is shown in Figure 23.

Table 4. Minimum number of LiFi devices for full coverage for a typical state room size. More devices may be needed in some larger rooms that sleep more than three people or Commanding Officer quarters.

Height (ft)	Room Width (ft)	Room Length (ft)	Area (sq.ft.)	Number of LiFi Devices
8	7	11	77	3

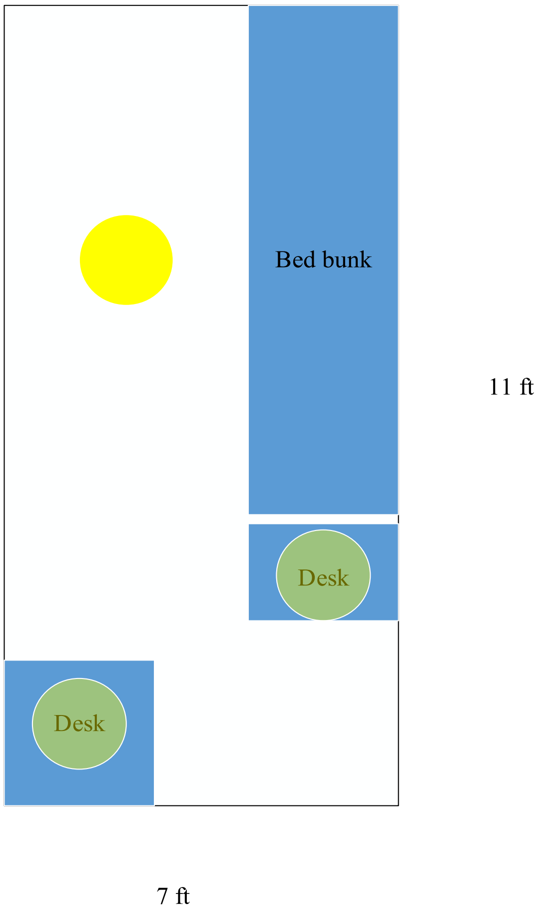


Figure 23. Example of a two-person stateroom on a ship configured for three LiFi access points. The three circles represent the placement of each access point designed to give sufficient coverage for the room.

The current price of a LiFi-XC starter kit with two devices is $2,420. Each system unit costs $1,210 before bulk order discount, taxes, and shipping costs are considered. Implementing four LiFi units costs $4840 per stateroom. For a PLC design, each light has a PLC power supply adjacent to the light fixture and one PLC device connecting to the NOC using the same lighting circuit. For PoE, several spaces use a 24-port switch, or each space uses a dedicated 4 port switch. The cost of additional Ethernet between each access point and the switch manufacturer will differ with each access point, but the CAT5e cable used by the Navy and manufactured by Belkin costs $99.99 per 500 feet. For a relatively small space like a state room, the additional cable costs are likely less than $20 per room assuming an overestimate of 77 feet of additional cable needed.

b. Office Compartment

Assuming a 120 square foot small office compartment and 8-foot ceiling height, four LiFi devices provide area coverage. Figure 24 shows a LiFi deployment in this space according the assumptions listed in Table 4.

Table 5. Minimum number of LiFi devices for full coverage of a small office. Each department or work center generally has a dedicated space to host computers and accomplish administrative tasks like recording training and maintenance completion.

Height (ft)	Room Width (ft)	Room Length(ft)	Area (sq.ft.)	Number of LiFi Devices
8	10	12	120	4

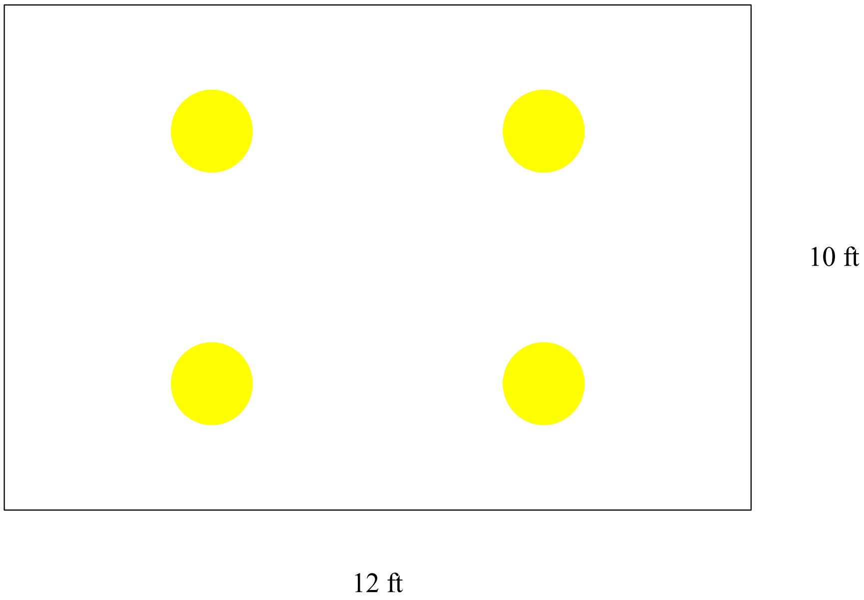


Figure 24. Example of four LiFi access point installed in a small office space.

Implementing four LiFi units costs $4,840 per stateroom. PLC and PoE switch and device considerations are the same as in the state room, with CAT5e costs only being marginally more for approximately $25 to $30 per room, assuming 120 feet of additional cable.

c. Passageway

The diameter of each access point at this size is approximately six feet, so installing each LiFi device five feet apart from one another can create overlap between coverage areas so users maintain connectivity walking through a passageway. The estimated number of required LiFi devices based on these assumptions is given in Table 5.

Table 6. Number of LiFi devices assuming a ceiling placement of 8 feet and a continual passageway of 100 feet. Passageway length in this case is an assumption based on a DDG 1000 Zumwalt class ship.

Height (ft)	Length (ft)	Number of LiFi Devices
8	100	20

Figure 25 shows a passageway LiFi deployment according to the assumptions in Table 5.

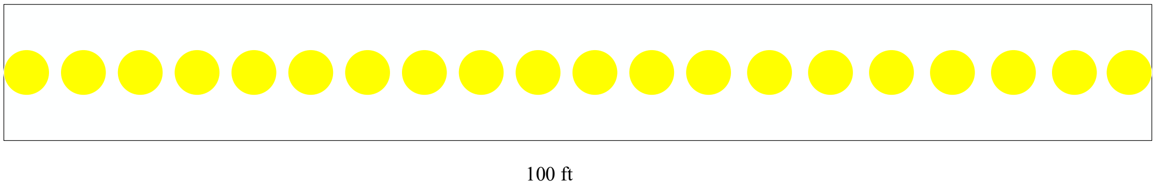


Figure 25. Example of a LiFi configuration for a 100-foot passageway. Twenty access points assumes the optimal distance between access point installation on the ceiling is 5 feet.

Implementing 20 LiFi units in this scenario costs $24,200. One hundred feet of additional CAT5e cable costs approximately $20.

d. Crew Mess

The number of LiFi devices for an area this size assumes each access point will cover an area of approximately 32.3 square feet. More devices may be necessary to create optimal overlap of footprints to ensure seamless handover. An estimate of the number of LiFi devices for a mess on an LSD class ship is listed in Table 6. Figure 26 is a visual representation of a LiFi deployment in this space.

Table 7. Estimate of the number of LiFi devices required to provide full coverage to a crew mess on an LSD class ship.

Height (ft)	Room Width (ft)	Room Length (ft)	Area (sq.ft.)	Number of LiFi Devices
8	30	50	1500	47

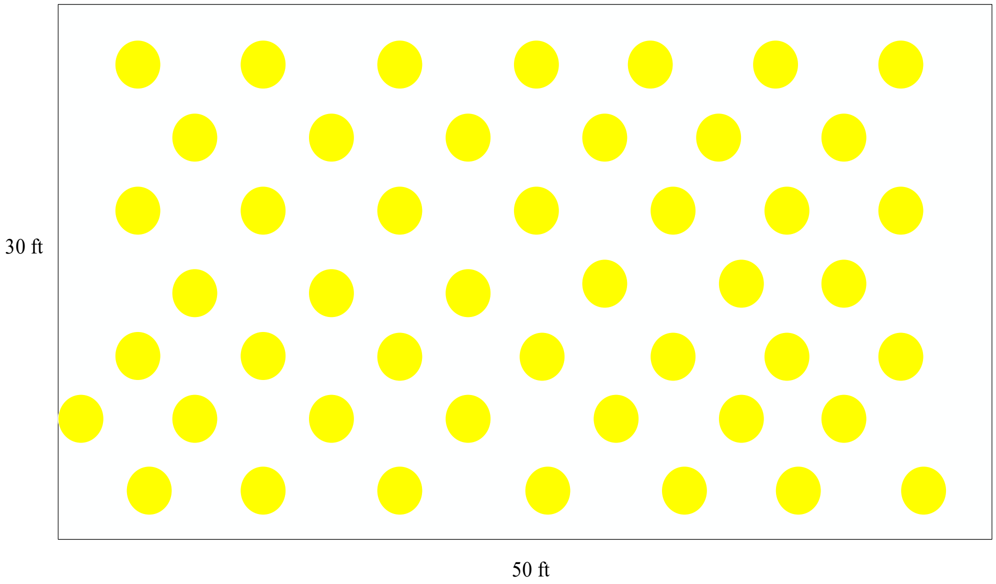


Figure 26. Example of a LiFi deployment in a crew mess with 47 LiFi access points.

Implementing 47 LiFi units in this scenario costs $58,080. Fifteen hundred feet of additional CAT5e cable costs approximately $300. This space needs either two 24 port switches or a larger 48 port device if there is sufficient space for the larger switch. The contractor must carefully consider the switch placement and distance between access points to minimize the cable length required between access points and the switch.

e. USS UNDERWAY LiFi Requirements Form

Table 7 condenses the previous tables into a single form that can document a ship's LiFi needs and assist the Program Officer in determining the number of access points needed per class of ship in a contract. The ship's Electronic Maintenance Officer (EMO) can uses this survey to provide guidance to the Commanding Officer on the ship's specific LiFi needs.

Table 8. Example of a combined survey of hypothetical ship USS Underway's estimated LiFi requirements

Compartment	Ceiling Height	Longest Side (ft)	Number of Devices
Officer Stateroom	8	11	3
Office	8	12	4
Passageway	8	100	20
Crew Mess	8	50	47
Total		173	74

4. Risk Management Framework (RMF) and Authority to Operate (ATO)

All DOD IT systems must satisfy the security requirements delineated in the Risk Management Framework (RMF) process before installation on government network (Department of Defense Chief Information Officer, 2017). Program Managers and Authorizing Officials (AO) are responsible for ensuring any system that handles data pertaining to national security meets all security requirements and can integrate into the existing IT infrastructure. The specific requirements are described in Figure 27 describes the specific RMF requirements and the entire systems life cycle applies for larger IT systems like CANES. IT below the enterprise system level do not have to go through the entire RMF process but must still undergo evaluation and testing and receive an Authorization to Operate (ATO) before connecting to a Platform IT or Information System.

If LiFi is implemented into a larger Program of Record, it has to still adhere to the security baseline requirements for technology deployed in a shipboard environment.

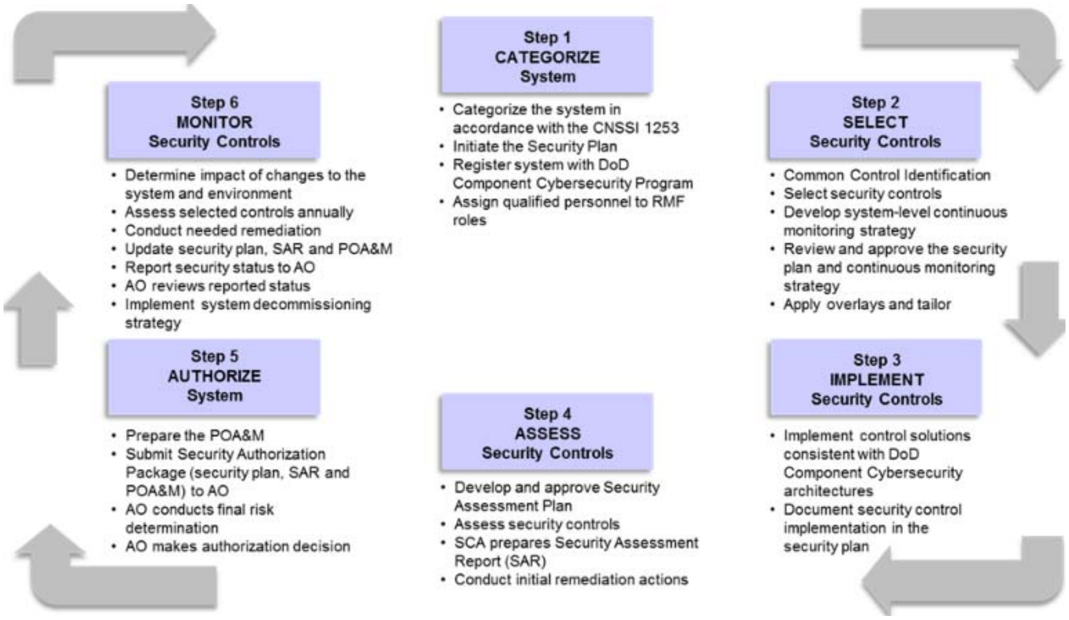


Figure 27. The six steps of the DOD Risk Management Framework (RMF). Source: DOD CIO (2017).

The Authorization to Operate (ATO) process only required once per system, called a Type Authorization (DOD CIO, 2017). One ATO can apply to the entire fleet for identical systems. A Navy Program Manager and AO need to verify LiFi system development in other DOD entities. If one DOD service tests an validates a system, the only additional testing requirement is specific to a different operational environment. The first step is to gain approval for an Interim Authorization to Test (IATT) that states the period for which it can be tested with specific operational conditions and constraints. An Interim Authorization to Operate (IATO) can be used for up to six months before an ATO. An ATO lasts for three years but has to be annually reviewed and must specify proper usage and modes of operation to prevent network problems and maintain a baseline across different.

Ensuring technology implements Security Technical Implementation Guides (STIG) is also a requirement in the RMF process (DOD CIO, 2017). A LiFi product must be assessed to determine if STIGs need to be developed specifically for light communication applications. Network STIG requirements are listed on the iase.navy.mil and can be accessed with a CAC card.

Security instructions also need changes to incorporate light communication technology. While the ATO can delineate use requirements and limitations, ship Commanding Officers must also ensure their command instructions follow the SECNAVINST 5239.3C DoN Cybersecurity Policy and LiFi use policy is articulated and enforced. Ship policy must also consider a contingency plan for disaster situations or other conditions where LiFi capability is degraded or unusable.

5. Acquisition Strategy

The three aspects underpinning DOD Acquisition are requirements development, acquisition, and budgeting (Department of Defense, 2017). These are interrelated processes that occur simultaneously and must be considered synchronously in order to successfully field to the DOD.

Figure 28 shows the Joint Capabilities and Development System (JCIDS) process. The JCIDs process is where requirements are translated into capabilities that can be developed on a system engineering level or can be procured (Department of Defense, 2017). The stages of the JCIDS process align with the Milestone A, B, and C decision points also seen in the acquisition process. LiFi can use an existing requirement to justify installation on a ship, as requirements are overarching concepts that usually do not drastically change. New equipment is often designed to update an existing requirement and usually not to solve an existing capabilities gap. Examples of requirements that LiFi fulfills are ensuring survivability of the network and secure communications.

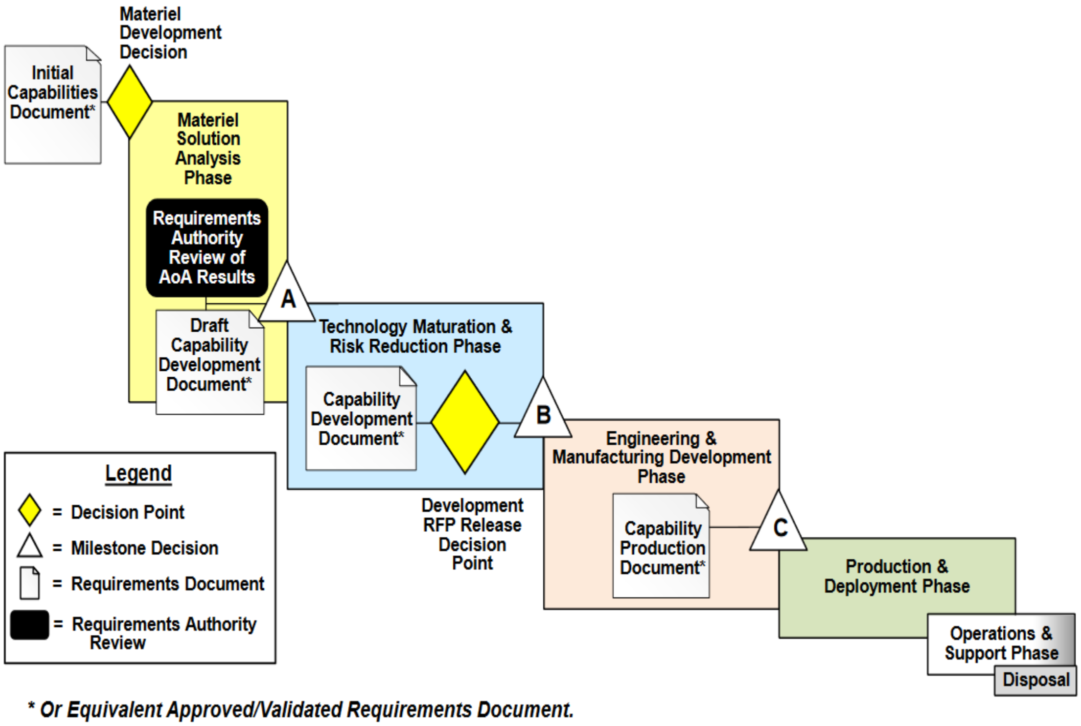


Figure 28. Joint Capabilities and Development System (JCIDS) process. The Initial Capabilities Document begins the development process and must be finalized in the Capability Production Document before full production and deployment of a product or system. Source: Department of Defense (2017).

Figure 29 shows the stages of the acquisition process, which is an event driven process (Department of Defense, 2017). Identification of a solution is required before a Milestone A decision. At Milestone B, technology maturation and risk decisions are made, and the project becomes a Program of Record. At Milestone C, a decision is made to produce or field a system in a limited capacity to perform operational testing. The final stage is full deployment and addressing sustainment requirements. Since procurement of LiFi doesn't require development, LiFi can be a post Milestone C procurement with a limited deployment and operational test used to develop solutions to configuration and integration problems that may arise.

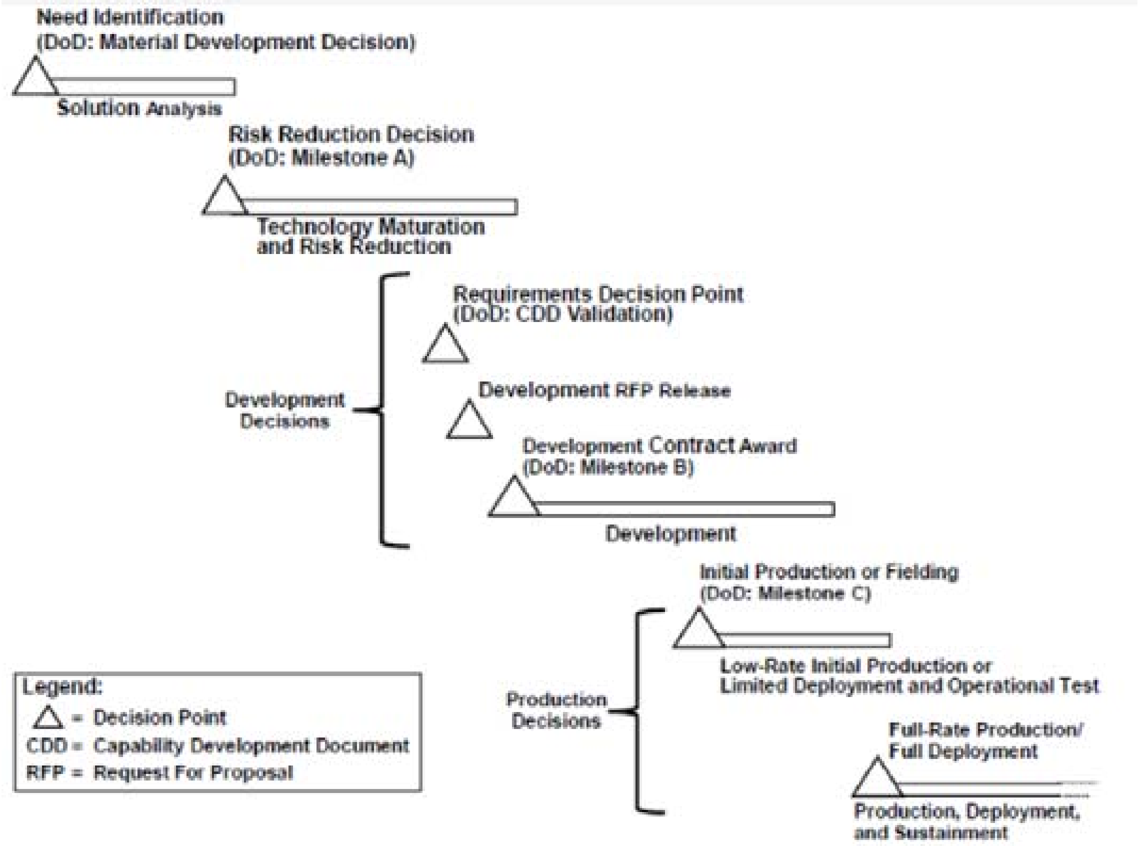


Figure 29. The DOD Acquisition Process. The process is meant to ensure the proper allocation of resources for a project and ensure optimal value is delivered to the warfighter. Source: Department of Defense (2017).

Planning, Programming, Budgeting, and Execution (PPBE) is the process that governs budgeting and requires services to think two years in advance to receive money necessary to develop and field desired capabilities (McGarry & Peters, 2018). Figure 30 shows this allocation process.

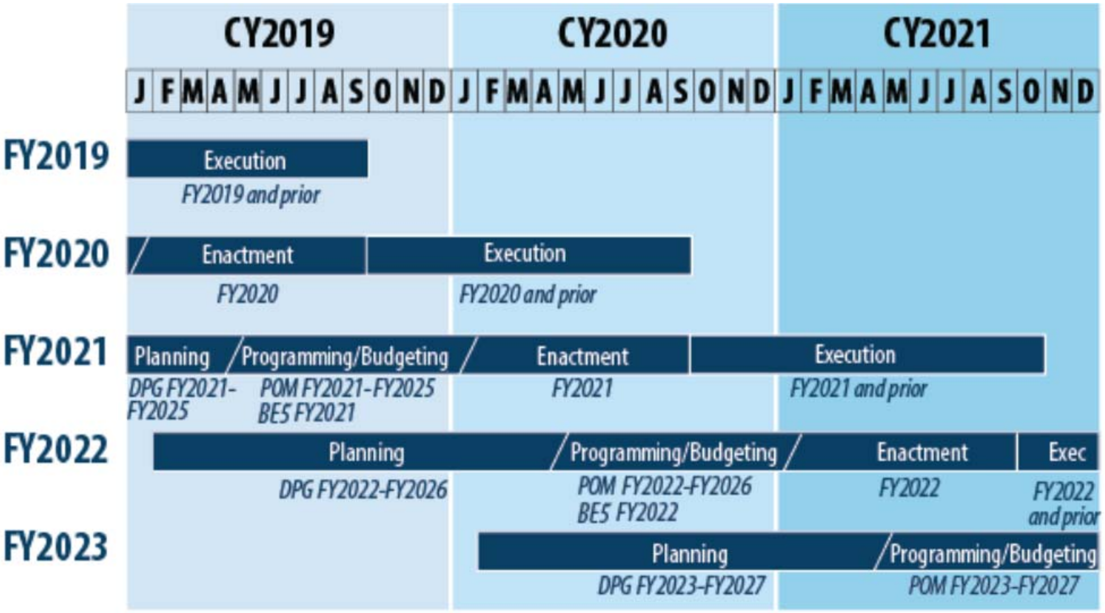


Figure 30. The PPBE process. Different stages are simultaneously occurring, although planning normally varies little from year to year. Source: McGarry and Peters (2018).

Budgeting is the biggest problem for deploying LiFi if not planned for properly and if congressional limits aren't followed. It is possible for LiFi to be implemented as a change to an existing program if the total costs are within specific limits. If a new procurement costs less than $10 million within a three-year period, the decision doesn't require congressional approval (Department of Defense, 2015). If the total costs are greater, procurement can still be justified but must be approved by Congress (Department of Defense, 2015). For the example of using existing CANES wireless access points, the program manager overseeing wireless installation must ensure any existing contracts were properly cancelled and the new contract didn't cause CANES to have program issues.

One of the challenges of technology acquisition is that the commercial sector develops state of the art technology faster and more efficiently than the Joint Capabilities and Development System (JCIDS) process, making procurement the best solution ("DOD Use of Commercial Acquisition Practices: When They Apply and When They Do Not," 2015). The most critical aspect for creating a contract that delivers maximum capability to the fleet is clearly define requirements to prevent offers that offer cost savings with less capability and procure modular systems avoiding vendor lock in. Metrics to specify in a procurement contract include minimum bandwidth for uplink and downlink of each LiFi device, ability to maintain performance in harsh operational environments ships are exposed to, and technological maturation levels of 8 or above. The sustainment phase also must be clearly defined to allow a technology refresh to take advantage of advancements in LiFi technology.

The most effective plan for an initial deployment might be to create a contract for DDG 1000 to perform operational testing and refine performance metrics. If LiFi satisfies desired capability, then budget requirements can be revisited, and a full fleet deployment can be efficiently planned.

D. SUMMARY

There is a myriad of factors to consider for achieving rapid and efficient deployment of LiFi in a shipboard environment. An adopted Light Communications standard is necessary for achieving enough technology maturation for approval by the DOD acquisitions system. There are no major acquisition barriers for deploying LiFi, but careful planning and coordination at the program manager level is important to ensure timely fielding to prevent budgeting problems impacting program success. LiFi can be installed on a ship using existing infrastructure with relatively few additions of cabling and networking devices required. A comprehensive site survey to determine the most optimal locations for LiFi access points is required to determine if there is any difference from CANES wireless access point placement and assess special requirements for designated ship spaces unique to each ship class.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

LiFi is emerging as a viable alternative to WiFi technology and current systems can provide high data rates and secure communications needed and desired by sailors afloat. There are no known impediments that rule out LiFi for shipboard communications. Because LiFi is an edge network device, it can use existing shipboard infrastructure and either complement or replace the wireless access points authorized for CANES. While LiFi-XC is only system discussed in detail, other companies are designing their own systems and providing market competition that increases performance and minimizing costs.

Power Line Communications (PLC) and Power over Ethernet (PoE) are both capable of supporting secure LiFi data traffic, but more testing and cost analysis is needed to determine which method facilitates faster delivery to the fleet while also providing the better long-term reliability. Using encryption and VPN software are ways to mitigate security concerns with either medium, although the metallic environment on ships decreases likelihood of signal leakage. While LiFi technology has been successfully tested onboard ships in operational environments, performance and integration with shipboard LED lighting for the LiFi-XC product is unknown in an operational environment. The extent of LiFi-XC’s tolerance in a shipboard environment is also unknown and additional research is required to ensure LiFi is interoperable with existing shipboard network enterprise systems. Coordination between NIWC and Naval Sea Systems Command (NAVSEA) program managers is important to implementing LiFi into shipboard architecture on vessels currently in the planning and construction stages.

Light Communication standardization is critical for meeting large scale deployment to the fleet. LiFi technologies must demonstrate technology maturation to meet the standard of the DoDs acquisition process, and procurement contracts must be carefully written so the best value system is implemented to the fleet that allows system upgrades so the Navy can take advantage of cutting-edge communications technology. Commercial over the

Shelf (COTS) technology must be prioritized for more rapid support to the fleet. Routing loops are exceptionally harmful and every effort must be made to prevent them on the network.

B. RECOMMENDATIONS FOR FUTURE WORK

The following are steps for ship personnel in deploying LiFi onboard a ship. This is intended as a useful checklist for an EMO and other officers responsible for communications equipment.

- Conduct a preliminary survey of desired spaces for LiFi installation. Estimate number of LiFi devices needed according to the performance parameters of the equipment.
- Determine if any CANES WiFi access points are in optimal spaces for LiFi and incorporate into survey.
- Compile a request form for LiFi installation with Commanding Officer approval.
- Request and order VPNs as part of LiFi installation plan. Verify the VPNs are allowed for shipboard installation in accordance with the DoDIN APL.
- After installation, ensure ATO includes documentation for acceptable use and configuration requirements for crew use to prevent network performance problems.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

A future thesis using a laboratory set up of a ship compartment with multiple LiFi-XC access points ship and testing performance at heights between 6 feet and 18 feet to account for variance in ship spaces would help in the development of specific needs for each ship platform. This can also be duplicated with other LiFi products for comparison and provide more guidance on the best product for ship networks. Commercial companies are also experimenting with devices with infrared downlink which has fewer bandwidth limitations than LED. Finding solutions for ceiling heights greater than 18 feet for hanger bays and well decks warrants further study. Another question for shipboard suitability is if a light communication channel can be created using only red-light LED for use on the bridge and hallways during night hours when white light can’t be used. Testing LiFi performance in smoky environments is needed to determine thickness and particle levels that can degrade communications capability. Another area for further study is exploring LiFi ATO requirements for Secret and Top Secret networks.

Forming a cooperative research development agreement (CRADA) between NPS and PureLifi presents opportunities to research and test products in development and collaborate on designing LiFi systems suitable for naval and other tactical applications.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX: PURELIFI VISIT REPORT

As part of a research grant from NIWC San Diego, I travelled to PureLifi headquarters in Edinburgh, Scotland, from October 21 to October 23 to gain insight into the development in LiFi communications and state of the art technology in development. Vice President of Standardization & Business Development Nikola Serafimovski, PureLifi cofounder Dr. Harald Haas, Vice President of Business Development West Coast (United States) Roger Jellicoe, and PureLifi CEO Alistair Banham volunteered their time to assist in my research and understanding of their LiFi technology and its real-world applications.

Listed are the highlights of information discussed during this trip that helped formulate the questions and scenarios considered in the thesis.

- Information on current collaboration with the DOD. PureLifi equipment test bed at a U.S. Army Group Europe Tactical Operations Center for wireless Wide Area Networks and and FSO. Forces in China Lake, California are also experimenting with LiFi using RGB LED and infrared technology.
- Progress of the development of proposed IEEE standard 802.11bb. Nikola Serafimovski is the chair of the working group.
- NSA plans for approving LiFi as a commercial solution for classified networks.
- Navy Research Labs incorporating LiFi into FSO communication links with TALON
- Ruggedized tablet options for LiFi enabled devices.
- Switch and AP configuration options for shipboard installation, and considerations for retrofitting existing Navy LED lights to work with PureLifi AP and dongles.

- Lab demonstration of the newest generation of LiFi transceiver that uses infrared for both downlink and uplink and the benefits of infrared compared to visible light.
- Security details of LiFi-XC hardware and software, and discussion of reliability and maintenance requirements for life cycle management.

LIST OF REFERENCES

Akinnikawe, A., & Butler-Purry, K. L. (2009). Investigation of broadband over power line channel capacity of shipboard power system cables for ship communication networks. 2009 IEEE Power & Energy Society General Meeting, 1–9. https://doi.org/10.1109/PES.2009.5275639

Atya, A. O. F., Sundaresan, K., Krishnamurthy, S. V., Khojastepour, M. A., & Rangarajan, S. (2015). BOLT: Realizing high throughput power line communication networks. *Proceedings of the 11th ACM Conference on Emerging Networking Experiments and Technologies - CoNEXT '15*, 1–13. https://doi.org/10.1145/2716281.2836124

Babcock International. (2019, September 11) *Babcock Delivers iFrigate Trial First for Royal Navy Warship*. Retrieved November 3, 2019, from https://www.babcockinternational.com/news/babcock-delivers-ifrigatetm-trial-first-for-royal-navy-warship/

PureLifi. (n.d). *Babcock smart facility powered by pureLiFi*. Retrieved November 3, 2019, from https://purelifi.com/case-study/babcock-powered-by-purelifi/

Barmada, S., Bellanti, L., Raugi, M., & Tucci, M. (2010). Analysis of Power-Line Communication Channels in Ships. *IEEE Transactions on Vehicular Technology*, *59*(7), 3161–3170. https://doi.org/10.1109/TVT.2010.2052474

Brutzman, D. (2014, March 2). *Network Optional Warfare (NOW) Concepts Exploration and Enabling Technologies*. [Working Paper]. Naval Postgraduate School.

Brutzman, D., Hughes, W., Kline, J., Buettner, R., & Jr, J. J. E. (2014, March 2). *Network-Optional Warfare (NOW)—Operational Employment Concepts*. [Working Paper]. Naval Postgraduate School.

Burchardt, H., Serafimovski, N., Tsonev, D., Videv, S., & Haas, H. (2014). VLC: Beyond point-to-point communication. *IEEE Communications Magazine*, *52*(7), 98–105. https://doi.org/10.1109/MCOM.2014.6852089

Wired. (n.d.). *ByteLight Solves Indoor GPS Mapping Problem With LED Lighting | WIRED*. Retrieved December 12, 2019, from https://www.wired.com/2013/01/bytelight-indoor-mapping/

Category 6 cable. (n.d.). In "What Really Changes with Category 6." Retrieved from https://en.wikipedia.org/w/index.php?title=Category_6_cable&oldid=926486614

CHIPS Magazine. (2018, July-September). *Navy Aims for "Compile to Combat in 24 Hours." (2018, July-September)*. Retrieved October 30, 2019, from https://www.doncio.navy.mil/chips/ArticleDetails.aspx?ID=10501

Chowdhury, M. Z., Hossan, Md. T., Islam, A., & Jang, Y. M. (2018). A Comparative Survey of Optical Wireless Technologies: Architectures and Applications. *IEEE Access*, *6*, 9819–9840. https://doi.org/10.1109/ACCESS.2018.2792419

Delgado, F., Quintana, I., Rufo, J., Rabadan, J. A., Quintana, C., & Perez-Jimenez, R. (2010). Design and Implementation of an Ethernet-VLC Interface for Broadcast Transmissions. *IEEE Communications Letters*, *14*(12), 1089–1091. https://doi.org/10.1109/LCOMM.2010.12.100984

Department of Defense. *Department of Defense Instruction 5000.02 Operation of the Defense Acquisition System*. (2017, August 10).

Department of Defense. *DOD Financial Management Regulation: Volume 3, Chapter 6*. (2015, May).

DOD Use of Commercial Acquisition Practices: When They Apply and When They Do Not. (2015, October). *Defense AT&L*.

Department of Defense Chief Information Officer. *DoDI 8510.01 Risk Management Framework (RMF) for DOD Information Technology (IT)*. (2017, July 28).

Firefly LiFi; Firefly LiFi Demonstrates Commercially Available and ITU G.vlc Standard Recommendation Compliant LiFi Solutions at the Broadband World Forum. (2018, November 5). *Network Business Weekly; Atlanta*, p. 59. http://search.proquest.com/docview/2128164692/citation/4C1ABB92F6F64CA2PQ/1

Galli, S., & Logvinov, O. (2008). Recent Developments in the Standardization of Power Line Communications within the IEEE. *IEEE Communications Magazine*, *46*(7), 64–71. https://doi.org/10.1109/MCOM.2008.4557044

Galli, S., Scaglione, A., & Wang, Z. (2011). For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid. *Proceedings of the IEEE*, *99*(6), 998–1027. https://doi.org/10.1109/JPROC.2011.2109670

Goodman, C. (2019). *An Introduction to Tempest*. SANS. Retrieved from https://www.sans.org/reading-room/whitepapers/privacy/introduction-tempest-981

Gorshe, S., Raghavan, A., Starr, T., & Galli, S. (2014). Power Line Communications. In *Broadband Access: Wireline and Wireless—Alternatives for Internet Services* (pp. 249–285). https://doi.org/10.1002/9781118878774.ch13

Haas, Harald. (2018). LiFi is a paradigm-shifting 5G technology. *Reviews in Physics*, *3*, 26–31. https://doi.org/10.1016/j.revip.2017.10.001

Haas, Harald, Chen, C., & O'Brien, D. (2017). A guide to wireless networking by light. *Progress in Quantum Electronics*, *55*, 88–111. https://doi.org/10.1016/j.pquantelec.2017.06.003

Haas, Harald, Yin, L., Wang, Y., & Chen, C. (2016). What is LiFi? *Journal of Lightwave Technology*, *34*(6), 1533–1544. https://doi.org/10.1109/JLT.2015.2510021

High-speed indoor visible light communication transceiver – System architecture, physical layer and data link layer specification: Recommendation ITU-T G.9991. (2019, March). International Telecommunications Union.

Institute of Electrical and Electronics Engineers. (2018a, August 31). I*EEE 802.3-2018—IEEE Standard for Ethernet.* IEEE. Retrieved November 14, 2019, from https://standards.ieee.org/standard/802_3-2018.html

Institute of Electrical and Electronics Engineers. (2019a, January 31) *IEEE 802.3bt-2018—IEEE Approved Draft Standard for Ethernet—Amendment 2: Power over Ethernet over 4 Pairs.* IEEE. Retrieved August 4, 2019, from https://standards.ieee.org/content/ieee-standards/en/standard/802_3bt-2018.html

Institute of Electrical and Electronics Engineers. (2016, December 14).*IEEE 802.11-2016—IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. IEEE. Retrieved November 14, 2019, from https://standards.ieee.org/standard/802_11-2016.html

Institute of Electrical and Electronics Engineers. (2019b, April 23). *IEEE 802.15.7-2018—IEEE Standard for Local and metropolitan area networks—Part 15.7: Short-Range Optical Wireless Communications*. IEEE. Retrieved November 14, 2019, from https://standards.ieee.org/standard/802_15_7-2018.html

Institute of Electrical and Electronics Engineers. (2010, December 30).*IEEE 1901–2010—IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications*. IEEE. Retrieved November 16, 2019, from https://standards.ieee.org/standard/1901-2010.html

Institute of Electrical and Electronics Engineers. (2019c, June 19) *IEEE 1901a-2019—IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications—Amendment 1: Enhancement for Internet of Things Applications*. IEEE. Retrieved November 17, 2019, from https://standards.ieee.org/standard/1901a-2019.html

Institute of Electrical and Electronics Engineers. (2018b). *IEEE P802.11—LIGHT COMMUNICATION TASK GROUP*. IEEE. Retrieved October 24, 2019, from http://www.ieee802.org/11/Reports/tgbb_update.htm

Institute of Electrical and Electronics Engineers. (n.d-a.). *IEEE SA - Developing Standards*. IEEE. Retrieved December 5, 2019, from https://standards.ieee.org/develop/index.html

Institute of Electrical and Electronics Engineers (n.d-b.) *IEEE SA-How are Standards Made?* Retrieved December 5, 2019 from https://standards.ieee.org/develop/develop-standards/process.html

Karunatilaka, D., Zafar, F., Kalavally, V., & Parthiban, R. (2015). LED Based Indoor Visible Light Communications: State of the Art. *IEEE Communications Surveys Tutorials*, *17*(3), 1649–1678. https://doi.org/10.1109/COMST.2015.2417576

Komine, T., & Nakagawa, M. (2003). Integrated system of white LED visible-light communication and power-line communication. *IEEE Transactions on Consumer Electronics*, *49*(1), 71–79. https://doi.org/10.1109/TCE.2003.1205458

PureLifi. (n.d.). *LiFi Technology*. Purelifi.com. Retrieved August 18, 2019, from https://purelifi.com/lifi-technology/

LiFiMAX®. (2019, January 8). *LiFiMAX® High speed internet through invisible light.* Oledcomm. Retrieved December 12, 2019, from https://www.oledcomm.net/lifi-max/

Lightbee. (n.d.). *LightDim Lightbee*. Lightbee Corporation. Retrieved December 11, 2019, from http://lightbeecorp.com/services/lightdim/

Lucas, A. R. (2013). *Digital semaphore: Technical feasibility of QR code optical signaling for fleet communications*.[Master's Thesis, Naval Postgraduate School].

Ma, H., Lampe, L., & Hranilovic, S. (2013). Integration of indoor visible light and power line communication systems. *2013 IEEE 17th International Symposium on Power Line Communications and Its Applications*, 291–296. https://doi.org/10.1109/ISPLC.2013.6525866

Majumder, A., & Caffery J, Jr. (2004). Power line communications. *IEEE Potentials*, *23*(4), 4–8. https://doi.org/10.1109/MP.2004.1343222

Department of Defense (n.d.). *Summary of the 2018 National Defense Strategy of the United States of America: Sharpening the American Military's Competitive Edge*.Retrieved from https://dod.defense.go/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

McGarry, B. W., & Peters, H. M. (2018). Defense Primer: Planning, Programming, Budgeting and Execution (PPBE) Process. *Congressional Research Service*.

Meenecke, R., & Holzinger, E. (2018). *Trident Warrior Li-Fi Test Report* (No. AOS-18-1171; p. 20). John Hopkins Applied Physics Laboratory.

Mendelson, G. (n.d.). *All You Need To Know About Power over Ethernet (PoE) and the IEEE 802.3af Standard*. PowerDsine Ltd.

Ni, W., Liu, R. P., Collings, I. B., & Wang, X. (2013). Indoor cooperative small cells over ethernet. *IEEE Communications Magazine*, *51*(9), 100–107. https://doi.org/10.1109/MCOM.2013.6588657

Papaioannou, A., & Pavlidou, F. (2009). Evaluation of Power Line Communication Equipment in Home Networks. *IEEE Systems Journal*, *3*(3), 288–294. https://doi.org/10.1109/JSYST.2009.2023202

Paspalaris, D. (2019). *Application and Feasibility of Light Fidelity (LiFi) and Power Line Communications (PLC) On U.S. Navy Ships*. [Master's Thesis, Naval Postgraduate School].

PureLifi (2017a). *LiFi-XC Access Point User Manual*. [Handbook].

PureLifi (n.d.). *Access Point Network, Electrical, and Physical Requirements*. [Handbook].

PureLifi (2017b). *Virtual Management User Guide*. [Handbook].

PureLifi (2017c). *LiFi-XC Station User Manual*. [Handbook].

Rajbhandari, S., McKendry, J. J. D., Herrnsdorf, J., Chun, H., Faulkner, G., Haas, H., … Dawson, M. D. (2017). A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications. *Semiconductor Science and Technology*, *32*(2), 023001. https://doi.org/10.1088/1361-6641/32/2/023001

Richter, S. P. (2013). *Digital semaphore: Tactical implications of QR code optical signaling for fleet communications*. [Master's Thesis, Naval Postgraduate School].

Routing loop problem. (2019). In "TCP/IP Exterior Gateway Protocol (EGP)." Retrieved November 26 from https://en.wikipedia.org/w/index.php?title=Routing_loop_problem&oldid=892596938

Signify. (2019, June 19). *Signify Launches Trulifi: The World's Most Reliable, High Speed Commercial LiFi Systems*. The Business of LiFi. Retrieved December 11, 2019 from https://lifireport.com/signify-launches-trulifi-the-worlds-most-reliable-high-speed-commercial-lifi-systems/

Song, J., Ding, W., Yang, F., Yang, H., Yu, B., & Zhang, H. (2015). An Indoor Broadband Broadcasting System Based on PLC and VLC. *IEEE Transactions on Broadcasting*, *61*(2), 299–308. https://doi.org/10.1109/TBC.2015.2400825

Tsonev, D., Chun, H., Rajbhandari, S., McKendry, J. J. D., Videv, S., Gu, E., O'Brien, D. (2014). A 3-Gb/s Single-LED OFDM-Based Wireless VLC Link Using a Gallium Nitride $\mu\rm LED$. *IEEE Photonics Technology Letters*, *26*(7), 637–640. https://doi.org/10.1109/LPT.2013.2297621

S.Venkatesulu, L.Hemasundar, M.Sreeja, K.Divya, G.Jeevan Kumar, M.Bhogendranadh (2014, April). Data Transmission and Reception using Power Line Communication. International Journal of Research in Advent Technology, 2(4), 250–255

VLNComm. (n.d.). *VLNComm—LumiStick II: LiFi USB Adapter.* (n.d.). Retrieved December 11, 2019, from https://vlncomm.com/LumiStick2.html

Wolfe, R. (2018). *LiFi Experimental Setup and Test Results*.

Xi, X., Tao, C., & Fang, X. (2007). A Health Care System Based on PLC and Zigbee. *2007 International Conference on Wireless Communications, Networking and Mobile Computing*, 3063–3066. https://doi.org/10.1109/WICOM.2007.761

Yousuf, M. S., & El-Shafei, M. (2007). Power Line Communications: An Overview - Part I. *2007 Innovations in Information Technologies (IIT)*, 218–222. https://doi.org/10.1109/IIT.2007.4430363

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California