Marine Infrared Communication Repeater with Optical Propagation

Senior Project 2021-2022

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ABSTRACT

Free space communication systems have enjoyed increased attention due to their high transmission speed, high throughput, and infrastructure-free applications. However, these systems are generally either expensive or static devices. An affordable, dynamic system is required for the creation of ad-hoc networks and to widen adoption of the system. An affordable dynamic system was designed using commercial off-the-shelf products and widely accepted standards, allowing for hobbyist and personal use. The components were tested and operation of greater than 900Mbps was confirmed for the system operating with a fiber optic cable as a transmission medium. This system was designed to operate in near-infrared and was chosen to be eye safe for wide adoption. Work remains to confirm operation of the system in free space and to implement the dynamic scanning system.

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INTRODUCTION

As data becomes increasingly important in warfare, large amounts of information must be transmitted between various units in the field. Current radio frequency (RF) communication is limited in bitrate and cannot continue to serve as the sole transmission medium. Free space optical communication (FSOC) systems offer high speed transmission without expensive infrastructure. However, FSOC systems are limited by their prohibitively high cost and inability to dynamically follow targets. High-performance systems can cost hundreds of thousands. Koruza, another cheap static system using similar items as this design costs over $2000. [1] They are therefore limited to large bases and some slow-moving ships. A cheap, dynamic system would expand utility to smaller units and allow for the sharing of data with more components. In civilian applications, this system can help in disaster relief and in rural communities by offering a high-quality communication system without expensive infrastructure.

Cheaper FSOC systems exist but are limited to hobbyist applications. A scientific testbed is required to advance the field of low-cost dynamic systems. Moreover, no open-source affordable dynamic systems currently exist. Creating such a system would allow for more researchers to enter the field by lowering the cost of research.

PROJECT OBJECTIVE

Background Information

The US Department of Navy (DoN) requires high-bandwidth secure communication in RF denied environments. [2] [3] DoN surface vessels collect large amounts of data that must be immediately shared fleetwide. For example, the Cooperative Engagement Capability and AEGIS systems of the DoN send large amounts of data between surface vessels. RF communication suffers from issues that FSOC a better option than traditional radio communication. First, RF communication suffers from high side lobe, sending signals in undesired directions. This undesired radiation allows for other vessels to receive the signal, including enemy ships. With the increasing importance of data in modern warfare, denial of enemy reception of data is paramount. Second, RF communication requires larger bandwidths to match the transmission rate of FSO systems. Larger bandwidths introduce issues of interference as RF bands become increasingly occupied by commercial interests. Third, the RF space has become contested through electronic warfare. Electronic attack systems are being investigated by multiple nations with the intention of disrupting RF systems. Making systems resilient to electronic attacks is vital to national security. Fourth, enemy vessels can track ships emitting RF through electronic surveillance systems. FSO systems operate in line of sight and emit primarily in a single direction, reducing the ability of enemy ships to track through surveillance systems.

However, despite these advantages, FSO systems suffer from the limitation of line-of-sight communication. Over the horizon communication is sometimes necessary for certain fleet configurations. Space-based FSO relays are available; however, space-based systems face interference from weather phenomena like clouds. Communication systems in military applications must be resilient to weather. Space-based communication faces additional difficulty as orbits might not always line up well, increasing project costs significantly as more satellites are required for relays.

Therefore, UAVs offer the ability to relay optical communication in areas where space-based relays are unavailable. They can be weather resilient and integrate well into the existing Navy infrastructure. The Navy has extensive air operation infrastructure in its aircraft carrier fleets, and most fleets have the capability to launch small fixed-wing aircraft. The US Airforce and US Navy both operate extensive UAV fleets that can be easily transitioned to data relays without significant interruption to their primary missions.

This project aims to create a prototype for an affordable dynamic FSO system capable of linking two moving targets. This dynamic link would create the backbone of future ad-hoc networks by linking pairs of nodes in the network.

Customer Requirements

1. High Bitrate: The system requires 1Gbps communication speed
2. Low-Sidelobe: The system must have low sidelobe
3. Over the Horizon Communication: The Navy requires over-the-horizon communication
4. Weather Resilient: The system must continue operating normally in inclement weather
5. Continuous Connection: The Navy requires continuous connections with low bit errors
6. Duplex Communication: The Navy must share information between two ships and their sensors bidirectionally.

PROPOSED SOLUTION

Technical Requirements

Our system will have:

1. Software drivers that can operate at 1 Gbps
2. Operating frequency in the infrared range (780 nm – 1 mm) in the eye-safe power range
3. Transmit/receive speed of 1 Gbps of data but we will most likely be working with 1 Gbps
4. A tracking device capable of tracking a device at 100m with tangential velocity up to 92m/s within 20mm
5. System to adjust tracking based on live data to account for variable distance and speed of the receiver
6. Two-way simultaneous communication
7. Costs less than $500 to build
8. System will have the ability to network with other UAVs to create a FANET

Figure 1 summarizes the technical requirements in relation to the customer requirements.

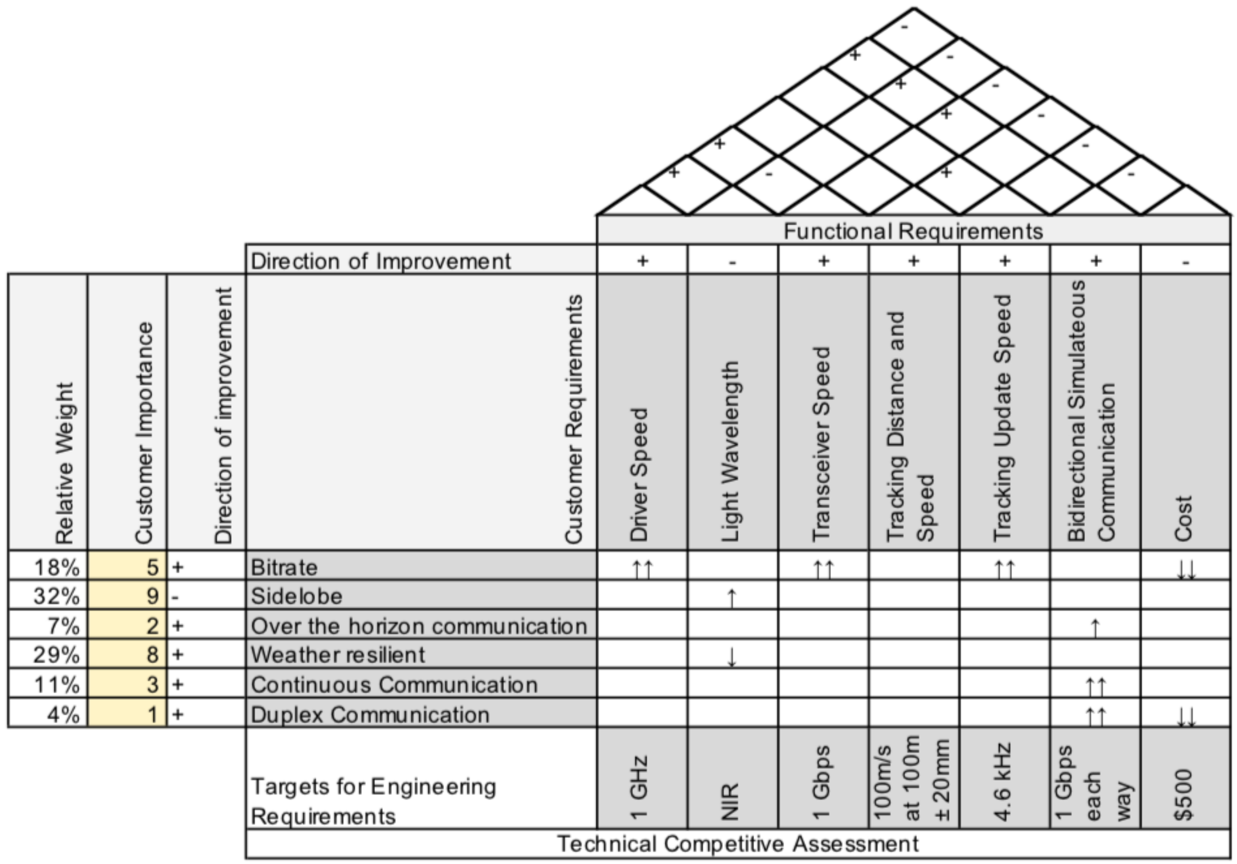

Figure 1: House of Quality

Concept Generation

SCAMPER is a method of generating ideas by differentiating the proposed idea from current industry solutions. The proposal differs by using the SFP as a laser generator in free space optical communication in a much cheaper solution. SCAMPER stands for substitute, combine, adapt, modify, put to other use, eliminate, and rearrange. The SCAMPER below is based off previous free-space optical communication systems in the industry. The proposed solution substitutes an SFP for the laser generator, combines the laser with cheap DJ scanners, adapts the SFP for use in free space, modifies existing hobbyist solutions like KORUZA, and puts free space optical systems to other use in dynamic systems. It does not eliminate or rearrange free space optical components from the system. The SCAMPER idea generation is summarized in Table 1.

Table 1: SCAMPER

S	SFP was substituted as a laser source
C	The dynamic system scanner was combined with the cheaper SFP system
A	Using the SFP in free space adapted its normal usage
M	Koruza was modified to match the needs of this project
P	Modifying the system for wider adoption put it to another use
E	No portions of the design were eliminated
R	No portions of the design were rearranged

The system is composed of an aiming mechanism, transceiver, computer connection, and software driver. Additionally, the operating wavelength must be chosen, and other transmit/receive options weighed. Ultimately, a scanner was chosen for aiming; SFP was chosen for the transceiver; Ethernet/Thunderbolt were both chosen for connecting; IR was chosen for wavelength; and C++ and Python were chosen for software. The available decisions are shown in Table 2.

Table 2: Concept Table

Aiming	Transceiver	Connector	Wavelength	Detector	Software
Scanner	SFP	Thunderbolt 3	Near IR	SFP	C++
Stepper motor	SFP+	Ethernet	Far IR	Photo detector	Python
Servo motor	Laser	SATA	Visible	Antenna	Java
	Radio	LC/SC			JavaScript

Figure 2 shows a concept fan to weigh various problems and solutions stemming from the proposal. Ultimately, the chosen solution best solves the issue at hand as mitigating solutions are not possible.

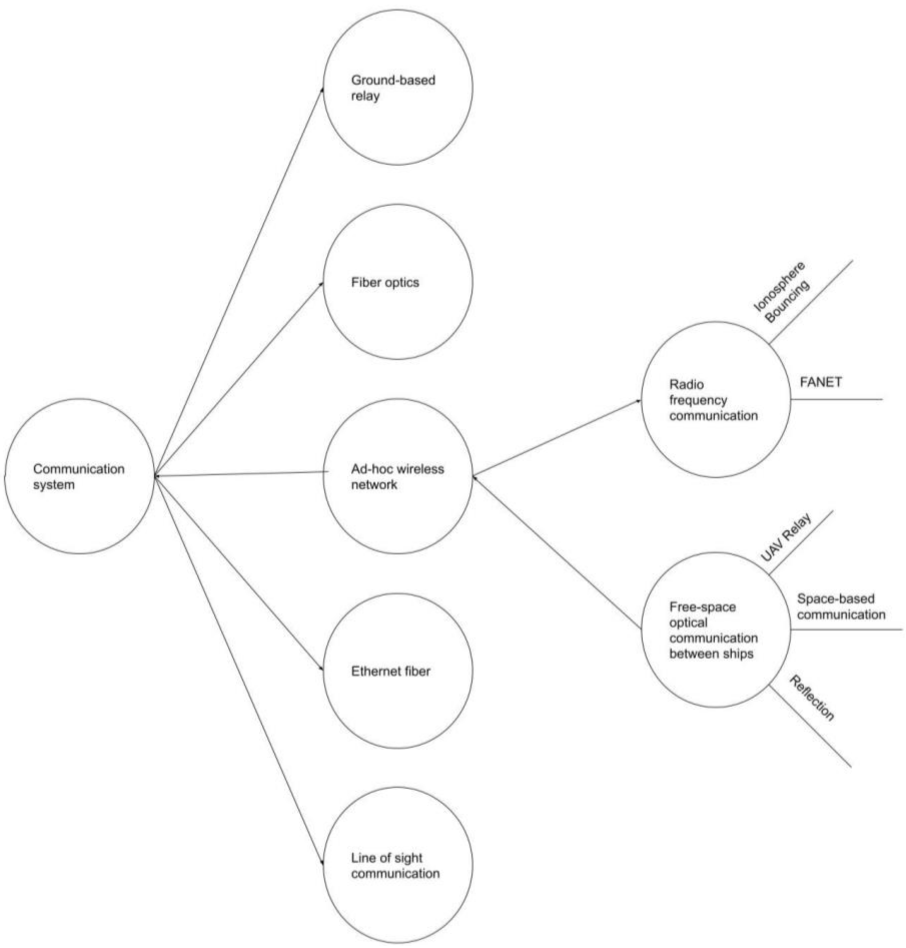

Figure 2: Concept Fan

The Pugh concept selection tables compare various solutions for the system components based on their relative performance in criteria based on the requirements of the system. From the weighted sum of the performances, the best option is selected. Table 3 through Table 6 show the concept selection table for each subsystem. The highlighted option is the one that was ultimately chosen for the design.

Table 3: Aiming Pugh Concept Selection

Solutions \ Criterion	Speed	Accuracy	Weight	Implementation	Cost	Total
	3	3	1	1	4	
Scanner	-	-	-	-	0	0
Motor	-1	-1	-1	1	1	-2

Table 4: Transceiver Pugh Concept Selection

Solutions\Criterion	Distance	Safety	Cost	Total
	1	2	3	
Multimode SFP	-	-	-	0
Single Mode SFP	0	0	-1	-3
Waveshare Receiver/Transmitter	1	-1	-1	-4

Table 5: Light Wavelength Pugh Concept Selection

Solution \ Criterion	Safety	Weather Resilience	SFP Availability	Cost	Total
	1	2	3	4	
Visible	-1	-1	-1	1	-2
Near IR (850nm)	-	-	-	-	0
IR (1300nm)	1	1	0	-1	-1

Table 6: Computer Connector Pugh Concept Selection

Solutions\Criterion	Speed	PC Connection	Power Provided	Cost	Total
	1	1	1	5	
SATA	-1	0	-1	-1	-7
RJ45	-	-	-	-	0
Thunderbolt 3	1	0	1	-1	-3

The decision matrices show the selection of a solution for each subsystem of the proposed system. Each solution is rated on a scale of 0 to 1 based on its performance in a criterion and the weighted sum of these performance ratings are compared to select a solution. The criteria are selected based on the requirements of the system. Table 7 through Table 11 show the decision matrices for each subsystem. The highlighted option is the option ultimately selected in the design.

Table 7: Aiming Decision Matrix

Solutions \ Criterion	Speed	Accuracy	Weight	Implementation	Cost	Total
Scanner	1	1	0.8	0.2	0.2	2.76
Motor	0.2	0.5	0.3	1	0.4	2.05
Weight	1	1	0.5	0.8	1	

Table 8: Light Wavelength Decision Matrix

Solution\ Criterion	Safety	Weather Resilience	SFP Availability	Cost	Total
Visible	0.2	0	0.1	0.9	0.85
Near IR (850nm)	0.5	1	0.9	0.5	1.85
IR (1300nm)	0.7	1	1	0.1	1.79
Weight	0.6	0.3	1	0.7	

Table 9: Data Connection Decision Matrix

Solutions\Criterion	Speed	PC Connection	Power Provided	Cost	Total
SATA	0.15	0.5	0	0.6	1.025
RJ45	0.25	1	1	1	2.025
Thunderbolt 3	1	1	1	0.2	1.6
Weight	0.5	0.7	0.2	1	

Table 10: Transceiver Decision Matrix

Solutions\Criterion	Distance	Safety	Cost	Total
Multimode SFP	0.7	0.8	0.7	1.67
Singlemode SFP	1	1	0.3	1.6
Waveshare Receiver/Transmitter	0.2	1	0.5	1.24
Weight	0.7	0.6	1	

Table 11: SFP Decision Matrix

Solutions \ Criterion	Speed	Precision	Complexity	Eye Safe	Cost	Total
SFP	0.1	0.5	1	1	1	2.95
SFP+	1	0.5	1	1	0.35	2.75
FSO Laser - Edmonds	0.8	1	0.5	0	0.04	1.49
Weight	0.5	0.8	0.5	1	1	

System Description

The system consists of a static free space optical communication system and a scanning system. The static system has a small form-factor pluggable (SFP) electro-optical transceiver connected to a compatible media converter. The electrical output from this media converter is an RJ45 port, commonly referred to as ethernet. This output can be connected to the desired platform, including personal laptops. To focus the optical output of the SFP transceiver, a mirror of focal length 10 cm is used. This static system has a maximum throughput of 1 Gbps.

The scanning system is composed of a control subsystem and a two-mirror scanner. The control subsystem has an aiming visible laser and a camera to find other transmitters. A Raspberry Pi using Python 3.7 will use the data from the camera to aim the scanner. The scanner has two motors controlling two mirrors which will redirect both the aiming laser and the signal. The Raspberry Pi and its connections to the control system can be seen in Figure 3: Koruza System DiagramFigure 3.

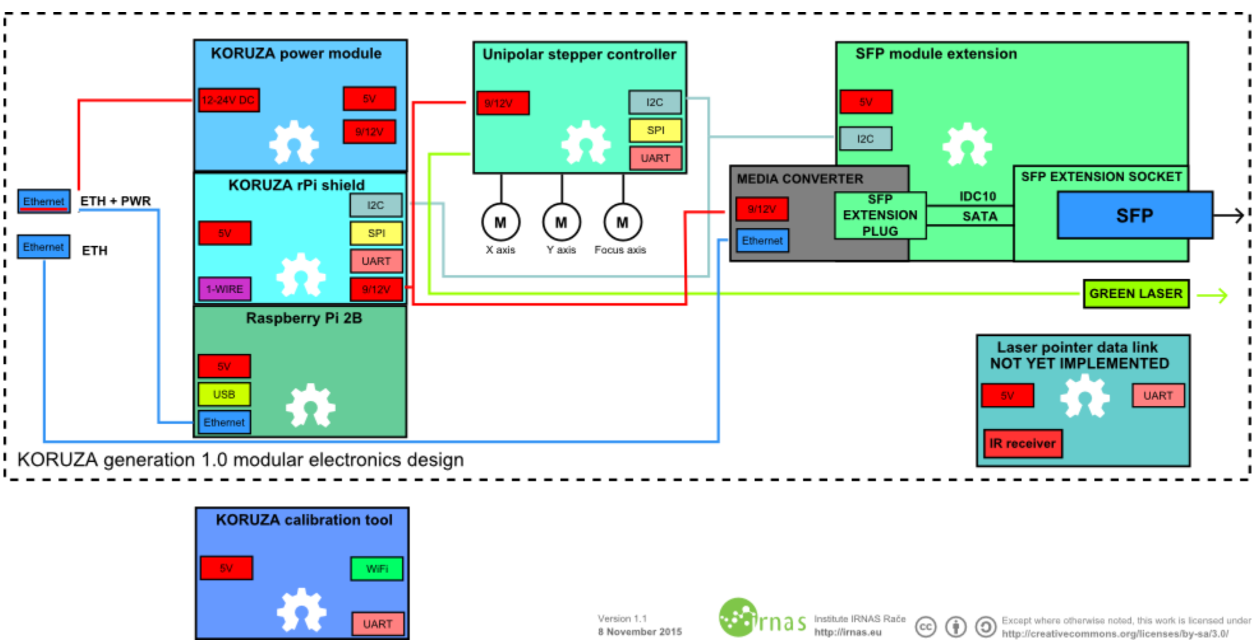

Figure 3: Koruza System Diagram [4]

Figure 4 describes the work breakdown structure of this project.

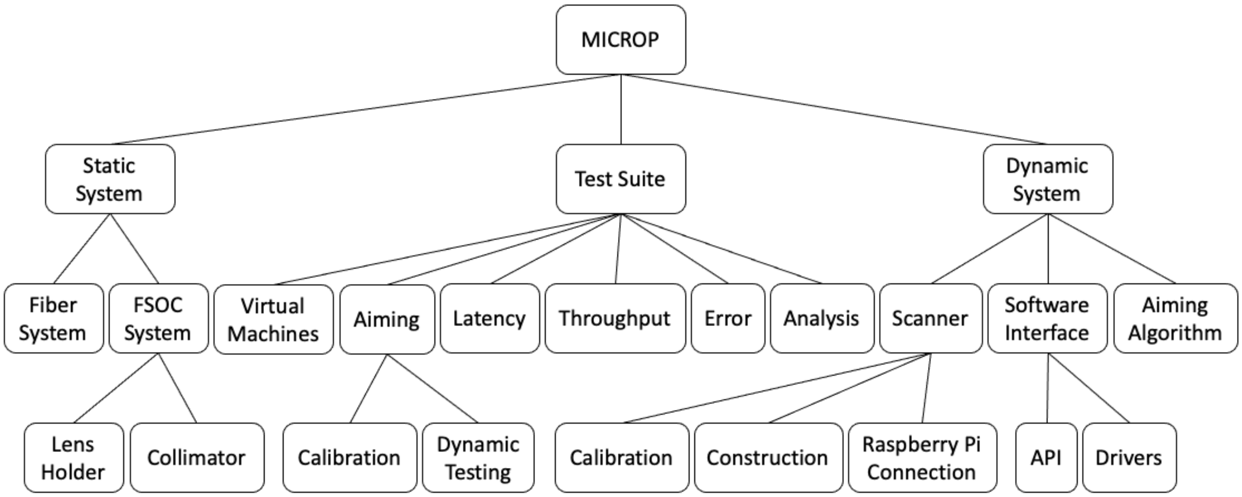

Figure 4: Work Breakdown Structure

Standards and Constraints

The design of this system, outlined in the System Description, was guided by Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), Internet Engineering Task Force (IETF), and Storage Networking Industry Association (SNIA) standards.

As detailed in the System Description, two SFPs are used as electro-optical transceivers. SFPs follow SNIA multi-source agreement INF-8074. [5] The SFPs purchased use the 850nm 1000Base-SX standard for speed and throughput negotiation. The media converters used similarly follow INF-8074 and 1000Base-SX standards for SFPs. Fiber connections between the SFPs for testing use the Lucent Connector (LC) fiber connection standard, following.

The media converters and ethernet cables use RJ45 connectors. RJ45 connectors are standardized in IEEE 802.3. [6] The ethernet cables used are category 8 (CAT8), following IEC 61754-20 and IEEE 802.3. [7] To connect a personal laptop to the ethernet cable, the USB-C interface was used, which is described in standard IEC 62680-1-3. [8] Communication utilized TCP/IP connections as described in IETF RFC-793. [9]

The system was constrained primarily by cost limitations and laboratory equipment. Equipment for wavelengths greater than 1000nm was prohibitively expensive, requiring the design to operate in near-IR at 850nm. A similar design produced on a larger scale would also benefit from the decreased costs associated with economy of scale. Industrial processes can reduce the cost by combining parts and buying in bulk. So, the final cost of this system is not representative of the possible cost if it were produced in large quantities.

Design Impact

This project has benefits in military, civilian, and research applications. In military applications, there is a need for dispersed ad-hoc networks in naval and ground communication systems. In civilian applications, it can be used for disaster relief and connecting hard to reach communities.

As a low-cost platform, it would benefit free space optical research by lowering the barrier for entry for a potential researcher.

In military applications, there is a persistent need for high-throughput, stable, and dynamic communication systems. Networks must span large areas with a variety of obstacles and endpoints, which requires a system that is able to adapt to changes rapidly. The increasing focus on data as a defense resource requires increased throughput to ensure units are kept updated on developments and intelligence. A cheap and dynamic free space optical communication system allows for a wide breadth of endpoints in the network, interconnecting a larger number of units.

This system also has humanitarian benefits. The use of ad-hoc networks in disaster areas is important to allow for rapid communication in disaster response teams. Current systems are cumbersome and limited by cost. A cheaper and dynamic system would allow for rapid deployment of networks to affected areas and reduce the setup time for humanitarian efforts. The system could be coupled with other response systems, including imagery systems, on drones to provide a rapid and complete picture of the area to assist in humanitarian efforts.

For hard to reach and small communities, infrastructure is hard to develop due to the difficulty of constructing the infrastructure, the challenge of maintaining infrastructure, and the low profit margin for small communities. Therefore, many rural and small communities have poor infrastructure, including communication systems. A free-space system allows for these communities to improve communication without requiring infrastructure. A low-cost system could be used by smaller communities, lowering the barrier to entry.

Free space optical research is expensive, limiting research to well-funded labs and universities. Lowering the cost of a simple system allows for research to be conducted by a larger range of parties, including amateurs. Widening the pool of potential researchers advances the field as a whole and will produce better communication systems, lending itself to the benefits discussed above.

DEVELOPMENT PLAN

Overall Project Description

The system is split into three sections. The first is a static fiber optic system operating at 1Gbps. LC fibers are used to connect the two endpoints. The second is a static FSOC system, able to communicate without a fiber. The third is a dynamic FSOC system that is able to move both endpoints and maintain communication. The static fiber system was constructed in the Fall 2021 semester.

The project is aimed at military applications but has a wide range of applications outside of the military. It can be used in disaster relief and in reaching rural communities without expensive infrastructure. By reducing cost and aiming the system dynamically, it is far less limited than current systems, widening the utility of the product.

Major Tasks

The project is split into three stages. Stage one is the construction of a static fiber optic communication system using the SFPs connected via LC fiber. This stage was completed in Fall of 2021. Stage two is a static free space optical system using the same hardware by removing the LC fiber. Additional collimators are added. The third stage is a dynamic free space optical system using scanners to aim the laser. The detailed schedule is found in Appendix A: Detailed Schedule.

Testing must be performed at each stage of construction to verify the continued operation of the system. A tracking algorithm must be created using the visible laser aiming system and ensuring continual connection.

Testing Results

To verify correct operation of each component, system throughput, latency, and packet loss were tested for a variety of experimental setups. These setups were limited to fiber and control experiments; free space has not been tested. Plans to test the free space system are found in Appendix C: Test Plan and will be carried out in the Spring semester. A hardware-in-the-loop setup was constructed by connecting the SFPs together through an LC cable and connecting the media converters to personal computers. An ethernet cable only test was performed where both endpoints were directly connected via ethernet cable to create a control. Further tests were done with the two endpoints sharing one port on a laptop, and the final setup had both endpoints sharing the same network adapter. To simplify these experiments and reduce errors from varying hardware, one laptop was used, and the endpoints were separated using virtualization.

The results of the throughput tests are shown in Table 12 and Figure 5. Table 13 and Figure 6 show the latency test results. Table 14 shows the numbers of packet loss per byte of transmitted data for each setup as an approximation of error.

Table 12: Throughput Results

Testing Setup	Bidirectional Throughput (Mbps)	Parallel Bidirectional Throughput (Mbps)	Unidirectional Throughput (Mbps)
Hardware-in-the-loop fiber	941 ± 24	899 ± 71	941 ± 22
Ethernet Cable Only	925 ± 125	863 ± 112	941 ± 24
Shared port	2894 ± 196	1633 ± 260	2913 ± 196
Shared network adapter	2719 ± 334	1578 ± 269	2714 ± 427

Table 13: Latency Results

Testing Setup	Unidirectional Latency (ms)
Hardware-in-the-loop fiber	1.32 ± 0.32
Ethernet Cable Only	1.32 ± 0.3
Shared port	1.06 ± 0.22
Shared network adapter	1.1 ± 0.26

Table 14: Error Analysis

Testing Setup	Bidirectional Error	Parallel Bidirectional Error	Unidirectional Error
Hardware-in-the-loop fiber	4.24E-08	2.18E-07	6.99E-08
Ethernet Cable Only	1.08E-07	2.46E-07	7.26E-08
Shared port	5.39E-06	2.78E-06	5.34E-06
Shared network adapter	5.53E-06	2.55E-06	5.49E-06

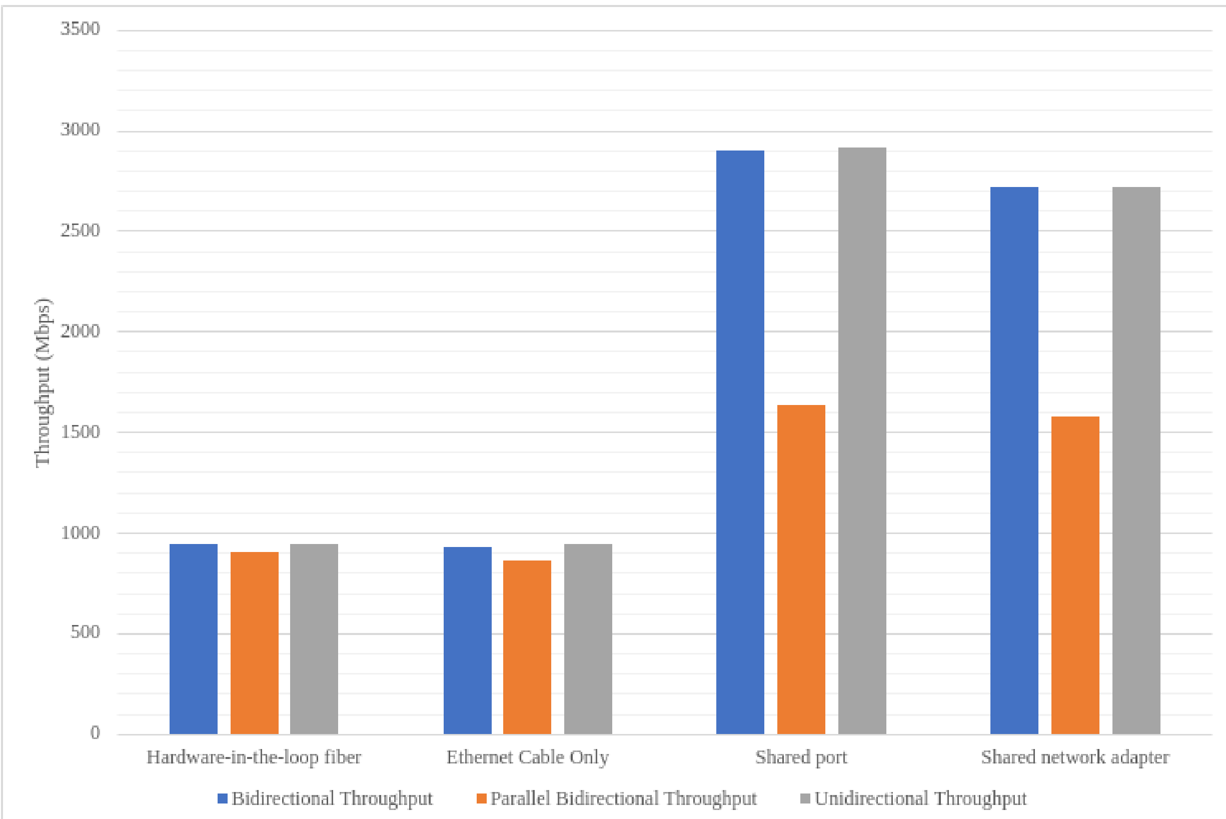

Figure 5: Throughput Results

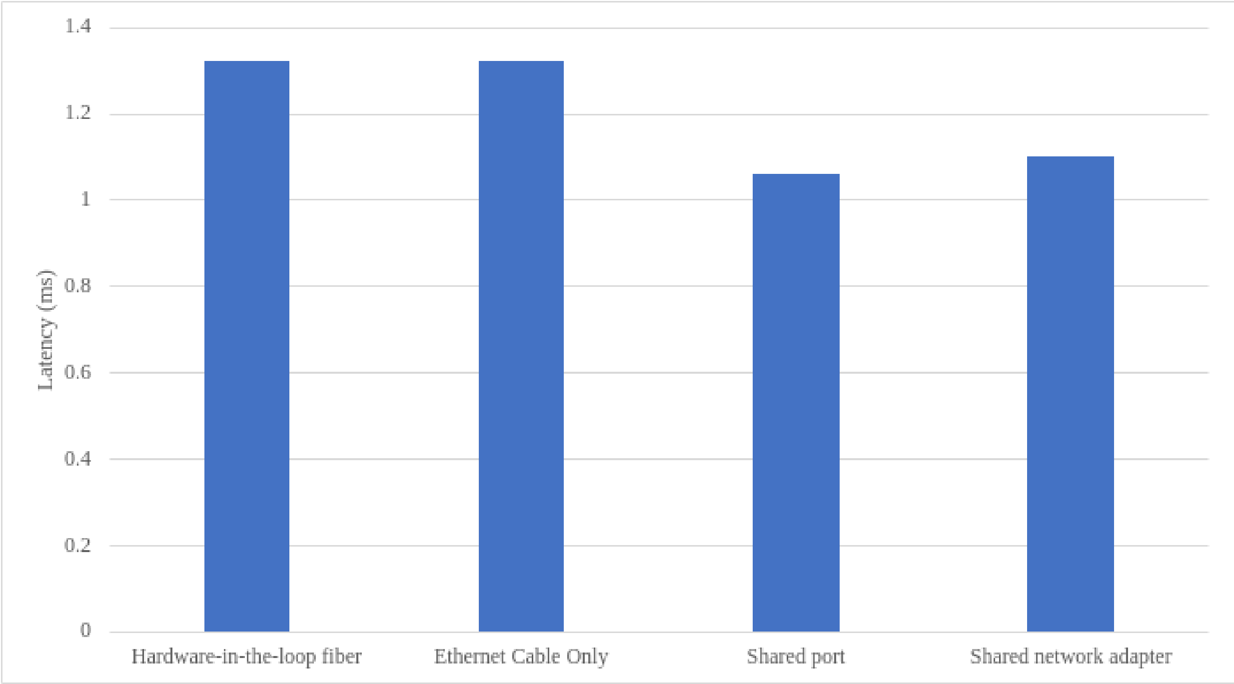

Figure 6: Latency Results

Materials & Cost Estimate

Table 15 describes the materials used for this project along with their respective cost breakdown. The cost represents the total price including tax and shipping if applicable.

Table 15: Bill of Materials

Item	Quantity	Cost
Raspberry Pi 2B	2	$0.00
Raspberry Pi NoIR Camera	2	$26.72
850 nm Multimode Fiber SFP	2	$26.01
50 mm Diameter, 100 mm Focal Length Plano-Convex Lens	2	$17.54
Galvanometer Scanner	2	$186.22
Media Converter	2	$42.54
Visible Light Aiming Laser	2	$39.00
RJ45 to USB-C Converter	2	$29.46
CAT-8 Ethernet Cable	2	$6.48
50/125 Multimode LC-LC Duplex Fiber Patch Cable	2	$18.46
Total	$392.43	

ETHICS CONSIDERATIONS

It is unethical to produce a device which would harm its users. Therefore, this design was constructed to be eye safe and electrically safe. The infrared laser was chosen over a visible light laser to ensure eye safety. A weaker laser was chosen despite limiting the abilities of FSOC systems because weaker lasers are less likely to be harmful. In addition, commercial off-the-shelf pluggable systems were chosen to reduce the chance of harm from electrical wires or improper wiring. This product was tested against safety standards. The laser power was found to be less than a harmful level. Tests were performed in closed rooms to limit the possibility of accidental harm to bystanders.

By reducing the need for infrastructure and the overall cost of the system, the public welfare is benefited. It reduces the environmental harm of the system as infrastructure destroys ecosystems and interrupts animal habitats. The reduced cost and lower installation cost further benefit those in hard-to-reach communities and rural areas by opening their communities to communication systems that had previously been denied to them. This expansion of systems increases the equity of access to high-speed internet and other communication systems.

CONTRIBUTION TO ABET PROGRAM & LMU MISSION AND VALUES

ABET Program

This project addresses all seven ABET student outcomes. [10]

The project addresses outcome one, "an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics." The project poses a nontrivial engineering problem that has not been achieved before. Free space optical communication systems are generally expensive and static, so achieving a dynamic and cheap system is unique and difficult.

The project addresses outcome two, "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." This project was designed for the safety of users by using eye-safe optical communication and standards that can interface with personal laptops, allowing a non-technical user to use the system. Through humanitarian and military applications, this system could be utilized to help public welfare.

The project addresses outcome three, "an ability to communicate effectively with a range of audiences." Presentations were given for audiences of nontechnical background, including those of different majors. Team members were expected and able to communicate effectively to both technical and nontechnical audiences.

The project addresses outcome four, "an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts." Safety and environmental factors were considered at every step of the design process, and only eye safe products were purchased.

The project addresses outcome five, "an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives." As part of the project, team members met weekly with advisors and established weekly goals and plans to ensure completion of the objectives. Agreed objectives were consistently met.

The project addresses outcome six, “an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.” Each component of the system was tested, and the data was aggregated and processed. From these test results, conclusions were drawn and presented.

The project address outcome seven, “an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.” A large portion of the assignment was the research and design process, which addressed this outcome.

LMU Mission and Values

LMU’s mission statement states, “by intention and philosophy, we invite men and women diverse in talents, interests, and cultural backgrounds to enrich our educational community and advance our mission: The encouragement of learning. The education of the whole person. The service of faith and the promotion of justice.” [11]

The project clearly aligns with the encouragement of learning as a research and design project. Team members were expected to learn about FSOC systems and participate in the design of such a system. In addition, team members were expected to consider the societal ramifications of the project, which required education beyond the scope of engineering. This led to the education of the whole person as team members learned about social justice issues and the role of communication in society. Towards the promotion of justice, team members ensured the project would have benefits for disadvantaged communities. While the main customer is the DoN, the project was tailored to ensure benefits for other communities. These benefits are discussed in more detail in the Design Impact section.

Final Product Demonstration

At the end of the Spring 2022 semester, a dynamic system using SFP will be demonstrated. It will be within a 500 USD budget and will be able to communicate as both endpoints move. Although this system will not be ready for use in military or civilian applications, it will serve as an important proof-of-concept and test system for development of the software and hardware. A test plan is in Appendix C: Test Plan to demonstrate that customer and technical requirements are met by the system.

The system will consist of two transceivers with aiming capabilities. Each will be mounted on a movable platform. Their bitrate will be tested along with their ability to maintain a link as both endpoints are moved randomly.

CONCLUSION

Affordable dynamic FSOC systems have a wide range of applications. The designed system would allow for high-speed communication without infrastructure between moving endpoints. The hardware tested can reach near 1Gbps. The limit of the system appears to be the test suite used, primarily the USBC to ethernet adapter. Further testing of the static free space system is required. Moreover, the scanner must be constructed and implemented to allow the system to dynamically track during communication. A tracking algorithm must be planned and coded.

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APPENDICES

Appendix A: Detailed Schedule

Table 16 describes the detailed schedule of the project with the major tasks detailed into subtasks.

Table 16: Gantt Chart

Task	Assigned To	Start	End
Research and Development			
Static Design	Both	9/12/21	9/15/21
Order parts	Ian	9/15/21	10/1/21
Scanner Design	Both	12/6/21	12/13/21
Tracking Algorithm	Both	2/14/22	2/19/22
FANET Design	Both	5/28/22	5/30/22
Static Design			
Construct Transmitter	Ian	10/25/21	12/6/21
Construct Receiver	Natalia	10/25/21	12/6/21
Lab Condition Testing	Both	12/6/21	12/13/21
Single Motion Design			
Scanner Parts Ordering	Natalia	12/13/21	12/18/21
Construct Scanner	Both	1/10/22	1/17/22
Test Scanner	Natalia	1/17/22	1/24/22
Scanner Tracking Implementation	Ian	1/17/22	1/31/22
One way tracking testing	Both	1/31/22	2/10/22
Dual Motion Design			
Mount receiver on drone	Natalia	2/10/22	2/17/22
Test drone receiver while moving	Natalia	2/17/22	3/10/22
Mount transmitter on drone	Ian	2/10/22	2/17/22
Test drone transmitter while moving	Ian	2/17/22	3/10/22
Test drone-to-drone communication	Both	3/10/22	4/14/22
Demonstrate FANET feasibility	Both	4/14/22	4/21/22

Appendix B: Teammate Roles and Responsibilities

Roles and responsibilities were evenly split between team members. Natalia was primarily tasked with hardware while Ian was primarily tasked with software. Details on the assignment for each task is found in Appendix A: Detailed Schedule.

Appendix C: Test Plan

Purpose

Prototypes for static and dynamic free-space optical communication (FSOC) systems will be created. The static system will primarily satisfy the high bitrate requirement and the dynamic system will primarily satisfy the over the horizon requirement. All other requirements will be satisfied in both systems.

Objectives

To determine the success of each system, the latency and throughput will be measured during various trials. The tests will be performed through two virtual machines, running Ubuntu 20.04. Various cores will be carried out for the throughput tests and various throughput setups will be used to help identify the root cause of bottlenecks.

The latency and throughput tests include unidirectional and bidirectional in both the control and experimental setups. The ping command will be used to perform latency tests, while Ipeff3 will be used to perform throughput tests. Python 3.8 will be used to analyze the data gathered during experiments.

Procedure

Static System Testing:

1. Connect ethernet to USB-C converters to USB-C ports on laptop.
2. Create two virtual machines registered to each port.
3. Create shared folders on each virtual machine to store data from test trials.
4. As a control, directly connect an ethernet CAT-8 cable to each port.
5. From virtual machine 1 (VM1), ping virtual machine 2 (VM2) to run several latency tests on the control system and store data to shared folder.
6. Run bidirectional latency tests by storing output of the ping command on control system and store data to shared folder.
7. Repeat control latency tests, pinging VM1 from VM2, and store onto shared folder.
8. Run throughput tests on one core using Iperf from VM1 to VM2 and store results to shared folder.
9. Repeat one core throughput tests, going from VM2 to VM1.
10. Run one core bidirectional throughput tests on control system.
11. Run bidirectional tests on both VM1 and VM2 simultaneously to increase traffic congestion.
12. Repeat all throughput tests with three cores and store data on shared folders.
13. Disconnect one end of the ethernet cable and connect it to one of the media converters.
14. Repeat this setup with the other port.
15. Connect the SFPs to their respective ports on the media converters.
16. For the experimental fiber setup, directly connect an LC duplex fiber between the two SFPs and power the media converters.
17. Repeat steps 5 through 12 for the fiber experimental setup.
18. Disconnect LC duplex fiber from one SFP and connect second LC fiber to SFP.

19. Tape open ends of LC fibers onto its respective media converter
20. Set lenses in lens holders and place each lens 10 cm away from the media converter.
21. Adjust set up of beams for collimation and align transmitting beams to receivers. Note the size of each beam and check for fiber light on media converters to ensure data is transmitting and receiving properly through the FSOC system.
22. Repeat steps 5 through 12 for the static FSOC system

Dynamic System Testing:

23. The setup will be placed in the FSOC configuration as detailed in steps 18 through 21 with a scanner system placed immediately after the lens of each endpoint.
24. The scanner will be calibrated by placing it at the distance from the lens at which the beam divergence is minimum.
25. The ability to connect with the scanner reflecting the beam will be confirmed.
26. The power loss of the scanner will be found by comparing the relative strength at an equal distance of the setup with the scanner and without the scanner.
27. The throughput and latency tests detailed in steps 5 through 12 be repeated for the dynamic system.
28. The dynamic system will be placed into a container to allow for easier movement
29. The system throughput and latency will be tested as detailed in steps 5 through 8 again inside the container. The values from this test will be used as the maximum rated throughput and latency of the system.
30. Both endpoints of the system will be connected to a different Raspberry Pi 2B+ (RPi).
31. The system will be tested again as detailed in steps 5 through 12 with both the scanner and RPi in use.
32. One dynamic FSOC and corresponding RPi will be placed on a movable mount.
33. The endpoint mounted on a movable mount will be moved in a predetermined random path at increasing velocities. The maximum speed at which the system can maintain connectivity will be measured.
34. Both endpoints will be placed on a movable mount with its corresponding RPi.
35. The test from step 9 will be repeated with both endpoints moving.
36. The final dynamic system will be tested as detailed in steps 5 through 12.

Test Specimen

The test will be performed on 5 separate setups. The static fiber system will be used to benchmark the maximum possible throughput and latency of the system's components and identify bottlenecks. The static free space system without the scanner will be used to find issues introduced into the system from free space communication. The static free space system with the scanner will be used to test the maximum realizable throughput and latency of the final system. This setup will be repeated using the RPi as a test system to find the effects of the RPi on the throughput and latency. The dynamic free space system will be used to test the ability of the system to track moving endpoints and to determine the maximum relative velocity of the two endpoints while maintaining connectivity.

Expected Results

The throughput results from the static system are expected to be approximately 1Gbps and about 300Mbps for the dynamic system. The difference in expected throughput is due to the use of the RPi, which has significantly lower throughput than larger, more powerful personal computers. The latency of the dynamic system is expected to be less than that of the static system due in part to the decreased processing power of the RPi and the increased packet loss from lag time in tracking the device.