Optical Communications: History and a Look toward APL's Future Contributions

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ABSTRACT

Over the past 15 years, the Johns Hopkins University Applied Physics Laboratory (APL) and others have developed and demonstrated impressive capabilities and technologies in optical communications. APL has conducted experiments, performed analysis, investigated designs, developed capabilities, coded algorithms, and conducted successful demonstrations. The critical optical communications challenge remaining for APL to solve over the next two decades is not in technology development. It is in partnering with the Department of Defense and national security space communities to apply and implement these technological achievements through the systems engineering and acquisition processes. This article discusses the history of optical communications, APL's contributions in several domains, current challenges, and the way forward.

INTRODUCTION

The 2018 *Johns Hopkins APL Technical Digest* issue titled "APL Celebrates 75 Years" looks back at APL's history, offering just a glimpse of where the Lab is going. This issue envisions APL at its 100th anniversary, realizing a future that is now beginning to quickly coalesce—a future, just over 20 years away, that for some Department of Defense (DOD) acquisition timelines is figuratively just around the corner. This article explores what optical communications might look like at APL in 2042.

For the past 15 years, APL has viewed optical communications as an essential capability to enable undeniable military access across all domains, and Lab leadership has championed internally and externally funded programs to develop and demonstrate its utility for the military. Beginning in 2006 with the successful 80-Gbps demonstration of a free-space optical (FSO) system between an aerostat and a ground terminal, to demonstration of longer fixed distances, then air-to-ground mobile testing, and finally mobile air-to-ground FSO network demonstrations in 2012, through this technology research and development, APL has built a family of capabilities that can now be combined to meet specific mission needs. In parallel with these developments, APL has championed research in optical communications for space-based systems, high-altitude platforms, and ground-based and underwater communications.

Despite these successes, DOD mobile FSO communications have yet to cross the science and technology (S&T) valley of death. As Jerry Krill notes in his introduction to this issue, "it is difficult to transition a revolutionary idea into operational use." Breakthroughs often take years, even decades, and sometimes face considerable resistance along the way. Although a few unclassified optical communications systems are in development, there appear to be few, if any, current programs of record in the government acquisition cycle to realize mobile FSO networked capability, even with strong endorsements from leading research experts such as John Malowicki (of Air Force Research Laboratory's Rome Laboratory), who notes:

> FSO communications has long held the promise of high data rates and the ultimate in physical security due to its tight directional beams. This has been demonstrated over significant ranges in the challenging air-to-air and air-to-ground environments. But few systems have transitioned due to problems with size, cost, and complexity. Significant progress over the last decade in reducing SWaP [size, weight, and power] and complexity makes FSO communications more attractive for transition to real platforms. In the coming years, FSO communications will likely be fielded in more areas and will provide a viable solution, most likely a hybrid RF [radio frequency]/optical solution, for challenges of varying atmospheric conditions and the challenges of A2/AD (anti-access/area-denial) environments (personal communication from Malowicki to K. T. Newell).

Today's communications improvement programs generally focus on improving RF capability and resilience, yet that area (Figure 1) represents just a (regulated) portion of the potential communications spectrum. DOD components and services have a critical need for communication methods that have low probabilities of interception and detection, and the optical band is wide open, unregulated, and ready for implementation of capabilities that provide warfighters with a diversity of communications options. The intent is not, and will never be, for optical communications to replace RF—it is an augmenting capability designed to provide options on the battlefield where few are currently available.

A challenge in integrating optical communications systems into the DOD is that every additional piece of hardware requires additional space. In many instances, the platform, whether it be an aircraft, a boat, or even an individual soldier, has minimal room for additional equipment, so an optical communications system may have to provide both unique and additional capabilities over existing RF systems. A prime example is Navy surface applications, where the optical communications system must be mounted high enough to provide significant range out to the horizon. There is limited space available on ships for a single-use technology, so the question is whether the core components of an optical communications system—laser, scanner/gimbal, detector/detector electronics—can allow for dual use, such as a lidar imager. A look at the history of RF communications provides insight into how we might realize a future for optical communications.

A BRIEF RF HISTORY AND AN OPTICAL LOOK FORWARD

In the late 1890s, radio pioneer Guglielmo Marconi began conducting experiments in the transmission of radio waves. After years of experiments, one of his first use cases and implementations was a simple installation on two transatlantic ships that reported results of yacht races to New York sports papers. In the 130 years since

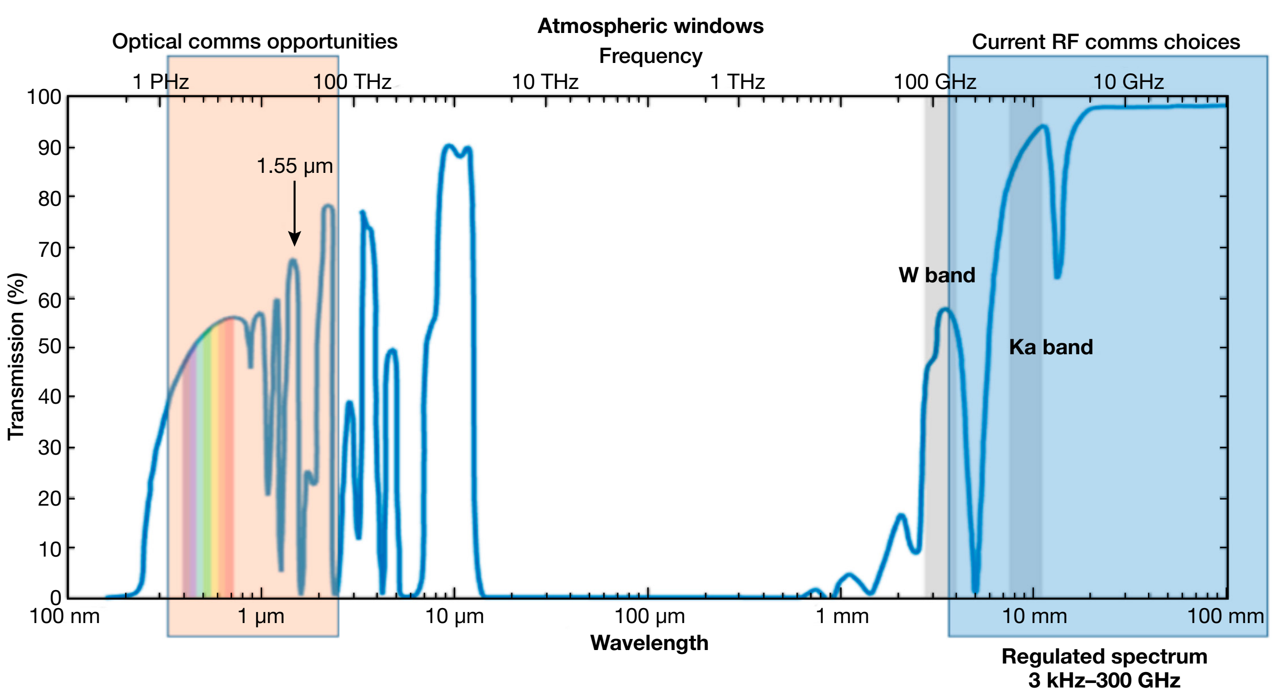

Figure 1. Focus areas of today's communications improvement programs. The optical (orange) part of the spectrum provides options to expand communications capability outside the RF (blue) regulated part of the spectrum.

those experiments, RF communications systems have proliferated to become part of daily life as well as essential technology in military applications. Yet, the start of this RF revolution was in the implementation of a simple use case to meet a simple set of operational requirements.

Over the past 15 years, APL and others have developed and demonstrated exquisite capabilities and technologies in optical communications. APL has conducted experiments, performed analysis, investigated multiple designs for optical information transmission, developed back-end modem and networking capability, coded advanced pointing and tracking algorithms to maintain terminal lock at long distances, and demonstrated the practical use of encrypting a data stream over a laser. What APL is only just beginning to do, though, is partner with its sponsor base to identify the simple use cases, conduct the systems engineering studies, and implement initial optical communications systems to meet a simple set of requirements.

The critical optical communications challenge remaining for APL to solve over the next 22 years is not in technology development. It is in partnering with its DOD and national space sponsor base to apply and implement through the acquisition process what has already been proven technologically. The idea that we are just one key invention away from the one optical system to solve all problems is naive—particularly when looking across the 130 years of RF communications advancements and realizing how many RF systems have been implemented in response to many mission use cases and many requirements.

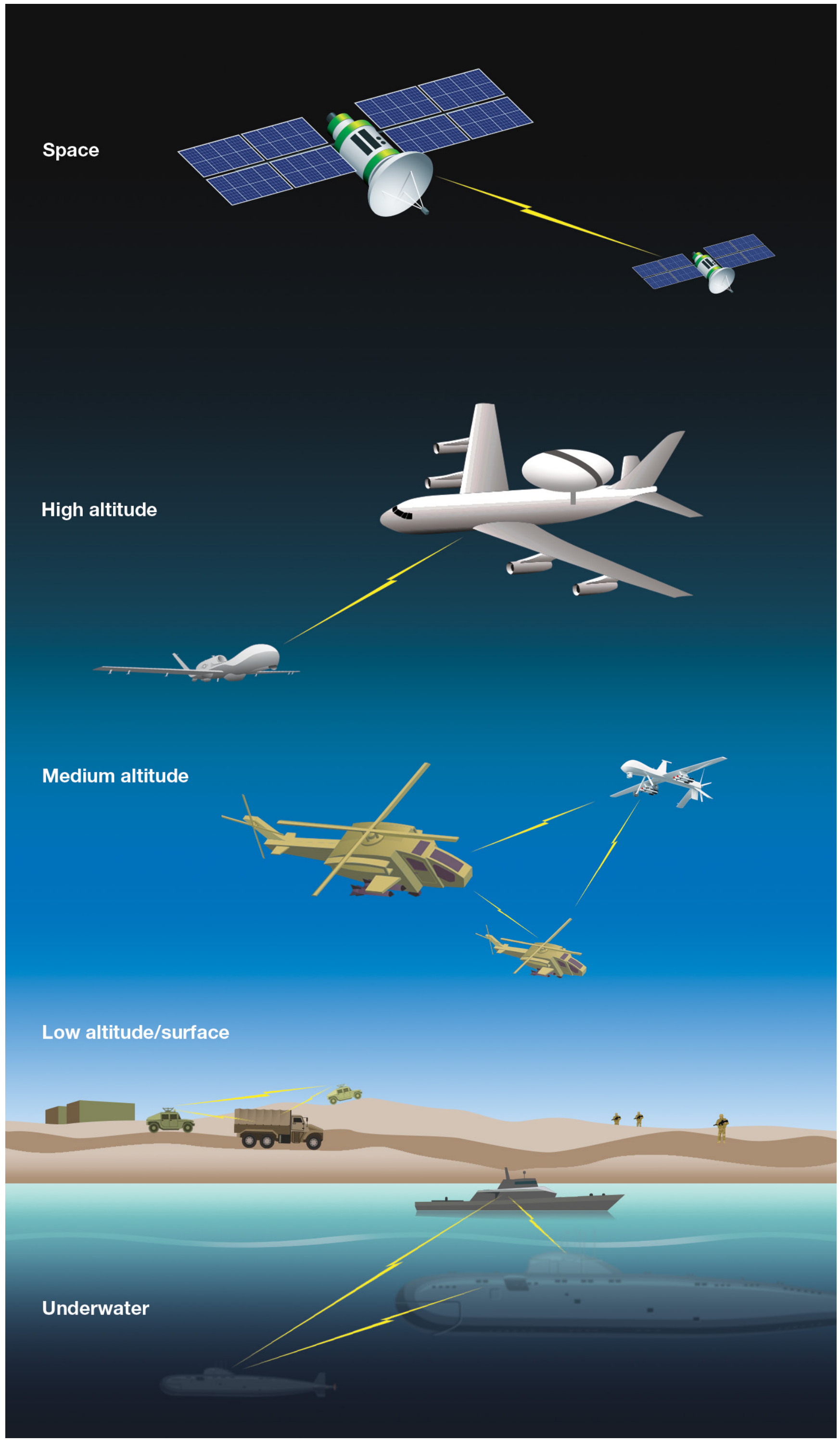

Figure 2. Optical communications technology can be applied across all warfighting domains. Solutions exist in all domains for applications through applied systems engineering.

Several optical communications technologies, such as Li-Fi (light fidelity), optical intersatellite links, free-space and tropospheric optical communications, and through-water high-data-rate communications, are long overdue for military application. APL's Space, Air and Missile Defense, Force Projection, and Asymmetric Operations Sectors, along with its Research and Exploratory Development Department, are well suited to assess the capabilities and limitations of these systems (including those that are functional but not commercially viable) to help their sponsors match those technologies against the communication gaps they will face in the coming decades. The next several paragraphs explore where we are today and where we should be by 2042 in the application of optical communications across the space, terrestrial, and underwater domains (Figure 2).

Optical Communications in Space Exploration

Were this article written 25 years ago, we would have predicted that the civil space community was on the cusp of a revolution enabled by FSO communications and its orders-of-magnitude increase in data capacity. Although this revolution has been slow to materialize, developments in recent years have advanced both the technology and the civil space ecosystem as a whole toward realizing a place for FSO. There are three use cases for which FSO would be an ideal solution:

1. Intersatellite links, providing high-bandwidth connectivity within satellite constellations to enable in-space networking
2. High-data-volume return, especially from low Earth orbit, either direct to ground or through a geosynchronous relay
3. Data trunking between Earth and high-interest areas for human exploration or concentrated robotic exploration, such as the moon or Mars

FSO solutions have had to overcome significant technological risks, including space qualification of critical components, maintaining critical pointing budgets, and (in the case of direct-to-ground links) atmospheric degradations. Furthermore, mission teams fit their mission concepts within the confines of available RF solutions. No "killer app" has yet materialized to provide the breakthrough case in either the scientific or the commercial world. However, this is starting to change. Multiple commercial companies are deploying low- and medium-Earth-orbit constellations to provide global communications access, believing the business case finally exists to succeed in this market. Intersatellite links are a key enabling technology for the operation of these constellations. The civil science world has seen multiple successes in both technology demonstrations and operational deployments. NASA's Lunar Laser Communications Demonstration aboard the LADEE spacecraft successfully demonstrated 622-Mbps downlink from lunar orbit to a ground-based telescope. Moreover, the European Space Agency continues deployment of the European Data Relay System in geosynchronous orbit and now successfully conducts optical forward and return relay communications to low-Earth-orbit spacecraft.

APL consistently exhibits strong in-house expertise in developing communications systems for its missions. The APL-developed Frontier Radio is a key enabling technology for APL's mission proposals. The next 20 years will see the infusion of FSO capability into this product line. Furthermore, mission concepts will evolve to better exploit this capability. The space community is better positioned now to gain operational experience with FSO technology and is more motivated to pursue the gains in data return capacity. These trends reduce risk: FSO will become mainstream in space as the community gains sufficient confidence to include FSO in mission proposals, ultimately leading to new mission ideas reliant on FSO's capabilities.

Optical Communications in Air and Missile Defense

As our forces fight to maintain situational awareness in highly contested environments, optical communications systems will provide the secure, quiet, anti-jam communications at high data rates that will allow missions to continue even in A2/AD environments. Looking forward, we envision that these systems will become capable of more than just communications as we start to realize additional advantages of these high-data-rate systems, such as IQ streaming or obtaining precise timing information through time and frequency transfer techniques, enabling coherent distributed systems and long baseline time difference of arrival that would not be possible without these optical links. As part of the Navy's CIIF (Communications and Interoperability for Integrated Fires) Future Naval Capability program, the vision for CaaS (Communications-as-a-Service) is to allow prioritized data flows to be delivered across any combination of available tactical data links. The CaaS product provides a foundation for building a much broader future capability to seamlessly bridge traffic flows through many available networks, as if operating as a single network, and enables future improvements to be delivered with an open-architecture/software-defined networking implementation. Leveraging expertise developed as FSO systems integrator of the Defense Advanced Research Projects Agency (DARPA) FOENEX (Free space Optical Experimental Network Experiment) program, and through leading research for Air Force Research Laboratory and internal independent research and development tasking, APL has demonstrated proof-of-concept hybrid RF/FSO links. These demonstrations established preliminary data prioritization functionality with a future goal of deploying an integrated and versatile tactical data link across RF and optical domains. This type of larger infrastructure is what will allow platforms equipped with optical communication links to tie back to platforms using more traditional links. Future optical communications development for the Navy should focus on interoperability within this architecture to truly provide the mission resilience and capacity that the Navy needs.

APL has filed multiple patents on FSO-related technologies in the last decade and a half, particularly for technology developments to mitigate the effects from what we refer to as the "soupy" part of the atmosphere. Numerous developments and demonstrations in the maritime domain through medium altitudes have shown resilience and capability to operate in different weather conditions. More recently, APL developed a simplified terminal design that uses a fiber bundle as a novel position sensor. This new design reduces the complexity of the system and provides thermal stability compared to traditional terminal architecture, which in turn creates a path forward toward system automation. When APL reaches its 100th anniversary, it will continue to be well suited to serving its sponsors as a technical direction agent for current optical communications systems and will be continuing the innovative prototyping that will enable advancements in this field.

Optical Communications in Asymmetric Operations

Low-SWaP Optical Communications

There is a growing need with many national security communities for secure methods of communication, especially in contested and congested environments at ground level through low-altitude domains. In conventional FSO communications, data are transmitted between two laser-based terminals, each having pointing, acquisition, and tracking subsystems. Because of the complexity of these systems, significant SWaP is required for each laser terminal. An internal research and development effort is evaluating the replacement of one of these laser terminals with a small modulated retroreflector (MRR). As shown in Figure 3, there are several advantages associated with using an MRR. First, the MRR is substantially smaller than a laser terminal, with sizes generally ranging between those of a pushpin and a pill bottle. Second, an MRR requires very little power, with some examples powered solely with a coin cell battery. Finally, the acceptance angle of an MRR is several orders of magnitude larger than that of a laser terminal, making it significantly easier to align and establish a link compared with conventional laser terminals.

However, the MRR's low SWaP and easier alignment come at the expense of range and data rate. MRR technology based on corner cube retroreflectors with diameters between 5 and 10 mm typically can support ranges between 1 to 5 km using eye-safe lasers. These estimates assume a low-SWAP interrogator with transmit and receive aperture diameters of 2 to 3 in. These ranges can be extended but require larger interrogator apertures, larger retroreflectors, or higher laser powers. The other primary limitation of MRR technology is the data rate. State-of-the-art MRRs with diameters between 5 and 10 mm have data rates between 100 kbps and 1 Mbps. This can be compared to conventional laser terminals, which may have data rates of 10 Gbps or greater.

Li-Fi Communications

The past several years have seen significant advances in the physical-link connections and proofs of concept for various approaches to light-based communications (i.e., optical wireless communication, FSO, and visual light communication). An additional approach to optical mobile communication systems that require a full

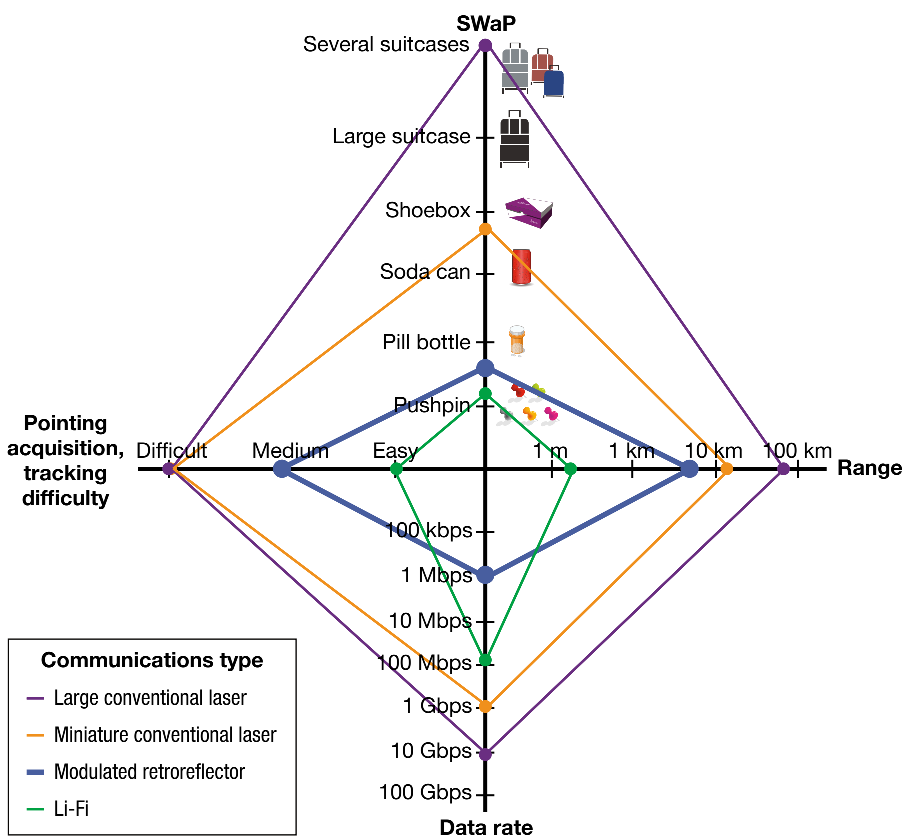

Figure 3. Advantages of using an MRR. The MRR is substantially smaller than a laser terminal, requires very little power, and offers a large acceptance angle that makes it much easier to align and establish a link compared with conventional laser terminals.

networking solution is emerging, and it has been deliberately termed *Li-Fi*. Li-Fi is not an LED light bulb, an access point, or a physical layer protocol. Li-Fi is a fully networked optical wireless communication protocol that is almost identical to the Wi-Fi protocol, a standard created by the IEEE 802 Working Group. Li-Fi is defined as "an optical wireless broadband access technology that uses the visible and/or infrared light spectrum to provide bidirectional (transmit and receive) capability. It is able to support uplink and downlink in a point-to-point or point-to-multipoint topology and provide multiuser access in this way."[1] The significance of the technology is in the integration of optical communications into a practical use case for the consumer. Once adopted, Li-Fi will relieve the ever-increasing burden on RF communication channels and increase capacity by enabling densification and bandwidth expansion for wireless networks.

In 2017 and 2018, APL developed and tested Li-Fi for the Defense Information Systems Agency as a potential solution for optical wireless area networks within the DOD infrastructure. APL participated in the formation of the IEEE 802.11bb Task Group currently developing the Li-Fi standard that will work interchangeably with Wi-Fi (IEEE 802.11ac/ax) and cellular protocols. The main difference between Li-Fi (IEEE 802.11bb) and Wi-Fi (IEEE 802.11ac/ax) is a modified physical layer for the optical medium and some changes to the media access control layer processing.

APL was also directed to participate in the 2018 US Navy Trident Warrior exercise by installing and testing Li-Fi equipment on the USS *Carl Vinson* for a feasibility study of the technology for the Navy.

For DOD to use Li-Fi, the National Security Agency/Central Security Service Commercial Solutions for Classified (CSfC) Program must accept the technology. Once IEEE 802.11bb has been approved through ballot, which is scheduled to begin in March 2021, and has been accepted by the IEEE 802 Working Group, it will be a candidate technology for CSfC. The National Information Assurance Partnership must approve and add the new IEEE 802.11bb standard to its protection profiles before the CSfC Program process for acceptance can begin. It is expected that the commercial sector will start to see wide use of this technology in 2021 or 2022. Assessment of Li-Fi for military use is ongoing.

Optical Communications in Force Projection

Sea Control (Underwater)

Unlike other domains where optical communications is in its infancy compared with RF communications, optical means have been used to communicate in the underwater domain for decades. To date, however underwater optical communications have connected two points on shore without free space connectivity. Communication modalities that are suitable for use underwater are typically limited in either bandwidth or range (see Figure 4)—and the right set of phenomena must be selected for the specific communication desired, allowing a choice in communications method (e.g., RF, optical, acoustic) based on mission needs for a particular data rate and range. For surface and airborne platforms, this kind of diversity of communications choices to balance covertness versus data rates versus range will be a seismic paradigm shift in above-water communications. The underwater domain provides a great example for the other domains to show the advantages of multiple communications options.

By the early 1970s, all the key components necessary for viable fiber optic communications systems had been developed by commercial industry. These technologies included photodiodes (developed by Bell Labs in 1948) and gallium arsenide laser diodes (developed by General Electric in 1962). In addition, in 1963 Tohoku University

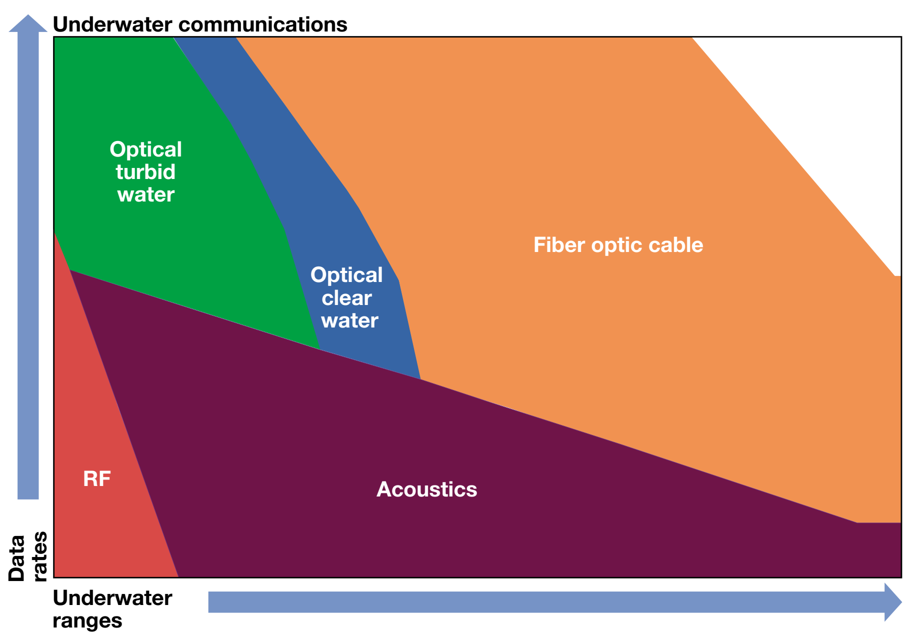

Figure 4. Physical limits of current underwater communications capabilities. Modalities suitable for underwater use are typically limited in either bandwidth or range, so the right set of phenomena must be chosen for the desired communication.

described the basic concepts involved in modern systems, and in 1970 Corning documented the manufacturing processes for low-loss optical fiber. Despite these advances, it was not until 1977 that working fiber optic systems were deployed commercially in Chicago and Long Beach.

Although it is uncharacteristic for technologies from the commercial sector to lag those in the military sector, the military used fiber optic communications 3–4 years before the first commercial deployments of this technology. An onboard optical communication system was installed on USS *Little Rock* in 1973, and in 1975 the North American Aerospace Defense Command (NORAD) installed fiber optic systems to link computers. In both cases, unique military needs (security and imperviousness to electromagnetic interference) led to the successful military applications of a commercial technology before the commercial adoption of the same set of technologies.

More often than not, DOD's successful adoption of new technologies is not driven by a moon shot but by a clear understanding of (1) the capabilities and limitations of a new technology and (2) latent military needs. This gap was clearly understood by Winston Churchill, who in 1916 described the hiatus that existed between "inventors who know what they could invent, if they only knew what was wanted, and the soldiers who know, or ought to know, what they want, and would ask for it if they only knew how much science could do for them."

Claude Shannon's pioneering 1940s work on communication theory described the upper limits on the ability of any channel to carry bits of information. By this measure, light can (and does) transmit information millions of times faster than most radio waves in a vacuum or in a waveguide such as an optical fiber. However, the limited propagation of light waves in water means that while it is possible to transmit lots of information between two nodes quickly, there cannot be very much water (even molecularly pure water) between those nodes. Distances and data rates are further reduced if the water is turbid. All in all, FSO communications in water must be complemented by other technologies (acoustics, very-low-frequency RF, etc.) to ensure a generally robust suite of tactical communications.

Over the coming decades, commercial technologies will continue to approach data transmission limits in turbid and clear water, but beyond a few hundred yards, these technologies do not have much utility. Future FSO communications will work in concert with RF, fiber optics, and acoustics to ensure robust netted communications underwater. To maintain stealth and security, network protocol stacks tying these communications together must support encryption, routing instructions, and network topology updates with very low overhead. The protocol stacks necessary to support these underwater netted communications must be effective over 9 orders of magnitude in data rate and 6 orders of magnitude in range and must meet DOD requirements for security and stealth. APL's ability to leverage subject-matter expertise across each of these communications channels, along with its expertise in encryption, networking, and tactical networking, will enable it to lead a revolution in tactical underwater communications that ties together each of the disparate channels into a functional whole.

In 2042—as in 2021—the scientists, engineers, and operators at APL will understand the missing links in future kill chains and will help Lab sponsors integrate and deploy technology in support of their needs. A focused understanding of sponsor problems as well as of the state of potential technical solutions will enable APL to point to the right set of commercial technologies and, where necessary, develop critical technologies to fill gaps; together, these technologies will enable APL's sponsors to complete their missions in a resilient way.

Optical Communications Networking

Many of the basic building blocks of FSO communication links are available, as discussed above, but a number of networking-related challenges must still be addressed.[2] The first relates to traffic flow across the physical set of links in the network. Typically networking infrastructure either is static (e.g., fibers in a building) or is mobile using a network connected by omnidirectional antennas. FSO communications' extremely narrow beamwidths introduce a new challenge called topology control. Suppose node A has two optical transceiver heads but has line-of-sight visibility to nodes B, C, and D. To which two nodes should node A point? Node A's choice must be coupled with the choices of the other nodes since optical receivers and transmitters must be aligned. This is the topology control problem that has arisen in both directional RF and FSO communications (Figure 5). It can be characterized as a graph edge-coloring problem that is NP-complete so various heuristics must be used to find suboptimal but effective approaches. Given that these networks are mobile and obstructions to FSO communications will disrupt the beams, this is not a one-time operation but must be performed dynamically.[3]

A second challenge that relates to the networking of FSO communications nodes is traffic routing. In many cases, routing protocols run over fixed infrastructures, but FSO communications will have a dynamic physical infrastructure. Many routing approaches developed for mobile ad hoc networks could be employed for FSO communications. APL created a class of routing based on a delay/disruption-tolerant networking (DTN) approach where the routing of network traffic is coupled to the topology control problem in an attempt to mitigate disruptions.[4–6]

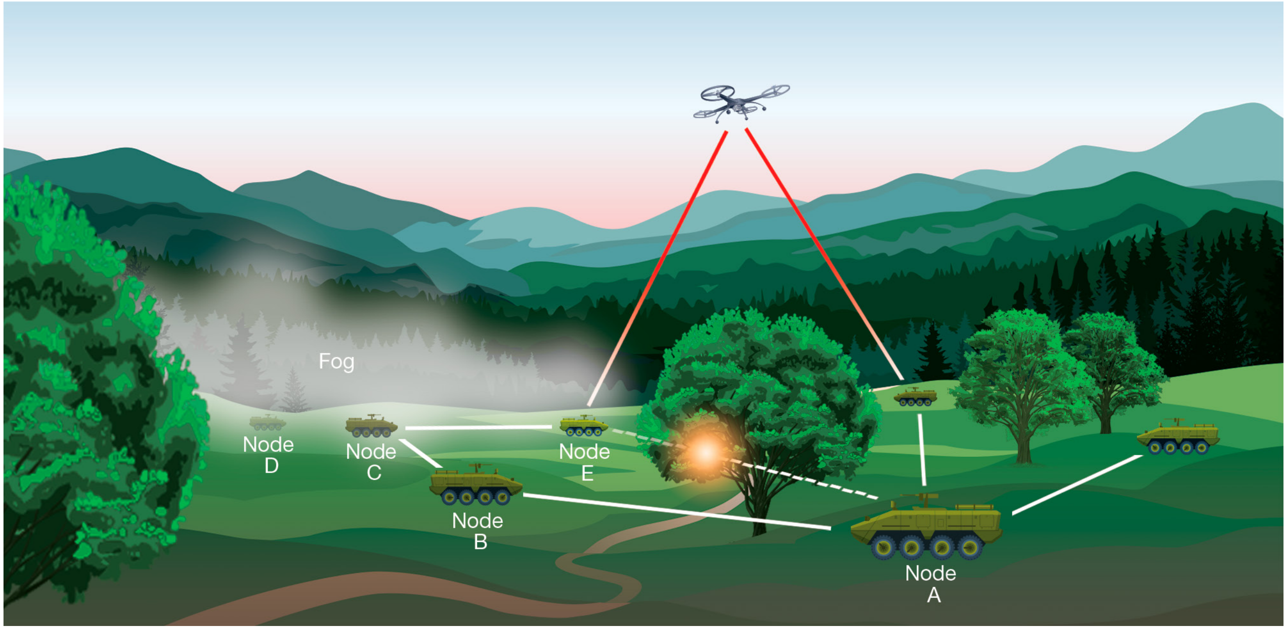

Figure 5. The topology control problem in FSO networking. Suppose node A has two optical transceiver heads but has line-of-sight visibility to nodes B, C, and D. To which two nodes should node A point? Node A's choice must be coupled with the choices of the other nodes since optical receivers and transmitters must be aligned.

Finally, we believe that FSO communications will be incorporated with other RF communication networks as hybrid solutions. All communication systems suffer from some environmental degradation, with the type based on the system's operating frequency, but by using a diverse set of modalities we can mitigate these issues. For example, FSO communications will have degraded performance in fog or sand, while millimeter-wave RF will degrade in rain. Applications running over these networks need to adapt as the communications data rate may change by orders of magnitude. This adaptation could be via coding to exploit diverse paths or quality-of-service approaches that orchestrate flow onto each network.[7] While applications have some dynamic ability to adapt over changing networks today, they cannot adapt to the extent that future optical/RF hybrids will require.

SUMMARY

When APL celebrates its 100th anniversary, modern civilization will have experienced over a century and a half of RF communications technology and capability. New developments continue to happen in RF, yet RF represents just a portion of the electromagnetic spectrum, and a highly regulated portion at that. The optical band of the spectrum provides a tantalizing opportunity to increase the diversity of communications choices, expanding beyond the regulated part of the spectrum. However, to realize these future optical communications innovations, we must facilitate current and initial simple applications. Moving toward 2042, the migration toward using optical communications to meet critical challenges in secure communications will be a matter of making it happen versus needing a research and development breakthrough. The past 15 years have depended on bold vision to develop useful technology; the next 20 years need to focus on getting back to basics by identifying initial use cases, taking a systems engineering approach to establishing requirements, focusing on solving platform integration and networking challenges, and applying (and building on) the fruits of past vision.

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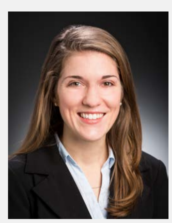

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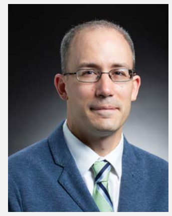

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