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THESIS

MOBILE AD-HOC NETWORKS (MANET) IN SHIPBOARD AND SHIP-TO-SHIP ENVIRONMENTS ENABLING AUGMENTED REALITY DEVICES FOR EMERGENCY MEDICAL CARE

by

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June 2019

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This thesis researches mobile adhoc network (MANET) configurations for the utilization of augmented reality devices in shipboard or ship-to-ship environments. The intent of this research is to discover necessary network requirements and equipment configurations within a MANET necessary to operate augmented reality devices capable of supporting communication between hospital corpsmen and physicians engaged in emergency care during shipboard or ship-to-ship operations.

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LIST OF ACRONYMS AND ABBREVIATIONS

1G	1st Generation of mobile telephony
2G	2nd Generation of mobile telephony
3G	3rd Generation of mobile telephony
4G	4th Generation of mobile telephony
1MC	1 Main Circuit
ACA	Affordable Care Act
AR	Augmented Reality
ARRA	American Recovery and Reinvestment Act
ATA	American Telemedicine Association
AuC	Authentication Center
BSC	Base Station Controller
BTS	Base Transceiver Station
CPU	Central Processing Unit
COTS	Commercial-Off-The-Shelf
dB	Decibel
DEPSECDEF	Deputy Secretary of Defense
DHA	Defense Health Agency
DoD	Department of Defense
DSL	Digital Subscriber Line
EIR	Equipment Identity Register
EHF	Extremely High Frequency
EPC	Evolved Packet Core
GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Services Switching Center
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPU	Graphics Processing Unit
GSM	Global System for Mobile communications
GUI	Graphical User Interface
HF	High Frequency

HITECH	Health Information Technology for Economic and Clinical Health
HLR	Home Location Register
HRSA	Health Resources and Services Administration
HSS	Home Subscriber Server
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
IP	Internet Protocol
ISDN	Integrated services Digital Network
ISO	International Organization for Standardization
ISP	Internet Service Provider
JP	Joint Publication
JCS	Joint Chiefs of Staff
KBPS	Kilobits Per Second
LAN	Local Area Network
LOS	Line-of-Sight
LTE	Long Term Evolution
MAC	Media Access Control
MAN	Metropolitan Area Network
MANET	Mobile Ad Hoc Network
MARTA	Mobile Augmented Reality Technical Assistance
Mbps	Megabits Per Second
MHS	Military Health System
MILSATCOM	Military Satellite Communications
MIMO	Multiple-Input and Multiple-Output
MLB	Motor Life Boat
MME	Mobile Management Entity
MPU	Man Portable Unit
MSC	Mobile Switching Center
NFL	National Football League
NM	Nautical Mile
NPS	Naval Postgraduate School
OFDMA	Orthogonal Frequency Division Multiple Access

OSI	Open Systems Interconnection
PCHM	Patient Centered Medical Home
PCRF	Ploigy and Charging Rules Function
PDN	Public or Packet Data Network
PDU	Protocol Data Unit
PGW	PDN Gateway
PTSN	Public Telephone Service Network
RAA	Remote Advise and Assist
RF	Radio Frequency
RNC	Radio Network Controller
RoIP	Radio Over IP
RV	Reality-Virtuality
SATCOMM	Satellite Communications
SGSN	Serving GPRS Support Node
SGW	Service Gateway
SHF	Super High Frequency
SMTP	Simple Mail Transfer Protocol
SNR	Signal-to-Noise Ratio
SPAWAR	Space and Naval Warfare Systems Command
SoC	System on a Chip
SSID	Service Set Identifier
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
UHF	Ultra High Frequency
UNREP	Underway Replenishment
Um	User Mobile
USDATL	Under Secretary of Defense Acquisition technology and logistics
USCG	United States Coast Guard
USSOCOM	United States Special Operations Command
USMC	United States Marine Corps
USN	United States Navy

VOIP	Voice Over Internet Protocol
VLR	Visitor Location Register
VPN	Virtual Private Network
VTC	Video-teleconference
VR	Virtual Reality
WAN	Wide Area Network
WHO	World Health Organization
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability of Microwave Access

I. INTRODUCTION

A. VIGNETTE

On a deployment to the Persian Gulf, a Sailor onboard the USS ESSEX (LHD-2) had the unfortunate experience of having her hand caught in a scuttle, falling off the vertical ladder she was on, and landing two decks below. As she was discovered, the Officer of the Deck (OOD) was notified and “man down” was called away over the 1MC (one-way central amplifier announcing system). The ship’s medical team was already stretched thin because of a breakout of diverticulosis onboard and a hand injury that had occurred just a few minutes before “man down” was called. Hearing the alert, the medical team quickly deployed two Hospital Corpsmen (HMs) to the site equipped with Hierarchical Yet Dynamically Reprogrammable Architecture (HYDRA) radios (a wireless interior communications system that provides wire-free mobile communications throughout the ship and supports communications for other functions) to enable situational awareness between themselves and the Medical Officer on Duty (MOOD). As the HMs reached the patient, they noted several easily visible severe injuries. However, they were more concerned about internal injuries, which are especially severe because they often lead to further complications or even death if improperly handled.

As the HMs tried to relay the information back to the MOOD, they were unsuccessful because the site where the Sailor had fallen was beyond the coverage area of the ship’s communication systems. Even if the radios had worked, they would have limited the MOOD’s ability to assess characteristics of the patient’s injuries, such as pupillary reactions, auscultation of heart or lung sounds, and motor reflex observations, because they do not provide the ability to visually monitor the situation. The HMs in this scenario were also limited in their ability to receive and observe any known information about the patient’s medical history in real time. The patient’s medical history would have been useful in illuminating any previous conditions the patient might have suffered from or allergies to any medications that may need administering onsite.

Realizing that the engineering space in which the injury occurred remained at a high temperature at all times, the HMs knew that they had to move the patient promptly, even at the risk of further injury. They quickly strapped the patient into a litter and spine board to immobilize her and transported her out of the space by hoisting her up the ladder well. Once the patient's move to the ship's medical department was complete, the Sailor was in the direct care of the MOOD.

The medical team provided the resuscitative care it was capable of and stabilized the patient. Without the subject matter expertise of specialty care that they did not have onboard, they felt the treatment needed for this patient was beyond their capabilities. The patient was evacuated to a higher echelon of care, and the ship was left with one less able body to complete its mission. It is possible that in the time required to evacuate the Sailor, her condition could have deteriorated. An augmented reality capability might have mitigated the need to send her to a higher echelon.

Imagine another scenario on the same deployment during an underway replenishment (UNREP) in which a sailor sustains a traumatic injury onboard the UNREP ship, which has no advanced medical personnel. The average distance between ships engaged in a UNREP is 180–220 feet. Since there are medical personnel onboard the USS ESSEX, they could be in a position to respond. In most of these situations, currently, a voice circuit is used to communicate between ships. However, without audio and video of the patient, physicians aboard the ESSEX would have to make decisions on triage and patient movement with an incomplete assessment of the situation. In many cases, this can lead to poorly informed decision making and further complicate the patient's injuries.

As was described in these afloat scenarios, it is often the case in operational settings that HMs will provide medical care at the site of a traumatic injury and later, physicians will engage the patient as they are moved to a higher echelon of care. During the time referred to as the "golden hour," the proficiency of triage and transport greatly impact results. Currently, medical teams are limited to voice communications onboard ships, and only in locations that are in range of the HYDRA (Lackey & Shumaker, 2016).

Advances in technology offer new communication tools that could provide medical teams faced with similar situations with the ability to communicate on a more capable network and leverage the advantages offered by augmented reality. More specifically, HMs could benefit from secure and reliable remote advise-and-assist (RAA) communications when operating in ship environments. These communications-challenged environments introduce significant difficulties in establishing links for RAA capability. The absence of a network capable of enabling technology that can deliver audio and video limits HMs from obtaining valuable remote subject matter expertise and limits their ability to gain and share an accurate situational awareness vital in emergencies. To fill this gap, the Navy needs a mobile ad-hoc network (MANET) aboard ships that can support medical personnel to utilize augmented reality devices in shipboard or ship-to-ship scenarios to aid emergency care efforts. A MANET is a self-organizing, self-healing, rapidly forming, autonomous network proficient in adaptive routing and peer-to-peer communication that is established via portable nodes without support of an existing infrastructure (Sinsel, 2015).

B. RESEARCH OBJECTIVE

This research explores the possibility of using the combination of augmented reality devices and MANETs for providing emergent or immediate life-saving medical care to individuals while in shipboard or ship-to-ship environments.

1. Context

Medical personnel as a resource at sea are already stretched thin and impending changes concerning force shaping indicate further personnel cuts are near. Not all vessels in the Navy enjoy full medical staffing. Therefore, all platforms at sea have a varied experience and expertise level among their medical crew. A journeyman-level medical care provider is typically referred to as a Navy Hospital Corpsman (HM), having received approximately 6 – 9 months of training in performing temporary life-saving medical treatment. The treatment is designed to keep their patient alive long enough to be transported to a location to receive treatment from the master-craftsman level medical personnel that will ultimately save the patient’s life. A master-craftsman is someone with advanced medical training, is a certified medical doctor (MD), and has undergone at least ten years of training that led to their MD certification. Currently, in most shipboard or ship-to-ship environments, the person that will generally be providing emergent care is the Navy HM, the journeyman-level medical provider. If the patient has an injury outside of the corpsman's skillset, this renders that patient at increased risk.

If there were a way to share the master craftsman-level knowledge and skillset of the medical doctor with the corpsman, then the life-saving capabilities of the corpsman are greatly enhanced under the various stressful conditions that can come with being in a ship environment. This situation is where the MANET could help, as HMs could receive real-time guidance from the medical doctor on potentially lifesaving techniques and procedures to implement via an augmented reality device with the reachback capability delivered over a MANET.

2. Research questions

The scenario involving the Sailor onboard the USS ESSEX demonstrates the potential to utilize a MANET capable of extending enough bandwidth to enable augmented reality devices in a particular environment. There are other scenarios and environments in which the same problem limits medical teams. The problem is particularly relevant to operational elements within the military forward deployed in areas remote from support mechanisms. Therefore, the research questions addressed by this thesis are:

(a) Could a commercial off the shelf (COTS) MANET network radio deliver the necessary bandwidth needed to support augmented reality devices such as Microsoft HoloLens in an emergency shipboard or ship-to-ship scenario and enable communication between medical teams separated by distance?

(b) What factors affect the use of augmented reality devices enabled by a MANET for emergency medical care during shipboard or ship-to-shore operations?

(c) What is the effect on the transmission rate as the distance between nodes in the MANET increases?

C. SCOPE

This thesis addresses considerations for customizing network protocols and radio equipment to be utilized in a MANET. The goal is to provide timely expertise over the MANET, utilizing only the guidance provided from the subject matter expert located at the distant reachback capability via the augmented reality headwear. We utilized the Microsoft © HoloLens augmented reality headwear glasses to receive the reachback guidance for performing the emergent medical care. Since the Microsoft HoloLens augmented reality headwear glasses are dependent on a network capable of delivering bandwidth in the range of 1.5 Mbps, we utilized the Persistent Systems MPU-4 and MPU-5 Wave Relay radios in order to establish the MANET in various network topologies to see which provides the best conditions suitable for the augmented reality headwear.

D. LIMITATIONS

- Since the research is aimed at simulating and testing environments and situations that usually are hazardous to life, the research is limited by a few factors.

- First, we did not conduct tests in real operational environments. The environment was limited to simulated internal shipboard and ship-to-ship, as well as actual internal shipboard testing on an interactive ship that was not equipped with HYDRA.

- Second, reachback, whether using an IP gateway or just reaching back to a remote site located within the MANET, requires nodes spread across distances of hundreds, sometimes thousands of feet. For this research, the "playing field" was limited to a range of 5 miles, but exceeds the typically required distance.

- Lastly, we did not employ a gateway reachback for RAA during this testing due to not having the proper licensing or authorization. More resource would have been required to allow for this extension of our research.

E. ORGANIZATION

This thesis contains five chapters detailing the precursory reviews, research, and findings discovered throughout our research. Chapters are as follows:

(a) Chapter I: vignette, research objectives, scope, and limitations.

(b) Chapter II: a literature review of technical concepts that should be understood before the research can be confidently understood.

(c) Chapter III: the research design, methodology, criteria for the system. Operational, theoretical and physical frameworks.

(d) Chapter IV: analysis of results.

(e) Chapter V: conclusions and recommendations for future research.

II. LITERATURE REVIEW

This chapter is divided into two sections and aims to address the problem of filling the gap in current communication between military medical teams. The first section provides background on telemedicine; the second looks at prior research conducted on augmented reality and MANET capabilities.

A. TELEMEDICINE

The vignette in Chapter I describes scenarios in which the ability to bridge the gap of healthcare information over distance could have been vital. Using technology to deliver care for patients over distance is referred to as telemedicine. This section will offer a definition of telemedicine, provide an account of its history, and offer an assessment of current DoD uses.

1. Timeline of Telemedicine

In order to discuss telemedicine, it must be clearly defined. The American Telemedicine Association (ATA) (2006) defines it as the “use of electronic communications and information technologies to provide clinical services when participants are at different locations” (p. 2). While telemedicine and telecare are used similarly, telemedicine is often utilized when discussing clinical settings, and telecare when discussing nursing or community settings (Wooten, Craig, & Patterson, 2017). We use the term telemedicine generically to be inclusive of all healthcare settings concerning the transfer of medical data from one location to another (Fatehi & Wootton, 2012). The primary benefit of telehealth as described by the World Health Organization (WHO) is that it improves access to healthcare.

The timeline of telemedicine was particularly crucial to this research, provided an understanding of its historical origin and trends in its application and facilitated the incorporation of previous findings into this research as well as a sense of direction for our experimentation. Although the technology necessary for the widespread use of telemedicine is just now becoming available to the masses, the idea of telemedicine has been around for over a hundred years. As can be seen in Table 1, the concept of telehealth had been thought of as early as 1879. Articles written in 1879 discuss the use of the telephone to diminish needless office visits (Lustig, 2012). According to Vinches (2014), "In 1948, the first radiologic images were sent via telephone across 24 miles in eastern Pennsylvania" (para. 3). In the 1990s, the rise of the Internet supported telemedicine efforts by allowing all types of information to be shared. In 2009, the American Recovery and Reinvestment (ARRA) and Health Information Technology for Economic and Clinical Health (HITECH) Act provided financial viability for medical technology advances and drove digital connectivity (Gruessner, 2015). In 2010, the Affordable Care Act (ACA) further inspired organizations within the healthcare industry to utilize telehealth as a means of reducing cost and increasing access to care. In 2014, President Obama introduced language in the National Defense Authorization Act (NDAA) that focused on expanding telemedicine services targeting military members (Ehley, 2014). The trend towards encouraging telemedicine has since continued. In 2016, the Health Resources and Services Administration (HRSA) granted $16 million to efforts like expanding the use of telemedicine for veterans without access in rural communities.

Table 1. History of Telemedicine. Adapted from CDW Healthcare (2016).

History of Telemedicine	
1879	-Lancet article talks about using the telephone to reduce unnecessary office visits CDW Healthcare (2016, para. 3)
1925	-Radio and publishing pioneer Hugo Gernsback predicts that doctors would someday use radio and TV to communicate with patients CDW Healthcare (2016, para. 4)
1948	-First radiologic images sent via telephone across 24 miles in eastern Pennsylvania CDW Healthcare (2016, para. 5)
1959	-The University of Nebraska uses interactive telemedicine to transmit neurological examinations CDW Healthcare" (2016, para. 5) -Canadian radiologist reports diagnostic consultations based on fluoroscopy images transmitted by coaxial cable CDW Healthcare (2016, para. 6)
The Late 1950s/Early 1960s	-Closed-circuit television link established between Nebraska Psychiatric Institute and Norfolk State Hospital for psychiatric consultations CDW Healthcare (2016, para. 7)
1961	-U.S. Space Program performs test flights using animals attached to medical monitoring systems, sending animals' biometric data to scientists on Earth via telemetric link CDW Healthcare (2016, para. 8) -Journal Anesthesiology reports on radiotelemetry for patient monitoring CDW Healthcare (2016, para. 8)

History of Telemedicine	
1967	-Physicians at the University of Miami School of Medicine and the City of Miami Fire Department report use existing voice radio channels to transmit electrocardiogram (EKG) rhythms from fire and rescue units to Jackson Memorial Hospital CDW Healthcare (2016, para. 9)
Late 1960s	-Telemedicine begins as a form of healthcare delivery, propelled by NASA and the Nebraska Psychology Institute CDW Healthcare (2016, para. 10)
1970s	-Kaiser Foundation International, in partnership with Lockheed Missile and Space Company, create a remote monitoring system capable of providing healthcare delivery CDW Healthcare (2016, para. 11)
1973-1977	-NASA tests STARPAHC (Space Technology to Rural Papago Health Care) program where mobile support units in rural Tohono O'odham reservation link patients with physicians in Indian Health Service hospitals CDW Healthcare (2016, para. 12)
1980s	-Radiologists begin using teleradiology systems to receive images for telemedicine consultations CDW Healthcare (2016, para. 13)
1990s	-Rise of the Internet allows support for practically all information and traffic needed for telemedicine CDW Healthcare (2016, para. 14)
2009	-ARRA and HITECH ACT propel medical technology advances drive digital connectivity CDW Healthcare (2016, para. 15)
2010	-CMS publishes a final rule on Meaningful Use, prompting electronic health record adoption and further laying the digital groundwork for telemedicine growth CDW Healthcare (2016, para. 16) -Patient Protection and Affordable Care Act spurs the formation of accountable care organizations, in which telemedicine and remote monitoring play essential roles CDW Healthcare (2016, para. 16)
2014	-President Obama signs the National Defense Authorization Act, which expands telemedicine devices specifically designed to help military members transition back to civilian life CDW Healthcare (2016, para. 17)
2016	-More than $16 million awarded by the Health Resources and Service Administration (HRSA) to improve access to quality healthcare in rural communities, including funds that will expand the use of telehealth technology for veterans and other patients CDW Healthcare (2016, para. 18)

2. Telemedicine in DoD

Telemedicine has also become integral to the Military Health System. Vice Admiral Faison, who is the Navy surgeon general and chief Bureau of Medicine and Surgery (BUMED), was recently quoted in an article as stating, "Our number one priority is keeping Sailors, Marines and their families healthy, ready and on the job," (Rosenfelder, 2016, para. 3). Telemedicine services are a vital part of achieving Vice Adm. Faison's number one priority. A report by Anthony Kurta (Acting Under Secretary of Defense for Personnel and Readiness) in response to section 718 of the National Defense Authorization Act for Fiscal Year 2017 (Public Law 114-328) acknowledges the, "Military Health System (MHS) has long recognized the value and strategic importance of the incorporation of telemedicine services in order to support a medically ready force and a ready medical force. Great strides have been made in the development and implementation of telemedicine within the

Department of Defense (DoD), due in large part to the cooperation between the Army, Navy, Air Force and the Defense Health Agency (DHA). The continued leveraging of telehealth will address the Quadruple Aim of improving readiness, enhancing population health, advancing health outcomes, and reducing health care costs" (Department of Defense, 2017, p. 4). MHS's efforts in the telemedicine space are centered on the concept of "connecting Service Members and MHS beneficiaries to health care globally, to increase readiness, access, quality, and patient safety" (Department of Defense, 2017, p. 5). There is an effort to emphasize telemedicine wherever MHS patients are regardless of whether they are deployed or in garrison. The MHS telemedicine plan intends to expand support across all echelons of care and within all phases of military operations (Department of Defense, 2017).

The Military Health System's (MHS) commitment to telemedicine continues to grow. Its current use of telemedicine coincides with the intent of recent legislation and guidance put forth by decision-makers. MHS Primary Care settings have the tools needed to connect patients and providers separated by distance. Over 20 percent of Patient-Centered Medical Home (PCMH) encounters utilize the telephone to complete virtual visits (Department of Defense, 2017). Patient education is disseminated via video-teleconference (VTC), webcam-based applications, and telephone (Department of Defense, 2017). MHS also endeavors to bring virtual primary care visits to the patient location in an initiative launched in 2016. The Nurse Advice Line was launched in 2018 and will be expanded globally to address urgent care with telemedicine. Behavioral health is currently the most substantial proportion of telemedicine encounters within MHS (Department of Defense, 2017). In a similar fashion to its delivery of primary care telemedicine, MHS is utilizing VTC, webcam-based applications, and telephone equipment to deliver synchronous provides to patient visits. Telehealth has the highest potential to improve efficiencies in specialty care. Currently, specialty care telemedicine services offered by MHS include synchronous virtual encounters and asynchronous consultations between patient and provider. Table 2 lists the specialty areas and synchronous or asynchronous capabilities.

Table 2. Synchronous and Asynchronous Telehealth Services by Specialty. Adapted from Department of Defense (2017).

Specialty Area**	**Synchronous**	**Asynchronous***
Alcohol/Drug Abuse	X	
Allergy	X	X
Anesthesiology	X	X
Audiology	X	
Behavioral Health	X	X
Cardiac Electrophysiology		X
Cardiology (Adult, Pediatric)	X	X
Critical Care Medicine (Adult, Pediatric)	X	X
Dermatology	X	X
Endocrinology (Adult, Pediatric)	X	X
ENT	X	X
Family Practice/Primary Care	X	X
Forensic Pathology	X	X
Gastroenterology (Adult, Pediatric)	X	X
Hematology/Oncology (Adult, Pediatric)	X	X
Infectious Diseases (Adult, Pediatric)	X	X
Internal Medicine	X	X
Interventional Cardiology		X
Neonatology – Perinatology	X	X
Nephrology (Adult, Pediatric)		X
Neurology (Adult, Pediatric)	X	X
Nutrition	X	X
Ob/Gyn	X	X
Occupational Therapy	X	
Ophthalmology	X	X
Pediatrics	X	
Pediatric Developmental – Behavioral		X
Pharmacy	X	
Physical Medicine – Rehab/Spinal Cord Injury Med	X	X

Physical Therapy	X	
Podiatry	X	X
Primary Care	X	X
Psychiatry (Adult, Pediatric)	X	X
Pulmonary Diseases (Adult, Pediatric)	X	X
Radiology/Radiation Oncology	X	X
Rheumatology	X	X
Speech Therapy	X	
Surgery (General, Hand, Orthopedic, Pediatric, Neurological, Thoracic, Plastic, Vascular)	X	X
Urology	X	X

*Asynchronous services represent consultations between providers, not provider-to-patient services.

**Health education services, as a component of listed specialty care area, could be provided either synchronously or asynchronously as appropriate.

Beyond MHS's current telemedicine offerings, the organization is pursuing several other services. The Virtual Medical Center is a concept that will utilize new technologies to enable reachback capabilities to providers 24/7, around the globe (Department of Defense, 2017). The first Virtual Medical Center is situated at Brooke Army Medical Center in Fort Sam Houston, TX, and was established in 2018. Operational telemedicine is another pursuit for MHS. Although all efforts in this type of telemedicine are still very early in the development phase, several pilots have shown to be successful and valued by the Warfighter (Department of Defense, 2017). In a recent report to the Chairman of the Committee on Armed Services, it was shared that, "The ultimate vision is direct patient care/support from providers in garrison to patients at all roles of care during all phases of a military operation for all types of medical or psychological threat" (Department of Defense, 2017, p. 11).

Telemedicine is being used in a myriad of ways within DoD at an increasing rate for several reasons. The ability to stretch medical capabilities over great distances and the ability to reduce costs are among those reasons. However, another prominent reason the

DoD is resourcing telemedicine efforts is to extend the capabilities to the warfighter, which this research is mainly focused.

B. AUGMENTED REALITY

The methods in which augmented reality is being used in medicine are developing at an increasing rate. This section offers a definition for the term augmented reality, provides a historical perspective, affords a detailed understanding at the Microsoft HoloLens, and explains why the HoloLens was chosen for this research.

1. Augmented Reality Defined

Interest in Augmented Reality (AR) and its capabilities is proliferating. In 2018, the U.S. Army awarded Microsoft a contract worth up to $480 million for its version of AR headsets (Kelly, 2018). Although Microsoft seems to be the early frontrunner in AR, other vendors like Magic Leap, Epson, Google, Vuzix, Meta 2, Optinvent, Garmin, Solos, Everysight and Osterhout Design Group have also brought devices to market in 39 different countries that cost from $300 to $3,000 (Kelly, 2018). With the availability of AR devices increasing, development of use cases for the live collaborative technology is at an all-time high. AR is improving how people visualize real-world environments, how they obtain support remotely, and how they interact and collaborate.

Although distinctions between augmented, virtual, and mixed reality exist, scholars disagree on how to define the terms. One attempt by Paul Milgram et al., recognized that AR and VR are not mutually exclusive. They saw these terms as being “within the context of a Reality-Virtuality (RV) continuum, encompassing a large class of ‘Mixed Reality’ displays, which also includes Augmented Virtuality (AV)” (Milgram, Takemura, Utsumi, & Kishino, 1995, p. 282) as depicted in Figure 1.

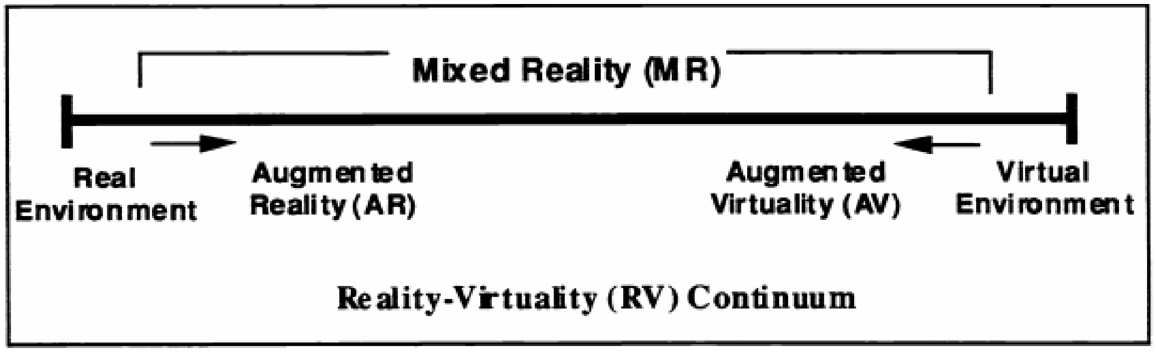

Figure 1. Reality-Virtuality Continuum. Source: Milgram et al. (1995).

At the left extreme of the continuum exists an environment completely made up of actual tangible objects, whereas the right extreme exists a virtual environment. In between the two exists the area referred to as mixed reality. According to the continuum, mixed reality is an environment in which tangible substances and computer-generated ones are exhibited together (Milgram et al., 1995)

For this research, we will define AR as "a live direct or indirect view of a physical, real-world environment whose elements are augmented by computer-generated sensory input such as sound, video, graphics or GPS data" (Chavan, 2016, p. 1947). Bimber and Raskar shared another relevant description on AR displays when they suggested, "Augmented Reality displays are essentially image forming systems that use a set of optical, electronic and mechanical components to generate images somewhere on the optical path in between the observer's eyes and the physical object to be augmented" (Bimber and Raskar, 2005, chapter 3, para. 1). Figure 2 illustrates the different display concepts of augmented reality. The head-attached portion of the display applies to how AR was applied in the research.

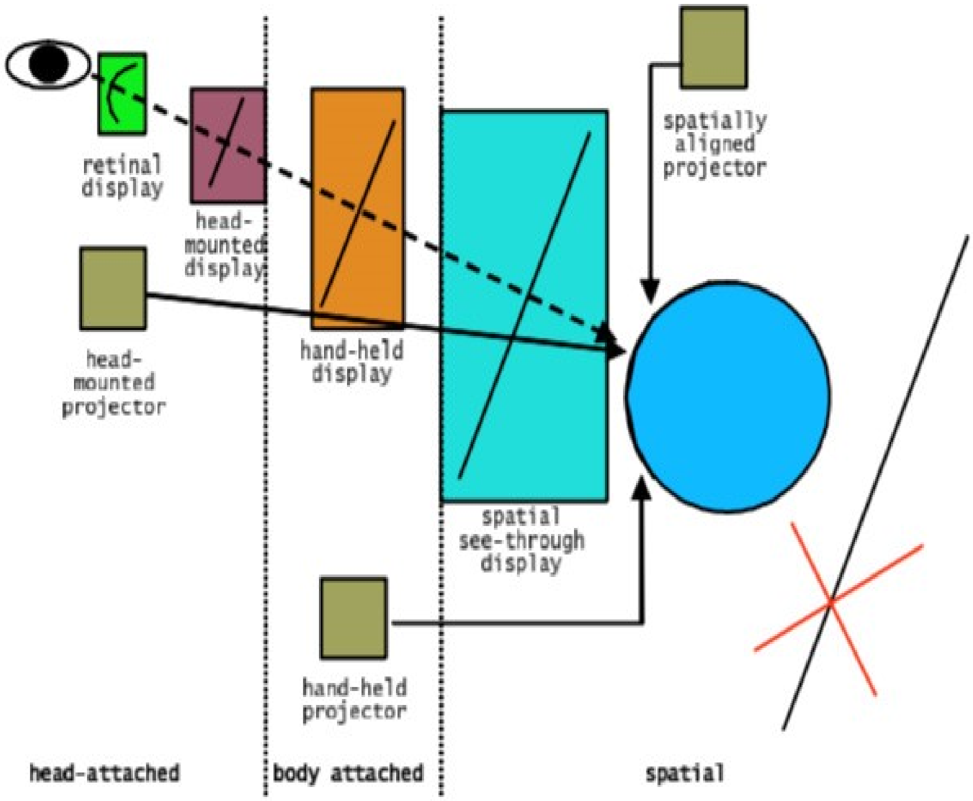

Figure 2. Image Generation for AR displays. Source: Bimber and Raskar (2005).

2. Augmented Reality Timeline

The history of augmented reality offers an understanding of its historical origin and trends in its use, as well as a sense of direction for our experimentation. As can be seen by Table 3, AR's origins trace back to 1968 when a gentleman named Ivan Sutherland put together the first head-mounted system that was capable of displaying wireframe drawings in real-time (Arth et al., 2015). In 1992, Tom Caudell and David Mizell created the label "augmented reality" to explain the overlaying of computer-generated information on real-world objects (Arth et al., 2015). In 1994, AR started to make its presence felt in the entertainment industry by its incorporation into a theater production called "Dancing in

Space" (Augment, 2016). The producer used virtual objects on the theater stage. A trend that would continue in the 1990s, the National Football League (NFL) would start casting a virtual yellow line for representing the first-down marker during live broadcasts (Augment, 2016). In 2013, Volkswagen used an AR app called MARTA (Mobile Augmented Reality Technical Assistance) to provide step-by-step assistance to technicians enabling them to witness a repair being done on the physical car they were looking at (Augment, 2016). In 2014, Google shipped its first Google Glass device to consumers, starting a wearable trend. In 2016, Microsoft HoloLens Developer Kit became available, and investments in AR reached over $1 billion (Augment, 2016). The most well-known use of AR was also in 2016. The AR mobile game "Pokemon Go" was released worldwide. This game uses GPS and AR technology on mobile devices to allow users to position, find, detain, fight, and develop avatar creatures in the user's real-world location. The game became wildly popular and grows in the number of users even today.

Table 3. The Lengthy History of Augmented Reality. Adapted from Arth et al. (2015).

The Lengthy History of Augmented Reality	
1968	-Ivan Sutherland developed the first head-mounted display system. The system used computer-generated graphics to show users simple wireframe drawings. Arth et al. (2015, para. 5)
1974	-Myron Krueger built an artificial reality laboratory called the Videoplace. The Videoplace combined projectors with video cameras that emitted onscreen silhouettes, surrounding users in an interactive environment. Arth et al. (2015, para. 6)
1990	-Boing researcher, Tom Caudell, coins the term "Augmented Reality." Arth et al. (2015, para. 7)
1992	-Louis Rosenberg develops Virtual Fixtures – one of the earliest functioning AR systems, built for the Air Force. The full upper-body exoskeleton allowed the military to control virtually guided machinery to perform tasks from a remote operating space. Arth et al. (2015, para. 8)
1994	-Julie Martin creates the first augmented reality Theater production. "Dancing in Cyberspace," featuring acrobats who danced within and around virtual objects on their physical stage. Arth et al. (2015, para. 9)
1998	-The 1st & Ten line computer system is broadcast by Sportsvision, casting the first virtual yellow first down marker during a live NFL game. Arth et al. (2015, para. 11)
1999	-Naval researchers begin working on Battlefield Augmented Reality System (BARS), the robust, original model of early wearable units for soldiers. Arth et al. (2015, para. 12) -NASA X-38 spacecraft is flown using a Hybrid Synthetic Vision system that used augmented reality to overlap map data to provide enhanced visual navigation during flight tests. Arth et al. (2015, para. 12)
2000	-Hirokaza Kato created the ARToolKit, an open-source software library that uses video tracking to overlay computer graphics on a video camera. The ARToolKit is still used widely to compliment many augmented reality experiences. Arth et al. (2015, para. 13)

The Lengthy History of Augmented Reality	
2003	-For the 2003 NFL season, Sportsvision unveils the first computer graphic system capable of inserting the 1st & Ten lines from the popular Skycam, the NFL's mobile camera that provides the field's aerial perspective. Arth et al. (2015, para. 14)
2009	-Print media tries out AR for the first time. Esquire Magazine prompts readers to scan the cover to make Robert Downey Jr. come alive on the page. Arth et al. (2015, para. 15) -ARToolKit brings augmented reality to a web browser. Arth et al. (2015, para. 15)
2013	-Car manufacturers begin to use augmented reality as the new age vehicle service manuals. Arth et al. (2015, para. 17) -The Volkswagen MARTA app (Mobile Augmented Reality Technical Assistance) provides virtual step-by-step repair assistance allowing service technicians to foresee how a repair process will look on the vehicle in front of them. Arth et al. (2015, para. 17)
2014	-Google announces shipment of google glass devices for consumers, thus starting a trend of wearable AR. Arth et al. (2015, para. 18) -Magic Leap announces the most significant AR investment to date of $50M, Series A. Arth et al. (2015, para. 18)
2015	-Augmented reality and Virtual reality investment reach 700 Million. Arth et al. (2015, para. 19)
2016	-Augmented reality and Virtual reality investment reach 1.1 billion. Arth et al. (2015, para. 20) -Microsoft HoloLens Developer Kit Ship and the Meta 2 Developer Kit set to ship this year. Arth et al. (2015, para. 20)

3. Microsoft HoloLens

Although many types of AR devices have been and continue to be developed due to the expanding list of use cases, the head-attached display devices are the interest of this research. Notably, (see Figure 3) Microsoft HoloLens was selected for use in our experiments.

Figure 3. Microsoft HoloLens. Source: Microsoft (2017).

The HoloLens is an AR headset developed by Microsoft. It is a descendent of Microsoft Kinect, which is an add-on for the Microsoft Xbox videogame system. It combines and expands on the capabilities of AR devices like Google Glasses, which add a digital window to the field of view, and the Oculus Rift that video gamers use to step into a virtual world. The HoloLens is the world's first untethered holographic computer and the first device of its kind to utilize 3D mapping in real-time. As is depicted in Figure 3, the display is connected to an adjustable headband. The red pieces on either side of the device are speakers that are capable of producing audio that can simulate spatial effects for the user.

Figure 4 shows the environment-scanning cameras within the unit that facilitate head tracking. Also shown is the depth camera that facilitates hand tracking and surface reconstruction. Surface reconstruction is necessary for the placement of holographic images on physical objects.

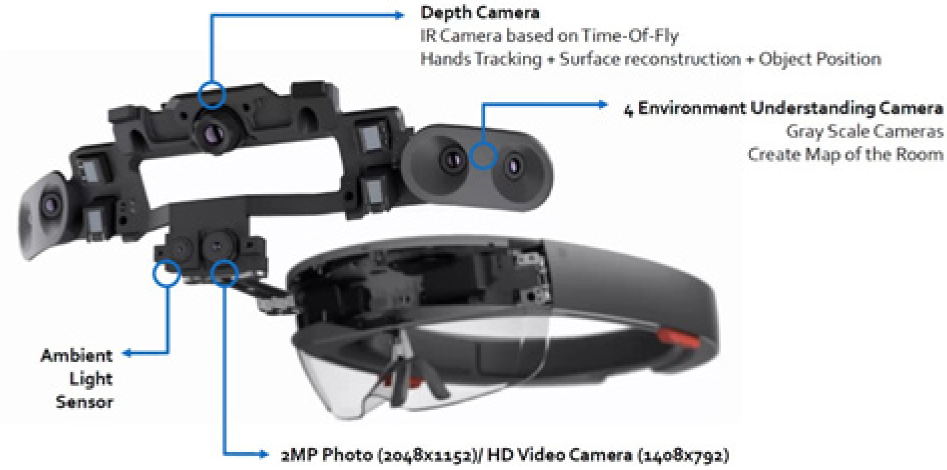

Figure 4. HoloLens Optical Sensors. Source: Valoriani (2016).

The Inertial Measurement Unit (IMU) depicted in Figure 5 contains an accelerometer, gyroscope, and magnetometer. As the user's head moves, the IMU helps keep the environmental images positioned properly and holograms where the user intended them to be.

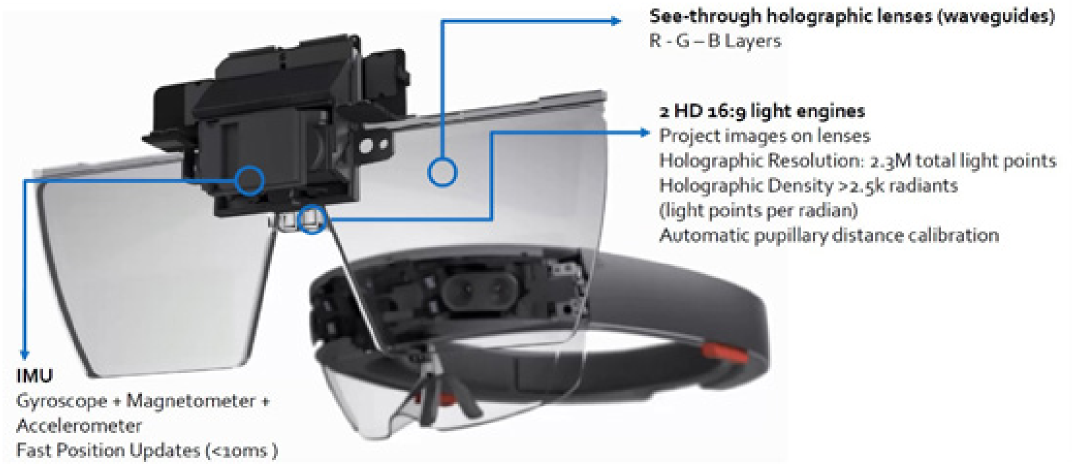

Figure 5. HoloLens Optic Lenses. Source: Valoriani (2016).

Figure 6 displays the HoloLens main logic board. It provides mobile computing utilizing an Intel Cherry System on a Chip (SoC) that contains the central processing unit (CPU) and graphics processing unit (GPU). The SoC is responsible for running the Windows 10 application, shell, and the two stereo displays. Also shown is the holographic processing unit (HPU) that helps relieve the burden of the SoC with regard to the environment's understanding and environment-sensing tasks. Figure 7 illustrates a block diagram with all of the system's electrical components. All of the items colored green represent items developed explicitly for the HoloLens.

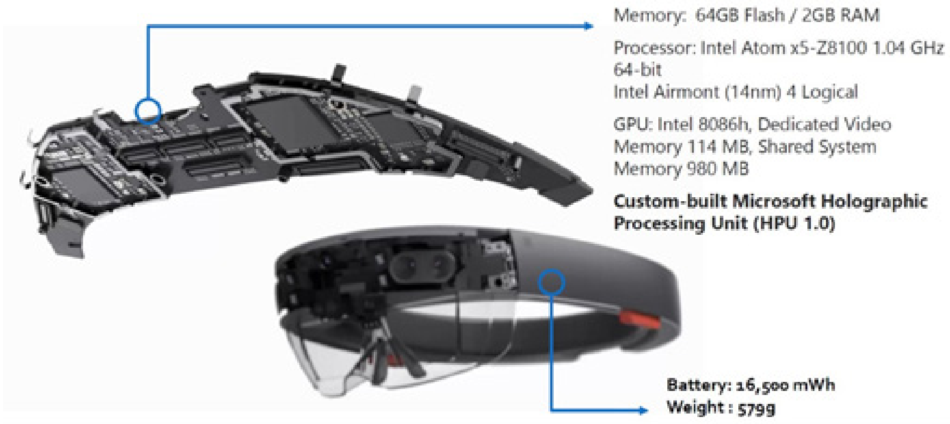

Figure 6. HoloLens Main Logic Board: Valoriani (2016).

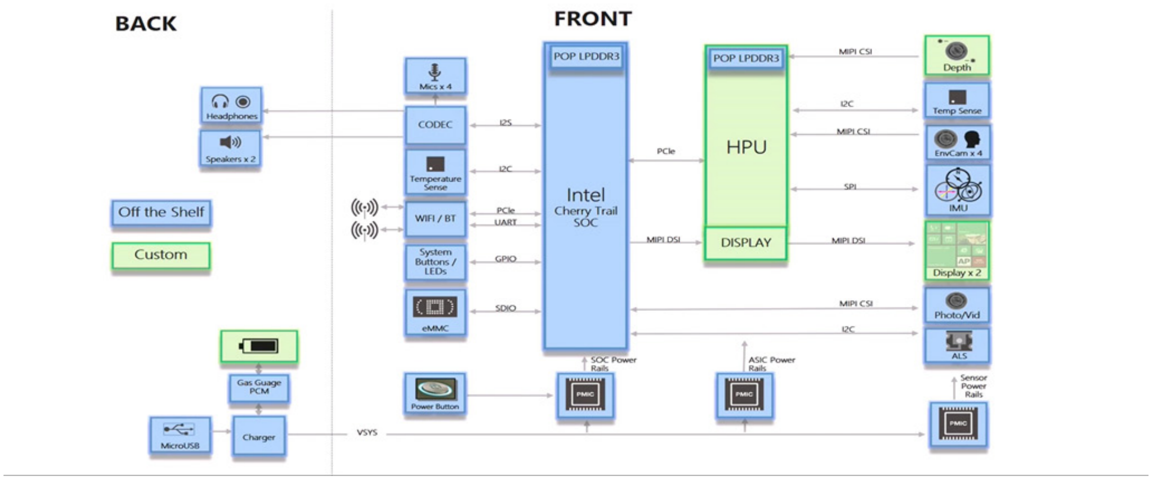

Figure 7. HoloLens Hardware Block Diagram Source: Valoriani (2016).

4. Why Microsoft HoloLens

HoloLens is the world’s first untethered collaborative mobile computing device that is capable of AR. Its wireless nature and integrated battery allow for mobility into remote locations, which was necessary for this research. The fact that HoloLens is a head-attached device enables users to utilize their hands constructively and effectively. Among AR devices, the HoloLens platform has already been utilized the most by the medical community in the U.S. Hospitals are using it to train their residents, TH-based physicians are using it to collaborate both with patients and other subject matter experts for consultations, and medical device companies have embarked on creating tools for providers based on the platform. It also has the most advanced applications that are currently available, which make it an attractive solution for this research. Bandwidth was another significant factor for choosing the HoloLens. The Microsoft website suggests, “The recommended bandwidth for optimal performance of Remote Assist is 1.5 MB/s. Though audio/video calls might be possible in environments with reduced bandwidth, experiences include HoloLens feature degradation, limiting the user experience” (Paul and Ho, 2019, para. 1). Because of the environments, the research focused on relatively low bandwidth constraints.

C. NETWORK

To deliver AR as a capability for medical teams on ships it is necessary to construct a network infrastructure that will allow for the technology's use. This section explains the attractive characteristics of MANET, offers a brief introduction to Wave Relay Radios, and provides OSI insight relevant to this research.

1. MANET

In addition to the MANET described in Chapter I, MANETs were a creation of the Defense Advanced Research Projects Agency. Although this type of network has attractive characteristics, it has not been widely used in the civilian sector. Instead, the growth in this application has come from the military. According to RFC2501, "the goal of mobile ad hoc networking is to extend mobility into the realm of autonomous, mobile, wireless domains, where a set of nodes—which may be combined routers and hosts—themselves form the network routing infrastructure in an ad hoc fashion" (Macker, 1999, p. 2). The network may work as a closed system or link to a static network. The components of the network are wireless and utilize antennas to transmit and receive information. Each device in the network uses either single or multiple hop wireless links (Misra et al., 2009).

MANETs have distinct characteristics that users can benefit from or be limited to, such as:

(a) "Self-forming, self-configuring, and self-healing. The multi-hop communication and its management in a MANET are automatic and spontaneous without any centralized network authority. In most scenarios, a MANET has no Internet accessibility for nodes" (Misra et al., 2009, p. 4).

(b) "Dynamic topologies: Nodes are free to move arbitrarily; thus, the network topology—which is typically multi-hop—may change randomly and rapidly at unpredictable times, and may consist of both bidirectional and unidirectional links" (Macker, 1999, p. 3).

(c) “Constrained resources: MANETs suffer from limited energy and network bandwidth. The mobile nodes are powered by battery for transmitting or receiving packets to/from other nodes. Thus, the node can only work for a limited period because of limited power. Also, all the nodes in a MANET usually operate in a shared wireless channel. Thus, the network bandwidth is limited, and nodes compete with each other for accessing the medium” (Misra et al., 2009, p. 4).

(d) “Limited physical security: Mobile wireless networks are generally more prone to physical security threats than are fixed-cable nets. The increased possibility of eavesdropping, spoofing, and denial-of-service attacks should be carefully considered. Existing link security techniques are often applied within wireless networks to reduce security threats. As a benefit, the decentralized nature of network control in MANETs provides additional robustness against the single points of failure of more centralized approaches” (Macker, 1999, p. 4).

Figure 8 is an example of a MANET in which various nodes serve to relay to other nodes. For example, the only way for node S3 to receive communications from the rest of the team at this moment is through node S6; however, node S7 can receive communications from the rest of the team via nodes S4, S8, or S9.

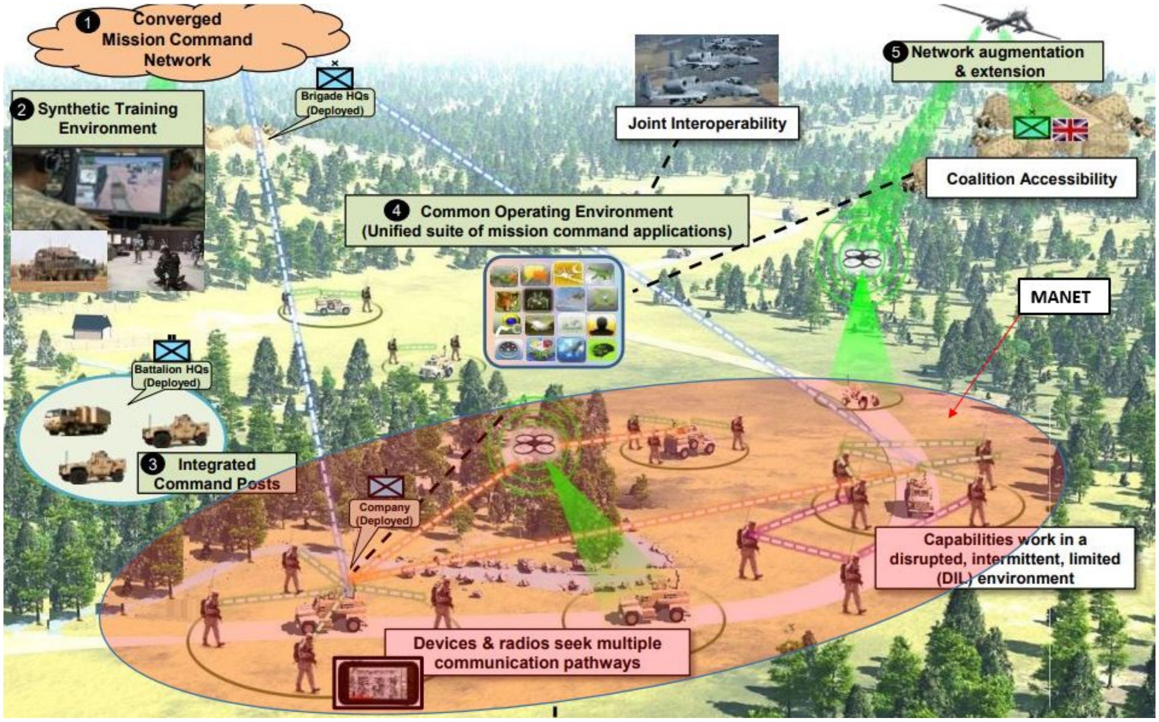

Figure 8. MANET Source: Witsken (2018).

For this research, these characteristics were vital and presented an opportunity for findings as we applied the MANET.

2. Persistent Systems Wave Relay Radio

> Wave Relay® is a Mobile Ad Hoc Networking System (MANET) designed to maintain connectivity on the move. A scalable, peer-to-peer network provides data, video, and voice even in the most challenging applications. With user throughput of 41 Mbps UDP and 31.1 Mbps TCP, Wave Relay provides a dynamic, reliable, and secure wireless networking solution beyond mesh. (Persistent Systems, 2016, para. 1)

For this research, the Wave Relay MPU-4 and MPU-5 radios were ideal. The Man-Portable Unit (MPU) GEN 4 shown in Figure 9 weighs under two pounds and packs a battery capable of 14 hours of runtime. These wireless OSI layer two radios are capable of constructing a peer-to-peer MANET capable of delivering secure high bandwidth for the transfer of data, video, and voice. It is also capable of real-time position location and is 802.11a/b/g AP compatible with MANET. The ability to produce a hotspot was a key feature critical to the needs of the experiments due to the wireless nature of the end devices involved.

Figure 9. MPU4. Source: Persistent Systems (2016).

3. Open Systems Interconnection (OSI)

The AR audio/video data traveling over the MANET in this research is in the form of audio bit stream and buffered video stream. An understanding of the OSI model allows a better understanding of possible constraints affecting transmission of data. The workings behind the OSI model enables communications between two or more devices from different vendors by standardizing the communications flow via the OSI standard. At its core, OSI means that every system communicating within the framework of this model is open for communication with all other systems in the OSI model by following the same communication rules and protocols (Zimmermann, 1980). Before the OSI model existed, each company would have custom proprietary standards for how their products communicate with each other, which almost forced customers to purchase all of their devices from one vendor for ease of compatibility. Since OSI has been around, it has made it easier for any device from any vendor to communicate with each other. OSI is a reference model defined in 1984 by the ISO. The ISO is an organization which develops and publishes most international standards (Yates & Murphy, 2009). The OSI reference model separates network functionality into seven distinct categories or layers (Zimmermann, 1980). The layers have specific features that it uses to handle data communications between two or more devices at each of the respective levels (Zimmermann, 1980).

Figure 10 illustrates the system on the left trying to communicate with the system on the right, via the network. The system on the left is transmitting the data from its seventh layer to its first layer, and that the system on the right is receiving said data at its layer 1 and pushes the data up to its seventh layer. For this example, we will call the data audio/video stream. The data travels through the OSI model, adding headers at each level starting with Layer 7, then moves down to Layer 6, Layer 5, Layer 4 and so on until it reaches Layer 1. The data then travels as binary bits or 1s and 0s over a transmission medium (copper line) until it reaches the receiving system's OSI reference model at Layer 1. The data then travels up that OSI model and strips off the header that was previously added by the sending system before passing the audio/video stream packet up to the next level in the OSI model until finally, the data ultimately reaches Layer 7 (Henshall & Shaw, 1990).

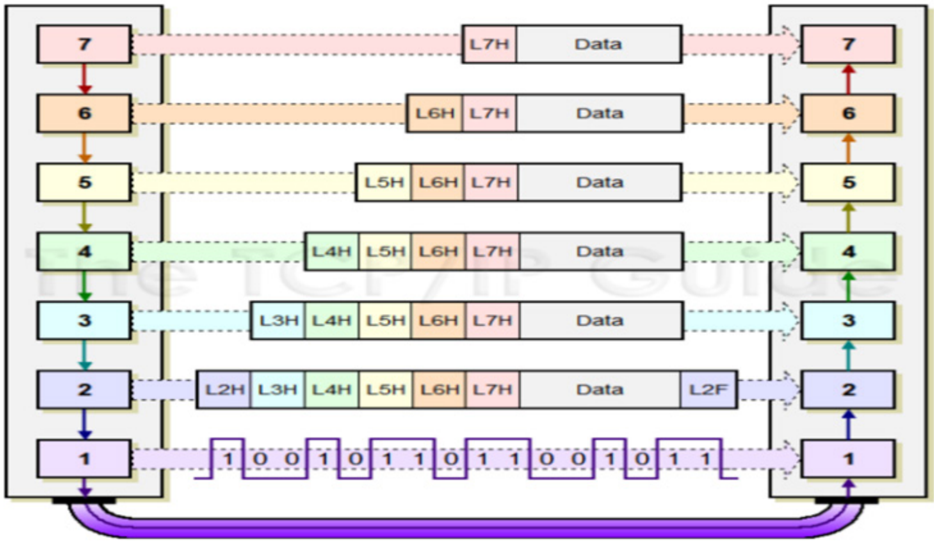

Figure 10. OSI Model Network Communication. Source: Kozierok (2005a).

This is how the seven layers in the OSI reference operate. The first layer, Layer 7, is called the Application Layer. It works by using protocols specific to a network application or function, such as user datagram protocol (UDP), used for sending large files that do not rely heavily on file integrity. An example would include streaming audio or video files where the loss of a few data bits would not corrupt the data enough to render it unusable. Transmission control protocol (TCP) is another protocol, which, unlike UDP, are dependent on file integrity. An example includes word documents where the loss of a few bits of the data usually result in data corruption. The end user can communicate with the program or application. Next, the data is transmitted to Layer 6, the Presentation Layer that is responsible for encryption/decryption, translation, and formatting of the data for the receiving application’s comprehension and data compression. Data then goes to Layer 5, the Session Layer, which is responsible for initialization and termination of device connections, authentications, and authorization. Layer 4 handles the data and is called the Transport Layer, which is used for error handling and sequencing to ensure no lost data. It divides the data into protocol data units (PDU) called segments, which contain a sequence number and source/destination port number, so that segments know where the destination and source are and in what order to reconstruct the segments when they arrive.

Layer 3 is the Network Layer, responsible for changing the PDUs into packets and adding/ handling source and destination IP address during IP address routing as well as determining the best data delivery path. It is used primarily for transporting data over the internet via routers. Layer 2 is the Data Link Layer. It is responsible for adding the source and destination physical address or media access control (MAC) address to its PDU called frames. Frames are primarily used for routing traffic within a network via network switches. Lastly, the Physical Layer, Layer 1, carries the data across physical hardware platforms. It converts the data into 1s and 0s called bits and transmits the signal created by the bits over a medium, either copper for electrical signals, fiber for light signals, or wireless for radio frequency signals. The data is then handled in the same way when it reaches Layer 1 of the receiving systems Layer 1 of the OSI model and is processed through Layer 7 and eventually the receiving end user (Henshall, 1993).

While the OSI model has transformed into the TCP/IP reference model, both models still perform the same functions they did from before the transformation. Individual layers in the OSI model were grouped and rebranded for the TCP/IP model. Typically, when discussing handheld radios communicating with one another, the type of information that is being passed from one radio to another is RF voice.

Since the data that we transmit between radios within the scope of this research is audio/video data, it is important to understand that the protocol for this medium is UDP and the protocol for the augmented reality data is TCP/IP. These protocols are all handled in the TCP/IP model, formerly known as the OSI Model. Figure 11 shows how the OSI model morphed into the TCP/IP model, the new standard for networked communications (Kozierok, 2005b). A quick comparison of the two models shows that a few layers were combined, yet maintain the same functionality as the previous iteration.

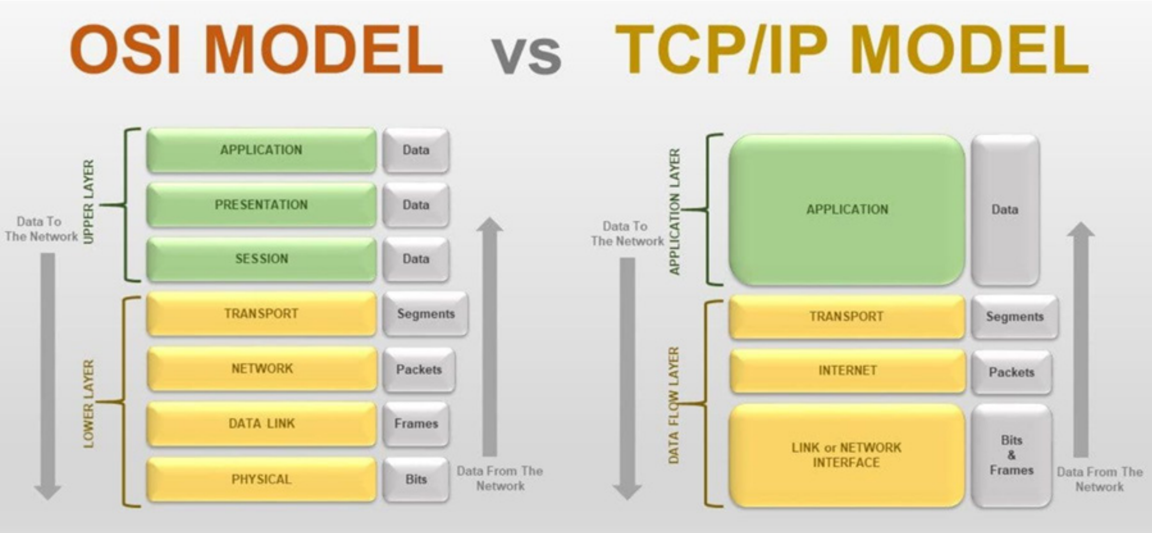

Figure 11. How the OSI Model Morphed into the TCP/IP Model.
Source: Kuthar (2018).

III. EXPERIMENT DESIGN

This chapter explains the methods used during the various experiment phases in our research. We endeavored to address the gap in emergency medical team communications using a MANET with the Microsoft HoloLens in shipboard or ship-to-ship environments. Experimentation was conducted in a phased approach that allowed for constant refinement and implementation of results and findings from previous testing phases into the subsequent phases. During this approach, we conducted 4 phases of testing, Phase 0 through Phase 3.

A. PHASE 0 (LAB TESTING)

In Phase 0, we sought to determine whether Microsoft HoloLens would be able to deliver its capabilities over a MANET. During the literature review for this research, we discovered a published recommendation from Microsoft that suggested a bandwidth of at least 1.5 Mbps for optimal performance of audio/video calls during remote assist tasks (Paul & Ho, 2019). We also discerned from literature by Persistent Systems that the MPU-4 Wave Relay radio can deliver a bandwidth throughput of 41 Mbps (Persistent Systems, 2016). These systems would have to work well together for this research. Because we could find no previous research conducted that utilized the two systems together, we conducted Phase 0 to determine if they would work together in our local environment, which was inside and around concrete buildings at the NPS campus. Figure 12 is a Google Earth image of the NPS campus and illustrates Root Hall's location in relation to other campus landmarks.

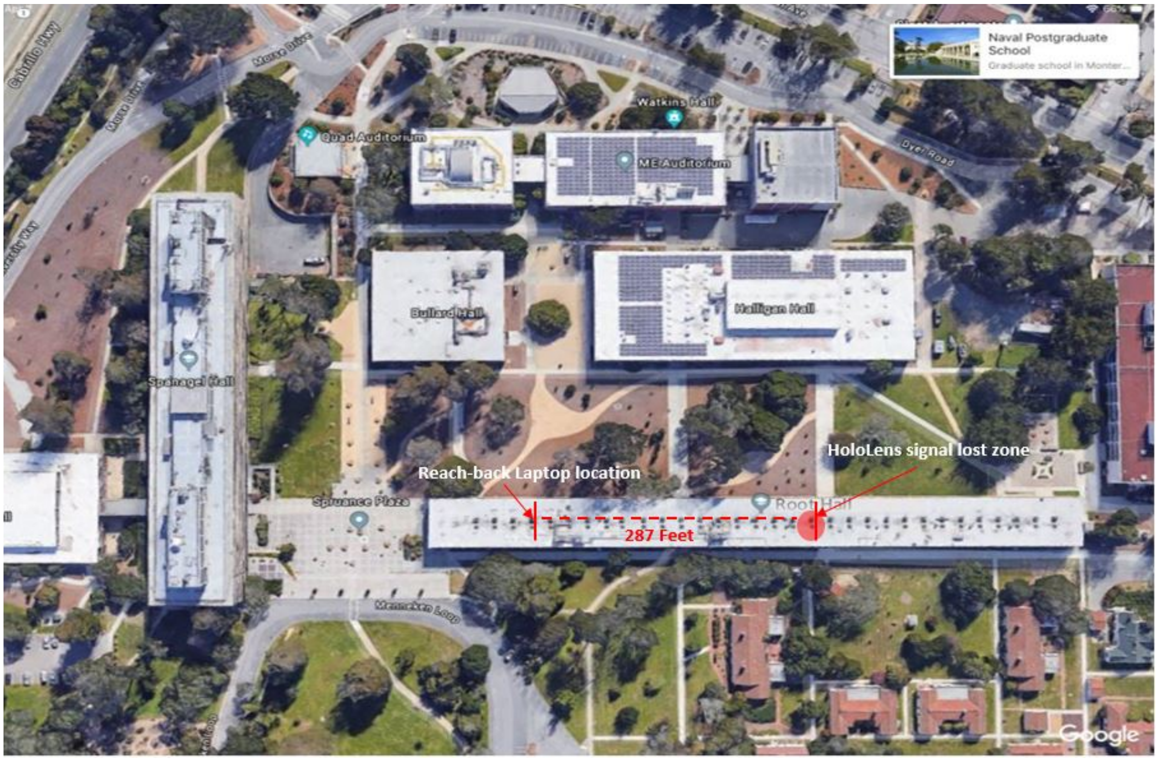

Figure 12. Phase 0 Area. Adapted from Google Earth (2019).

First, we set up and configured a 192.168.87.1 network. To this network, we added two MPU-4 radios designated "Team 3" with a static IP of 192.168.87.86 and "Team 4" with a static IP of 192.168.87.87 that each broadcast an SSID of Team 3 and Team 4 respectively. Next, we configured the Microsoft HoloLens with a static IP of 192.168.87.135 and connected it to the Team 3 radio wireless SSID. Then, we used a laptop as a remote portal to log into and access the Microsoft HoloLens GUI. We connected the laptop to the Team 4 radio via WIFI to the Team 4 SSID. In this portal, we were able to use the Microsoft HoloLens's Spectator feature, which allowed the remote portal user the ability to observe audio and video streaming from the individual wearing the HoloLens as depicted in Figure 13. Figure 14 illustrates the equipment used in Phase 0.

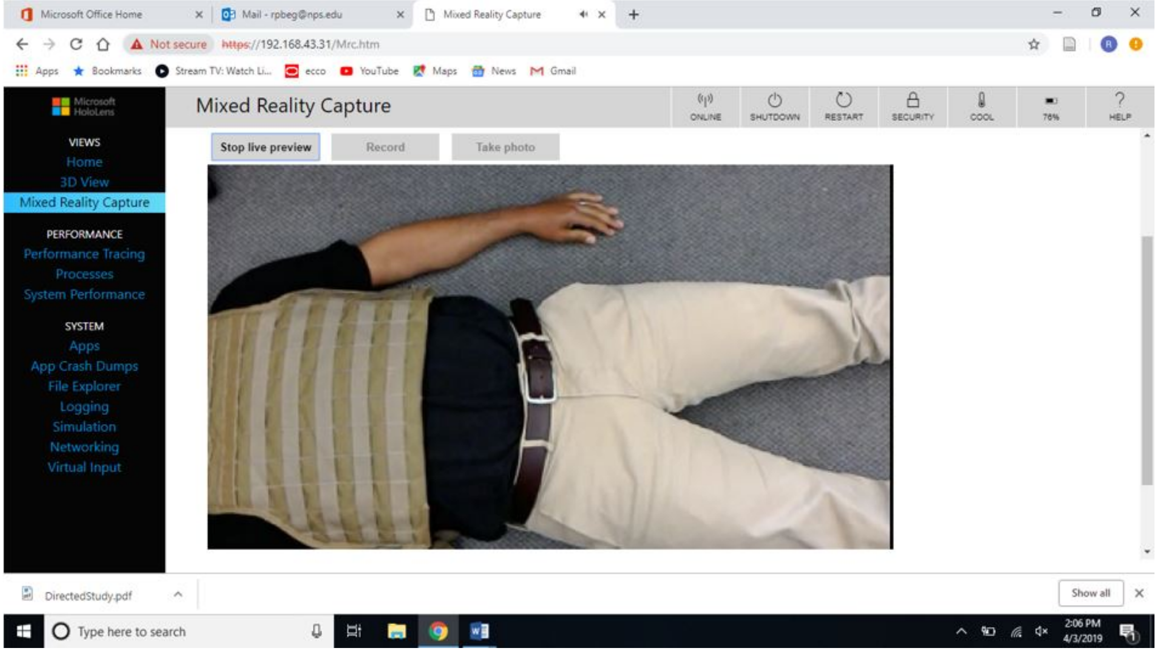

Figure 13. First Person View of Microsoft HoloLens as Seen from GUI of Reachback Laptop

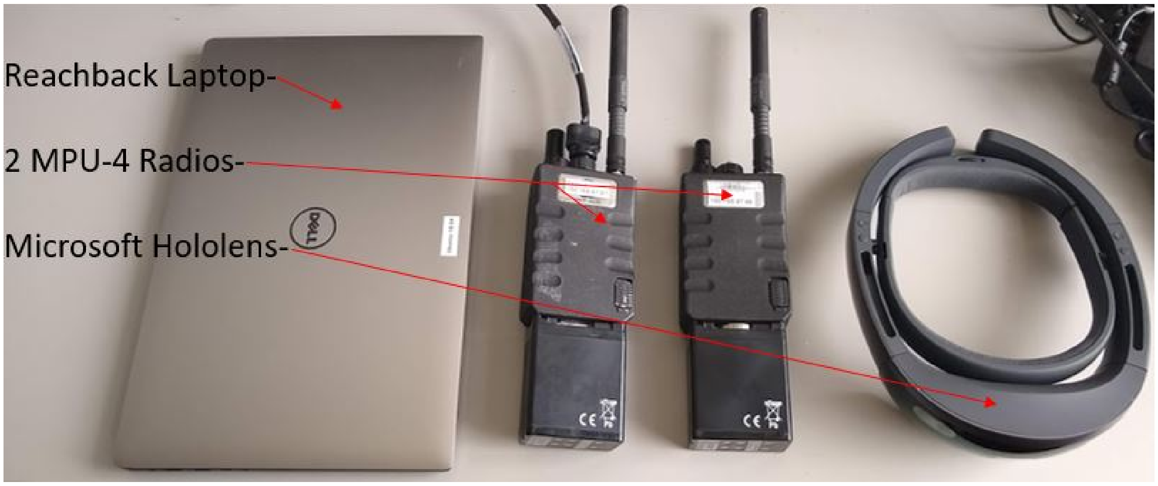

Figure 14. Phase 0 Equipment

After configuring the network and devices, we performed four lab tests.

1. Lab Test 1

The first test conducted on the second floor in the Cenetix Lab of Root Hall simply set up and connect the equipment. The operator of the HoloLens was equipped with the HoloLens and Team 3 Radio. The operator of the laptop with the Microsoft HoloLens GUI was equipped with the laptop and the Team 4 radio. Within the Cenetix Lab, synchronous communication between the two operators was tested successfully. A reliable audio/video connection remained useable for the duration of the testing.

2. Lab Test 2

In the second lab test, we stretched the mobile nodes of the network within the building. While the operator of the laptop stayed in the Cenetix Lab, the operator of the HoloLens moved until the augmented reality audio/video ceased to appear on the laptop portal. In this test, the operator of the HoloLens was able to travel 290 feet before the connection terminated.

3. Lab Test 3

The third lab test required the operator of the HoloLens to travel down the corridor of the second floor to the stairwell that leads to the first floor to determine the reliance on Line Of Sight (LOS). As the HoloLens operator walked down the stairwell, we sought to stretch the nodes vertically but also make LOS impossible. The movement down the stairs introduced a barrier to LOS as the connection was lost when HoloLens reached the first floor. The image on the portal froze, as the connection was lost.

4. Lab Test 4

The fourth and last lab test in Phase 0 was designed to test operability as we stretched the nodes from the inside the Cenetix Lab to the outside of the building. The laptop operator remained in the Cenetix Lab while the operator of the HoloLens traveled across the courtyard to the other building. Connectivity remained uninterrupted as the HoloLens traveled and increased distance between the two nodes by 354 feet.

B. PHASE 1

In Phase I, our purpose was to overcome the drop in bandwidth caused by interruptions in LOS. To accomplish this, we introduced additional nodes into the MANET in a manner that would allow each respective node in the series of nodes to maintain direct LOS with its neighboring node. We chose to conduct the experiment in Phase I on the rooftop of Spanagel Hall. The rooftop of Spanagel Hall has a flat walkable area around its perimeter of approximately 1,150 feet. It also has a 490-foot by 40-foot raised rectangular superstructure in the center made of metal and concrete. This location served the experiment well by disrupting LOS as we attempted to communicate from one static location with the mobile nodes communicating at all locations around the perimeter of the roof. Figure 15 shows an overhead view of Spanagel Hall and its rectangular superstructure.

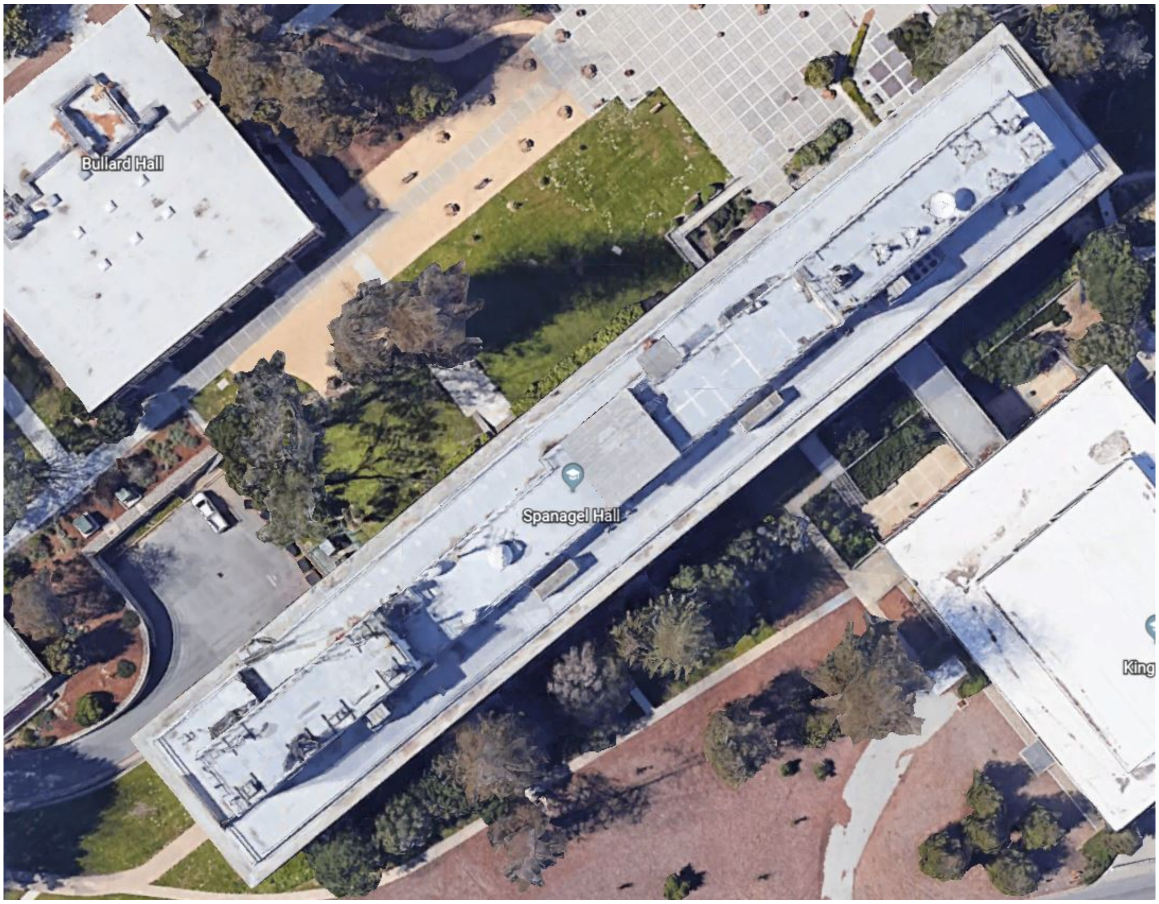

Figure 15. Spanagel Hall. Source: Google Earth (2019).

For this Phase, the equipment we used was similar to Phase 0. However, we added two additional MPU-5 nodes to the MANET as a means for extending LOS around the rectangular superstructure. The concept was to simulate a situation such as that shown in Figure 8. No additional changes to the configuration of the MANET occurred. Figure 16 shows the equipment used in this phase.

Figure 16. Phase 1 Equipment

Once all of the equipment was powered up and functional, we set up the laptop and team 4 MPU-4 near the start HoloLens walk point located adjacent to the rooftop elevator access. The operator of the HoloLens walked towards the first turn, which was 350 feet away. Connectivity was lost as he turned the corner because LOS was lost, resulting in a frozen image on the reachback laptop. The operator returned towards the start point to reestablish connectivity. Next, we set up an MPU-5s at turn 1 and attempted to walk past the turn again. This time the operator was successful in maintaining connectivity and a high-quality image as he rounded the first turn. However, as he rounded the second turn, which was approximately 50 feet away from the first turn, connectivity, as well as image quality, was lost once again due to the obstruction disrupting LOS. Once again, an MPU-5 was set up and placed at the second turn. The operator again reestablished connectivity by walking back towards the start point. As connectivity was reestablished, the operator was able to round both the first and second turns on his way to the third turn, which was 480 feet away from the second turn. As the operator surpassed the third turn, connectivity was again lost along with the image on the laptop. During each step in testing, connectivity was lost around the turns completely and not in a decremental manner as we expected, confirming the importance of LOS. Figure 17 shows a graphical depiction of all locations and operational movements described above.

Figure 17. Overhead View of Phase 1 Operational Test. Adapted from Google Earth (2019).

C. PHASE 2

In Phase 2, we tested the systems within a shipboard and ship-to-ship environment. The location for this phase was the GTS Admiral W. M. Callaghan (T-AKR-1001) at Old Alameda Point in Alameda, California. The ship is 694 feet in length, has a 92-foot beam, a draft of 29 feet, and its make-up is entirely steel. All onboard testing occurred on the main deck and below. Figure 18 shows the GTS Admiral W. M. Callaghan (T-AKR-1001) and its relative location to Old Alameda point.

Figure 18. GTS Admiral W. M. Callaghan (T-AKR-1001) Relative Location to Old Alameda Point. Adapted from Google Earth (2019) and Stan56 (2012).

For Phase 2, much of the same equipment and configuration was similar to Phase 1. The HoloLens and laptop functioned as end devices. The MPU-4s and MPU-5s facilitated the construction of the MANET. The main equipment difference in this phase was the addition of three extra MPU-5s, which aided in the stretching of the MANET as the operator of the HoloLens traveled from the main deck to the decks below. We did this in order to examine the behavior of the network and throughput in an environment that highly resembles the structure of a naval ship in use today. Figure 19 illustrates the equipment used in this phase of experimentation.

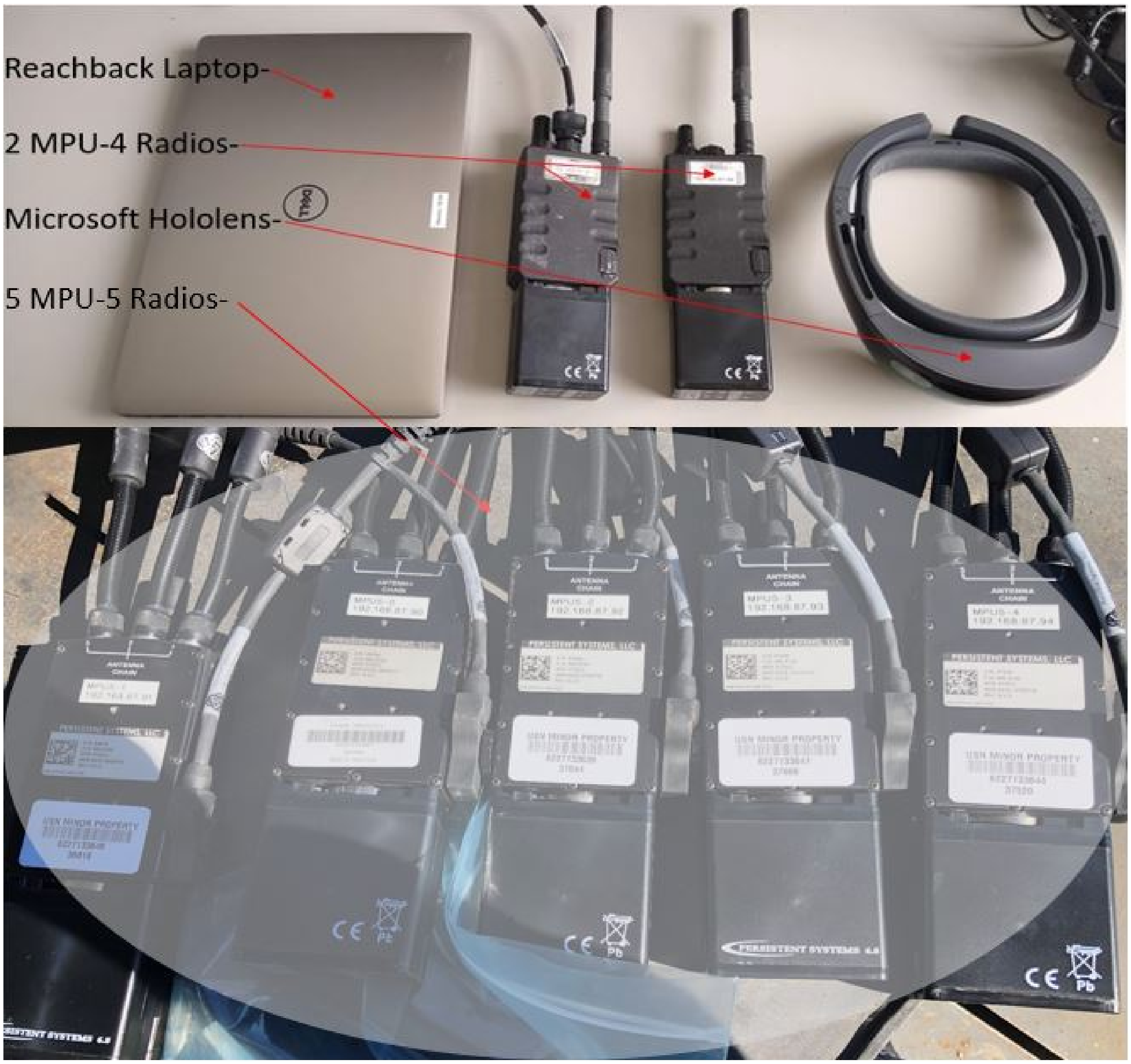

Figure 19. Phase 2 Equipment

To begin field-testing in Phase 2, all equipment gathered on the main deck and staged just outside the aft hangar bay opening. All equipment was powered on and successfully tested for connectivity. Figure 20 illustrates the layout of the main deck, positioning of the reachback laptop with spectator view enabled, the location of the entrance to the first ramp. A dotted line depicts the path of the HoloLens operator as he started the descent to the decks below.

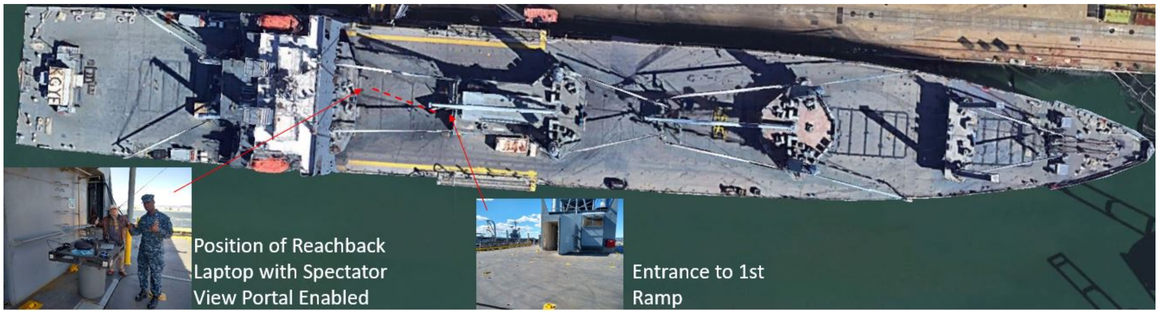

Figure 20. ADM Callaghan Over Head View. Adapted from Google Earth (2019).

The HoloLens operator traveled away from the reachback laptop through the entrance to the first ramp and walked down the ramp to the first deck below as depicted in Figure 21.

Figure 21. HoloLens Operator Traversing the First Ramp to the First Deck Below

As the operator made the turn into the first deck below and towards the second ramp, connectivity was lost with the reachback laptop. As a result, the audio and video on the reachback laptop ceased. Due to the lost connectivity, an MPU-5 was placed on the first deck below to re-establish LOS as depicted in Figure 22.

Figure 22. MPU-5 Radio Added to MANET on First Deck Below

The HoloLens operator then walked back in the direction of the reachback laptop until audio/video communication was re-established. Upon gaining connectivity, the HoloLens operator resumed his descent towards the second deck below by way of the second ramp as depicted in Figure 23.

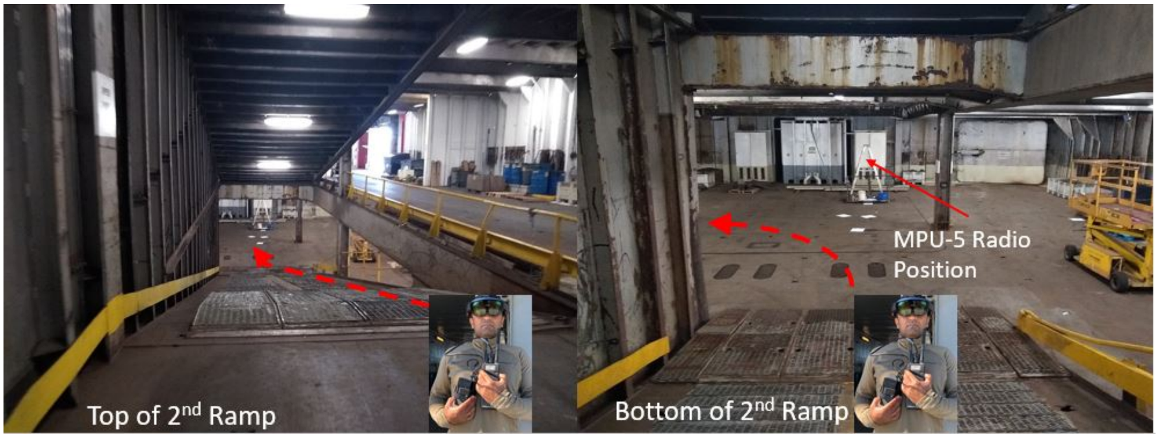

Figure 23. HoloLens Operator Traversing Second Ramp to the Second Deck Below Enroute to the Third Ramp Via Left Turn

As the HoloLens operator made the turn at the bottom of the second ramp onto the second deck below, LOS was lost again, ceasing audio/video communications. Again, the addition of an MPU-5 radio restored LOS and connectivity. This time the MPU-5 was placed on a ladder at the bottom of the second ramp as indicated in Figure 23. After re-establishing connectivity once again, the HoloLens operator continued his descent towards the third deck below via the third ramp. The HoloLens operator maintained connectivity as he traversed the third ramp well into the third deck below before losing audio/video for the final time, midway into the third deck as indicated in Figure 24. Another MPU-5 was staged midway down the third ramp as well as on the third deck in an attempt to regain connectivity and stretch the MANET once again. After several attempts to regain audio/video, it was clear that communications would not be revived. This was due to the MANET being stretched to its capacity in this particular environment.

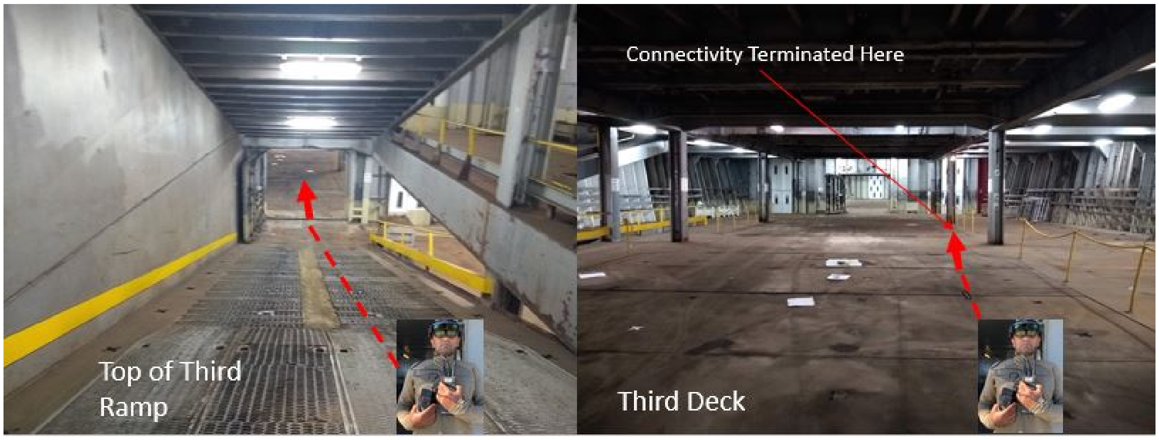

Figure 24. (Left) Top of Third Ramp (Right) Point at Which Connectivity Terminated on Third Deck

Once the shipboard testing was complete, the HoloLens operator regrouped with the reachback laptop operator on the main deck just outside of the aft hangar bay depicted in Figure 20. We then shifted to the next step of Phase 2, which was ship-to-ship operations. The purpose of this step was to test the ability of the Microsoft HoloLens on a MANET that consisted of two MPU-4 radios in a ship-to-ship scenario. One radio would be on the main deck of the ship adjacent to the reachback laptop operator, and the other would travel with the HoloLens operator to the predetermined locations ashore pictured in Figure 25. As can be seen in Figure 25 we elected to locate the HoloLens operator ashore instead of on the closest ship to demonstrate a greater range of operations. The distance recorded between the reachback and the HoloLens at both predetermined locations indicated in Figure 25 was .57 miles. This range is more than sufficiently realistic to simulate the distance between ships engaged in a UNREP.

Figure 25. Ship-to-Ship Operator Positions. Adapted from Google Earth (2019).

First, all of the equipment was powered down and reset for the ship-to-ship step. The HoloLens operator then traveled to the first location and established connectivity successfully. As we stretched the nodes of the MANET in the course of conducting the test at the first location, the quality of audio/video communications between the HoloLens and the reachback laptop did not diminish. As the testing at the first location concluded, the HoloLens operator traveled to the second location indicated in Figure 25 to conduct another identical ten-minute field test. Upon reaching the second location, connectivity was established once again. During this test, the audio/video connection remained robust and remote-advise-and-assist capabilities via the reachback laptop were conducted successfully.

D. PHASE 3 (FIELD EXPERIMENTATIONS)

In Phase 3, the object of this field experiment was to gain an understanding of how constraints affect the nodes in the MANET and whether or not the nodes could communicate audio/video between the HoloLens operator and the reachback operator. We set out to capture distance, throughput, and signal-to-noise ratio which would facilitate analysis of our proposition. To achieve this understanding, it was necessary to expand the geographical distance between the nodes of the MANET. The location of the Phase 3 testing stretched from the rooftop of Spanagel Hall on the NPS campus to the Municipal Wharf Pier and surrounding body of water known as the Monterey Bay off the coast of Monterey, California as illustrated in Figure 26. The one-mile distance between Spanagel Hall and the Municipal Wharf Pier exceeds the average distance between ships engaged in a UNREP.

Figure 26. Phase 3 Location. Adapted from Google Earth (2019).

The equipment used in Phase 3 was similar to the ship-to-ship field experiment in Phase 2 with a few distinct additions and replacements. First, we replaced the two MPU-4s with three MPU-5s for this phase because the bandwidth capabilities and resident antennas were superior to that of the MPU-4s. Also, two Raspberry Pi devices were used and each of them loaded with an SNMP agent and a 2.4GHz 802.11n wireless chip. These were used for performance monitoring during the operational tests and configured to enable the collection of data points to measure the intended performance metrics as well as act as a WIFI hotspot for the end devices used. Each Raspberry Pi attached to the end user MPU-5 radios by ethernet cable. Figure 27 shows all of the equipment used in Phase 3.

Figure 27. Phase 3 Equipment

The Phase 3 operational test began with the setup and configuration of equipment on the roof of Spanagel Hall. The equipment consisted of a reachback laptop (192.168.87.111), three MPU-5 radios (192.168.87.90, 192.168.87.91, 192.168.87.93) two Raspberry Pi devices (192.168.87.42, 192.168.87.44) and the HoloLens (192.168.87.224), all of which were powered on and tested for initial connectivity. The HoloLens operator then traveled to the Municipal Wharf Pier. The distance between the reachback laptop and the HoloLens operator was recorded to be 1 mile. The operational test conducted at this distance was successful, resulting in the reachback laptop being able to receive a strong audio/video stream from the HoloLens and lasted approximately 3 minutes. Figure 28 illustrates all test locations during Phase 3. The rationale for the positioning of the radios atop a building was intended to simulate the approximate height that a MANET node would be expected to have aboard a ship, in order to ensure connectivity with another ship within a battle fleet.

Figure 28. Phase 3 Locations. Adapted from Google Earth (2019).

The next step in Phase 3 was to stretch the nodes of the MANET and better understand its distance constraint. We enlisted the help of the United States Coast Guard (USCG) Station, Monterey for this endeavor. The USCG allowed us to utilize a Motor Life Boat (MLB) 47321 to expand the MANET and track its performance at range. First, we traveled a distance of 1.46 nautical miles into the Monterey Bay away from the MPU-5 that we stationed at the Municipal Wharf Pier and resumed testing for three minutes. The test conducted at Position 1 was successful and resulted in the reachback laptop atop Spanagel Hall being able to receive a reliable audio/video stream from the HoloLens as can be seen in Figure 29.

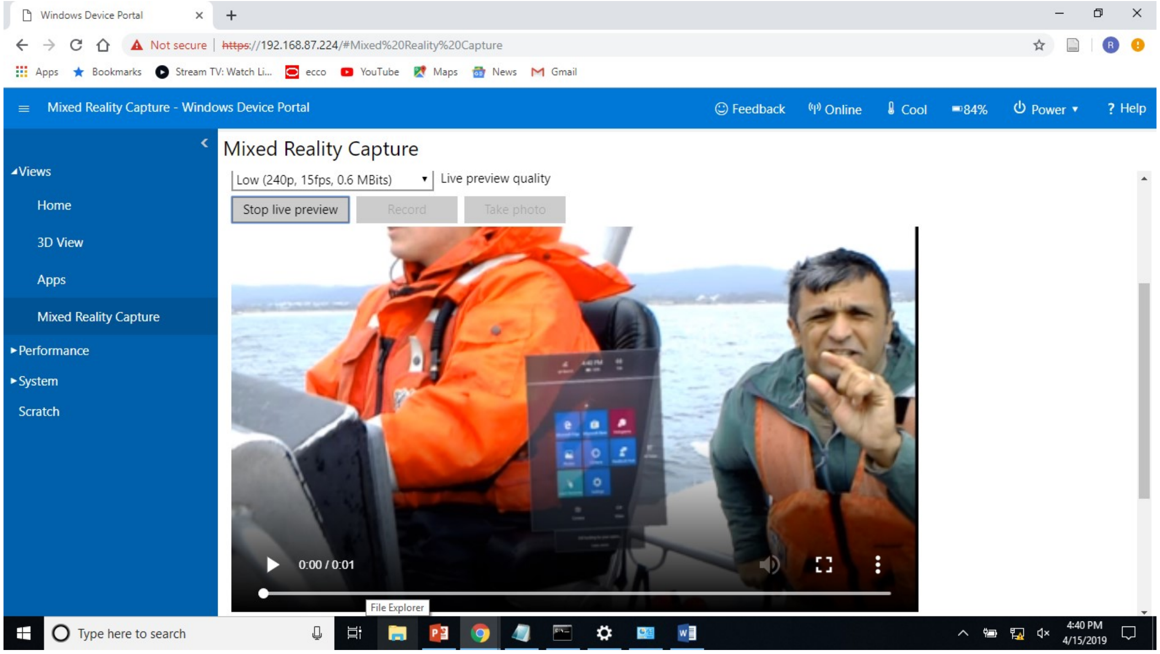

Figure 29. Phase 3 Screenshot (Position 1)

Based on the positive results at this distance, we continued expanding the MANET. The MLB 47321 continued on its course until we were 2.17 nautical miles away from the pier. At this distance, we resumed testing, which yielded the same consistent video. Since the failure of the network did not occur at Position 2, we decided to stretch the MANET to a distance of 3.04 nautical miles away from the pier. We proceeded to move the vessel to Position 3 and resumed testing. At this point, we expected the failure of the network, yet we were able to establish a connection and stream audio/video. Connectivity degraded as we drifted to a distance of 3.3 nautical miles away from the pier and our connection started to experience its first signs of failure in the form of an intermittent buffering of the image on the reachback laptop. The signal degraded as the vessel moved to a range of 4.2 miles past the pier. At this distance, we were not able to establish a connection to the reachback laptop and concluded stretching the MANET.

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IV. OBSERVATIONS AND ANALYSIS

This chapter provides observations and analysis from all phases of testing of the proof of concept of using an augmented reality device on a MANET to deliver enhanced RAA to medical teams facing emergencies in shipboard scenarios. Each sequential phase outlined in Chapter III has a corresponding observation and analysis section in this chapter. We have also included conclusions and discussion regarding the research questions proposed in Chapter I.

A. PHASE 0

Before this phase, we had a basic understanding of the problem, as outlined by the vignette, and intuition on how to provide a solution for medical teams. What was unknown was whether the HoloLens' capabilities could be enabled on a MANET constructed by the MPU integrated Radio Over IP (RoIP). Phase 0 supported this research by scoping the proof of concept testing that helped us to determine if the concept was viable, enabling us to avoid more advanced testing only to find out that the underlying principles and equipment needed for the concept to work might be insufficient.

Fortunately, the basic principles did exist, and our observations during the four tests in this phase supported our expectations. During the first test in Phase 0, we confirmed that the two systems would work together reliably and that a synchronous audio/video stream could be achieved to allow medical teams to communicate better. As shown in Figure 18, the HoloLens captured audio/video of the patient that was relayed over the MANET to the end user who was then able to advise and assist over the MANET back to the HoloLens operator. During the second test, which involved stretching the network within a building, we discovered that the HoloLens operator was able to travel 290 feet through the corridor before the audio/video stream was lost resulting in a frozen image on the reachback laptop. The third test was an effort to stress LOS between nodes in the MANET. The result was a robust synchronous audio/video connection that stretched approximately 350 feet.

From Phase 0, we learned that the systems could indeed work together in a manner that could aid medical teams in their efforts to assess patients as well as leverage capabilities that augmented reality devices can provide. We also gained an understanding as to how LOS might affect shipboard applications due to the many barriers to LOS within the interior. These findings prepared us to gain a more profound knowledge of the connectivity issues and generate solutions to address them.

B. PHASE 1

The focus of this phase was to address the LOS issues observed in Phase 0. To properly understand the issue, we moved our experiment efforts to Spanagel Hall where the rectangular concrete superstructure in the center of the roof provided an environment in which the HoloLens operator could disrupt LOS by walking around each corner of the superstructure as described in Chapter III.

1. Observation

Phase 1 allowed us to make several essential observations with regard to obstructions of LOS. As was expected, connectivity was lost as the HoloLens operator rounded the first turn depicted in Figure 17. How the signal was lost was of note. The loss of stream was abrupt and not decremental in manner. To overcome the deficiency in LOS, we added a node to the MANET in the form of an MPU-5 radio, which acted as a relay for the network, resulting in a positive test of the network's ability to maintain a reliable audio/video stream as the user of the HoloLens rounded the first turn. Sequentially, we saw a similar loss of stream and overcame it in the same manner as the HoloLens operator rounded the second corner of the roof. As the two additional MPU-5 nodes were introduced to the MANET, no degradation of audio/video quality was noted.

2. Analysis

From this phase, we concluded that in order to utilize the concept of a MANET as an enabling network for augmented reality devices aboard a ship, LOS is critical. Maintaining LOS would be a challenge on a ship with a steel structure, where there are numerous twist and turns. Additionally, we learned that the integration of extra nodes to the MANET in instances where LOS is not possible between two nodes is a feasible experimental solution to overcome disruptions to audio/video streams. Medical teams will face these types of issues frequently due to the composition and organization of ships. The rooftop experiments also reinforced the need to test the HoloLens and MANET in a shipboard environment.

C. PHASE 2

The purpose of Phase 2 was to test the systems' operational capabilities within a ship and in a ship-to-ship scenario. As described in Chapter III, testing within the ship consisted of stretching the MANET vertically through several decks by adding nodes to the network while enabling audio/video communications to simulate a medical emergency. Optimistically, we estimated that we might be able to reach the bottom deck, which is five decks below the main deck. The second part of testing during this phase aimed to simulate communication between medical personnel on two ships. For this purpose, we staged the reachback laptop on the main deck of the CALLAGHAN and utilized two shore locations around the shipyard as staging points to simulate the other ship locations as described in Chapter III. It is important to note that in actual operational setting at sea, both ships would need a MANET radio on the main deck or above in order to achieve and maintain a link.

1. Observation

Our observations from the test within the ship revealed some of the same results regarding LOS in Phase 1. Audio and video streams were initially successful; however, as the HoloLens operator turned at the bottom of each ramp of the respective deck, LOS was lost due to a structural barrier and with it, the ability to maintain audio/video connection. Much like Phase 1, to overcome this, we utilized MPU-5s as relay nodes to ensure LOS. The result was that the HoloLens operator reached the third deck before the signal was not possible. Unlike testing in previous phases, the reachback laptop operator observed intermittent buffering of the audio/video transmitted from the HoloLens operator during turns around the barriers to each deck. In this manner, communications gradually and not abruptly terminated. We assess from these results that a reliable AR link would depend on either an internal MANET on a ship or the rapid emplacement of multiple relay nodes.

Our observations from testing the ship-to-ship scenarios revealed data that other phases did not afford us. The actual shipyard environment allowed us to test beyond the normal UNREP range of 220 feet. The two tests conducted at a range of .57 miles or 3000 feet, were successful in allowing for strong synchronous audio/video communication for ten minutes. At this point we well beyond the typical range for the use case in our research and confident in the feasibility of the concept.

2. Analysis

From Phase 2 we ascertained information on how the HoloLens and MANET would perform if needed in the two scenarios discussed in the vignette. Testing within the ship resulted differently from the testing conducted on the roof (Phase 1) because the obstructions to LOS on the ship were composed of steel whereas the obstructions on the roof were concrete. Medical teams desiring to use the concept would find the system practical for communication to a range of two decks below the main deck similar to the scenario in the vignette. Observations in communicating past the second deck revealed that the composition of the ship became a factor and resulted in an intermittent buffering of the stream. Testing for the ship-to-ship portion of this phase supported our notion that medical teams faced with an emergent situation during a UNREP could utilize the HoloLens capabilities over a MANET that stretched between ships. This testing imparted confidence that communications could be stretched much further than the needs of a UNREP scenario. Although we were not able to utilize two ships in our research, the addition of relay nodes could, in theory, allow medical teams to employ the concept.

D. PHASE 3

In the previous phase, the data was useful but insufficient to explore the effects that greater distance between nodes would have on performance as we stretched the MANET. Our thought was that if we could understand these constraints, we could make a better estimate/evaluation of how the system would perform under a situation such as an emergency breakaway during UNREP where the ships would ultimately have to part ways to avoid catastrophic danger, or in the event that a smaller ship in the group might have an emergency that exceeded their medical crew's capabilities. In Phase 3, we further measured the constraints of the MANET with regard to distance, throughput, and SNR in a simulated ship-to-ship scenario. Tests were conducted at three different positions as illustrated in Figure 28.

1. Observation

This phase was unique in that measurable performance metrics were captured. The first test, conducted at the Municipal Wharf Pier, resulted in a reliable audio/video stream. Figure 30 represents the SNR data captured between the HoloLens operator MPU-5 radio and the respective MPU-5s within the MANET. As can be seen by the image, SNR for the Roof Relay MPU-5 (Yellow) and the Pier MPU-5 (White) remained healthy for the duration of the test. The Pier MPU-5 SNR was the highest due to its proximity.

Figure 30. SNR during Pier Test

Figure 31 represents the throughput data captured from the HoloLens operator MPU-5 during the same time corresponding with the SNR data captured. The illustration shows consistent throughput capable of enabling the capabilities of the HoloLens except at the 1545 time stamp, which can be explained by the HoloLens operator re-initializing the audio/video stream.

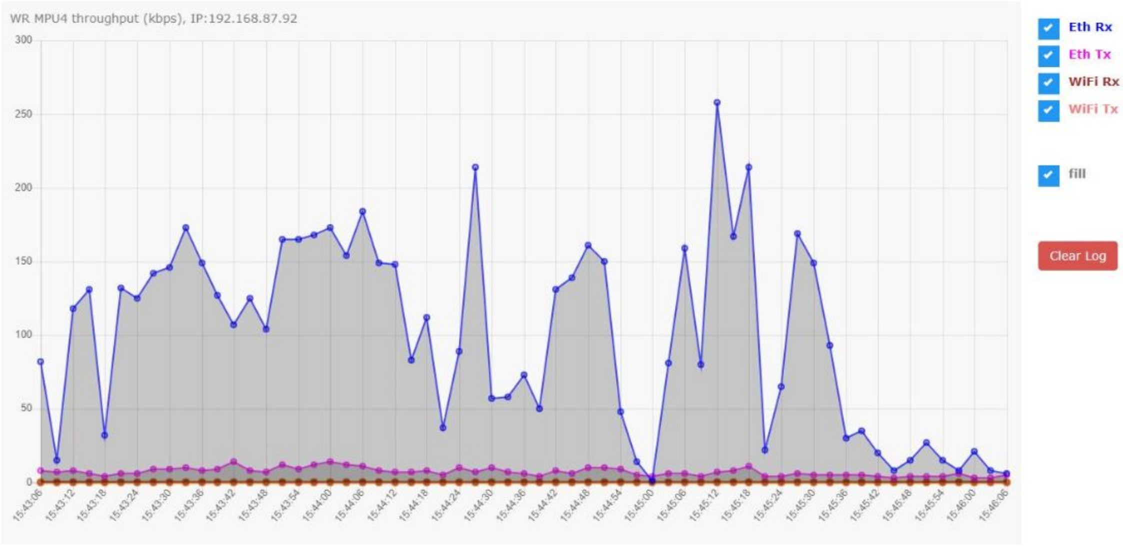

Figure 31. Throughput during Pier Test

The second test in this phase mirrored the first with the only difference being a change of location to Position 1 depicted in Figure 28. Again, we experienced a reliable stream of audio/video through the duration of testing. Figure 32 represents the SNR data captured at Position 1. As can be seen, the only SNR data recorded was between the HoloLens operator MPU-5 and the reachback operator MPU-5. The single source of SNR in the image can be explained by the lack of LOS by all other links in the MANET. Compared to the previous test, the SNR is slightly lower during this test. We assessed that this hold implications for corpsman who need to act below decks where a physician is not present.

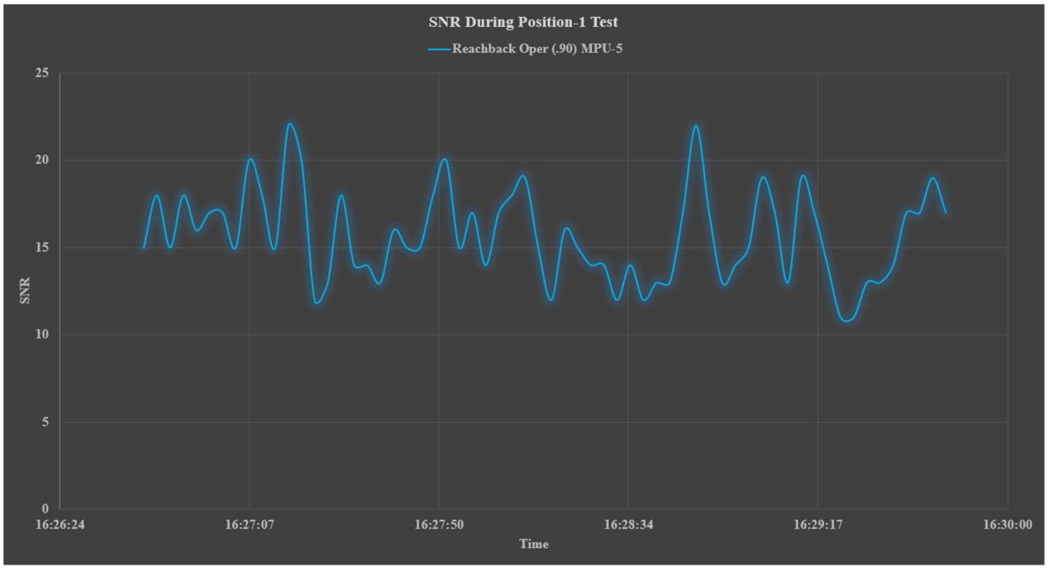

Figure 32. SNR during Position-1 Test

Figure 33 represents the throughput data captured from the HoloLens operator MPU-5 during the same time corresponding with the SNR data captured. The data in the image reflects several periods in which throughput experienced a sharp drop. These periods can be accounted for each time the Reachback laptop operator selected a different streaming quality and reinitialized the image. Aside from these interruptions to the stream, the audio/video communications link remained strong.

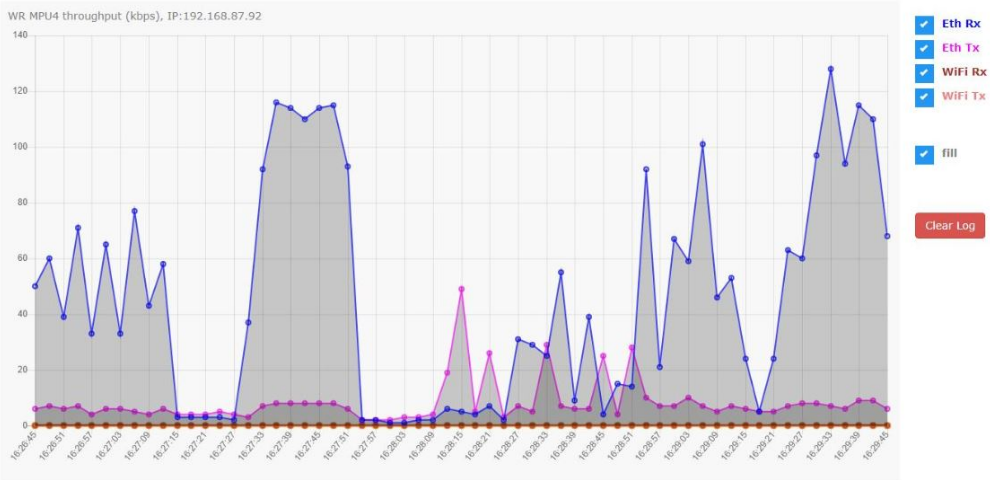

Figure 33. Throughput during Position-1 Test

After moving to Position 2 to stretch the MANET once again, we resumed testing and yielded the same positive results as the previous test. Figure 34 represents the SNR data from this location at a distance of 2.62 NM from the reachback. This time the Pier MPU-5 acted as the primary link as can be seen in the image throughout the testing. SNR is once again slightly lower than the previous test.

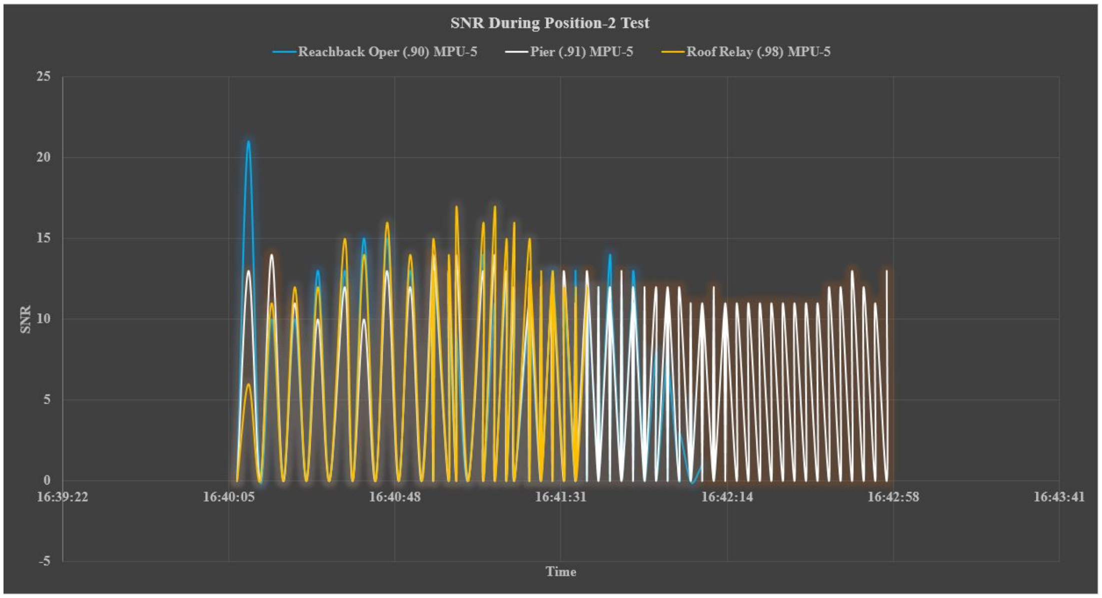

Figure 34. SNR during Position-2 Test

Figure 35 shows the corresponding throughput data captured. The data indicates throughput consistent with previous tests at this location and audio/video quality remained stable during the test. The HoloLens was operational during the spikes in throughput as can be seen in the figure. This indicates that 80 Kbps was sufficient bandwidth for communications during this test.

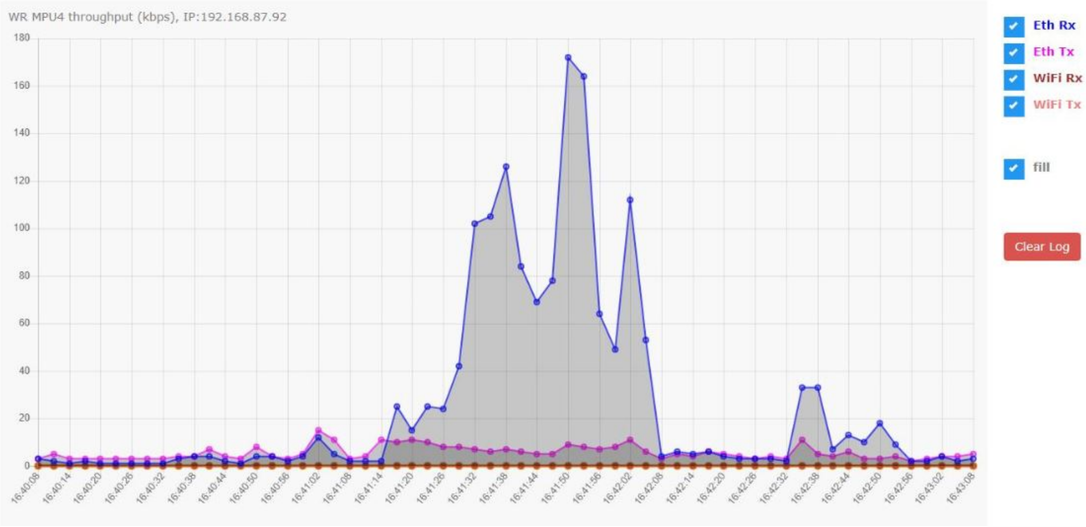

Figure 35. Throughput during Position-2 Test

Connectivity at Position 3 was expected to yield a failure; however, initially, an audio/video stream was established. As we drifted further past Position 3, we experienced our failure as stated in Chapter III. Figure 36 represents the SNR data collected during this period. The data in the image is consistent with the previous test except that the Reachback operator MPU-5 was the main link testing at this position.

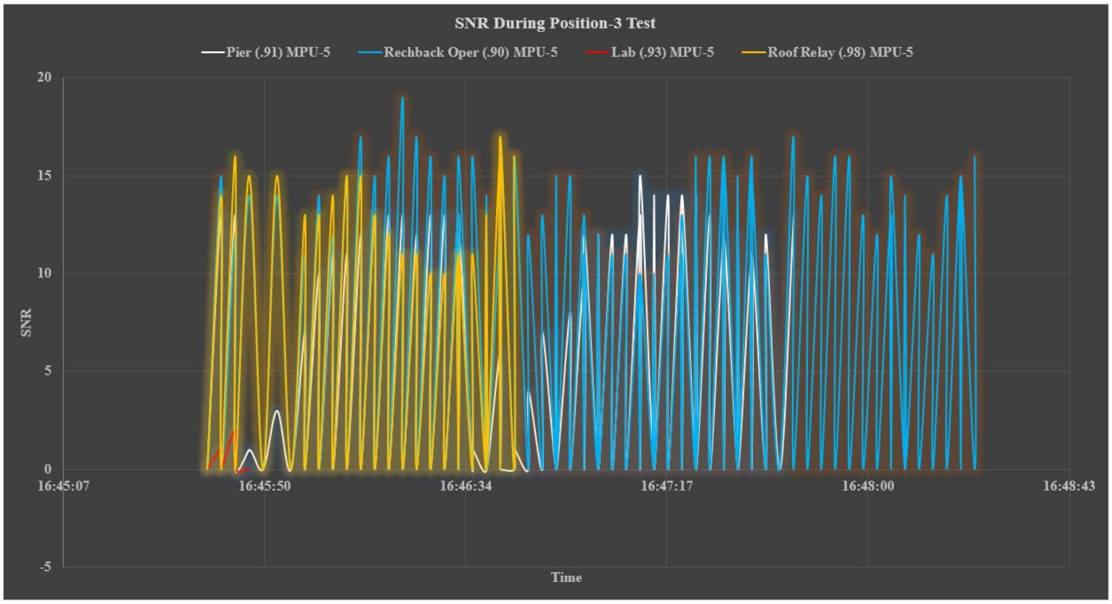

Figure 36. SNR during Position-3 Test

Figure 37 represents the throughput data captured and highlights the first instance of failure as we drifted past Position 3 experiencing intermittent buffering of the image on the reachback laptop during the time-period that stretched from 16:47:34 to 16:47:52.

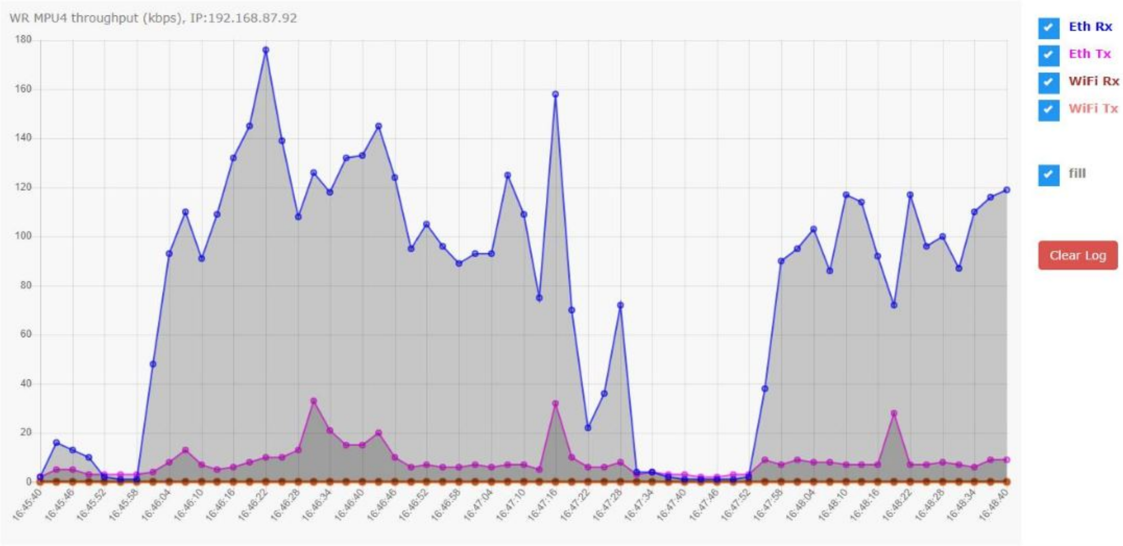

Figure 37. Throughput during Position-3 Test

A fourth test was conducted at just over four nautical miles away from the pier, but no connection could be established nor could data be collected at this range. We were not able to establish an audio/video stream as we remained in position and attempted to connect three times.

2. Analysis

Phase 3 supported the proposition that medical teams facing an emergent situation during a UNREP could use the HoloLens capabilities projected over a MANET. It also produced performance measurement metrics that indicate that the range at which this solution would be useful is much higher than what is likely to be required in an afloat group situation. The three-mile effective distance of the solution validated by testing and measured by performance management tools also could be critical to medical teams in ship-to-shore operations. The data in this phase were superior to those observed in previous phases and is due to the complete replacement of the use of MPU-4 radios and the integration of more advanced MPU-5 radios. The Multiple-Input and Multiple-Output (MIMO) technology feature on the MPU-5 radio allowed for a more reliable and fast data transmission rate by taking advantage of multipath propagation. The selected replacement radio is also superior in throughput by more than 2.5 times allowing for a more vivid image as was noted throughout this phase.

Table 4. Phase Testing Summary

Phase	Significance
0	Initial internal building testing for proof of concept ensured viability.
1	LOS testing to understand constraints of the concept.
2	Testing the systems' operational capabilities within a ship and in a ship-to-ship scenario.
3	Testing the systems' distance constraints in ship-to-ship scenario.

E. THEORETICAL ANALYSIS

Our observations throughout the testing phases in this research revealed that a reliable augmented reality communication stream between a HoloLens operator and a medical reachback capability via a MANET could be stretched from two decks below to the main deck of a ship. They also confirmed that medical personnel on the main deck of two separate ships could communicate in the same manner. We assess that, theoretically, if an injury occurred on one ship two decks below the main deck, that an AR device enabled by a MANET could be able to support medical personnel in their attempt to provide RAA between the two ships, given that additional relay nodes are added to the MANET as illustrated in Figure 38.

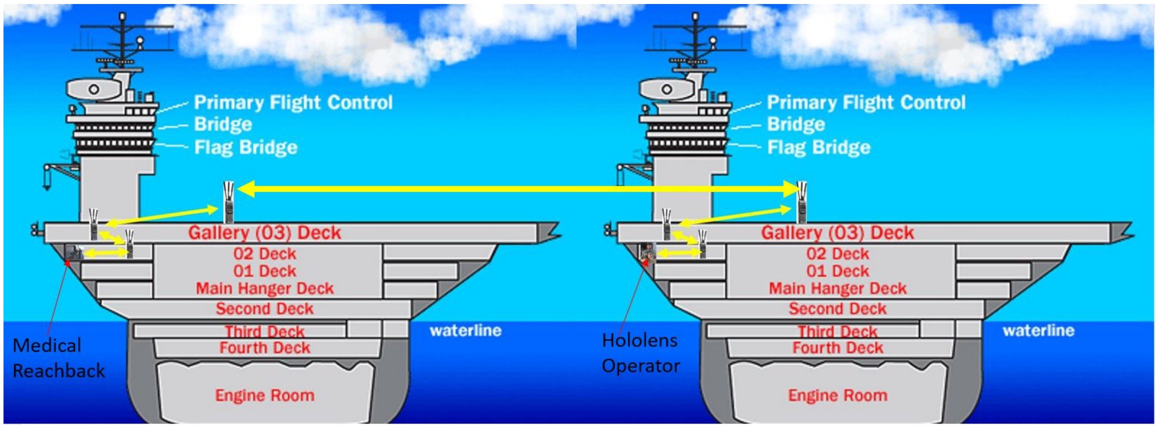

Figure 38. Theoretical Ship-to-Ship RAA. Adapted from HowStuffWorks (2002).

Practically, we assessed that if a ship were setup internally with a robust network of MPU devices in a manner where each node is in a fixed location yet maintains its ability to be mobilized throughout the ship, we estimate that medical personnel could employ RAA with AR in approximately 80% of the ship.

F. RESEARCH QUESTION CONCLUSIONS

Based on the above general conclusion, this section focuses discussion toward research questions that it addresses.

1. Research Question I

Could a commercial off the shelf (COTS) MANET network radio deliver the necessary bandwidth needed to support augmented reality devices such as Microsoft HoloLens in an emergency shipboard or ship-to-ship scenario and enable communication between medical teams separated by distance?

a. Conclusion

We confirmed a COTS MANET network radio such as the MPU could deliver the sufficient bandwidth needed to support augmented reality devices such as Microsoft HoloLens in an emergency shipboard or ship-to-ship scenario and reliably enable communication between medical teams separated by distance.

b. Discussion

As noted in Phase 2, audio/video communications were successful as the HoloLens operator traveled two decks below the main deck in a test conducted within the GTS Admiral W. M. Callaghan (T-AKR-1001). To put this into the context of the vignette scenario where the Sailor had fallen two decks into an engineering space on the ESSEX, had the medical team been able to communicate in this fashion, they would have been able to make better medical decisions regarding the patient’s care. The communications lasted until we reached the third deck before we started to lose communications intermittently. Although we were able to get intermittent audio/video on the third deck, it was not reliable enough for the needs of medical personnel in an emergency situation. In the ship-to-ship scenario tests conducted in Phase 3, communications were successful to a range of 3.52 NM. At this range, SNR and throughput were measured and remained at reliable levels indicating that in the UNREP scenario mentioned in the vignette, medical teams could reliably use the concept to communicate at the typical lateral separation range of 220 feet. There was connectivity observed past 3.52 NM, however, not at a level which would reliably serve medical personnel.

2. Research Question II

What factors affect the use of augmented reality devices enabled by a MANET for emergency medical care during shipboard or ship-to-shore operations?

a. Conclusion

LOS affects the use of augmented reality devices enabled by a MANET for emergency medical care during shipboard or ship-to-ship operations.

b. Discussion

In Phase 1 we tested communication over the MANET near a natural barrier that impedes LOS. Our observations reinforced that without LOS the MANET would not be capable of supporting augmented reality devices and would need to be accounted for within any solutions we employed, especially within ships where many barriers to LOS exist, necessitating relay nodes, unless a ship-board system is put in place.

3. Research Question III

What is the effect on the transmission rate as the distance between nodes in the MANET increases?

a. Conclusion

Increasing distance between nodes in the MANET effects transmission rates negatively and eventually failed the communication stream as we expanded the MANET, however, for this research, communications within the ranges required were tested to be sufficient.

b. Discussion

Validation of our conclusion was presented in Phase 3 where a correlation between distance and SNR was observed during the testing. As the distance between nodes increased beyond 3.5 nautical miles, it was observed that SNR would dip below 15 dB rendering the audio/video stream into an intermittent state and ultimate failure. Although we stretched the MANET to its point of failure, we found that these ranges were well beyond the needs of the use cases presented in this research. SNR at the typical ranges of our use cases was extremely positive and indicated significant reliability.

V. CONCLUSIONS AND RECOMMENDATIONS

This chapter offers a summary, limitations, motivation, and conclusion of the research conducted as well as recommendations for future research related to themes covered in this thesis.

A. SUMMARY

This research aimed to determine whether COTS MANET radios would be capable of enabling communications between medical teams faced with emergencies in shipboard or ship-to-ship environments via augmented reality devices such as Microsoft HoloLens. In our literature review, we looked at the trends in telemedicine and studied current efforts in DoD, allowing us to confirm a gap in telemedicine capabilities in shipboard and ship-to-ship environments. Then we explored how augmented reality devices could fill this gap and allow medical teams to communicate together in an improved manner. After concluding a MANET would be ideal as a network solution for devices of this nature in this environment, our review shifted to understanding network fundamentals and equipment necessary to investigate a solution. Lastly, our review looked at gateway solutions to facilitate extended RAA.

Based on the literature review, we were able to find suitable COTS devices capable of delivering audio/video communications that could benefit medical teams separated by distance in emergency situations in shipboard and ship-to-ship environments. In Chapter III, we explained proof-of-concept and our designs for testing. Although we encountered challenges in proving that the concept would work reliably within a ship, we were able to suggest that it is theoretically feasible. Also, we were able to show that in the ship-to-ship use of this concept, the solutions tested yielded results that exceeded our standard range of use.

B. LIMITATIONS

Our research into solutions to fill the gap in telemedicine for medical teams at sea was limited in several ways:

- No test for this research was conducted in real operational environments.
- We limited our testing to 5 miles, which goes well beyond the typical distance required for this research.
- Our MANET was constructed with Persistent Systems MPUs and Microsoft HoloLens was our augmented reality device of choice however, other equipment from the same respective categories could have been utilized.
- No actual testing of the theoretical ship-to-ship scenario depicted in Figure 38 was conducted.

C. MOTIVATION

The inspiration for this research, was our real world operational experiences at sea combined with newfound knowledge on the topic of network operations gained at NPS. The current trend in Navy medicine is to utilize TH where gaps in care exist; however, more effort could be put forth to leverage innovations in technology to fill the gaps in operational medicine at sea. Medical teams on ships face the prospect of making spontaneous life-sustaining decisions but lack the advanced communication tools that modern technology can enable.

D. SIGNIFICANCE

As the Navy continues down the path of “Power Projection” and “Sea Basing,” scenarios like the ones mentioned in this research will occur more often. Because of the shortage of medical personnel in the Navy as a resource at sea, we must focus on projecting the capabilities of the medical personnel we have through TH enabled by new technology throughout the fleet. Currently, no COTS system will enable the capabilities proposed in this research; however, the concept as presented in this thesis is feasible. The findings in this research are not the final answer. Indeed, more research is necessary, and we hope that someone will continue this line of research toward developing a viable solution worthy of implementation.

E. CONCLUSION

This research studied the feasibility of utilizing current network solutions and technology available to fill the gap felt by medical teams onboard ships in their effort to communicate in a manner that could deliver synchronous audio/video stream and ultimately lead to better decision making in emergent situations. This section offers a general conclusion regarding the use of a MANET and an augmented reality device to fill the gap.

Arming medical personnel with a solution such as the HoloLens for RAA enabled by a MANET could enhance their decision-making ability by allowing for a synchronous audio/video communication during emergent patient care. After having tested the concept of using a MANET constructed of MPUs and an augmented reality device such as the Microsoft HoloLens in shipboard environments to facilitate communications between medical personnel, we were able to affirm the concept's feasibility. Although the concept should be considered to be in an early development phase and more research must be done to facilitate seamless integration into naval operations, the impact that it could have on decision making for medical personnel in emergency situations cannot be overstated. Allowing medical teams in these scenarios and environments the ability to synchronously utilize augmented reality devices to communicate will directly lead to decisions being made in a more informed manner.

F. FUTURE RESEARCH

This section includes recommendations for continued research into utilizing MANETs to enable augmented reality devices to help medical teams communicate more effectively when separated by distance.

1. Radio

Only one MANET radio was utilized during this research; however, several COTS radios were available on the market, and additional work is needed to find the best fit for a military MANET radio that can be adapted to support the requirements of medical teams aboard ships. As we learned during the testing within the ship, the composition of the environment is relevant, and other radios may perform better. We also recommend that the shipboard experiment conducted in this research be replicated with the replacement of all MPU-4 radios with MPU-5s. The addition of MIMO technology and higher bandwidth may produce better results.

2. HoloLens

Only one augmented reality device was utilized during this research; however, there have been several new devices that have become available since this research began including the second version of the HoloLens. Additional research should be conducted to identify ideal device characteristics as well as exploit any additional features that may be to the advantage of medical teams on ships.

3. Additional Experimentation

Although the experimentation conducted in this research produced baseline findings related to the questions proposed at the inception of the study, there is still much exploration that could lead to the refinement of the concept. We recommend the theoretical ship-to-ship scenario mentioned at the end of Chapter IV be designed and tested in an operational setting during an actual UNREP. Although one could easily conceive that our findings would lead to the concept working in the scenario mentioned, the opportunity to perform live testing and utilize newer technology that has become available since we began research could produce additional value.

4. Networks on Ships

Although the focus of this research is primarily medical use of the proposed concept, there are other uses for MANETs and augmented reality devices onboard ships. Everything from general ship maintenance to sailor training can easily be envisioned as a spectrum of uses that could benefit the Navy. It is our recommendation that additional research is conducted to develop networks onboard ships that would better integrate these technologies. The current networks need to be upgraded.

5. Common Server

Future research in this area would benefit from the acquisition of licensed common server software such as Remote AR by Scope AR or the resources to construct a virtual private network tunnel for the purpose of using a gateway to facilitate RAA. This will facilitate an understanding of how RAA is affected beyond the confines of the MANET.

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APPENDIX. EXTENDED REACHBACK SOLUTIONS

Since this research depends on various networks to enable RAA capability, it is useful to highlight the various types of networks that may be available in shipboard or ship-to-ship environments and their many characteristics that affect bandwidth and latency. This section provides relevant information regarding 4G, WiMAX, and Satellite. Note that for our research we did not employ a gateway.

A. 4G

4G means 4th Generation and is a standard of wireless technology that enables fast and reliable IP services to any mobile handheld device supporting the technology. 4G evolved to its current state starting from the first generation (1G) of mobile wireless technology. With every new generation, wireless technology gets a little more advanced but loses backward compatibility with the previous generation. For example, while 3G has seen many improvements to its technology, none of the 3G standards are compatible with 4G or 2G. 1G stems back to when mobile phone networks only allowed voice calls due to the technology at the time not supporting the bandwidth necessary to do more. Soon after came 2G digital mobile communications that combined calling and texting 10KBPS to 200 KBPS. Figure 39 depicts a typical 2G network.

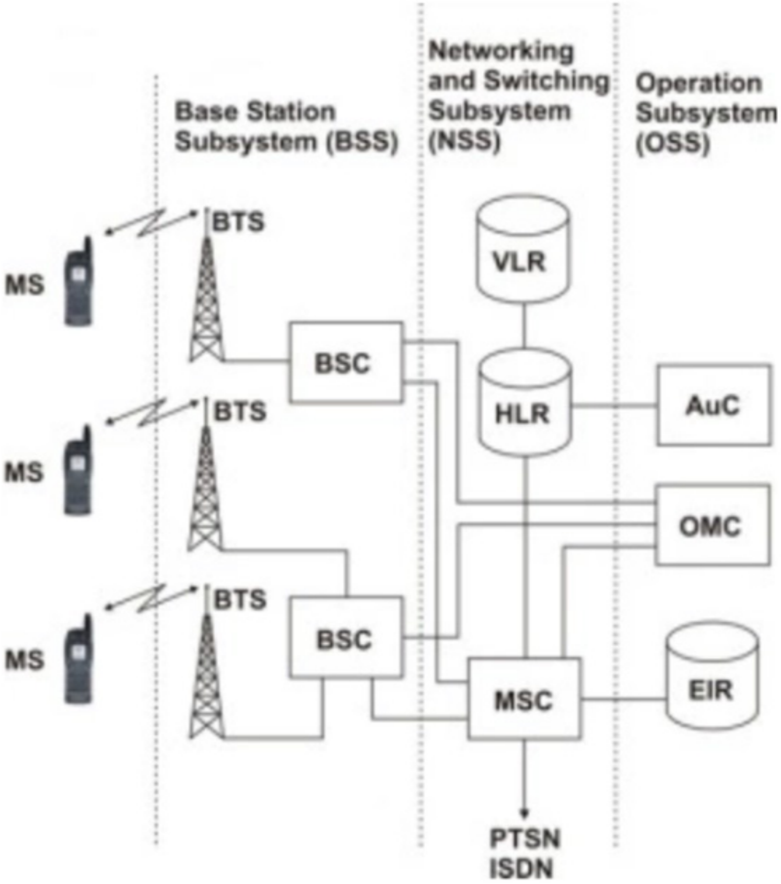

Figure 39. 2G Diagram. Source: InteliSecure (2019).

The ability to access the internet from a mobile device came with the advent of 3G, and at speeds of up to 384 Kbps, it was a significant achievement (Huang et al., 2012). Users could send e-mails, read news articles, view videos or even review the latest social media craze with this new capability. 3G was built on top of the 2G infrastructure and shared some of the existing components with the exception of the radio tower which was with the radio network controller (RNC) in order to support higher data rates (InteliSecure, 2013). Figure 40 depicts 2G with 3G.

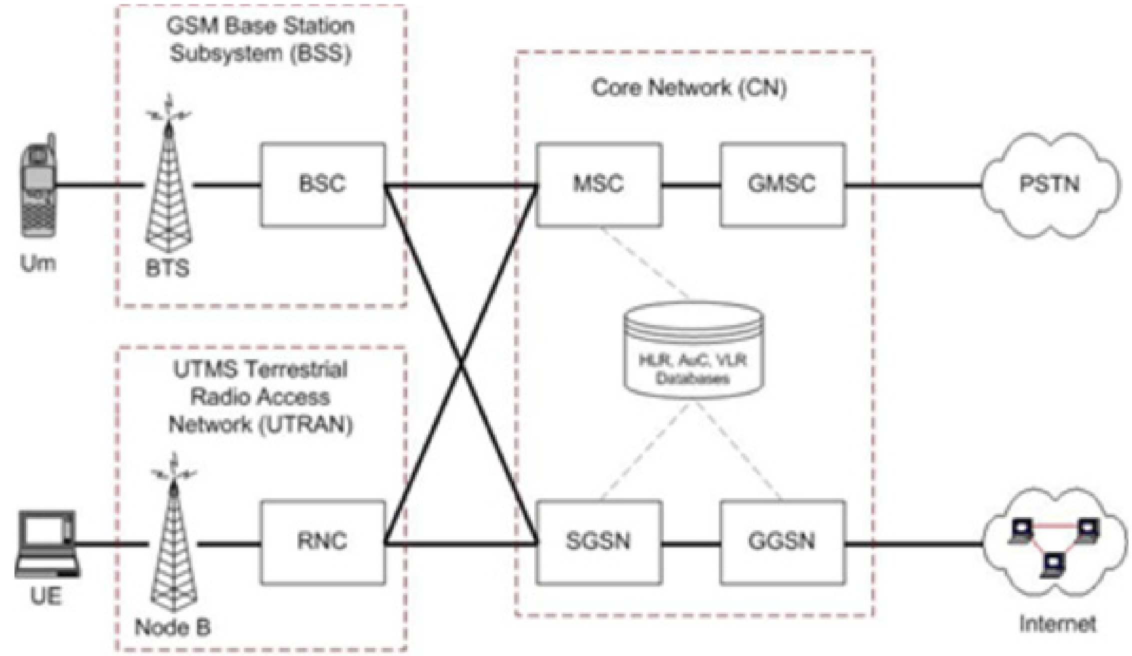

Figure 40. Illustration of 2G BTS working with 3G. Source: InteliSecure (2019).

4G allows for high-speed mobile internet, essentially allowing speeds of a household ISP on a mobile device. 4G supports up to 86 Mbps download and 28.8 Mbps uploads. The 4G network also provides faster network reaction times due to lower latency and much more stable connections, even in weak coverage areas. The actual speed is influenced by many factors, such as the distance of the receiver from the antenna, whether indoors or out, the number of users in the area, the network resources available, and the type of device. If each of the listed factors were not ideal, the 4G device would still be capable of reaching an average speed of around 20 megabits per second downloads and 12 megabits per second uploads. 4G can accomplish those fast speeds due to the frequencies' management system it utilizes. The bandwidth model that 4G uses is orthogonal frequency division multiple access (OFDMA) (Bank, Hill, & Gavan, 2006). Therefore, the available bandwidth is shared with other users in a way that the frequency division is a much more efficient radio coding format; this means users receive bandwidth dedicated explicitly to individual users (Kivanc, Li, & Liu, 2003). 4G uses all IP technology, the universal language of data systems. A 3G network uses different styles to transport data over the network to the users while 4G network uses only one single language to transport data, and 4G's network architecture is smarter and flatter. Finally, there is not a requirement to utilize a controller for traffic flow regulation anymore due to 4G's intelligent network architecture; antennas will immediately find the best way to connect. The radio tower connects to the eNodeB which intern connects to the EPC containing the mobile management entity (MME). This connects to the service gateways SGW and PGW to perform bandwidth shaping and billing, therefore allowing users to connect to the Internet (InteliSecure, 2013). Figure 41 shows a 4G network diagram.

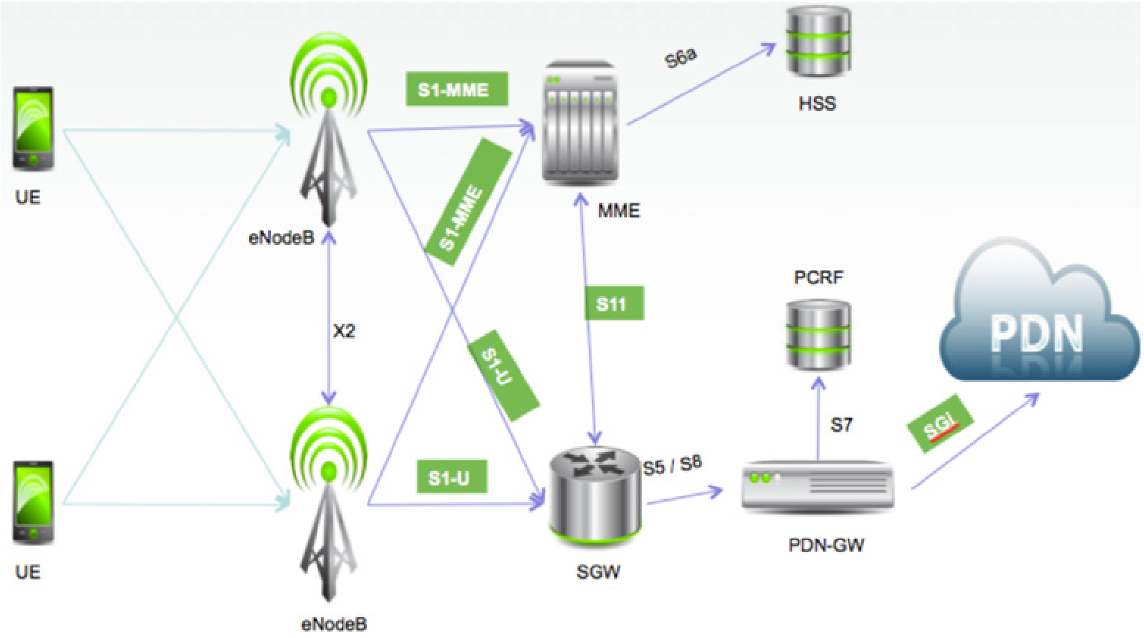

Figure 41. Diagram of 4G Network. Source: InteliSecure (2019).

B. WIMAX

Worldwide Interoperability of Microwave Access (WiMAX) is a capability that allows for connecting wireless metropolitan area networks (MAN) consisting of IEEE 802.11G standards to the internet by providing a wireless means of accessing DSL, cable and T1 lines (Andrews, Ghosh, & Muhamed, 2007). WiMAX allows IP service to be rendered from up to 50 kilometers away. A WiMAX Transmitter connects to an Internet gateway via an ISP network. Then the WiMAX transmitters are connected to allow the home local area network connectivity to a WiMAX transmitter via transmission that is normally non-line-of-sight (Nuaymi, 2007). Figure 42 depicts a WiMAX network.

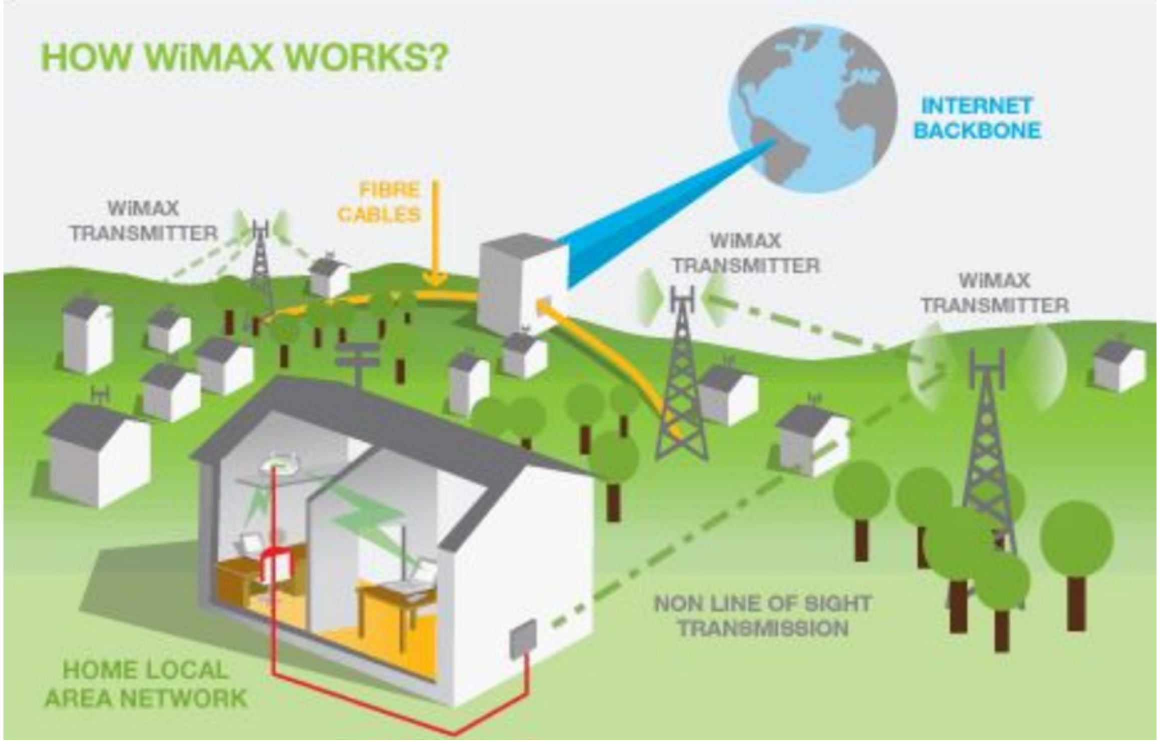

Figure 42. WiMAX MAN. Source: Muhammad (2016).

A few notable advantages of WiMAX are:

- A single station can serve hundreds of users.
- Great for providing services in remote areas due to minimal infrastructure requirements.
- Supports VOIP, Audio/Video streaming and similar services requiring large amounts of internet throughput.
- Encryption and Virtual Private Networks.
- 75 MBPS.
- Customer Distances of 30+ miles.

WiMAX is a viable primary choice, or at least an option, for adding an Internet gateway to areas whose location and other environmental considerations make it abnormally tricky to provide Internet Protocol (IP) services—such as remote and austere environments.

C. SATELLITE COMMUNICATIONS

A satellite is a manufactured object placed into orbit around a planet. The communication satellite that we are interested in is utilized for extending radio frequency (RF) beyond line-of-sight (LOS), usually around the world from one side of the Earth to the other, allowing for voice communications and the transfer of data to take place from one location to any other location on Earth.

Communication originates at a ground station's earth terminal. A ground station transmits and receives signals from a satellite, called uplink and downlink. Ground stations send ultra-high-frequency (UHF), super high frequency (SHF), or extremely high frequency (EHF) radio frequency waves to satellites which receive and then rebroadcast the waves to an awaiting ground station. The ground stations that are in the coverage area of the broadcasted waves then receive and process them accordingly (Cook, 1996). The entire zone where the broadcasted signal can be received is called the satellite footprint. When the ground station transmits to the satellite, that transmission is called the satellite uplink; conversely, when the satellite broadcasts to the ground station, the transmission is called the satellite downlink. The uplink and downlink frequencies are kept separate to maintain frequency de-confliction. Figure 43 illustrates satellite uplink and downlink communications.

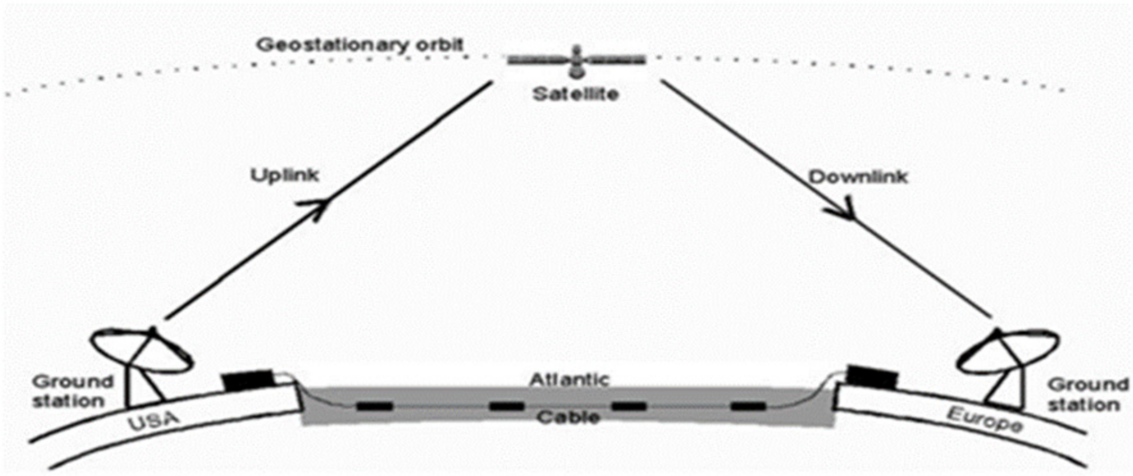

Figure 43. Uplink/Downlink. Source: Flowers (2015).

Satellite systems have three main orbit types, geostationary, polar circular and inclined highly elliptical orbits. Geostationary orbits circles the Earth every 24 hours. Since the satellites revolution around the Earth is equal to the Earth's rotation, its position in the sky appears to be in a fixed location. In 1945, Arthur C. Clarke, determined that when three geostationary satellites were positioned at certain points from one another, the footprint of each satellite combined could cover the entire Earth for a robust communications network (Benford, 2008; Cook, 1996). The polar circular orbit is one thousand kilometers above the Earth, passes over the North and South poles, maintaining an angle inclination of 90 degrees, and scans the whole earth every 12 hours. A polar orbit is used on satellites whose purpose is weather monitoring. Finally, inclined highly elliptical orbits with inclination angles of 63 degrees are designed for higher latitudes.

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