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Connecting Land-Based Networks to Ships

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***Abstract*— Today it is important for Navy ships at sea to be able to communicate and exchange information with a shore network for services such as file transfer, database access, e-mail, web/intranet browsing or video conferencing. To accomplish this, most ships use satellite communications, which is an expensive and slow method.**

When a ship is near shore, it can use alternate methods of communicating with the shore network, which are typically faster and cost less than satellite-based services. Examples of these methods are IEEE 802.16 WiMAX, 2G/3G cellular networks and Wave Relay systems. This paper evaluates the various methods available in terms of cost, range, bandwidth, quality of service (QoS) and reliability, by conducting experiments in Monterey Bay, CA. The experimental results are reported and used in this paper to determine which method would be best suited for various use cases.

Keywords— WiMAX, Wave Relay, Cellular Networks, Satellite Communications, Ship Shore Communications, Wireless Networks

I. INTRODUCTION

Most ships today have built-in local-area networks (LANs) that support the ship's basic networking needs. Navy ships, for example, have a LAN that is used for combat systems integration or for message distribution. The usefulness and functionality of the ship's LAN can be extended significantly if that LAN could become a subnet of a wide-area land-based network. Examples of ways to implement a network connection between a ship and a land-based network are satellite communications, IEEE 802.16-based (Worldwide Interoperability for Microwave Access (WiMAX), commercial-off-the-shelf radio-based data networks, and cellular networks (either 3G or 4G). Each of these operates differently and has associated cost, range, access control, throughput, and reliability characteristics.

This paper evaluates several such technologies to connect a shipboard LAN to a land-based network. The equipment/hardware needed for each is described, a thorough analysis of each proposed connection implementation is presented, and the various alternatives in terms of cost, range, bandwidth, quality of service (QoS) and reliability are compared. Furthermore, experiments are conducted using cellular networks, satellite communications, WiMAX, and Persistent System's proprietary Wave Relay. The results of the experiments are used to determine the method that would be best suited for various use cases.

Our research helps military users who operate their ships near coastal waters and need to make their Navy's warships a part of the military network to participate in the generation and maintenance of a common situational awareness between the ashore elements and the afloat elements. A ship connected with the shore network enables the ship's personnel access to functionality that they would normally have only if the ship was docked. Commercial ships can also benefit from this study, since a ship will be able to connect with its corporation's network.

This paper is organized as follows. Section II provides the necessary theoretical background for the technologies proposed to connect a ship with a shore network, providing the concept and terminology description that will be used throughout this paper.

Section III gives examples of related projects, either military or commercial, that are related to the ship-to-shore connectivity problem.

Section IV explains the experiment described above, explaining its geographical locations, its architecture, the hardware specifications and the experiment procedures that were followed.

Section V describes the results of the experimentation conducted and data gathered from the experiment, as well as the problems encountered during its execution.

Sections VI and VII summarize the results and provide conclusions of this research, and Section VIII makes recommendations for future work.

II. BACKGROUND

A. IEEE 802.16 (WiMAX)

Worldwide Interoperability for Microwave Access (IEEE 802.16 WiMAX) is an IP-based, wireless broadband access technology providing performance equivalent to 802.11 (WiFi) with the additional advantage of having coverage and quality of service (QoS) similar to that of the wide-area cellular networks. It has a range for broadband access of up to 30 miles (50 km) for fixed stations and up to 10 miles (15 km) for mobile stations.

The architecture of a WiMAX network, depicted in Figure 1, consists of the following three parts:

a. Mobile Stations (MS): Used by the end user to access the network.

b. Access Service Network (ASN): Comprised of one or more base stations (BS), which are responsible for providing the air interface to the MS, and one or more gateways acting as layer 2 traffic aggregation points within an ASN and forming the radio access network at the edge.

c. Connectivity Service Network (CSN): Provides IP connectivity to the Internet or to other public/corporate networks, as well as the entire IP core network functions. The CSN also provides the policy management for QoS and security functionalities.

QoS classes used by the 802.16 protocol include Best Effort (BE), used for data transfer and web browsing; Real-time Packet Services (rtPS), used for Streaming Audio/Video; and Extended Real-time Packet Services (ertPS), used for VoIP.

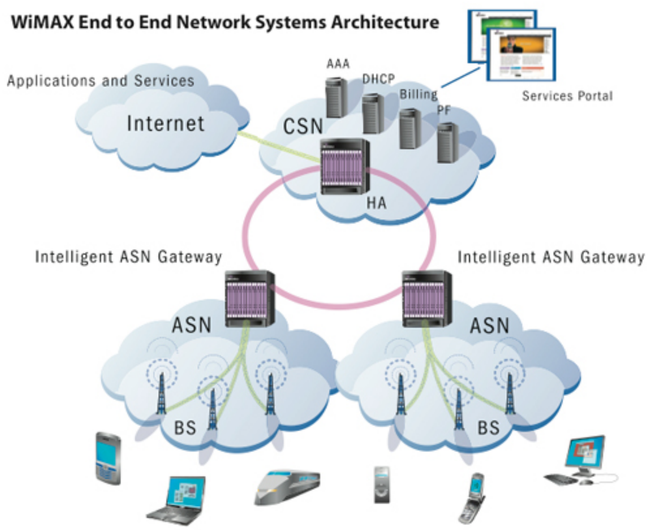

Figure 1. WiMAX architecture [From 1]

IEEE 802.16 wasn't designed with mobility in mind; it was initially developed for LOS-based point-to-multipoint wireless broadband systems, and WiMAX networks were initially deployed for fixed and nomadic (portable) applications. These standards, however, evolved to support mobility over time. The IEEE 802.16e-2005 standard defined a framework for supporting mobility management, and supported subscribers moving at vehicular speeds. The latest IEEE 802.16m (WiMAX Release 2), approved by IEEE on March 2011, supports peak data rates over 1Gbps (fixed) and over 100Mbps (mobile), up to 500km/h mobility, and, as of the writing of this report, it is being finalized.

Figure 2 shows where WiMAX stands in terms of mobility and speed related to WiFi 802.11 networks and the cellular networks. IEEE 802.11 networks offer a very high network throughput but are limited in terms of mobility, while cellular networks offer, by definition, the best mobility possible but at a usually lower speed. 802.16 WiMAX networks are effectively a solution combining these characteristics, offering a good throughput with good mobility. For the application of ship-to-shore communications, the amount of mobility offered should be sufficient, since a ship is moving at relatively slow speeds; commercial ships are usually traveling at speeds of 20–25 knots, a typical frigate or destroyer has a top speed of 30 knots, and even a fast missile-boat has a top speed of about 40 knots (about 46 miles/h or 74km/h). So all ships are well within the vehicular speed profile, and the IEEE 802.16e standard shouldn't have any problems for serving their mobility patterns.

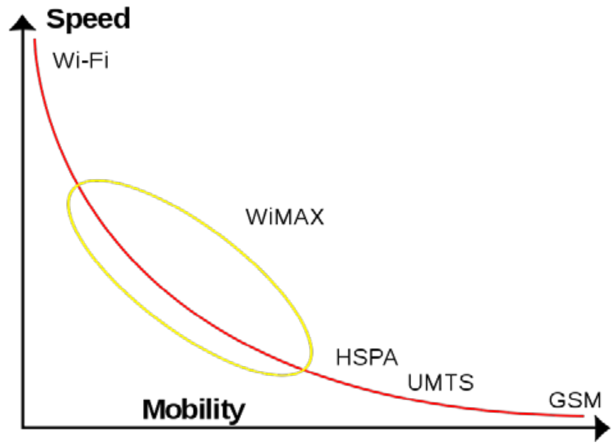

Figure 2. Mobility vs Link Data Rate

B. *2.5G/3G/4G Cellular Networks*

General Packet Radio Service (GPRS), often categorized as 2.5G, is packet-switched Wide Area Network (WAN). GPRS is implemented as hardware and software upgrades to the existing Global System for Mobile Communications (GSM) network. GPRS offers data rates up to 171.2Kbps, depending on the network availability, the terminal's capabilities and the channel coding scheme used. It's an important step in the evolution from GSM to 3G cellular networks, and there are already several GPRS implementations worldwide. Another extension of GSM is Enhanced Data rates for GSM Evolution (EDGE), also known as Enhanced GPRS (EGPRS). It was first deployed on GSM networks in 2003, and it offers data rates two to three times higher than GPRS (up to 470Kbps for indoor and 144Kbps for outdoor operation, as most outdoor applications would involve mobility and greater free space loss). Together, these extensions to 2G GSM networks are often referred to as 2.5 or 2.75G. Third generation systems integrated both the data and the voice into a packet-switched network, moving away from the circuit-switch roots of the service.

Third-Generation (3G) systems are designed to offer higher data rates that can support Internet access and wireless multimedia services, including audio, video and imaging. These rates offer 2Mbps for a fixed station, 384Kbps to a station moving at slow speeds and 144Kbps for vehicular speeds. For the application of ship-to-shore communications, the 384Kbps bandwidth should be considered.

Fourth-Generation (4G) cellular WANs are designed to provide even higher data rates than 3G. 4G networks, while expanding in their coverage, are not implemented as widely as 2.5G and 3G networks. It is likely that in the technologically-developed countries, in the next 2-3 years, 4G coverage will become as wide spread as 3G is today.

C. *Satellite Communications*

A satellite communications system consists of at least two earth stations and at least one satellite that serve as relay stations. Satellites can be categorized according to their coverage area or footprint (global or regional), service type (Fixed Service, Broadcast Service and Mobile service) and their usage (commercial, military, and experimental). Although a satellite system's cost is relatively high, the transmission cost is independent of distance. The system offers potentially high bandwidth and a very high quality of transmission, even after any short-term signal outages or degradations due to the earth's atmospheric conditions.

There are two common satellite network configurations, depicted in Figures 3 and 4. In the first one, the satellite provides a point-to-point link between the two earth stations; while in the second, it provides communications between a single transmitter and many receivers. The second configuration can be modified to support bidirectional communications between many earth stations, one of them having a central hub, also known as the very small aperture terminal (VSAT) system. The stations, equipped with VSAT antennas, share the satellite's transmission capacity to transmit to the station having the central hub. That hub station can then act as a relay between the other stations [2].

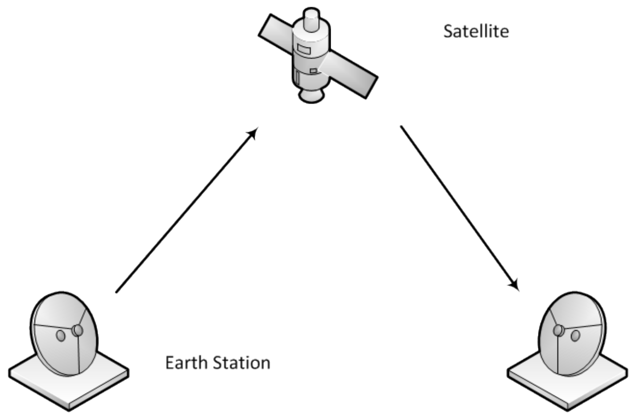

Figure 3. Satellite point-to-point link

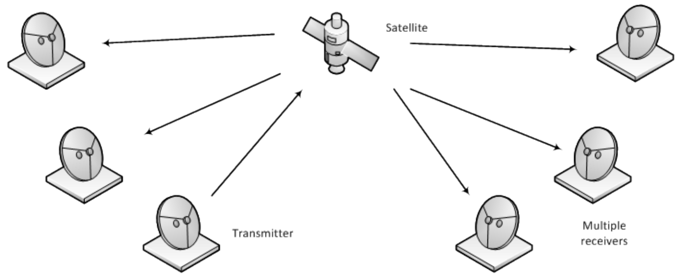

Figure 4. Satellite broadcast link

A satellite, typically having a large bandwidth, would divide it into channels of smaller bandwidth, each for a capacity allocation task. Each channel may be shared by many users, so there's a need for multiplexing. Frequency Division Multiple Access (FDMA) is the multiplexing scheme where each earth station transmits at different frequencies to the satellite (a guard band is used to prevent overlapping frequencies). In Time Division Multiple Access (TDMA), the earth stations are assigned a periodic time frame for them to transmit. During that frame, they have the entire satellite bandwidth available to them. In some cases, the traffic burst preassignment might prevent reallocation of any unoccupied channels. This may have a negative impact on the satellite's utilization. To improve it, Demand Assignment Multiple Access (DAMA) might be used. In this scheme, each earth station is assigned its capacity on demand, which is released after it has finished transmitting or receiving. In addition, the capacity the station is assigned can be proportional to its traffic intensity, to further improve the system's overall efficiency [3].

D. Wave Relay

Wave Relay is a "Mobile Ad Hoc Networking system (MANET) designed to maintain connectivity among devices that are on the move" [4]. It is a peer-to-peer mesh networking solution, using a proprietary algorithm. According to its manufacturer, it is designed to adapt in difficult environmental conditions to maximize connectivity and performance. It uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access algorithm, which avoids collisions by only transmitting after the channel is sensed to be "idle." Its physical layer is based on orthogonal frequency division multiplexing (OFDM), similar to WiMAX described earlier.

The Quad Radio Router, which may be used to implement a large geographic coverage network suitable for maritime deployment, has up to 37Mbps throughput on a 20 MHz channel [5]. Its security algorithm is CTR-AES-256 HMAC-SHA-512 (Counter Mode AES encryption with a SHA-2 512bit hash-based message authentication code), and is validated by the governments of the United States and Canada.

III. CURRENT CAPABILITIES OF SHIP-TO-SHORE COMMUNICATIONS

A. US Navy Automated Digital Network System (ADNS)

The U.S. Navy's Automated Digital Network System (ADNS) serves as the interface for managing the Navy's tactical wide WAN. It was introduced in 1997 when it made the connection between a ship and a shore network possible. It has been deployed on surface ships, submarines, aircraft, and at Navy shore installations [6]. On the ship itself, the ADNS interfaces connect the ship's local area network (LAN) and the radio equipment. Similarly, on the shore it connects the radio equipment with the land-based switching networks. When it was initially developed, it used satellite communications as ship-to-shore link [7].

The ADNS has been developed in three stages, or increments. The initial Increment I supported baseline routing and encryption, e-mail, web browsing and file transfer, all up to a 2Mbps bandwidth, and combined IP traffic from different enclaves to a Time

Division Multiplexed (TDM) network across a single radio frequency path [6], [7]. Between 2004 and 2008, Increment II was developed (including sub-stages Increment IIa and Increment IIb) added load balancing capabilities, compression, application prioritization (Quality of Service – QoS), increased the maximum supported bandwidth to 8Mbps, transitioned from Proteon to Cisco routers, and enabled a traffic flow over multiple satellite communication paths [7], [8], [9]. While these increments were developed and installed by the Navy itself, for Increment III the Navy turned to a private-sector contractor, the General Dynamics Company, hoping to improve the system even further. Its capabilities were to be enhanced even further by implementing "dual stack" IPv4/IPv6 architecture, a bandwidth up to 50Mbps, provide additional compression, but more importantly, expand the ability of the ADNS to use alternative, non-satellite paths. These paths can be high frequency (HF) radio, line-of-sight (LoS) data relay, and even 802.11 network functionalities. A Navy ship, which had a limited bandwidth and its only option was satellite communications, now has the ability to manage its bandwidth and utilize radio channels for ship-to-shore communications, a much cheaper and efficient solution.

Figure 5. ADNS Overview [From 10]

B. *US Navy Floating Area Network*

Mobilisa, Inc. developed for the U.S. Navy another way to enable ships at sea to communicate with each other, called Floating Area Network (FAN). Their technology is based on long-distance 802.11 antennas, having a line-of-sight range. Ships within range of each other create a mesh Ad-Hoc network that lets them communicate and exchange information directly without having to rely on slower and expensive satellite communications. The U.S. Navy demonstrated the technology during the exercise Trident Warrior in June 2008. Although this is not an example of direct ship-to-shore communication, this technology might be used if a ship is out of range of shore cellular or WiMAX antennas, but another ship in the fleet is closer to the shore nd can provide a relay. This way, instead of using satellite communications, the FAN would be used to logically extend the shore antennas range, using ships as relay platforms [11], [12]

C. *Combined Enterprise Regional Information Exchange System (CENTRIXS)*

Combined Enterprise Regional Information Exchange System (CENTRIXS) was developed in 1998 as the first maritime Coalition Wide Area Network (CWAN). It was designed to provide secure and robust connectivity between U.S. and coalition forces, initially providing secure e-mail service over an INMARSAT satellite link for Navy ships and over dedicated circuits for allied shore commands. Later it was expanded to support data sharing through web browsing, e-mail with attachments, secure VoIP, collaboration and near-real-time situational data display and imaging. It has been the primary coalition network supporting Operation Enduring Freedom, a standard for information sharing between some 68 nations [13]

D. *Satellite – Inmarsat and iDirect*

INMARSAT is a British company that offers some of the most well-known commercial solutions for broadband communications at sea. These solutions can be used by a ship practically anywhere in the globe to connect to any shore network through the Internet. One of the commercial products INMARSAT is offering is FleetBroadband, which along with voice and SMS services, offers a 432kbps Internet and intranet connection through a secure VPN channel [14], [15].

iDirect is another Company that provides maritime communications solutions. Their services have the Automatic Beam Switching feature, which seamlessly performs a handoff from one satellite beam to another as the ship moves, as well as a Group Quality of Service, which prioritizes traffic for individual applications or users on individual vessels and also manages the available bandwidth across the fleet [16].

E. Satellite – MCP

MCP Company has implemented a way to bring cell phone and Internet connectivity to commercial vessels while at sea, even when there is no contact with regular terrestrial base stations. Their implementation includes ship-board antennas and base stations, which are connected to the ship's VSAT system by which the voice and data connections from the phones are routed from the ship to the shore gateway and then to the land network. GSM and Code Division Multiple Access (CDMA) phones are supported; the on-ship cellular network appears to the subscriber as a visited network, and the registration/billing process is handled through roaming. Also, the on-ship cellular network is automatically turned off as the ship approaches the shore to prevent interference with the relevant country's own cell networks, as ship-board cellular base terminal transmission would only be allowed in international waters.

MCP's implementation also extends Internet connectivity while at sea using WiFi antennas that can be installed throughout the ship. Passengers and crew use their laptops or smartphones to connect to the ship's WiFi network using the browser, and then a captive portal handles the registration process and billing [17], [18].

F. WiMAX - Singapore's WisePort

WisePort, standing for WIreless-broadband-access at SEaPORT, is a project offering wireless broadband connectivity to Singapore's coastal waters, up to a range of 15 km (about 8 nautical miles). Its trial started on March 2008 and its commercial launch took place on March 2009. It was implemented using a mobile WiMAX network, created by 6 WiMAX base stations along the shoreline, and initially offering up to 8Mbps unlimited data access. The WisePort project enabled ferries, as well as arriving and anchored vessels, to access the Internet to send engine reports to shore, receive schedules and instructions, submit digitally any necessary documents to the terminal operators, contact their logistics providers, access tidal information and receive electronic chart updates. Islands and offshore oil platforms are also potential customers to the system. Aside from Internet access, they can implement a remote live video surveillance security system and access company databases.

As a much cheaper, faster, more efficient and more reliable alternative to satellite communications, WisePort had 250 subscribers even before its official launch. Its cost was 12 million Singapore dollars (about $8 million US) [19], [20], [21].

G. WiMAX and WiFi - Seattle ferries

The U.S. Department of Transportation funded the Washington State Ferries Wireless Connection Project (WSF WCP) [22]. The project was to provide a seamless 802.11 wireless connectivity to passengers waiting on the ferry terminals and aboard the ferries while in transit. The contractor was Mobilisa, Inc. and it installed WiFi directional antennas on specific shore sites and onboard the ferries. The connection was then routed to the ferry's onboard 802.11 access point. They managed to cover a range up to 5 miles, while the ferry routes length vary from 2.8 to 15.5 miles [23], [24]. This project shows that even WiFi can be used to connect ships traveling near the coast.

Six years later, in 2009, WSF contracted with Proxim Wireless, Inc. to upgrade the network using WiMAX point-to-multipoint antennas that would provide over 12Mbps throughput to each ferry, as well as 11 ferry terminals [24]. There were reports, however, that Proxim experienced difficulties with interference caused by the scattering of the wireless signal, as the water acts as a mirror for these signals. The company had to install a greater number of shore antennas to improve the reliability of the network [25]. Proxim's equipment were used later in 2010 in San Francisco Bay, where a WiMAX network was implemented providing a 12Mbps to 36Mbps connection speed to commercial vessels covering all of the bay area, about 62 square miles. Additionally, a WiFi connection was extended to recreational vessels that are closer to shore, up to 0.5 mile [26].

H. 2G/3G cellular Networks

Ships that are near the coast may have the option of accessing a commercial land-based 2G or 3G cellular network for their voice and data communications. If the ships operate in multiple countries, however, additional roaming charges may apply that can be comparable to the cost of a satellite link.

3G is usually limited to a line-of-sight range. That said, 2G range in some conditions can be even greater than WiMAX, providing coverage up to 30 miles or more, depending on the height of the cell tower from sea level and the use of directional antennas. Of course, a 2.5G GPRS data connection is not considered broadband, especially compared with the latest wide-area cellular networks. Maximum available bandwidth for a single GPRS connection would be about 150Kbps, so its bandwidth is comparable to an ISDN line. It's still a cheap and efficient solution compared to a satellite link, depending on the ship's bandwidth needs.

In some areas in the world, like in the Aegean Sea, the islands scattered throughout the region can uniformly cover a very large area. As shown in the following images, taken from one of Greece's major cellular providers, the 3G network covers about 90% of the Aegean (without specifying, however, the actual available bandwidth). Further, 2G coverage exists almost everywhere. So a ship, for example, traveling through the Aegean Sea to the Black Sea would almost always have at least 2G connectivity (a distance of about 300 nautical miles).

Figure 6. 2G network coverage in Greece [From 27]

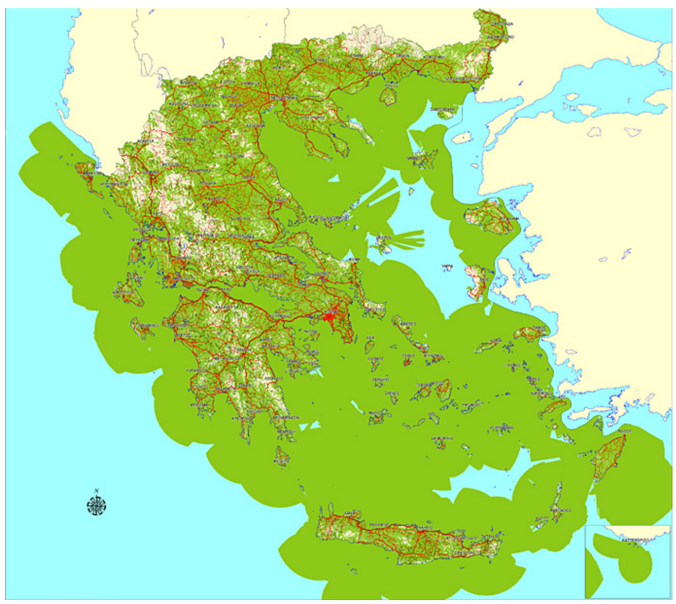

Figure 7. 3G network coverage in Greece [From 27]

IV. EXPERIMENT SCENARIO

A. Geography

The experiment took place in the Monterey Bay area, and consisted of two main parts. In the first part, the experiment was conducted alongside the bay's shoreline, starting from Monterey and moving northwards to Santa Cruz, following California Highway 1. A WiMAX and a Wave Relay radio were set up on top of Spanagel Hall on the Naval Postgraduate School (NPS) campus. These radios, serving as the master access point for their network, respectively, used 120-degree sector antennas. The radios on the mobile end of the links used omni-directional antennas, as the purpose of the experiment was to show the possibilities for connectivity to a moving ship, and if directional antennas were used the user would have to be constantly adjusting the ship-borne antenna bearing according to the ship movement. Firstly, an initial testing of the equipment from within NPS was performed, which also served as a "best case" scenario. Then, the mobile unit moved from Monterey towards Santa Cruz, increasing the distance between the mobile terminal and the base radios, and conducted measurements related to the network's performance. The bay's curving shape also ensures that the radio signal will propagate over the ocean, which impacts the network's performance, as the radio waves "bounce" off the water. The limitation to this part of the experiment was that appropriate measurements could not be taken for 2G/3G cellular connectivity, as the density of cell towers precluded sufficient degradation of the connection due to range, that is, hand-off between servicing towers mitigated the range changes due to the vehicle travel.

In the second part of the experiment, the mobile-termonal equipment was loaded on a boat and as the boat moved away from the shore, measurements were taken as to how each connection method performed at the designated waypoints. These waypoints are shown in the following figures, and were selected in such a way that the distance increases from the base WiMAX and Wave Relay radios, as well as from the commercial cellular towers on shore. It should be noted that the distance for each of the waypoints from the WiMAX and Wave Relay radios was precisely known, but the exact distance from the cellular tower was not known. This is because the precise cellular tower for the connection was not determined. Thus, in the range calculations it was assumed that the cellular tower is located at the closest point to the shore. All of the waypoints also had a direct line-of-sight connectivity to the base radios, with no physical obstacles in between, ensuring an optimal connectivity configuration. The only exception to this was the tree line between NPS and the beach, which indeed impacted the performance.

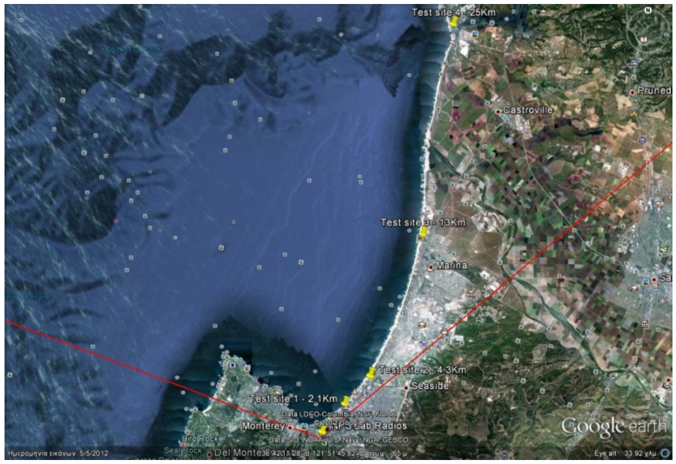

Figure 8. Test sites on Monterey Bay coast

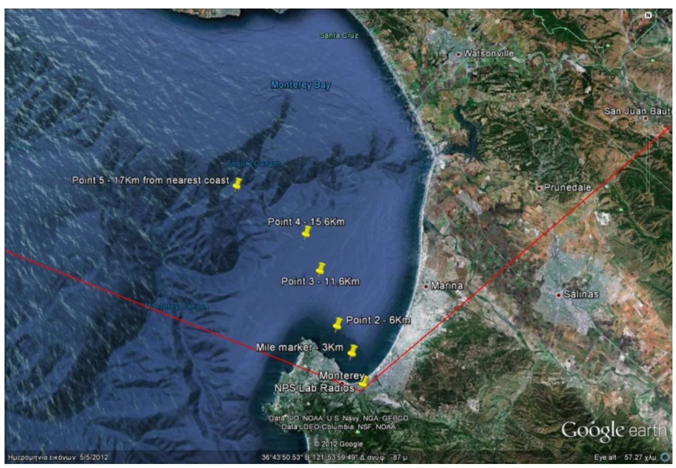

Figure 9. Waypoints for sea testing

The experiment's architecture is depicted in Figure 10. This architecture was divided into 2 main parts: the reception side, located on the mobile terminal (on the car or on the boat), and the laboratory side, located at the Naval Postgraduate School. For the reception, or mobile, side of the experiment, a laptop could be connected to one connection path at a time. In the fixed side (laboratory space in NPS), there was a laptop directly connected to the WiMAX and Wave Relay radios using an Ethernet switch and CAT5 Ethernet cable. To achieve connectivity with the mobile terminal using cellular and satellite networks, the server was also connected to the Internet using an NPS gateway, allowing ports 80, 441 and 5001 through NPS's firewall. Access to these ports was forwarded to the experiment's server.

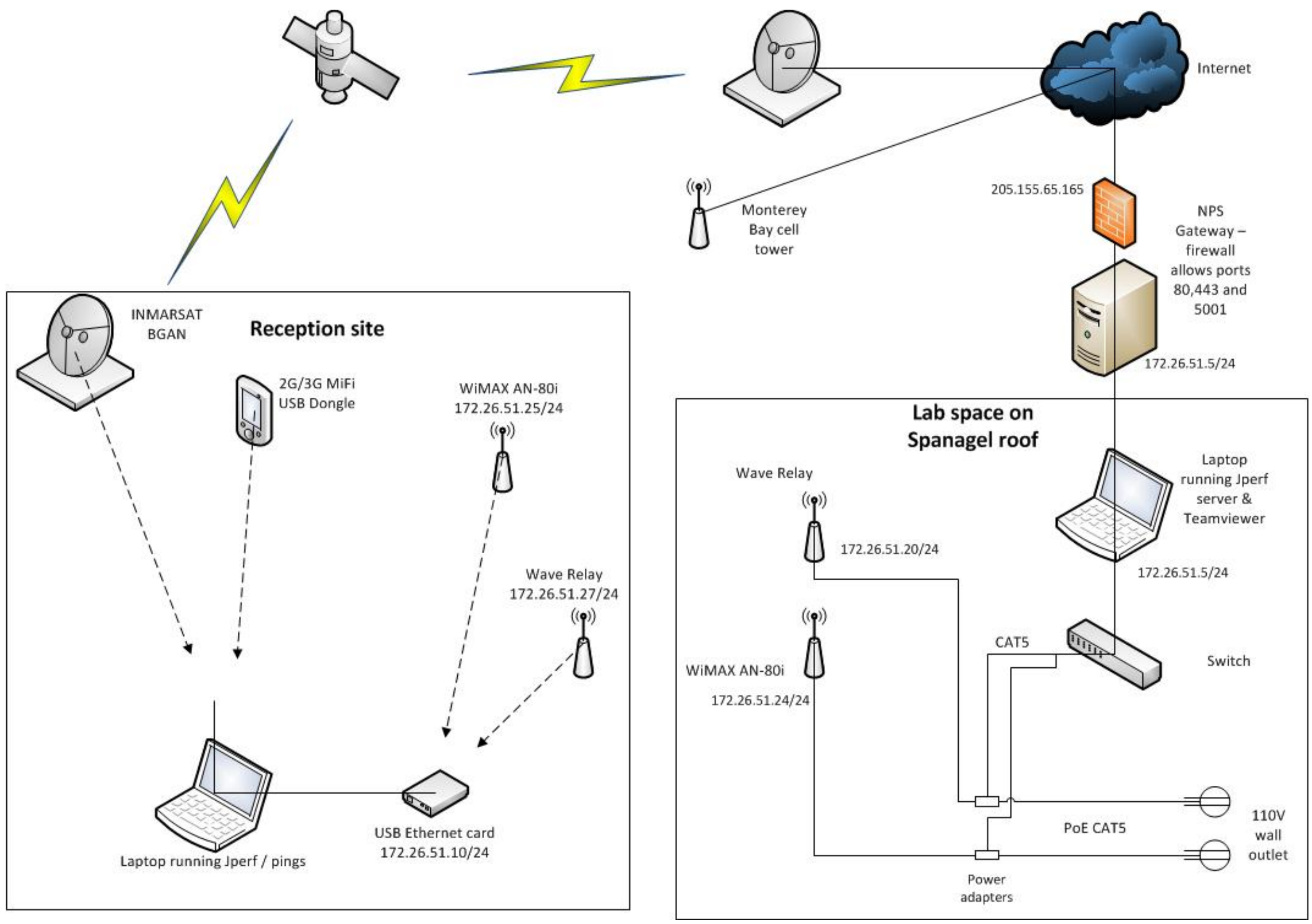

Figure 10. Experiment architecture

The server was running the "iperf" bandwidth measurement tool in server mode, while the mobile client ran "iperf" transmitting fixed-file sizes for a specific amount of time. A Linux script was used to run these commands and collect/analyze the data. The script also "pinged" the server several times to measure the RTT.

B. Hardware Specifications

For communicating using IEEE 802.16 WiMAX, two (2) identical AN-80i Radio Platforms were used, both of which were manufactured by Redline ® Communications. According to the manufacturer's datasheet, the radio can achieve a range of over 80 kilometers (50 miles) and deliver up to 90Mbps [28]. Notable specifications for the AN-80i are AES-128 and AES-256 encryption options, up to 40 MHz channel size, and 25dBm maximum transmission power (just less than 400 mW). The antenna used was an SA58–120–16-WB 120-degree, vertically polarized, sector antenna manufactured by Laird technologies. Its sector covered Monterey Bay as well as the coastal areas, as depicted on Figures 8 and 9. The antenna is weatherproof, has a 5470 - 5850 MHz frequency range, 16 dBi Gain and weighs 1.2 kg (2.6 lbs.). Its gain pattern is depicted on the following figure, where the purple line defines its gain horizontally and the green line defines its gain vertically. It should be noted that its vertical beamwidth is only 7 degrees, so the antenna installation must be precise enough to ensure optimum performance. For the slave (mobile) terminal, an ODN9–5725 omni-directional antenna was used, manufactured by Mobile Mark, Inc. The experimenters preferred using an omni-directional antenna over a sector or directional antenna, since in the sea phase of the experiment, the boat changes its heading periodically, and also pitches and rolls from the ocean waves. The antenna used has a 5.72–5.83 GHz response range, 9 dBi gain, and weighs less than 1 lb. [29].

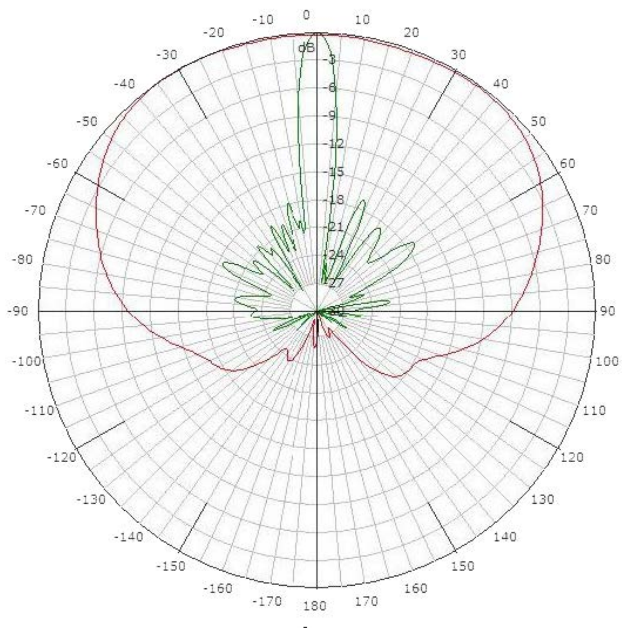

Figure 11. SA58–120–16-WB antenna gain pattern[From 30]

For Wave Relay communications, two (2) identical Wave Relay WR-RTR2 Quad Radio Routers were used, manufactured by Persistent Systems, LLC. These radios can operate in the 2.3 – 2.5 GHz frequency range (S-Band) and 5Ghz (C-Band). For testing purposes, the S-Band frequency range was used. According to the manufacturer's website, it has a range of more than 2 miles using an omni-directional antenna, and a 27Mbps maximum throughput on TCP and 37Mbps on UDP, using a 20MHz channel. Notable specifications for the WR-RTR2 are AES-CTR-256 bit encryption with SHA-512 MAC, 600 mW transmission power (military version has 2 Watt transmission power which doubles the range) and up to 40MHz channel size. [31][32]. The antenna used at the lab site was an HG2414SP-120 120-degree, vertically polarized, sector antenna manufactured by L-com. It points to the exact direction as the antenna for the AN-80i to achieve comparable results in the experiment. This antenna is similar to the SA58–120–16-WB, except it's operating within the 2.4 GHz ISM band. It has a gain of 14 dBi and weighs 2 kg (4.4 lbs.). Its gain pattern is depicted by Figure 12. Its vertical beamwidth is 15 degrees (compared to 7 degrees for the SA58–120–16-WB).

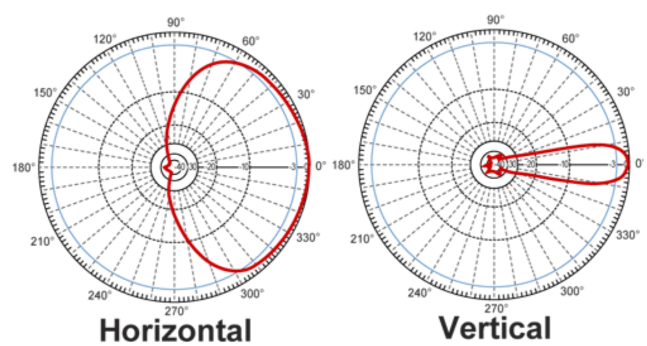

Figure 12. HG2414SP-120 antenna gain pattern

The slave (mobile) antenna for the Wave Relay link was an OD24M-5 omni-directional antenna, manufactured by Laird technologies. It has a 5 dBi gain, operates in the 2400–2485Mhz band, and weighs 0.2 kg (0.5 lb.) [33].

To test 2G/3G cellular communications, an AT&T Mobile Hotspot MiFi® 2372 was used, manufactured by Novatel Wireless. This device supports tri-band HSUPA/HSDPA 7.2 operating at 850, 1900 and 2100 MHz, and quad-band GPRS/EDGE operating at 850, 900, 1800 and 1900 MHz. It can connect to the experiment's testing computer using either 802.11b/g or USB, and it can be battery or USB-powered. The device itself is very small and light, weighing only 3 ounces [34].

For satellite communications testing, this thesis' equipment was a Hughes 9450 BGAN (Broadband Global Area Network) Mobile Satellite Terminal. According to its manufacturer, it has a maximum throughput of 464 Kbps while on-the-move. An autonomous tracking antenna acquires and tracks the BGAN satellite. The transceiver weighs 2.3 kg and the antenna weighs 2.0 kg. It requires a 12V or 24V DC input voltage. Like the 2372 MiFi, it was connected to this experiment's testing computer using an 802.11 connection [35].

The above hardware specifications are summarized in the following figure.

	WiMAX	**Wave Relay**	**2G/3G cellular**	**Satellite**
Maximum Range (km)	80	24.3 (40MHz channel), 52.5 (20Mhz channel)	35 (GSM)	Unlimited
Maximum throughput	90 Mbps	27Mbps (TCP), 37Mbps (UDP)	7.2Mbps (HSDPA commercial user devices)	464Kbps
Encryption	AES-128, AES-256	AES-CTR-256 with SHA-512 MAC		
Channel size	40Mhz	40Mhz		
Max Tx power	25dBm	28dBm (civilian version), 33dBm (military version)		
Antenna Gain	16dBi (120° sector), 9dBi (omni)	14dBi (120° sector), 5dBi (omni)		
Frequency	5.8Ghz	2.3-2.5Ghz and 5Ghz	850Mhz, 900Mhz, 1.8Ghz and 1.9Ghz	

Figure 13. Comparison of hardware specifications

To keep track of any existing interference at the test sites, an Anritsu MS2721B handheld was used. It is a battery-operated spectrum analyzer. It weighs 3.1 kg (6.9 lbs.) and can measure frequencies from 9 kHz up to 7.1 Ghz [36].

V. DATA COLLECTION

A. Land-based testing

The first step was to perform the initial testing of the WiMAX and Wave Relay connections, which also served as the “best case” scenario, at a distance between the fixed master radios and the mobile radios of 450 meters, with no physical obstacles in between. After running the Linux script for Wave Relay, which runs iperf 30 times for a 3MB file, an average bandwidth of 4449 Kbits/sec was observed. The results have a standard deviation of 80, indicating that the available bandwidth was relatively stable. Latency measurement from “pings” averaged 5ms and was also stable. For WiMAX, after transferring a 3MB file 30 times, an average bandwidth of 4350Kbps was observed, comparable to that of Wave Relay. The standard deviation, however, was 1060, much higher compared to Wave Relay, meaning that the connectivity fluctuated much more. In the detailed results file, the maximum bandwidth for a 1-second interval was found to be 8300Kbps, but the minimum was zero (indicating that for some time slots the radios were not communicating at all, probably because of a low signal-to-noise ratio). The latency measurements were stable, at 1ms.

After successfully completing the baseline test of the equipment, making sure everything was functional, the next step of the land-based testing began. The time was chosen to be during the afternoon, when the fog or low clouds that could negatively impact the measurements are cleared by the sunshine. The first waypoint (Test Site 1) was at a distance of 2.1Km from the fixed radios, and at an angle of approximately 48 degrees right of the sector antenna aim. As this test site had some elevated sand dunes around it, even after mounting the tripod at the highest point possible, connectivity was impossible, either with Wave Relay or with WiMAX. This indicates that even if at a close range, well within the 120-degree sector antennas coverage (both antennas gain pattern have approximately 95% of maximum gain for a 50-degree angle, according to the figures in the previous section), a very good line of sight without any physical obstacles is necessary to get any connectivity.

The next stop was (Test Site 2) at a distance of 4.3Km, and at an angle of approximately 50 degrees. This site offers better LOS to our base antennas. A successful connection was made using the Wave Relay mobile radio, although the SNR was not very high (15.06 dB). By running the iperf script, an average bandwidth of 408Kbps was observed, but it fluctuated significantly (standard deviation 162). When pinging the server, an average latency of 7ms was observed, with a minimum measurement of 4ms and a maximum measurement of 11ms. The WiMAX radios, however, could not connect, although the wireless signal box in the radios’ web interface was blinking green, indicating that they were picking up each other’s radio waves, but these were not strong enough to establish a connection.

The next waypoint, Test Site 3, offered perfect visibility to the ocean. This was at 13Km from the fixed radios at NPS, at an angle of approximately 35 degrees. The Wave Relay connection was successful, at a SNR of 15.84 dB, which is slightly better than that of the previous location even though the distance had tripled) This is probably because of better LOS conditions and of a smaller incident angle. The average bandwidth measured by iperf was 936Kbps, with a standard deviation of 120. So the connection bandwidth was then much higher (more than doubled) and more stable, compared to the previous site. Pinging times were also improved, being constant around 5 – 6ms. That said, a connection using WiMAX could not be established as the radio signal was still weak.

The next stop was Test Site 4, at a distance of 25Km, where the angle was 28 degrees. Even though the test point had direct LOS to Monterey and NPS, a connection could not be made using either Wave Relay or WiMAX. The WiMAX radios did not detect up any signal.

On the way back, a stop was made again at Test Site 3 to make another Wave Relay test because low clouds and fog appeared. SNR was then 11.18 dB (compared to 15.84 dB previously in the day). Average bandwidth dropped to 571Kbps, and the average RTT increased to 16ms, with a standard deviation of 30.9ms and 4% packet loss. These results, compared with the previous ones for the same point, indicate that weather does indeed affect measurements.

A land test was also executed for the experiment's cellular connection, which serves as the "best case." An elevated point north of Moss Landing, CA was chosen as the testing site. As described above, this was to achieve the best reception from the nearby cell towers. With 3 out of 5 bars for 3G connectivity, the average bandwidth observed from the Linux script is 941Kbps, which was also relatively stable. In addition, a bandwidth measurement was performed using the Speedtest.net website (Ookla Net Metrics). The result is shown in Figure 13. Note that the comparable value to the experiment's script should be the upload speed, since iperf measures data sent from the mobile client to the server at NPS.

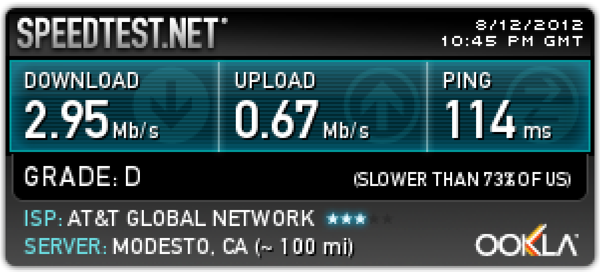

Figure 14. 2G/3G cellular connection speed test result on land

Satellite connectivity and performance is always the same, at least for a specific region covered by the same satellite, barring differences in obstacles such as foliage. Thus, instead of carrying the INMARSAT BGAN device to the boat, the decision was made to perform tests on land. The test site selected was the same as above, north of Moss Landing: an elevated, rural area with no buildings or trees that might block the satellite signal. Any chance of interference is also minimized in this area. The Linux script computed an average bandwidth value of 255Kbps. Similar to the 3G testing, a bandwidth test was run from Speedtest.net. The result is depicted in Figure 14. Note that RTT was then over 1 second due to the geosynchronous satellite's large propagation delays, as discussed before.

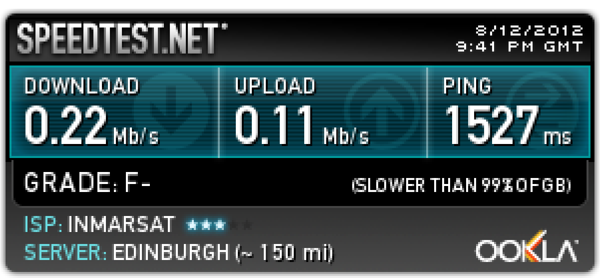

Figure 15. INMARSAT speed test result

B. Sea-trials

With the land-based experiment results in hand; the next step was to test how WiMAX and Wave Relay would perform in the ocean surface environment.

While moving south from Moss Landing towards Monterey, the first connection was acquired with Wave Relay at 13.6Km, at a 10-degree angle. Since the departure was in the afternoon, to save time, the vessel continued moving but the iperf script was run. The link achieved average bandwidth of 1237Kbps. The bandwidth was not stable, however, mainly because of the constant movement of the vessel and the rough sea-state. A WiMAX connection was not yet possible.

While arriving at the closest waypoint to NPS, at a range of 3Km, it was still not possible to connect with WiMAX, although the radio seemed to detect the signal from NPS. Wave Relay connectivity was present, but was very unreliable, as the SNR was low, at 15.68 dB. After trying several points near the area, it was concluded that the trees along the NPS beach perimeter were mainly responsible for the signal problems. Upon moving westward, and acquiring a clear LOS to NPS while maintaining the same distance, a stable connection was achieved with WiMAX. An even better connection was obtained while then moving to Test Point 0. This is depicted in the following figure. The Linux script measured an average bandwidth of 2122Kbps. Wave Relay connectivity was also greatly improved. SNR increased to 38.83 dB, and the average bandwidth was 707Kbps. While staying in the area, it was also noticed from the spectrum analyzer that lots of interference was received in the 2.4GHz range, which impacted the bandwidth for Wave Relay. These interfering signals were probably coming from land-based radio sources, like 802.11 wireless networks. In contrast, the 5.8GHz frequency range was interference-free.

Figure 16. Area affected by high trees between boat and NPS

With these lessons learned, a course was plotted northwest at 338 degrees, staying out of the ‘blind’ sector. As distance increased from NPS, WiMAX connectivity was lost very quickly, right after the 3Km mark.

The next test point (Test Point 2, depicted in Figure 9) was 6Km from NPS and 15 degrees left of beam-center. The average bandwidth there for Wave Relay was 820Kbps and the SNR was around 38dB, without any interference in the 2.4GHz frequency area. There was a faint WiMAX signal, so a bandwidth measurement for that system was also run. The script could not be completed, however, because the connection was intermittent and very unstable. The decision was made to manually run a quick iperf measurement before the signal was lost. An average bandwidth of 138Kbps was observed. The pings resulted in 69% packet loss with an average RTT of 12ms, but with standard deviation of 31ms.

The next move was to Test Point 3, 11.6Km away and a 12 degrees left angle. Running only Wave Relay tests, an average bandwidth of 483Kbps was observed, at a SNR of 17.89 dB, which meant that the signal had weakened significantly.

At Test Point 4, a 15.6Km distance and maintaining the same angle, the SNR was 14.66 dB. Connectivity started to become unstable; average RTT from pings was 47ms, with a standard deviation of 137.6ms, and 9% packet loss. Average bandwidth was only 167.39Kbps, with a standard deviation of 93.3Kbps. At 17.7Km, Wave Relay connectivity was completely lost.

Having lost both of the experiment’s private network connections, the course was set westward, away from the shore and the cell towers, to test 2G/3G cellular connectivity. At Test Point 5, 17Km from the northern point of Pacific Grove (the closest shore point), a 3G signal of 2 bars out of 5 was acquired by the AT&T MiFi. Average bandwidth was 686Kbps and average RTT was 137ms. After moving less than a mile westwards, however, the signal now was only 1 bar, while other AT&T phones in the boat did not connect. The last measurements were 174Kbps bandwidth and 197ms RTT just before the MiFi lost connection, too.

VI. RESULTS

A. WiMAX Performance

The experimental results for WiMAX were much different than anticipated. As described before, WiMAX has a theoretical range of up to 50Km, but in the experiment only an intermittent, unstable, and unreliable connectivity at 6Km was achieved. Part of the reasoning for this result is the use of a 120-degree sector antenna for the experiment's fixed radio (with a 16 dBi Gain) and an omni-directional antenna for the mobile radio (with a 9 dBi gain). The free space loss for 6Km according to the formula is:

$$L_{FS(dB)} = 20\log_{10}\left(\frac{4\pi df}{c}\right)$$

where d: distance (6 x 103 meters), f: frequency (5.8 x 109 Hz), c: speed of light, $\approx$ 3 x 108m/s, is calculated 123.27 dB. So the estimated receive power at 6Km, having a 25dBm transmit power, can be found as follows (assuming only free-space losses):

$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{FS}$ = 25 + 16 + 9 – 123.27 = -73.27dBm.

In the experiment, it was found that the minimum receive power to successfully achieve a connection between the two radios was around -68dBm. So this analysis shows how this setup greatly decreases the total antenna gain, which in turn decreases the maximum range that can be achieved. This setup, however, is intentional as a sector antenna for the fixed station is needed to cover as much area as possible, since the ship in a real scenario won't be at a specific bearing at all times. Also the ship will be moving about, and it might change its heading at anytime. So for the experiment's mobile station, an omni-directional antenna has to be used. In other words, highly directional antennas would not be practical, although the use of a multi-input multi-output (MIMO) device might help.

Another potential issue is weather conditions: fog and low clouds that are present most of the time in Monterey Bay have a negative impact on the overall propagation conditions. The experimenters assume that the range would improve if a similar experiment took place elsewhere. Nevertheless, WiMAX's overall performance was much lower than anticipated.

B. Wave Relay performance

Wave Relay proved to be a preferred option compared to WiMAX for the purpose of connecting a ship network with a shore network. It has a maximum coverage range of more than 17Km, where Wave Relay can still be used for low-bandwidth applications, like web-browsing, mail, or small file transfer, with the same antenna constraints. At a closer range of 11Km, bandwidth is around 0.5Mbps, which could be used to support real-time video applications. So the ship could stay at the edge of the coverage sector if it just needs to send some e-mails or photos, or move closer to the shore for more bandwidth-demanding applications.

C. 2G/3G cellular performance

Cellular networks led the way in terms of performance. Even at distant locations, more than 17Km away from the nearest shore, they still have 0.6Mbps throughput. Average round-trip-time, which must account for the cellular system-to-Internet routing of the packets back to the NPS location, however, is much higher compared to Wave Relay, so they may not be as useful for real-time applications.

In the experiment, the cell tower's exact location is even further away, as it's usually placed on top of a hill to maximize its coverage area, and not near the coast. In addition, in the experiment only a simple USB MiFi was available aboard the boat, instead of some more sophisticated 2G/3G antenna on the boat's mast, like was used for Wave Relay or WiMAX. So 2G/3G cellular networks could be even more promising with a more capable antenna afloat.

The other potentialdownside is the use of a commercial network. This network cannot be controlled and manipulated like a Wave Relay or WiMAX private network, a feature that might be desirable for some ship-to-shore connectivity applications. Also, the ship's connectivity is more susceptible to denial of service (DoS), eavesdropping or other major security threats, as the encryption between the mobile device and the base station is generally weak as compared to military standards.

D. INMARSAT Satellite Communications performance

The experiment's satellite tests results were as expected. A throughput of 255Kbps was realized, less than the 432Kbps the company advertises but reasonable. RTT is very large, mostly over a second, but that was expected too, since the experiment's connection not only goes through the 500ms GEO satellite propagation delay, but also through INMARSAT company headquarters in the United Kingdom, as confirmed by the testing.

Nonetheless, a satellite link offers connectivity that should be considered as an alternative, especially when the distance from shore stations is greater than is suitable of LOS radio networks. In also suffers from the same security threats as cellular networks, since it is mostly a commercial networking solution (at least for this experiment's purposes). This of course is not the case if a Navy ship uses government satellite systems, which are only accessible to certified users.

E. *Summary*

The results discussed above are summarized in the following figure.

	WiMAX	Wave Relay	2G/3G cellular	Satellite
Maximum range	6Km	17Km	>17Km	-
Throughput at 6Km	138Kbps, 12ms RTT, 69% packet loss	820Kbps	-	
SNR at 6Km	-	38dB	-	
Throughput at 11.6Km	-	483Kbps	-	
SNR at 11.6Km	-	17.89dB	-	255Kbps, 1527ms RTT
Throughput at 15.6Km	-	167.39Kbps, 47ms RTT, 9% packet loss	-	
SNR at 15.6Km	-	14.66dB	-	
Throughput at 17Km	-	-	686Kbps, 137ms RTT	

Figure 17. Summary of experiment results

F. *Use Cases*

Given these results, the experimenters derive some use cases for which one of these methods of ship-to-shore communications is preferable.

1) *Navy Ship Operating in Coastal Waters*

This use case assumes an operational theater similar to that of the Aegean Sea. The overall presence of a nearby coast would ensure that the warship is always within a 10 - 15 nautical mile radius from the nearest shore (e.g., small islands scattered in the area; see also Figures 6 and 7).

In this scenario, the most preferable solution would be a constellation of Wave Relay radios, installed in key locations on these islands (e.g., on top of navigation beacons). These radios should have 120-degree sector antennas, similar to that in the experiment, to balance range and coverage area. In some locations, sector antennas with a smaller sector angle and higher gain might be used to cover more distant areas. These Wave Relay radios would form a mesh network that would finally include a radio in the Navy's HQ.

In this way, the Navy ship would be connected to the HQ shore network, at data rates of around 500Kbps, depending on range. Real time applications that might be useful to the ship's mission (e.g., streaming video) are supported, since the RTT is very low. In addition, the ship itself could become part of the mesh that could enable other friendly ships nearby to connect, even if they are even further from the coast. This private network is fully controlled and administered by the Navy, and is secured by the AES-CTR-256 encryption algorithm. Lastly, the overall infrastructure cost is relatively low, as the Navy would only have to purchase the Wave Relay radios and the antennas, placing them on existing structures.

2) *Commercial Ship Operating in Coastal Waters*

A commercial ship might prefer using a 2G/3G cellular network to connect to its company headquarters infrastructure. The cellular network requires no initial purchasing cost, and the range is better than Wave Relay. As long as the company is not interested in high security and real-time applications, this method of communications should be the most cost-effective solution. Should security become a significant issue, it would be appropriate to pursue commercial-off-the-shelf encryption tools.

3) *Commercial Ships Operating or Anchored Near Harbors*

Here the range from the coast is short (well within the 6Km range WiMAX in the experiment), and a WiMAX solution might be considered. An 802.16 connection would offer very high bandwidth, which might be divided among users aboard the ship using either WiFi or Picocells. The examples of Washington State Ferries and Singapore's WisePort project analyzed in Chapter II illustrate these capabilities.

4) *Navy and Commercial Ships Operating in Ocean Waters*

These ships have no other choice but to use satellite communications for medium or higher rate data communications, since they are outside the range of any land-based network.

VII. CONCLUSIONS

Wave Relay seems to be a preferable solution for most cases, especially for military users; its good overall performance in terms of data rate, reliability, and range, along with the security it provides and the rugged design of the device itself, make it a good choice for any ship-to-shore communication application. A cellular network might also be chosen for increased performance and cost-effectiveness but at the cost of potentially lower security standards. WiMAX's performance was not encouraging, as it seems to be adversely effected by the sea environment (ocean waves reflecting the EM waves, ship's variable pitch-and -oll and weather conditions). However more testing needs to be done with different devices and antenna types to confirm this.

VIII. FUTURE WORK

A. Implementation of a Routing Algorithm

A ship (Navy or commercial) might have more than one option for connecting to the shore. In Use Case 1, above, for example, the Navy ship might also have access to a satellite network and a cellular network at the same time. So it could set up a router on board, properly configured and connected to the shore routers, which would seamlessly connect the ship to the shore network in a way similar to the IEEE 802.21 protocol. The connection method chosen would be made according to the parameters set in that routing algorithm. These parameters might overall bandwidth, round trip time, cost-effectiveness, security and simplicity.

B. Weather Impact in Ship-to-Shore Communications

The experiment took place in Monterey Bay, where a typical day may include dense fog and low clouds. These weather conditions can have an impact on maximum range and bandwidth, especially for higher frequencies. This experiment's second bandwidth measurement at the Marina, CA, beach, as previously explained in Chapter IV, is also an indication that some weather conditions might have an impact on communications. Follow-up experiments in a variety of weather conditions might derive important results.

C. Methods of Improving WiMAX Range And Reliability

In this experiment, WiMAX connectivity had a short range and was not reliable. These results are much different than those expected. Perhaps a different hardware setup with different brands and up-to-date equipment will improve the WiMAX performance, extending its possibilities. Another alternative would be experimentation with various antenna types for the mobile node, particularly in various sea-states.

D. Interference Impact on Ship-to-Shore Communications

Wave Relay connectivity in very short range in this experiment was problematic. Interference from land-based wireless networks seemed to cause the problem, as shown by the spectrum analyzer. Other frequencies that are close or a fraction of this experiment's frequencies might also interfere. While the experiment's Wave Relay and WiMAX devices had the option of frequency change, in real deployed situation, changing the frequency for all of the radios might be a very expensive, costly, and time consuming activity. Research is needed into how other transmitting signals, especially those commonly found in coastal areas, might impact the ship's data communications. One such experiment might include the use of a quad-radio Wave Relay router, making use of 700 MHz, 900 MHz, 2,4 GHz, and 5.8 GHz bands.

DISCLAIMER

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

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