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Title: Performance of Wireless Networks in Highly Reflective Rooms with Variable Absorption

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Principle Author:
Anibal L. Intini, Colonel, Argentine Army

Contributing Authors:
Steven J. Iatrou
John H. Gibson

Point of Contact:

Steven J. Iatrou
Naval Postgraduate School
1411 Cunningham Rd. Rm GW-3006
Monterey, CA 93943
(831) 656-3770
sjiatrou@nps.edu

Abstract

Waterborne amphibious movement begins in an amphibious ship's well deck. Once embarked on landing craft assault forces are isolated from the ship's C2 assets. Communication during this stage of operations would benefit greatly from the use of wireless technologies; however, the radio frequency environment of well deck configurations presents significant challenges. This problem is compounded by constant changes in the geometry and reflective properties of objects in the space. This paper proposes a methodology for discovering optimized positioning of COTS 802.11ac wireless local area network devices in well deck spaces. The discovery begins with modeling and simulation using a 3D ray tracing engine in conjunction with CAD software to better understand the behavior of WLAN frequencies in these enclosed spaces. These data are then tested through experimentation in a steel shipping container designed to simulate conditions found in an enclosed shipboard space. Using the positions determined by these simulations in the worst propagation cases the data show that a WLAN based on the IEEE 802.11ac standard can be used to effectively and efficiently exchange data in this environment. The analytical study of WLAN performance under these austere conditions can be applied to any organization operating within highly reflective areas.

INTRODUCTION

This paper is a distillation of research conducted as part of a master's thesis at Naval Postgraduate School, Monterey, CA [1].

During the past three decades, the world has seen significant changes in the telecommunications industry. There has been rapid growth in wireless communications, as seen by the large expansion in mobile systems. Wireless communications have moved from systems primarily focused on voice communications to systems dealing with Internet connectivity and multimedia applications [2].

With the Internet and corporate intranets becoming essential parts of daily activities, the world has become increasingly mobile. The traditional wired networks that have been successfully used up to now seem to be inadequate in their ability to meet the challenges of the modern world. Wireless Local Area Networks (WLANs) are a relatively new form of local networks that allow users to be connected and communicate without the need of physical connections. Wireless networks offer several important advantages over fixed (or wired) networks [2], such as:

- Mobility: It is the ability to freely move within a wireless coverage area with connectivity to existing networks.
- Ease and speed of deployment: WLANs do not require cables through walls or ceilings, and they can be installed in places that are very difficult to implemented wired local area networks.
- Flexibility: Wireless networking allows users to quickly form small-group, ad hoc networks for support of an impromptu meeting; simplifies moving between the offices of a building; since the wireless network medium is available everywhere, the expansion of wireless networks is easy and quick.
- Cost: In some cases, using wireless networks can reduce costs. Although the initial investment could be expensive, in the future a wireless network will have a negligible monthly operating cost, as well as low barriers to adding new users.

Despite the aforementioned advantages, WLANs have some limitations compared to wired networks, as follows [3]:

- Throughput: Wireless networks are slower than wired networks. Although a great increase in the wireless data rate has occurred during the last decade, the difference is considerable. The available bandwidth is an upper limit on the speed of wireless networks.
- Interference and Reliability: Radio waves can suffer from a number of propagation problems, mainly due to multipath propagation and electromagnetic interference (EMI), causing denial of service.
- Data and Access Security: the wireless medium cannot be controlled and it is easy to be accessed by anonymous attackers. In order to address this problem, proper protection is needed to ensure data privacy and user authentication; encryption algorithms are used, reducing the throughput of the wireless system.

WLANs provide opportunities to extend the reach of command and control assets to military members separated from traditional wired networks. These opportunities were underscored in the Secretary of the Navy Instruction (SECNAVINST) released by the Department of the Navy Chief Information Officer (DON CIO) in November 2006, wherein it was stated, “Secure application of WLAN technology offers substantial opportunity to extend the ability to connect to the enterprise network and accomplish the Department of the Navy (DON) mission in a more flexible and mobile fashion. Wireless local area networks are core components of enterprise mobility. Strategically designed, they foster efficiency, agility and interoperability throughout enterprise network architectures” [4]. Further, both the PEO C4I and Space, Space and Naval Warfare (SPAWAR) Center San Diego and SPAWAR Charleston Wireless Network Branch generated position papers or Concepts of Operation that explicitly highlighted the potential benefit of employing WLANs on combatant vessels to extend shipboard network access to underserviced compartments, such as hangers and well decks [5][6]. The concept of leveraging unclassified shipboard wireless networks to tunnel sensitive information to distributed operational personnel as a means of enhancing the accessibility of command and control information was explored during Trident Warrior 2011 sea trial experiment. In his Master’s thesis explicitly analyzing the results of that sea trial, Marshburn notes, “By extending the classified network, ship’s company technicians can rapidly and painlessly provide a C2 node in any space throughout the ship to support the requirements of the embarked commander and his staff” [7].

However, highly radio frequency (RF)-reflective rooms, such as internal shipboard compartments, well decks, amphibious combat vehicles, or armored vehicles represent extreme conditions for the use of these communication systems. The purpose of this research is to identify and explore a solution for the use of WLAN devices to provide acceptable throughput in the presence of reflected RF-energy and variable signal absorption by analyzing the propagation behavior of radio waves using technology features to mitigate the effects. The analytical study of wireless communications performance under these particular conditions provides a better understanding of the phenomena in order to produce recommendations applicable to any organization that will operate within reflective areas. This research was done using commercial off-the-shelf communications devices as their expected employment is unlikely to require the robustness associated with similar military grade systems. Further, the choice of IEEE 802.11 as the WLAN implementation is due to the large base of common consumer devices available that are suitable for adoption by military applications.

1. BACKGROUND

The IEEE 802.11 standard, commonly referred to as Wi-Fi (a moniker used to market 802.11 WLAN technologies), is designed to enable local area network (LAN) communications using radio frequencies, also known as a WLAN [8]. The range of a WLAN depends on its usage and the environment in which the system is operated. It may vary from 30 meters inside a building to several thousand meters in an outdoor environment if directional antennas are used. The communication is established in a part of the radio spectrum designated as license-free in many countries, allocated in the bands between 2.4 to 2.5 GHz and 5.15 to 5.875 GHz.

IEEE 802.11 has had several amendments since the standard was first published in June 1997. In particular one of the most recent amendments, 802.11ac, is already available in the market, and ready to implement optimal solutions, providing enhancements by using more sophisticated modulation schemes, cryptographic algorithms, and new technologies such as multiple-input-multiple-output (MIMO) data streams, in order to take full advantage of wireless solutions.

This version utilizes dual-band wireless technology, supporting connections on both the 2.4 GHz and 5 GHz bands simultaneously. It offers backward compatibility to 802.11b/g/n and data rates up to 1300 Mbps on the 5 GHz band, and up to 450 Mbps on 2.4 GHz band. The most significant improvement pertinent to well-deck operation is the addition of Multi-user MIMO *(MU-MIMO)*: This new feature allows an access point to transmit different streams to several clients simultaneously using beam-forming, or spatial filtering, a signal processing technique used for directional signal transmission or reception by combining multiple antenna elements, in a manner analogous to phased array, such that signals at particular angles experience constructive interference, while others experience destructive interference. MU-MIMO increases the utilization of the network by transmitting to multiple users simultaneously.

These improvements introduced by the new standard are very useful to mitigate the negative effects in RF reflective areas. Wave propagation and how it interacts with the environment are the most important factors to be considered when using these technologies in order to take full advantage of wireless solutions.

Interference caused by simultaneous transmission of electromagnetic waves in the same frequency by multiple users and by multipath fading can greatly alter WLAN performance in terms of range and achieved throughput. Also, the signal frequency and the environment determine which propagation mechanisms are dominant; therefore, factors that must be considered to adequately model environmental impacts on various frequencies include absorption, reflection, refraction diffraction, scattering, free space attenuation through spreading, and fading [2] [13].

Amplitude variations can produce weak signals, sometimes impossible to be detected; phase differences produce constructive and destructive signal interference, and deviation in arrival time results in symbols overlapping each other in time, known as inter-symbol interference [3]. Additionally, relative motion between transmitter and receiver, or the objects between them, can be observed in the frequency domain as a Doppler shift, proportional to the relative velocity of the objects [3]. The complexity of the multipath phenomenon in an indoor environment between a given source and receiver pair using simulation is shown in Figure 1.

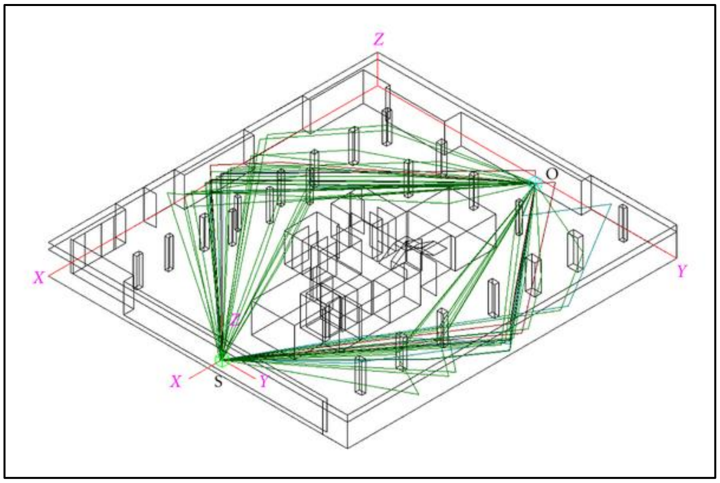


Figure 1: Multipath phenomenon in an indoor environment.

IEEE 802.11ac includes new solutions to mitigate multipath propagation effects, particularly *orthogonal frequency division multiplexing* (OFDM) and *multiple-input, multiple-output* (MIMO) technique. In a typical indoor environment, multiple RF signals sent by a MIMO radio will take multiple paths to reach the MIMO receiver, in general, using multiple dipole antennas.

Perhaps the most important factor on the hardware side of the equation is antenna design. Most Wi-Fi wireless LAN access points are shipped from the factory with the common omnidirectional half-wave dipole, 5-inch long, straight, black antenna as standard equipment. Many 802.11 access points use several of these antennas to implement space diversity. Factors to be accounted for in terms of antenna design include the antenna's efficiency, directivity, and polarization.

Every antenna has the directivity reduced due to losses, known as the efficiency, η. Antenna gain is usually stated as the peak gain mathematically; it is the product of directivity and efficiency. In general, gain is expressed in decibels relative to the isotropic radiator, typically measured in dBi (Decibels relative to an isotropic radiator) or in dBd (Decibels relative to a lossless resonant half-wave dipole radiator) [11]. The antenna polarization refers to the orientation of the electric field vector of the wave radiated by the transmitting antenna as it travels along the direction of propagation. According to how vectors behave along its path, the wave polarization can be elliptical, circular, or linear. In most wireless applications, the transmitting and the receiving antennas are linearly polarized, either vertically or horizontally.

Polarization mismatch loss occurs if the transmitting and receiving antennas are not similarly polarized. For linearly polarized antennas, the received power will be maximum when both the received signal and the antenna have the same polarization, and theoretically zero when they are rotated 90 degrees. This consideration is important to be taken into account for mobile communications [10].

Orthogonal frequency division multiplexing (OFDM) is one of the techniques that can help to mitigate multipath effects. It is a multicarrier modulation scheme, consisting of dividing the information to be transmitted into a large number of bit streams at lower bit rates individually and modulating each on an individual orthogonal carrier [10]. OFDM can be seen as either a modulation technique or a multiplexing technique. If the multiple carriers are used for a single user the technique is modulation, whereas if the separate streams are allocated to different users, then it is multiplexing. OFDM increases the robustness against frequency selective fading and narrowband interference because in a single carrier system fading or interference can cause the entire link to fail, while, in a multicarrier system, only a small percentage of the carriers will be affected. These errors can be corrected using a forward error correction (FEC) protocol [12]. An OFDM modulation scheme makes efficient use of the spectrum by allowing overlap of adjacent channels, resulting in more resistance to frequency selective fading than single carrier transmissions, and providing better protection against co-channel interference and impulsive parasitic noise [10].

Increasing the transmit power to improve the reliability of a fading wireless signal is usually an expensive or impractical solution. One of the solutions is the implementation of diversity schemes in which multiple copies of the same signal are transmitted over different propagation channels. During deep fading periods on one channel the probability of experiencing a simultaneous deep fade on the other channel(s) is very low [13]. All of the channels have to be sufficiently independent to experience different fading behaviors. For example, this can be accomplished by transmitting the same signal at different times, frequencies, or polarizations, or by using multiple transmitting and receiving antennas conveniently separated in the physical space. This last case is known as a multiple-input, multiple-output (MIMO) system [13].

Smart antenna techniques, such as MIMO systems, can provide better ability for a system to achieve increased data throughput. MIMO systems use multiple antennas at both the transmitter and the receiver to increase the capacity of the wireless channel. With MIMO, different signals are transmitted simultaneously in the same bandwidth over independent channels, provided the multipath environment is rich enough, and then separated at the receiver. Using four antennas at the transmitter and receiver has the potential to improve the system capacity by four times the data rate of a single antenna system without increasing transmit power or bandwidth [2].

2. SOFTWARE SIMULATION

The first step to implementing wireless networking in a well deck was to model antenna placement in the well deck to determine how multipath propagation affects the signal stability.

Propagation and scattering analyses generally fall into two categories: ray based techniques (geometrical optics, GO, and the geometrical theory of diffraction, GTD) or current based (physical optics, PO, and the physical theory of diffraction, PTD). For these ray methods, the sum of all reflected, transmitted, and diffracted rays arriving at the observation point is computed. The field strength is determined by the value of the reflection, transmission, and diffraction coefficients along the ray paths, and their divergence and spreading factors [15].

In this case, this simulation is oriented to determine the amount of reflection a wave can have before arriving at the receiving antenna and how this amount changes for different positions. Software for this portion of the research consisted of Savant for modeling the propagation and scattering and SketchUp for graphic rendering.

Savant is a Windows-based program developed by Delcross Technologies. It is one of several commercially available software packages for propagation and scattering simulation for predicting the performance of antennas in their intended installation environment, such as on aircraft, ships, cars, spacecraft, buildings, and other platforms.

Savant can determine the signal level for wireless networks with predefined inputs, such as building geometry, antenna types, frequency, and polarization.

Savant uses a 3D ray tracing engine to characterize electromagnetic wave propagation. The ray tracing simulation engine is based on the Shooting and Bouncing Ray (SBR) method which is an asymptotic method and therefore relevant to modeling electrically large platforms and environments. The SBR method is considered a *hybrid* method because it contains elements of both ray and current methods and can be thought of as a hybridization of GO and PO [15]. Specifically, Savant uses high-density ray tracing to approximate the surface currents induced by the antenna. These currents are then radiated to determine the influence (blockage, reflection, diffraction, etc.) of the platform on antenna radiation and antenna-to-antenna coupling [15].

SketchUp Version 14.0 software was chosen to generate the 3-D model. It is a user-friendly CAD software product, supplying a very effective toolset to create, analyze, render, edit, and precisely build a 3D model. SketchUp supports many file formats. For this project, the *.obj format was chosen. The model for this research is a simplified version of an *amphibious assault ship*, including particularly the well deck.

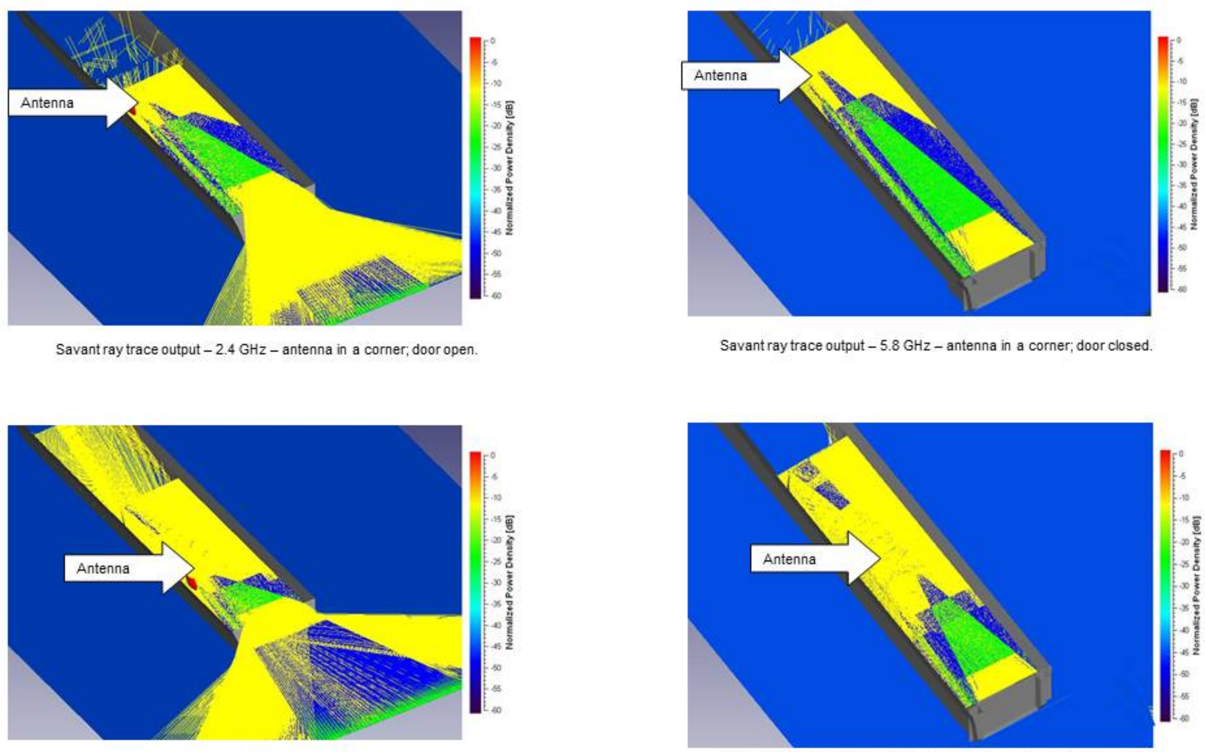
The model represents two materials, steel and seawater with different propagation characteristics. The steel was considered as a perfect electric conductor (PEC) for the simulation, a reasonable approximation to its electromagnetic behavior. The model was built according to an approximation of a Tarawa-class amphibious assault ship, in this case, the USS Peleliu (LHA-5). The simulation parameters were set to provide conditions similar to the well deck environment under various operational configurations with a WLAN using a half-wave dipole antenna, the most prevalent antenna type found in commercial WLAN devices.

When appropriately populated, Savant computes the components of the electric field at observation points with three-dimensional coordinates (x, y, z). The observation plane is a set of points where the electromagnetic field is computed. Using the graphical tool, the observation points can be modified in order to observe a specific plane. Models were constructed to account for different horizontal and vertical placements of the antenna within the confines of the well deck. The propagation conditions were simulated for both 2.4 and 5.8 GHz to develop an approximation of the real propagation in such an environment.

The ray tracing simulation provides a visual representation of the power distribution for different positions of the antenna. Examples of these power distribution graphics in the well deck are shown in Figure 2. The colors of the rays indicate the different power levels, according to the scale on the right-hand side of each graphics.

The upper deck has been clipped to show the rays in the interior. The ray tracing itself is relatively independent of wavelength; however, material properties can change with frequency.

Therefore, the resulting transmission, reflection, and refraction may be frequency dependent. The total power field is the sum of the incident and scattered rays. The power distribution in the room changes abruptly in some areas, decreasing to very low levels (blue rays).



Savant ray trace output – 2.4 GHz – antenna in a corner; door open.

Savant ray trace output – 5.8 GHz – antenna in a corner; door closed.

Savant ray trace output – 2.4 GHz – antenna in the center; door open.

Savant ray trace output – 2.4 GHz – antenna in the center; door closed.

Figure 2: Savant ray tracing in well deck

Considering different planes parallel to the sea, it can be observed that the signal changes its intensity for different heights. Figure 3 shows the power intensity for a various height planes of 3, 6 and 9 meters. Comparing this with Figure 2 at different heights, the intensity changes in all directions, sometimes falling to low power intensity (blue and black). This pattern also changes every time the internal geometry is modified; that is, every time a person or an object change position within the room, the power distribution changes.

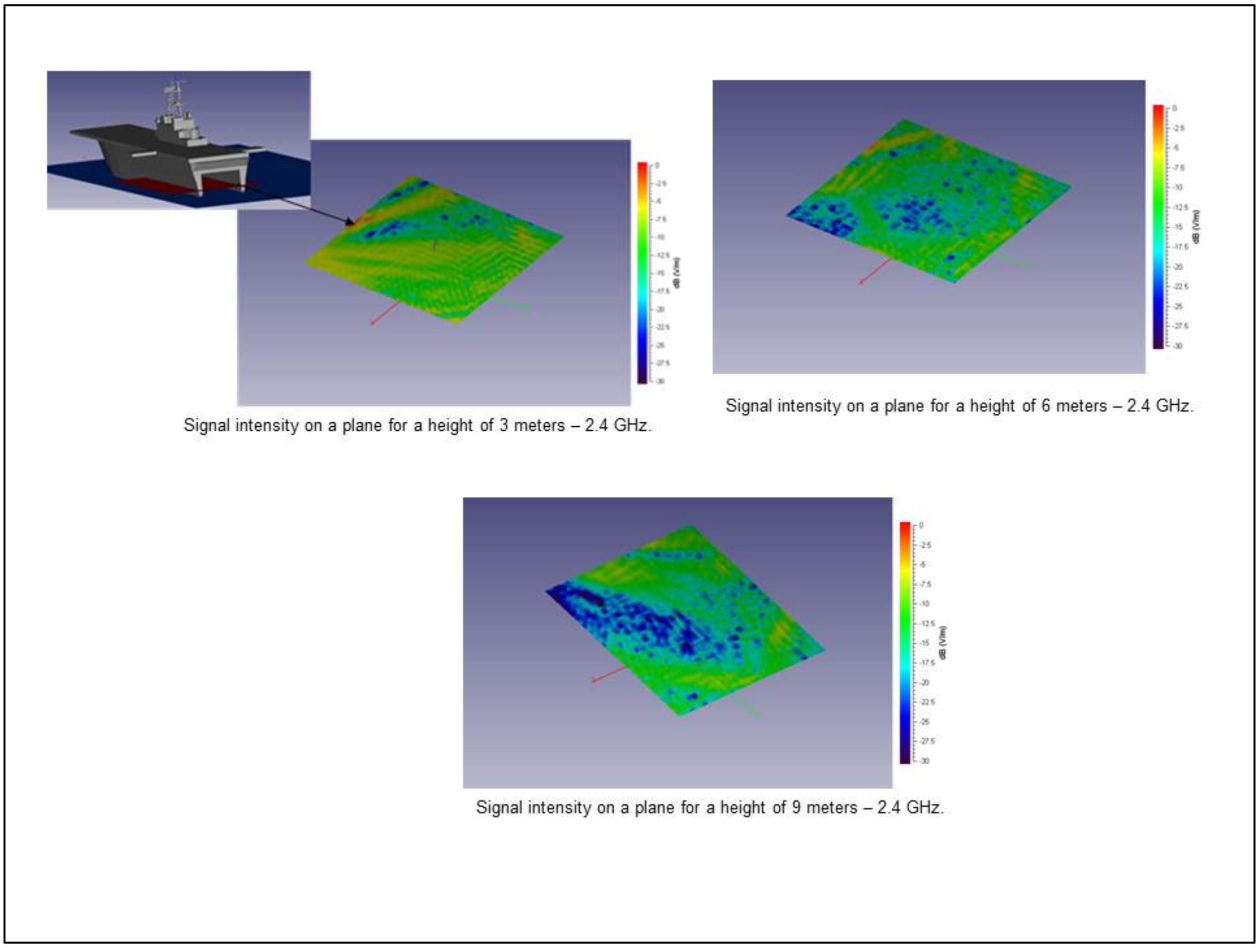


Figure 3: Single intensity at 3, 6 and 9 meter heights

It is clear that the channel performance for a mobile device will be very low, given that the signal changes with its position and any other modifications in the surrounding environment. These simulation results include the most significant observations. Many others were obtained for both frequency bands and different conditions with similar observations and conclusions. They were not included in this paper given that they do not add more information or details. The chaotic characteristics of the propagation in a simplified model could be observed, and how the signal intensity changes in a reflective room, resulting in the need to use other techniques to mitigate this problem, such as OFDM and MIMO. The power distribution within the room and how it changes abruptly in some areas could be observed, for different positions of the transmitting antenna. These positions were used in the next chapter to take performance measurements of a WLAN inside a reflective room, using the features included in IEEE802.11ac to verify how effective they are in this environment.

3. FIELD MEASUREMENTS AND RESULTS

This section presents the results of implementation of an 802.11ac WLAN in a highly reflective environment, in this case a 40-foot metallic shipping container, in order to further investigate and validate the model outputs. The metallic container served as a sufficient analogue to measure how the new standard using OFDM and MIMO mitigates fading multipath.

The measurements were taken inside a 40-foot metallic shipping container, modifying the position of the access point and connecting it wirelessly to two different computers and a mobile device using both frequencies 2.4 and 5.8 GHz. The access point was mounted on a tripod at an approximate height of two meters and placed at various positions in the container selected according to the observations in the simulations. The computers were placed in the corner where the received power is the lowest, and the access point was placed in four different positions, numbered from one to four, as seen in Figure 4.

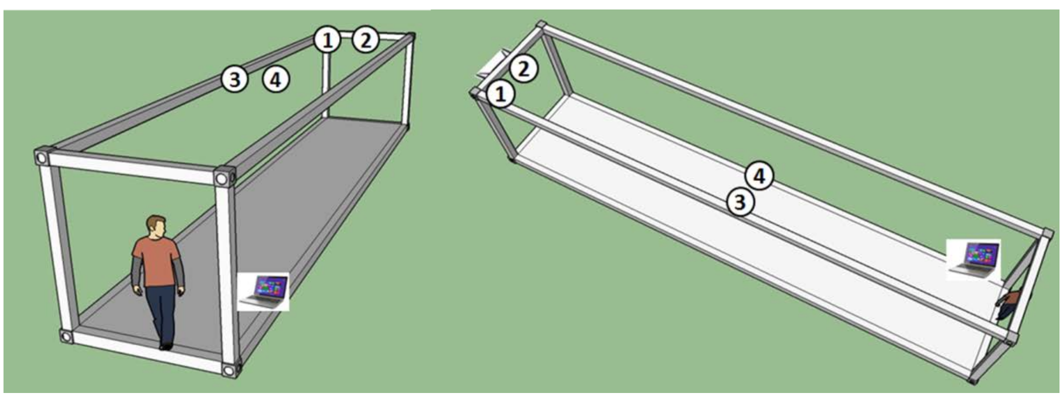


Figure 4: Positions of the computer and the access point within the container.

In a previous survey, using Metageek's inSSIDer 2.1 software, it was determined that there were no ambient signals in either 2.4 and 5.8 GHz bands, due to the isolation provided by the metallic walls.

The web-browser interface of the Linksys Dual-Band AC Router WRT1900AC wireless access point was used for the configuration by entering settings of the 802.11ac WLAN. It also provided necessary information about the radio interfaces and the principal parameters of interest, such as received signal strength. Two computers running Windows 7 and connected via Linksys Wireless AC 1200 Dual-Band USB Adapters (WUSB6300) were used within the metallic container to establish the wireless link to the access point and measure system performance. Also, one Apple iPhone 5 with an 801.11n chip was configured to perform some tests.

The Linksys WRT1900AC Dual Band Wi-Fi Router has a dual-core 1.2 GHz processor, four removable antennas, and eSata and USB 2.0/3.0 connectivity ports. It also includes management tools and a Network Map feature. The four removable, customized, and adjustable antennas provide antenna diversity enabling the router to use the three best signals out of the four antennas to transmit and receive data [17].

It is capable of speeds of up to 1.3 Gbps, on the 5 GHz band and up to 600 Mbps on the 2.4 GHz band; both speeds are the maximum performance for wireless derived from the IEEE Standard 802.11 specifications [17]. The main characteristics are included in Table 1.

Technology	Wireless-N & AC
Bands	2.4 & 5 GHz
Processor	1.2 GHz dual-core ARM-based
Antennas	4 x External antennas
Ports	4 x Gigabit LAN, 1 x Gigabit WAN, 1 x USB 3.0
Power Adapter	100-240V -50-60- Hz
VPN Support	PPTP IPSec pass-through
Memory	128MB Flash, 256MB DDR3 RAM
OS compatibility	Windows, Mac

Table 1: Specifications of the LinksysWRT1900AC. From [17].

The Linksys Wireless USB Adapter AC 1200 Dual Band is a compact wireless device used for connecting a computer to an existing wireless network or hotspot. It is compatible with most of the wireless 802.11ac routers, access points, and extenders [18]. The main characteristics of this device are included in Table 2.

Technology	Wireless AC
Bands	2.4 GHz or 5 GHz
Antennas	2 Internal
OS Compatibility	Windows
System Requirements	PC running Windows XP SP3, Windows Vista SP1 or later, Windows 7, Windows 8 - Available USB 3.0 port

Table 2: Specifications of the Linksys AC1200. From [19].

Using Packet Internet Groper (PING) and Mocha Ping Lite several ping tests were conducted from different locations within the container, observing the stability impact of moving the mobile devices (computer and cellular phone). The data showed that at both 2.4 GHz and 5.8 GHz the time delay remained stable at 1ms for the Windows machines and 27ms for the iPhone. This difference was attributed to different processing delays within the devices. Of interest was the dramatic instability demonstrated by the system when the same ping tests were run for the system configured with the 802.11g standard. Ping times varied between 1ms and 94ms. This comparison means that the implementation of the new standard IEEE802.11ac improves the data link performance, as can be seen in Figure 5.

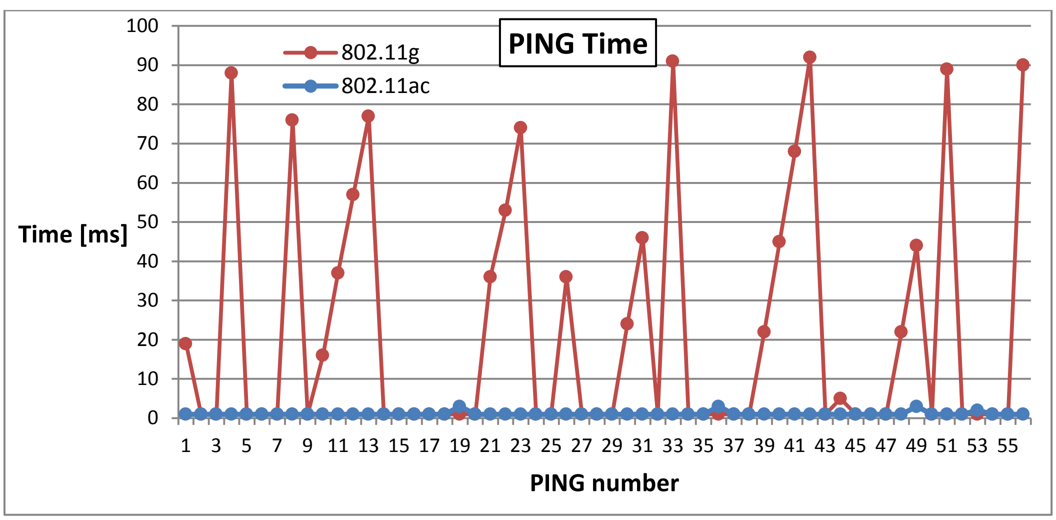


Figure 5: PING time for 802.11ac and 802.11g (2.4 GHz).

Once the stability of the 802.11ac network was established measurements were taken on the transfer of two different sized files between two computers, one of approximately 25 Mbytes and another one of approximately 100 Mbytes. In this case, one computer was connected to the access point via an Ethernet cable to leave the wireless channel to be used for only one link between the other computer and the access point, resulting in a two-hop connection between the sending host and the receiving host.

The measurements were carried out using two different frequencies and several positions for the access point inside the metallic container. The effective data rates are shown in Table 3, according to the positions depicted in Figure 4.

Position	**2.4GHz**		**5.8GHz**	
	Time [sec]	**Data rate [Mbps]**	**Time [sec]**	**Data rate [Mbps]**
1	0.42	499.3	0.21	998.6
2	0.41	511.5	0.22	953.3
3	0.43	487.7	0.20	1048.6
4	0.40	524.3	0.21	998.6

Table 3: Effective data rate results using a 25-Mbyte file.

The same exact measurements were repeated with a file size of approximately 100 Mbytes. The results for the effective data rate are tabulated in Table 4.

Position	**2.4GHz**		**5.8GHz**	
	Time [sec]	**Data rate [Mbps]**	**Time [sec]**	**Data rate [Mbps]**
1	1.62	517.8	0.82	1023.0
2	1.63	514.6	0.85	953.3
3	1.70	493.4	0.79	1061.8
4	1.59	527.6	0.81	1035.6

Table 4: Effective data rate results using a 100-Mbytes file.

Under reflective conditions, the resulting measurements were stable for all conditions and better than previous versions of the 802.11 standard, as could be seen from the simple PING test.

As expected, the effective data rate resulted in lower than the maximum performance established by the manufacturer of the access point given that this last data rate specification includes overhead and does not include some processing delays. However, these considerations are part of hardware implementation and not an evaluation of how the standard solves the instability due to fading multipath.

Independent of implementation issues, it is more important to observe that the link was stable, even when the position was changed, demonstrating that the standard is capable of working in this kind of environment.

4. CONCLUSIONS AND FUTURE WORK

The objective of this paper was to investigate the WLAN performance in reflective compartments, and explore the ability of COTS WiFi to mitigate the negative effects of the propagation characteristics inside such rooms. Radio wave propagation presents difficulties for WLANs implemented in reflective rooms due to multipath fading. As a consequence, a WLAN, such as an IEEE 802.11 based WLAN, face problems working in these areas. This paper reported the performance of an 802.11 network under such conditions. Particularly, the emerging IEEE 802.11ac standard was selected for this research based on its ubiquitous compatibility with commercially available software and hardware elements and its advanced antenna and signaling properties.

The simulation results depicted the signal distribution over a plane of observation points representing the locations of possible wireless devices. It was observed that the signal was very unstable for different positions and moments, resulting in difficult conditions for wireless mobile devices. Using the positions determined by simulation as the worst propagation cases, a WLAN based on the standard IEEE802.11ac was implemented and tested in this particular reflective operational environment. The wireless devices that were selected for the implementation of the network included a low-cost, a commercially available portable wireless access point and USB wireless adapters from Linksys. This specification improves new features, such as OFDM and MIMO, which help to mitigate the effects of the multipath fading. This experiment confirms that these features of IEEE 802.11ac effectively mitigate such fading and result in a good possibility of having wireless access to the network during tactical and logistics operations using mobile devices.

One important practical test that might be conducted in the future is the implementation and measurement of the WLAN within an actual well deck or hanger bay, oriented to evaluate not only WLAN performance, but also Electromagnetic Interference (EMI) from other systems.

The final conclusion is that the indoor 802.11ac WLAN, implemented in a highly reflective operational environment, can be successfully used for military operations in this environment. This implementation would allow access to Command and Control or logistics applications during operations, adding flexibility and mobility to the military user. Further, providing this access to personnel within amphibious vehicles in the well deck could provide communications between well decks of several ships by leveraging the host vessels' network infrastructure and inter-ship links, thereby facilitating pre-debarkation collaboration between landing forces.

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