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Beyond Line-of-Sight Communications with Smart Antennas (BLoSSA)

ABSTRACT
We describe and analyze adaptive antenna array technology to improve naval communications systems to beyond line-of-sight at microwave frequencies by using the ducting layer as a leaky waveguide and the adaptive array to resolve and coherently combine multipath in this layer.

INTRODUCTION
We can provide a communications link between naval assets using a ship-based communications suite using adaptive array antennas under various fading and shadowing conditions. The ability to provide line-of-sight (using the 4/3 earth model) is limited to relays (airborne platforms) located at higher altitudes for these extended ranges; during operations and under hostile conditions this high altitude requirement may be prohibitive (see Figure 1). Aerosols cause high losses in the ducting layer; however, the ducting layer can be considered a leaky waveguide, lossy due to the absorptive effects of the sea surface and penetration of the duct by the EM field. Even with these losses, a marine boundary ducting layer acting as a waveguide has propagation advantages over isotropic propagation. Since the ducting layer is a disk that confines the signal to the volume of a disk, the spreading loss for the duct-confined propagation path is linearly proportional to the range, versus at least the range squared for line-of-sight propagation. For specific conditions, the use of ducting can provide as much as a 40 dB stronger signal at 1000 km.

However, the ducting layer also creates multipath, since the duct acts as a leaky waveguide, with the signal reflecting or being absorbed into the sea surface (the bottom of the duct) and the ill-defined duct transition. Multiple copies of a signal may arrive at different phases, as the different copies have traversed different path lengths. If the phases of these different copies add destructively, the signal level relative to noise declines, making detection more difficult. Additionally, intersymbol interference (ISI) due to the arrival of separate copies arriving will degrade the signal; one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit.

Adaptive antennas can mitigate these effects, employing proven techniques, such as maximal ratio combining (MRC) or optimum combining. The multipath channel is estimated at the receive antenna array to determine the best pattern to combine the diversity branches, and the adaptive array uses the same pattern on transmit as receive (assuming the same frequency) — thus learning can be done on receive only. Using smart antenna techniques to combine the various multipath elements coherently allows for effective communications, providing array and diversity gain, as well as interference suppression.

FIGURE 1. Using natural phenomena to provide ubiquitous high capacity beyond line-of-sight communications.
Problem Definition

Communication links between naval assets can be improved using an expanded ship-based communications suite under various environmental, fading, and shadowing conditions. For most operational conditions, line-of-sight communication requires relays (airborne platforms, such as the LAMPS helicopter) located at higher altitudes to achieve these required extended ranges; however, during tactical operations and under hostile conditions, this high altitude requirement may be prohibitive. For example, since the primary LAMPS missions are to support surface warfare (SUW) and Undersea Warfare (USW) during which the LAMPS helicopter operates at low altitude, requirements to rise above the horizon to transfer data expose the crew and craft to possible hostile action and consume valuable mission time. Current antenna systems do not take advantage of multipath and delay spread.

The current line-of-sight communication method is subject to higher probability of detect/intercept. Given the multitude of antennas and RF systems competing for ever scarcer physical and spectral real estate on modern aircraft fuselages and ship superstructures, both multipath from the structures and unintentional jamming from adjacent channels or platforms present greater interference challenges over the intentional adversarial jamming our military systems must detect and mitigate.

As an alternative to line-of-sight communications using relays, over-the-horizon communications capabilities at high frequency (HF) are well known [Adams], but the limited spectrum and bandwidth at these frequencies preclude HF solutions for many applications and thus motivate new techniques. The need to exchange high bandwidth data emerges as cooperative networked radar and electronic warfare uses legacy systems against emerging threats.

The multitude of RF antennas on the mast of naval platforms causes spectral and physical crowding problems, the mechanical wear of rotating dish equipment, poor performance due to the blockage of these antennas, and size, weight and power (SWaP) considerations.

Solution

We propose to use adaptive antenna array technology to extend naval communications systems beyond line-of-sight at microwave frequencies using the ducting layer as a leaky waveguide. Our new techniques allowing low elevation communications at long distances increase both mission safety and effectiveness. When the system capacity is unavailable, natural phenomena will provide a reliable and high throughput alternative.

Adaptive arrays allow the resolution and coherently combining of multipath signals in the ducting layer while supporting related multiple-input-multiple-output (MIMO) communications techniques. While relays and ducting methods may be limited by the current environmental conditions, these enhanced channels, in combination with ad hoc networking, can maintain high data rate communications even with a low probability of detect/intercept. The traditional view of the duct being lossy and degraded by multipath and delay spread is reversed by the new adaptive array, MIMO, and orthogonal frequency division multiplexing (OFDM) capabilities which provide additional benefits because of these effects.

Recognizing the Navy’s current investment and development efforts, our proposed implementation can leverage off a shared aperture using an appliqué approach. We analyze and demonstrate the feasibility of beyond line-of-sight communications using the ducting layer with adaptive arrays to provide multipath mitigation and MIMO communications, as well as using a shared aperture, appliqué, and ad hoc networking. We quantify both the probability distribution of the communication data rates supported by these channels, and note the reduction in signal probability of detect/intercept.

Specifically, adaptive antennas, MIMO (multiple channels in the same bandwidth), and OFDM waveforms turn impairments into facilitators.

Our technical solution (see Figure 2) uses:

1. Adaptive antennas to mitigate multipath fading and provide MIMO capabilities.
2. **Ad hoc networking** to provide reliable communications at the highest possible data rates using a variety of channels, some of which are unreliable, such as the ducting layer.

3. **Shared apertures** with appliqués to minimize changes to existing systems.

**FIGURE 2. Adaptive arrays offer ducting layer channels to provide enhanced Naval Communications.**

Adaptive antennas can mitigate multipath fading effects and suppress interference by employing proven techniques such as maximal ratio or optimum combining. With these techniques, the multipath channel is estimated at the receive antenna array and the best pattern is determined by combining the multiple antennas. Assuming the same transmit and receive frequency, the adaptive array uses the same pattern information on transmit — allowing all learning to be done on receive only. Adaptive array techniques combine the various multipath elements coherently to allow for effective communication, providing array and diversity gain, as well as interference suppression. Using diversity with adaptation to establish communications, the mission can be achieved with higher data rates and fewer communications outages than would typically occur at long distances and low altitudes. With multipath, MIMO techniques can increase the data rate $M$-fold with $M$ transmit/receive antennas. MIMO also decreases probability of detect/intercept, since an eavesdropper with less than $M$ antennas and channel knowledge will see a multitude of noise-like/faded, interfering signals. With adaptation, MIMO versus gain can be traded off as conditions vary, for example by using diagonal loading techniques.

**Ad hoc networking** uses a variety of channels to provide reliable communications. A marine boundary-ducting layer acting as a waveguide has some propagation advantages over isotropic propagation. While losses in the ducting layer are high due to aerosols, the ducting layer can be used as a leaky waveguide (lossy due to the absorptive effects of the sea surface and penetration of the duct by the electromagnetic field). The ducting layer creates multipath with the signal reflecting or being absorbed into the sea surface (the bottom of the duct) and the ill-defined duct transition. This leaky waveguide will create several eigenmodes due to the uneven nature of the top of the ducting layer. Multiple copies of a signal will arrive through the leaky waveguide at different phases, as the different copies have traversed different path lengths. If the phases of these different copies add destructively, the signal level relative to noise declines, making detection more difficult. Additionally, intersymbol interference (ISI) due to the arrival of separate copies will degrade the signal: one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit. Studies of the ducting layer have measured this delay spread in the ducting layer, as well as the distribution of the losses over time.

Since the ducting layer confines the signal to the volume of a disk, the spreading loss for the duct-confined propagation path is linearly proportional to the range, versus at least a range-squared loss for line-of-sight propagation. The loss due to aerosols in the ducting layer is compensated by the lower propagation loss due to the smaller spreading volume of the duct versus the isotropic case. For specific conditions, the use of ducting can provide as much as a 40 dB stronger signal at 1000 km. Although ducting does not provide a highly reliable communication channel, ad hoc networking techniques can sustain reliable high data rate communications even though the ducts between
two ships may be unreliable at times. There is a lower probability of detection/interception when using a variety of communication channels with continuously changing routing and adaptive arrays with MIMO.

Previous analysis and measurements have focused on delay spread as a data rate limiting factor. However, these studies were generally performed before the widespread use of orthogonal frequency division multiplexing (OFDM) and adaptive arrays. With OFDM, delay spread does not limit the maximum data rate. Rather, with coding, delay spread provides diversity against multipath fading. With MIMO-OFDM, multipath and delay spread can be exploited to substantially increase performance, rather than being considered as impairments as in previous studies. The model of the duct is unimportant in operation as the adaptive array processing learns the eigenmodes and uses them. For existing wide bandwidth systems without OFDM, adaptive arrays can be combined with temporal processing techniques, such as space-time adaptive processing (STAP) or tapped delay lines, to improve performance in the presence of multipath and delay spread. Specifically, our techniques can still work with legacy waveforms (e.g., quadrature phase shift keying (QPSK)) but are much more powerful and simpler to implement with MIMO-OFDM.

*Shared array apertures* have an integrated, multi-function, multi-beam top-side aperture construct that provides a solution to the adaptive array requirement of multiple antennas while on naval platforms that already contend with a significant RF antenna farm on the mast. The addition of multifunction, shared antenna arrays on Integrated Topside (InTop) and SubSatComm allows for the insertion of this technology, resulting in affordable capability improvement. This approach can be implemented as an appliqué, with minimal changes to the existing architecture, with a final evolution of approach using commercial off-the-shelf (COTS) Software Defined Radio (SDR) solutions with RF interfaces that allow for multi-branch-diversity combining. Thus, using diversity with adaptation to establish communications in the ducting layer, a mission can operate with fewer communications outages.

**PRELIMINARY PERFORMANCE ANALYSIS**

Although analysis of the performance of these techniques requires further refinement and development of the respective channel models, we have performed preliminary performance analysis. To illustrate this improvement, we simulated using MATLAB a link using 274 Mb/s offset QPSK (OQPSK). This link used a concatenated coding scheme: an inner convolutional coding with an outer [256,238] Reed-Solomon encoding. The results show that the adaptive array can provide communications with a 20 dB improvement for two-branch diversity combining and a 27 dB gain using three-branch diversity combining. In addition, MIMO arrays can provide high capacity communication between surface vessels and suitably equipped airborne vessels. Further low cost approaches to multipath and interference mitigation include designing the current system as an appliqué, with a final evolution of approach using COTS SDR solutions that have RF interfaces that allow for multi-branch-diversity combining. Thus, using diversity with adaptation to establish communications in the ducting layer, a mission can operate with fewer communications outages.

**EXTENSIONS**

We have completed initial research on each individual solution. However, additional work is needed to fill in the required additional pieces and integrate them to demonstrate feasibility. This includes:

1. Analyze the ducting channel to develop models and determine the angular spread (which has not been previously studied), delay spread, and multipath. Angular spread is the range of angles over which the signal is received and determines the antenna spacing for the required diversity with adaptive antennas. This angular spread will be measured in both azimuth and elevation.
Wireless InSite software is one means to simulate the channel information.

2. Measure ducting channels to verify the models of part 1.

3. Use this analysis and measurements with well-known adaptive array techniques, as well as ad hoc networking techniques, to analyze the ability of our approach to provide high data rate, highly reliable beyond line-of-sight communications. The effect of interference and the reduction in probability of detect/intercept also should be analyzed.

4. Evaluate practical implementation techniques for shared aperture/appliqués. The Integrated Topside (InTop) concept can provide a basis to develop and demonstrate an integrated, multi-function, multi-beam top-side aperture construct that meets our goals with shared aperture apertures.

5. This technology can be demonstrated using developed channel models with computer simulation of the techniques verified with measured channel data.

Our technical approach uses a combination of well-known and tested techniques, including adaptive arrays, MIMO, and ad hoc networking, in a novel way that has not been previously considered for well-known propagation media, such as ducting channels. These techniques use multipath and fading, which were previously considered impairments, to enhance communications. Additional measurements are needed to determine the channel parameters relevant for these techniques. There is high potential payoff of such high data rate, highly reliable, beyond line-of-sight communications to both operational mission safety and success.

Further low cost approaches to multipath and interference mitigation include designing the current system as an appliqué, with a final evolution of approach using COTS Software Defined Radio (SDR) solutions that have RF interfaces that allow for multi-branch-diversity combining. Thus, using diversity with adaptation to establish communications in the ducting layer, a mission can operate with fewer communications outages.

CONCLUSIONS

We have proposed the use of the ducting layer, with adaptive antennas, MIMO, ad hoc networking, appliqués, and shared apertures, to improve naval communications systems to beyond line-of-sight at microwave frequencies. By using the ducting layer as a leaky waveguide and the adaptive array to resolve and coherently combine multipath in this layer, we are exploiting natural phenomena that were previously considered impairments to enhance performance using sophisticated signal processing. Our preliminary results show significant gain can be achieved, but further research as outlined in this paper is required to fully quantify the gains and tradeoff.

REFERENCES


**Michael Luddy** has 27 years experience in Signal Processing, communications, wireless systems, protocols and network system design. Since joining Lockheed Martin in 2005, he adds six years in design of radar systems, where he currently leads the Aegis-4G coexistence systems design team. In addition to his duties on Aegis, he has extensive research level investigation and discovery in MIMO radar, linearization, and interference cancellation. Additionally, he developed and leads the Top Gun training program, an in-house program that delivers technology training across MS2. He has 15 granted patents in communications and signal processing, and two publications.

Mr. Luddy received his B.S.E.E., Computer Systems at Newark College of Engineering (NJIT) in 1984; his MSEE, concentrating in communications and DSP from Brooklyn Poly (Polytechnic University) in 2002; he has completed various graduate courses at Lehigh University, and Villanova University and completed several continuing education courses.

**Dr. Jack H. Winters** received his Ph.D. in Electrical Engineering from The Ohio State University in 1981. He was with AT&T Bell Laboratories for more than 20 years where his last position was Division Manager of the Wireless Systems Research Division. At AT&T he did research on wireless and optical systems, including pioneering research on MIMO and smart antennas for wireless systems, and equalization for optical systems. From 2002 to 2009, he was a consultant on wireless and optical systems to various high technology companies. He is currently a senior scientist for research into various programs at Lockheed Martin MS2. He is a Fellow of the IEEE, Area Editor for Transmission Systems for the IEEE Transactions on Communications, a former IEEE Distinguished Lecturer, and a 2001 New Jersey Inventor of the Year. He has over 50 issued patents and 60 journal publications.

**Alex Lackpour** has developed novel wireless system technologies for commercial and government programs for more than a decade. Since joining Lockheed Martin Advanced Technology Laboratories in 2004, he has been a core technical member of research teams that developed the following technologies: cognitive radio jammers, 3D passive radio geolocation systems, novel chaotic modulations implemented on software defined radios, noncoherent cooperative MIMO communication techniques, and high fidelity electromagnetic simulations of ground penetrating radar systems. He is currently developing novel reconfigurable antenna technologies that enhance C4ISR RF system performance. Prior to joining Lockheed Martin, he played a key technical role in developing a MAC-layer WLAN intrusion detection system and a high-rate wireless gateway based on an optimized WLAN protocol.