

Maritime Channel Modeling and Simulation for Efficient Wideband Communications between Autonomous Unmanned Surface Vehicles

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Abstract—In this work we present an analytical channel model for the optimization of wideband communication systems with specific application to autonomous unmanned vehicles (UV) operating in maritime environments. In particular, we focus on the impact of maritime atmospheric conditions and phenomenon on the transmission of radio frequency signals. The Advanced Propagation Model (APM), developed at the Space and Naval Warfare Systems Center San Diego, is used to characterize the transmission channel in terms of evaporation duct induced signal propagation loss. APM uses a hybrid ray-optic and parabolic equations model which allows for the computation of electromagnetic (EM) wave propagation over various sea and/or terrain paths. The signals are then normalized to an APM computed communications threshold communications value, indicating the ability for a UV to communicate or not communicate.

Keywords— *fading channel; maritime communication; atmospheric propagation; autonomous unmanned vehicles*

I. INTRODUCTION

The objective of this work is to present an analytical channel model for the optimization of wideband communications systems used in maritime USV-to-USV (Unmanned Surface Vehicles), and ship-to-USV communications. The U.S. Navy concept-of-operations (CONOPS) for USVs includes having multiple USVs as sensor platforms controlled from a manned platform (e.g., a Littoral Combat Ship (LCS)) and providing payload sensor data back. The control platform(s) and USVs will ultimately share one or more communications resources for the ship-to-USV communications. The communications resources will include line-of-sight (LOS) systems and (potentially) satellite links for beyond-line-of-sight (BLOS).

The performance of the communications system is impacted by many factors. A key factor is the effect of the state of the transmission channel (or channels) between nodes. The channel is a function of both the mean propagation loss and statistics of the variation about the mean, also known as fading. The propagation loss and fading characteristics are a function of frequency, the atmospheric refractivity structure, that structure's time dependence, the earth's surface

characteristics, as well as node positions and their time dependence.

The mechanisms that govern the propagation of radio wave signals in maritime environments are complex and a factor of multiple atmospheric variables including temperature, moisture, and pressure. As the EM waves propagate through the atmosphere they undergo refraction and—particularly at C-band and higher, rain attenuation and gaseous absorption. These effects alter the orientation of the EM wave fronts and causes convergence or divergence of Radio Frequency (RF) energy.

In this work we take these factors and mechanisms in consideration for assessing communication links between the unmanned platforms, focusing primarily on the S and C band center frequency range of a ~16 MHz bandwidth (BW) wideband radio system. Under the maritime conditions considered here, low-altitude propagation on over-water paths between surface platforms can be characterized by a “standard atmosphere”, but is usually impacted to some degree by the evaporation ducts. Evaporation ducts are a ubiquitous feature of the marine environment. They are the result of the impact on the vertical refractivity structure arising from the decrease in humidity from saturation at the ocean surface to a nominal value (e.g., 70%) in the mixed layer region of the marine atmospheric boundary layer (MABL). The climatology for the evaporation duct is available in the Ducting Climatology Survey (DCS). The evaporation duct height changes on a scale of tens-of-minutes to hours in coastal regions and on a scale of hours in the open ocean.

II. MODELING AND SIMULATION APPROACH

Results are generated using a framework we developed called ACF-UV (Adaptive Communications Framework for Unmanned Vehicles). ACF-UV is also used in the analysis of intermittent communications, which includes models to predict the state of transmission channels in maritime environments, as well as a simulation environment that is used as an operations view of the signal links between heterogeneous teams of unmanned vehicles (UxVs). The central propagation loss module implemented by ACF-UV is

the Advanced Propagation Model (APM) [1]. ACF-UV utilizes APM to calculate maritime signal propagation loss using atmospheric and environmental conditions (temperature, humidity, pressure, etc) and phenomena (evaporation ducts) to predict signal transmission channel quality. APM uses a hybrid ray-optic and parabolic equations model to compute electromagnetic (EM) propagation over various sea and/or terrain paths, and is the only EM propagation (applicable between 2 MHz to 57 GHz) model accredited for use in Navy systems by the Chief of Naval Operations [2]. A commercial off the shelf (COTS) lightweight 48 MB/s multi-band network radio [3] configured for maritime communications was used as the radio model in this work. The methodology for the experimental work presented is as follows:

- Compute loss versus range based on radio, environmental, and platform inputs using APM.
 - Range partition is determined by model physics
- For each range partition, loss is classified as a function of above or below threshold values.
 - Transition probabilities for link state changes are computed
- Assume azimuth-independent propagation.

III. ADVANCED PROPAGATION MODEL

The Advanced Propagation Model (APM) is a hybrid model built from the combination of the Radio Physical Optics (RPO) model, and the Terrain Parabolic Equation Model (TPEM). RPO is an over-water model used for calculating propagation loss coverage at all heights and ranges, while TPEM is an integrated over-water and land model used for calculating propagation loss coverage at only low angles and heights. The result of merging the RPO and the TPEM is an EM propagation model that can compute propagation effects given environmental inputs/mechanisms such as; range-dependent refractivity environments consisting of an unlimited number of height-varying refractive profiles, variable terrain, range-varying dielectric ground constants for finite conductivity and vertical polarization calculations, troposcatter, and gaseous absorption [3].

A. Multipath Propagation

Propagating RF signals experience phase interference from signals reflected off the sea surface, ships, land, etc., as well as from signals refracted down from the atmosphere. These reflections and refractions lead to constructive or destructive interference at the receiving antenna. This phenomenon is known as multipath propagation induced fading [8], which results in zones of communication loss between transmitters and receivers (skip-zones). Communication links under maritime conditions can, in basic cases, be modeled as a two-way propagation channel with a direct line-of-sight path and a reflected path, effectively constituting a multi-path model. In this case, APM can be used to perform calculations to compute the field resulting from coherent interference of both the direct and sea-reflected rays. The computation is based on the path length difference between the two rays, and accounts for the

appropriate magnitude and phase of the reflection coefficient for the reflected ray.

B. Evaporation Ducts

Signal propagation in the troposphere, the lowest layer of the earth's atmosphere, is affected by many parameters of which the index of refraction n is the most influential [5]. In maritime environments, ocean water evaporation results in the occurrence of atmospheric layers. The vertical gradient of refraction of these atmospheric layers varies sharply, and can significantly affect the propagation of electromagnetic waves. These atmospheric layers are known as Evaporation Ducts. The variations in the index of refraction can result in a waveguide-like conduction of electromagnetic waves, which not only has the potential to increase the range of transmitted signals, but also generates signal skip-zones or blind spots where a signal cannot be received. Evaporation ducts function as porous waveguides which trap radiated energy, and are able to propagate EM waves over long distances, even surpassing the normal horizon range.

Evaporation ducts are characterized by their heights h_{ed} and modified refractivity profiles $M(z)$. The modified index of refraction takes into account the curvature of the earth and the index of refraction n , and is defined as [6, 5]

$$M(z) = \left(n - 1 + \frac{z}{a}\right) \times 10^6 \quad (1)$$

Where z is the altitude of the measurement point above the sea surface of the earth, and a is the earth's radius. APM uses meteorological, environmental and Digital Terrain Elevation Data (DTED) inputs to compute over-water propagation loss.

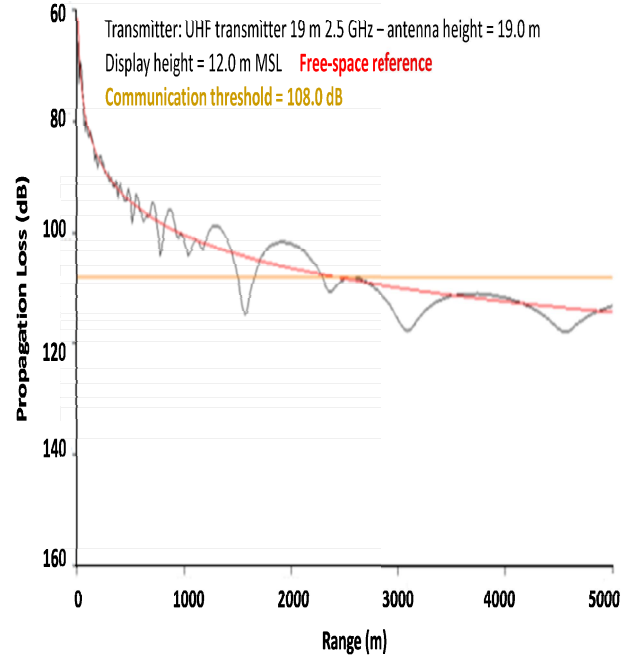


Fig. 1. Communications threshold propagation loss vs. Range for a fixed radio transmitter and receiver height

C. Propagation Loss

Propagation loss can be defined as the amount of signal lost experienced by an EM wave, as a function of distance, during transmission between transmitter and receiver antenna nodes. The propagation factor F is the fundamental quantity in the radio wave propagation model, and is defined as the ratio of the electric field E at a point, to the ratio of the electric field strength E_0 which occurs at a point under free space conditions [1]; $F = |E/E_0|$. Propagation loss in decibels (db) as a function of F is given by:

$$P_{loss} = 20 \log \left(\frac{4 \pi r}{\lambda} \right) - 20 \log(F) \quad (1)$$

Where $20 \log(4\pi r/\lambda)$ is the Free-space-loss parameter, r = range, and λ = wavelength. APM is capable of computing threshold propagation loss which is the maximum attenuation a signal can absorb without dropping the communications link. An example is shown in Fig. 2, which shows propagation loss of a signal with a threshold value, computed as a function of range or distance between the transmitter and receiver.

IV. FADING CHANNEL MODEL

The RF propagation channel is modeled as a slow time varying fading channel with additive white Gaussian noise (AWGN). The primary property of the fading channel is that it is a correlated and time varying random process. Specifically, the communications channel is dynamic and the fading channel gain fluctuation is a random process that varies with time in a correlated way [9]. The signal fluctuation is due to multi-path effects caused by reflection and the scattering of the radio waves as they propagate through the environment. The multi-path induced fluctuation of the transmitted signal results in a received signal envelop that can be modeled using a Nakagami- m distribution. A special instance of the Nakagami- m multi-path fading channel is the Rayleigh fading channel, which is considered in this work. Combined with AWGN, the received SNR is proportional to the square of the signal envelop and is distributed exponentially.

A standard performance criterion for evaluating communication systems operating over fading channels is outage probability (P_{out}). In this work P_{out} is defined as the probability that the instantaneous SNR falls below a specified communications threshold value [12]. Given that the probability density function (pdf) is:

$$p_{pdf}(x) = \frac{1}{\Omega} \exp \left(-\frac{x}{\Omega} \right) \quad (2)$$

Where x is the envelope of the signal, Ω the average SNR and can be defined as $\Omega = \sigma^2(E_s / (N_0/2)) = 2\sigma^2(E_s/N_0)$, where σ^2 is the fading power gain, E_s is the energy per transmitted symbol, and $(N_0/2)$ is the variance of the AWGN.

P_{out} can be thus the cumulative distribution function (cdf) of x evaluated at Ω and is given by:

$$p_{out}(x) = 1 - \exp \left(-\frac{x}{\Omega} \right) \quad (3)$$

The cdf, expressed in eqn. 3, by definition expresses the percentage of bit packets contained within the signal envelope x , that have a reception power less than Ω .

Threshold communications Ω_T is computed as [2]

$$\Omega_T = P_T + G_T + G_R + L_{rec_sen} - L_{sys} - L_{cp} \quad (4)$$

Where P_T is the transmitted power (in dBW), G_T is the transmitter antenna gain (in dBi), G_R is the receiver antenna gain (in dBi), L_{rec_sen} is the receiver sensitivity (in dB), L_{sys} is assumed system losses (in dB), and L_{cp} is cross polarization loss (in dB).

The SNR parameter x (in dB) is computed as follows:

$$SNR = P_R - P_N \quad (5)$$

Where P_R is the received power (in dBW), and P_N is the AWGN power (in dBW). The received power P_R can be decomposed into the following contributions and losses:

$$P_R = P_T + G_T + G_R - L_{APM} - L_{sys} - L_{cp} \quad (6)$$

Where LAPM is the propagation loss calculated by APM

A. Nakagami- m Fading Channel Model

In the Nakagami model the m parameter describes the effect of the fading channel, which can be used to capture a wide range of fluctuation intensities. This model is particularly valuable because the m parameter of the Nakagami model can also be used to approximate other fading distributions such as Rician and Lognormal distributions [13]. The Nakagami model can hence be used in this work to model certain environmental conditions and their impact on the RF signal power [14]. It also offers greater flexibility for fitting empirical data, making it an ideal candidate for use while modeling intermittent communications under maritime conditions. The Nakagami- m fading channel model is given by:

$$P_{Nakagami}(x(d); m(d)) = \left(\frac{2m^m x^{2m-1}}{\Gamma(m) \Omega^m} \right) \exp \left(-\frac{mx^2}{\Omega} \right), \quad x \geq 0 \quad (7)$$

Values of $m < 1$ correspond to deeper fading characteristics more severe than Rayleigh fading and values of $m > 1$ correspond to shallower fading distributions trending towards free-space behaviors. For the purposes of this paper only the special case Rayleigh fading ($m = 1$) is considered.

V. SIMULATION RESULTS AND ANALYSES

In this section the effects of evaporation ducts on signal frequency diversity is simulated and analyzed. The impact of evaporation ducts on wideband and narrowband frequency selection is analyzed as a function of the communications link platforms.

A. Ship-to-USV and USV-to-USV Link Analyses

We present another approach for specifically analyzing the communication link states of the vehicles. These results represent a first order proof of concept study.

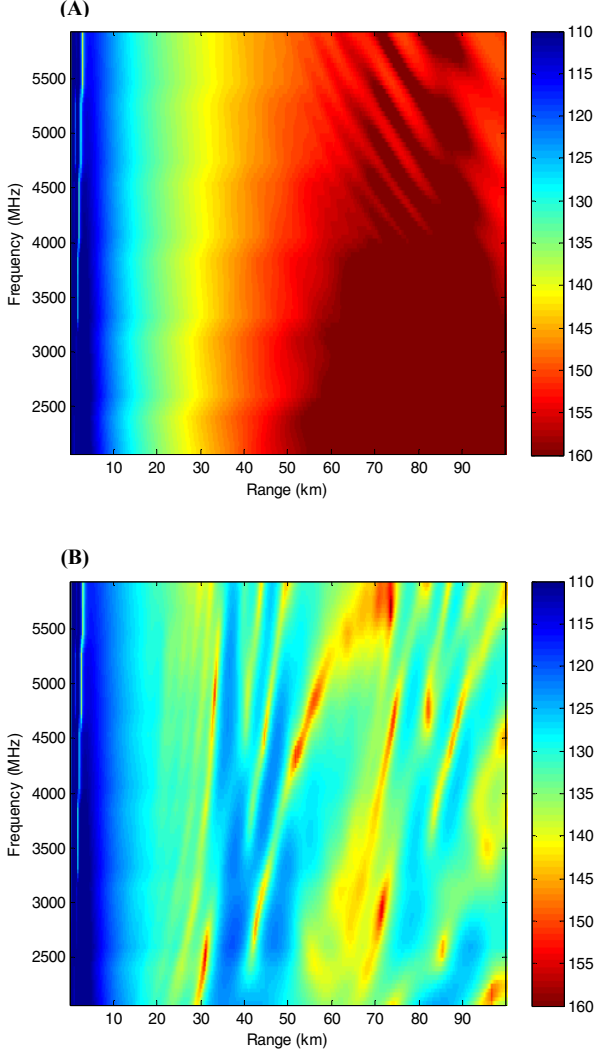


Fig. 2. Propagation loss versus range (in km) and frequency (MHz) for a Ship (transmitter height = 25m) to USV (receiver height = 3m), and duct heights of A.) 14 m and B) 24 m respectively.

Fig.2 shows inverse propagation loss (L) for 14m (worldwide mean) and 24m evaporation duct heights for a 25m transmitter antenna height, and a 3m receiver antenna, this is consistent with Ship-to-USV link for a superset of the range of center frequencies for which the COTS radio can be tuned. The impact of the evaporation ducts on signal

attenuation and diversity is evident in Fig.2. The lower the elevation duct, the higher the signal attenuation. It can also be inferred that the antenna height relative to the duct elevation also affect transmission performance. Results moreover indicate that better signal transmission occur for USV-to-USV communications (Fig.3), most likely due to the height of their transmitting antenna relative to the evaporation duct elevation. The 14m and 24m duct elevations allow the transmitting signals of the USVs 3m antennas to be better trapped within the confines of the waveguide-like ducts.

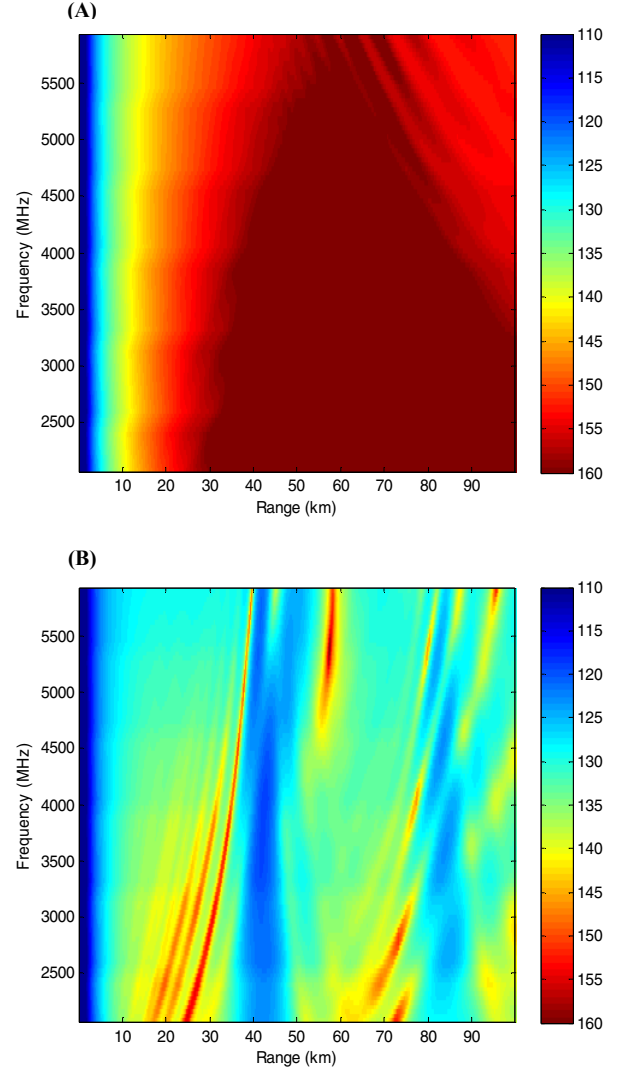


Fig. 3. Propagation loss versus range (in km) and frequency (MHz) for a USV-to-USV (transmitter and receiver height = 3m), and duct heights of A.) 14 m and B) 24 m respectively.

Extending these analyses further, the impact of frequency diversity on propagation loss can also be investigated. From the plot of Figs.2 & 3, it can be seen that over wide frequencies propagation loss differs greatly, even at the same range. However, when looking at a narrowband of 16 MHz, as simulated in Figs.4 & 5, it can be observed that the 16 MHz bandwidth of the cots radio will offer a substantial advantage over wideband transmissions.

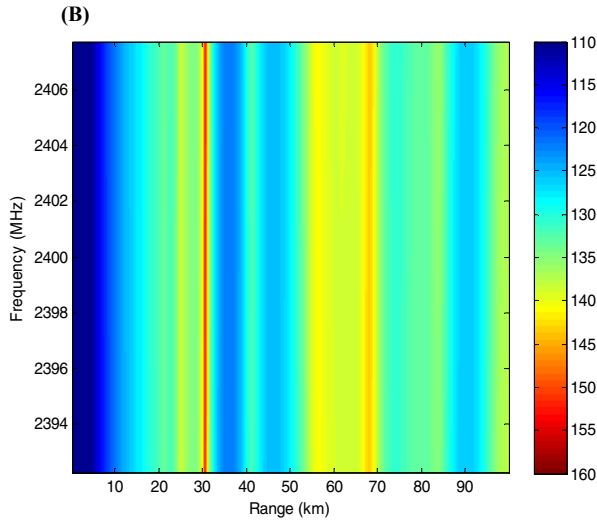
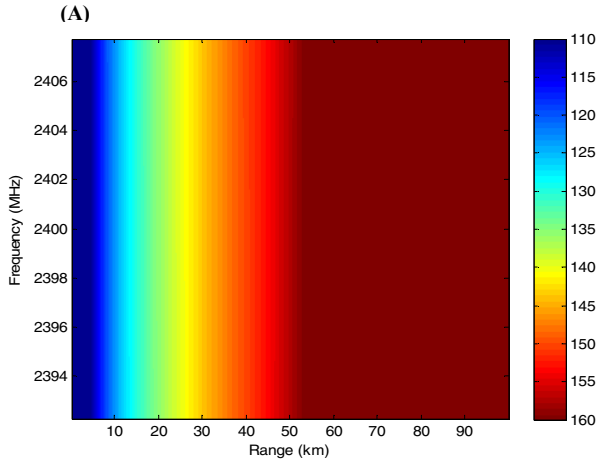


Fig. 4. 16MHz bandwidth Propagation loss versus range (km) and frequency (MHz) for a Ship (transmitter height = 25m) to USV (receiver height = 3m), and duct heights of A.) 14 m and B) 24 m respectively.

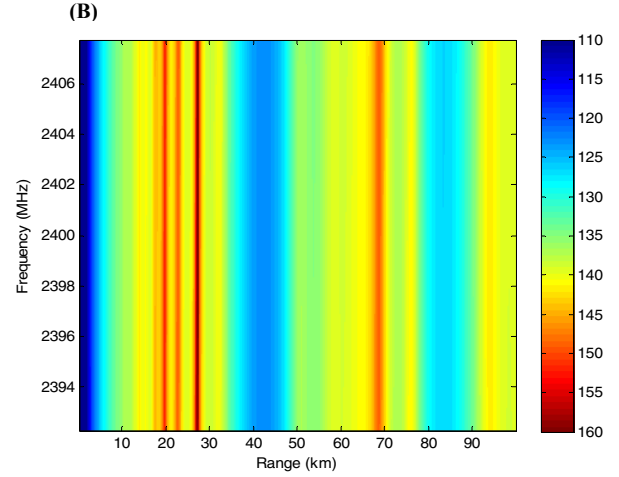
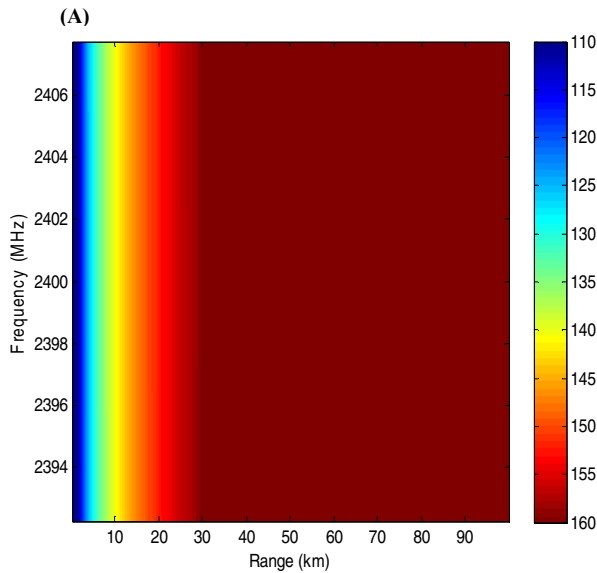
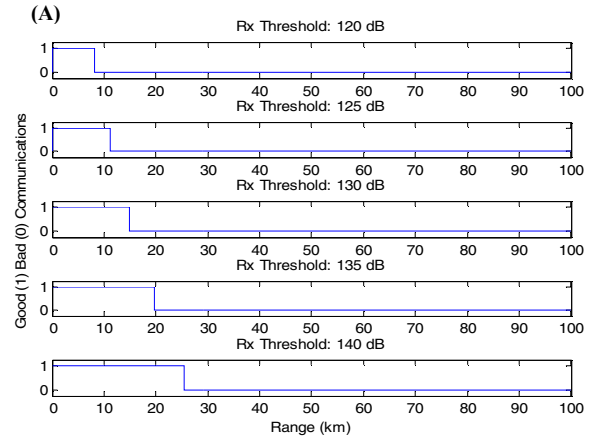


Fig. 5. 16MHz bandwidth Propagation loss versus range (km) and frequency (MHz) for a USV -to USV (transmitter and receiver height = 3m), and duct heights of A.) 14 m and B) 24 m respectively

B. Communications Awareness Approach

Fig.6 shows threshold crossings for Ship-to-USV link. The specifications of the COTS radio under test indicate that data rates of 6 MB/s to 48 MB/s should occur over a range of ~ 25 dB. The plots in Fig. 6 correspond to threshold crossings for propagation loss values from 120 dB to 140 dB. Generally, the lower propagation loss values correspond to higher data rates. Ranges where the propagation loss goes from above threshold (+1) to below threshold (0), would correspond to a drop in data rate, or loss of communications. Due to the depth of the nulls, it is evident that when either opening or closing range between the two vessels, the data links can transition through several thresholds. Threshold crossings for the USV-to-USV link are shown in Fig.7B. Comparisons of simulation results presented in Figs.6B & 7B show that null crossings occur more frequently for the USV-to-USV link than they do for the Ship-to-USV links. This is due to antenna heights of the USVs being so close to the water that they become more susceptible to the attenuation inducing effects of evaporations ducts, sea roughness, ocean spray etc



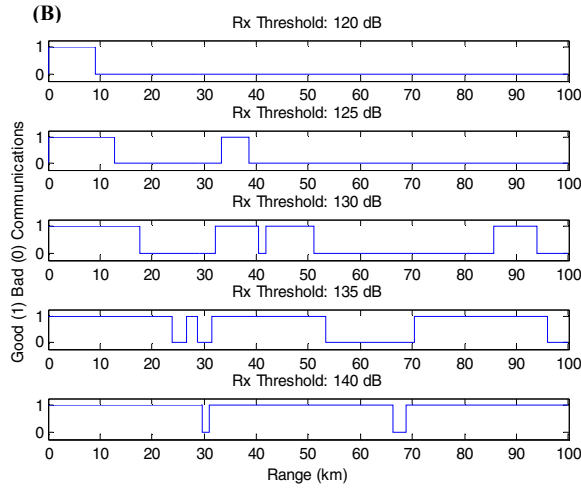


Fig. 6. Ship-to-USV range of communications with various receiver threshold values A.) 14 m evaporation duct and B.) 24 m evaporation duct

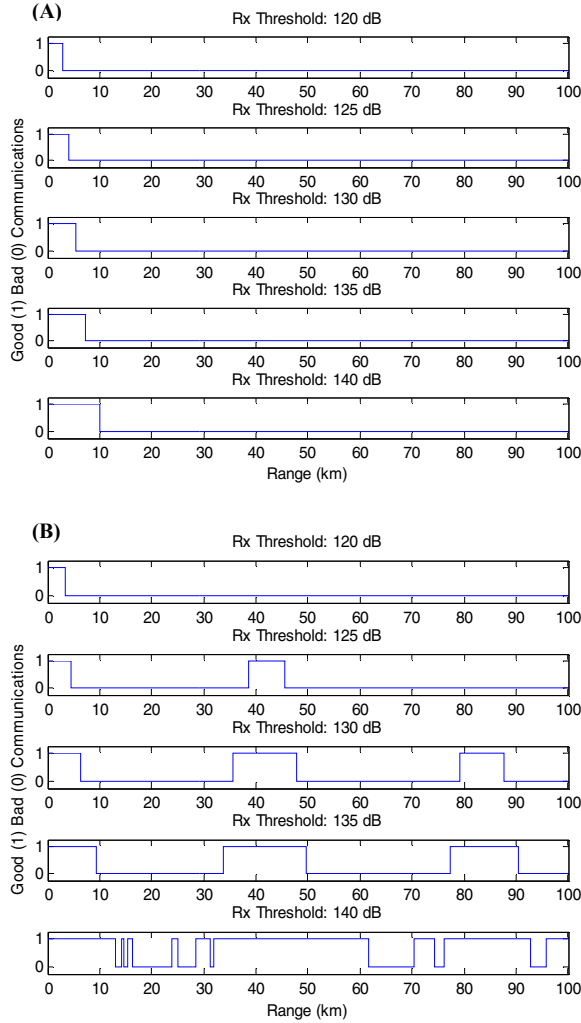


Fig. 7. USV-to-USV range of communications with various receiver threshold values A.) 14 m evaporation duct and B.) 24 m evaporation duct

Since communications channels do not have absolute thresholds, we expand our model by adding a Nakagami fading channel model. This gives us a probabilistic model that can be used to better simulate a real communications channel. The following simulations use the Nakagami-m model, with $m = 1$ (Rayleigh fading), and calculate the probability that the channel is able to support communications. The following figures have set $L_{rec_sen} = 135$ dB and are using the 14 and 24 m evaporation ducts.

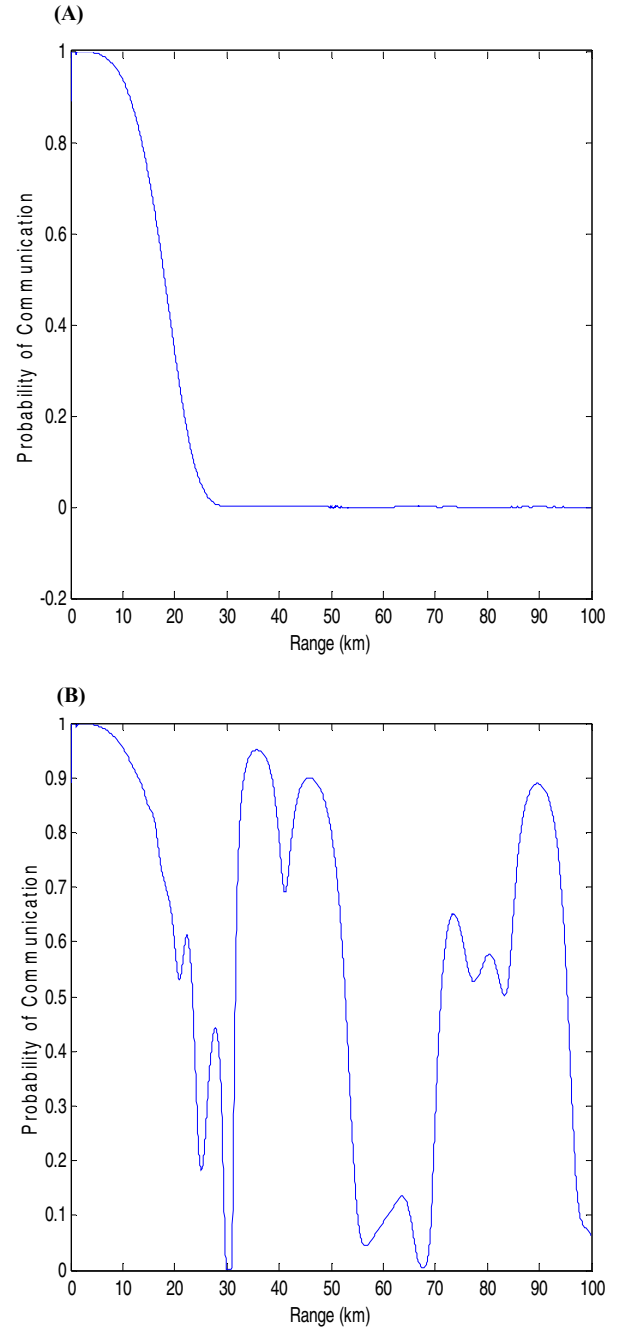


Fig. 8. Probability of communications using a Rayleigh fading channel of Ship-to-USV A.) 14 m evaporation duct and B.) 24 m evaporation duct

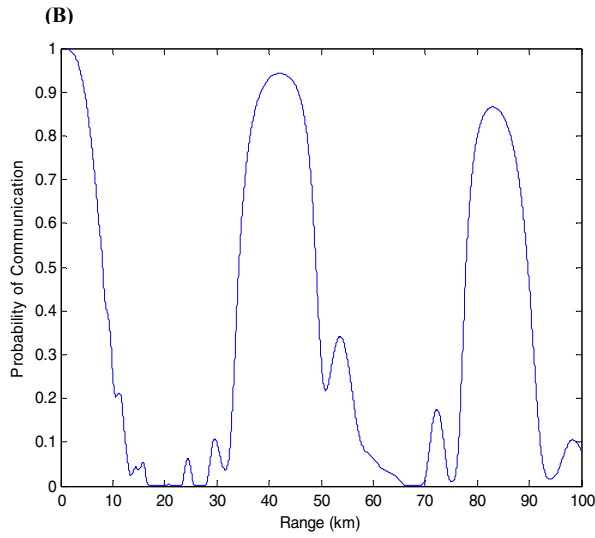
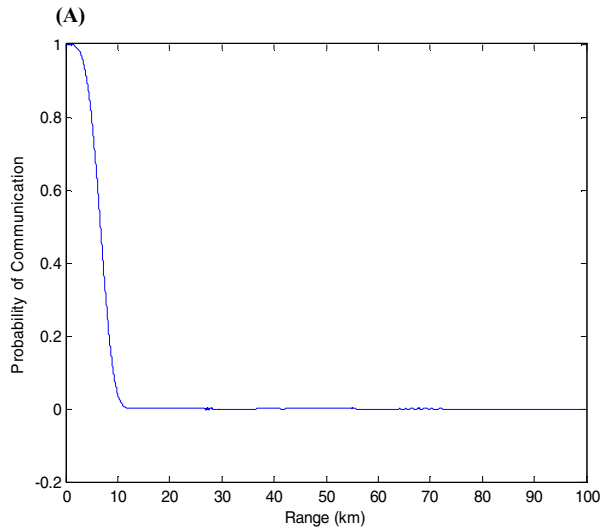


Fig. 9. USV-to-USV probability of communications using a Rayleigh fading channel A.) 14 m evaporation duct and B.) 24 m evaporation duct.

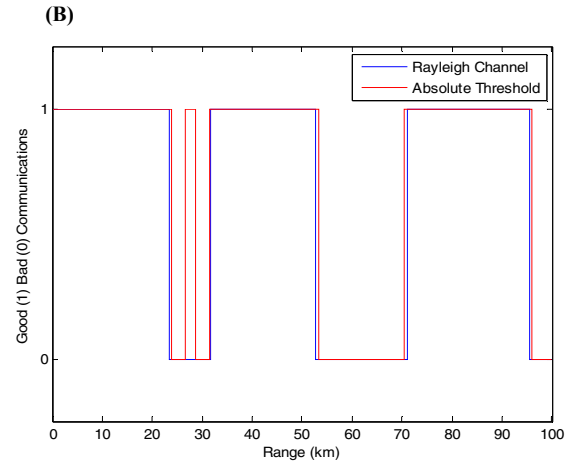
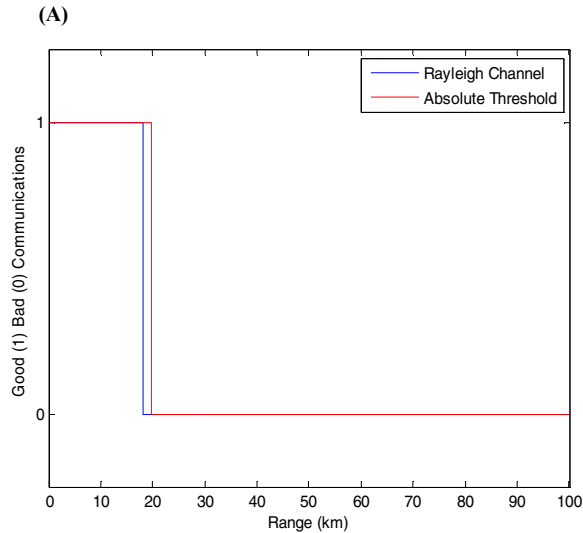


Fig. 10. Ship-to-USV range of communications using a Rayleigh fading (50%) channel compared to the absolute threshold method A.) 14 m evaporation duct and B.) 24 m evaporation duct.

By applying a secondary threshold of 50%, we can closely model the original absolute threshold scheme, as can be seen in Fig.10. However, one would typically set a more stringent probability of communications.

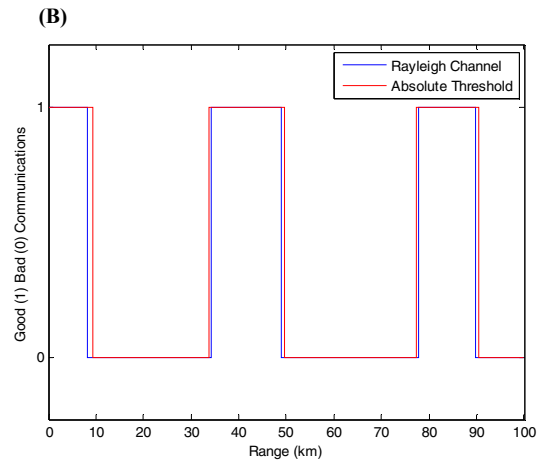
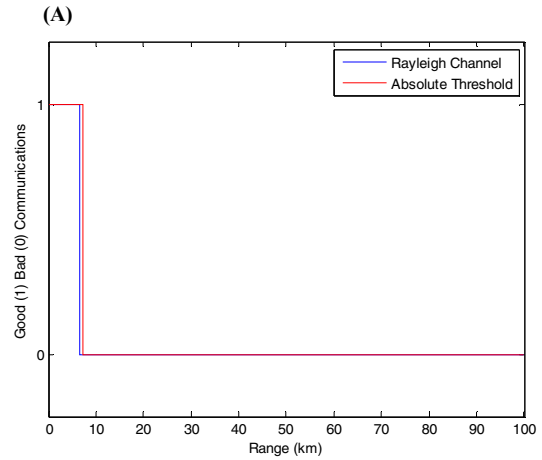


Fig. 11. USV-to-USV range of communications using a Rayleigh fading (50%) channel compared to the absolute threshold method A.) 14 m evaporation duct and B.) 24 m evaporation duct

The fading channel model was included to improve the robustness our model and to more importantly improve the accuracy of the channel analyses.

VI. UNMANNED SYSTEMS OPERATIONAL VIEW APPLICATION

In this section we discuss the operational use case for the analytical methodologies presented in the previous section. The driving scenario in this work is the UV Sentry mission scenario, for which a combination of UxVs and LCS work together to provide perimeter protection for a high value asset (e.g. carrier group), mine countermeasures, surface ship tracking, anti-submarine warfare, or other such similar missions. In these types of scenarios, maintaining persistent connectivity with and between the UxVs is critical to the success of the operations. The ability to analyze and predict maritime communications probabilities is important in mission planning as well as USV autonomy. This communications analysis methodology presented constitutes part of the communications module of the ACF-UV framework described in section I. This module will be used by ACF-UV to provide mission planners and operators with the information to make such vital decision as:

1. Placing and relocating UxV and LCS assets to ensure persistent connectivity as they conduct their missions.
2. Discern optimal data transmission frequencies

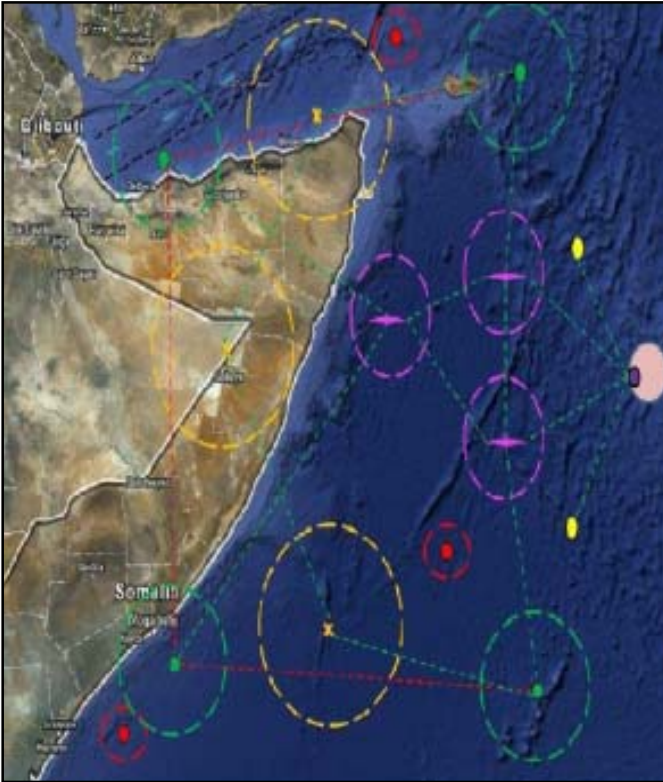


Fig. 12. Sample engagement simulation snapshot with communication overlays

In Eqn. 6, where Ω_T is computed for the data of Fig. 2 to demonstrate how the methodology we describe can be used to determine expected communication null locations and their inducing frequencies. Take the instance of the 14m duct analysis of Fig. 6, The UxV is able to use this data to make the observation to expect to encounter major communications nulls at ~8km away from it point of observation. The autonomy module on the UxV can either use this information to tune its radio configuration or decide to navigate away from the communications null.

The ACF-UV framework is being developed to integrate communications channel analysis with an operational simulation to perform predictive analysis of communications at the mission level. Currently, two UxV Sentry missions are being implemented as scenario drivers in the framework, including a surface ship tracking mission and a mine countermeasures missions. These missions are being simulated using an agent-based framework developed in Matlab. When communications are required within the simulation, the communications channel between the vehicles can be modeled to return a probability of communications. The simulation is visualized within Matlab using a two dimensional map with asset positions overlaid, as shown in Fig.12. The communications channels can also be visualized and represented based on the probability of successful communications. This integration of the communication channel modeling with the engagement simulation can give mission planners important information about how to best place and use their assets, as well as to help develop mitigation plans in the case of communications loss.

CONCLUSION

In this paper, a methodology for analyzing the frequency diversity dependency of transmitted signal as a function of evaporation duct heights is presented and demonstrated. The integrated APM module is used to compute maritime signal propagation loss, and a Nakagami-m model is used to model the fading channel.

Several approaches for evaluating intermittent communications in maritime environments has been presented and demonstrated. Authors show how the Navy validated APM in combination with an effective channel model can be used to predict maritime communications. Using this approach simulation results showing the impact of evaporation ducts wideband frequency diversity, as well as communication links states are presented. These types of analyses have very important applications in mission planning, and are a promising solution which can be used to provide enhanced communication autonomy in unmanned maritime vehicles.

ACKNOWLEDGMENT

The authors acknowledge support from both the Office of Naval Research sponsored Naval Innovative Science and Engineering (NISE), and the Naval Engineering Education Center (NEEC) programs. The authors would also like to thank Amalia Barrios of SSC Pacific for helpful discussions and suggestions.

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