Intermittent Communications Modeling and Simulation for Autonomous Unmanned Maritime Vehicles using an integrated APM and FSMC Framework

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ABSTRACT

In this work a framework is presented for addressing the issue of intermittent communications faced by autonomous unmanned maritime vehicles operating at sea. In particular, this work considers the subject of predictive atmospheric signal transmission over multi-path fading channels in maritime environments. A Finite State Markov Channel is used to represent a Nakagami-m modeled physical fading radio channel. The range of the received signal-to-noise ratio is partitioned into a finite number of intervals which represent application-specific communications states. The Advanced Propagation Model (APM), developed at the Space and Naval Warfare Systems Center San Diego, provides a characterization of 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. These models which have been integrated in the proposed framework provide a strategic and mission planning aid for the operation of maritime unmanned vehicles at sea.

Keywords: Nakagami; FSMC; Rayleigh fading

1. INTRODUCTION

The purpose of this paper is to introduce an Adaptive Communications Framework for Unmanned Vehicles (ACF-UV). This work differs significantly in its purpose from the numerous communications frameworks which exist for handling unmanned communications. The established frameworks such as ROS, MOOS-IvP, ACS, etc., focus on the structure and interoperability of the message being passed, while ACF-UV focuses on providing a predictive estimation of the future state of an intermittent communication link between two or more autonomous platforms as well as their respective command and control (C2) stations. Stated simply, previous work has focused on the structure of the message, while this work focuses on the physics of intermittent transmission. The purpose of such a framework is to allow system designers, performance engineers and System of Systems (SoS) designers the ability to make improved design choices that lead to better connectivity between unmanned vehicles (UxVs). A second purpose of ACF-UV is to allow mission planners and onboard operators to make intelligent choices in the path planning and operational placement of assets to ensure network connectivity can be maintained. ACF-UV accomplishes the goal of providing a predictive model of intermittent communication through the use of a modular framework that integrates a series of detailed models used to study the potentially detrimental effects of the physical and electromagnetic environment. This paper will describe the overall framework as well as a number of the modular components necessary for accurately creating a SoS predictive model of maritime communications. The effort this paper describes is ongoing, and the description of the components has been limited to the effects of the physical maritime environment on electromagnetic communication links.

ACF-UV, using an Advanced Propagation Model (APM) [1], calculates 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 EM propagation over various sea and/or terrain paths, and is the only EM propagation model (applicable between 2 MHz to

57 GHz) accredited for use in Navy systems by the Chief of Naval Operations [2]. It has also performed well in predicting field strength from the VHF to Q-band for both over-water and over-terrain propagation in the presence of range-dependent refractive conditions for surface-to-surface, surface-to-air, and air-to-air geometries [3]. To predict the stability of the transmitted signal, a Finite State Markov Channel (FSMC) scheme is used to model the APM-characterized physical fading channel. The FSMC is based on the Gilbert-Elliot channel model [4, 5] and has been effective in the modeling of fading channels [6]. The FSMC is a probabilistic state transition model and is implemented by partitioning the range of the received signal-to-noise ratio (SNR) into a finite number of intervals and then representing each state as an application-defined communications channel quality [7]. The APM and FSMC models are integrated within ACF-UV to create communications awareness picture; analogous to a communication aide for each maritime UxV. The APM is used to generate UxV-to-UxV signal transmission profiles, and the FSMC to predict the transmission link quality and stability.

Together, the communications model and operational simulation environment in the framework provide a unique predictive capability for the state of transmission channels and the anticipated impact on the performance of UxVs.

2.   COMMUNICATIONS MODEL

2.1 Atmospheric Propagation Model

Central to the ACF-UV is a predicative estimation of the quality of communication. This estimation is driven by a set of physics based models of EM propagation. The mechanisms that govern the propagation of radio wave signals in maritime environments are complex and dependent on multiple atmospheric variables including temperature, moisture, and pressure. As the EM waves propagate through the atmosphere they undergo degradation or attenuation due to the effects of gaseous and particulate absorption of energy, or molecular refraction. These effects alter the orientation of the EM wave fronts and causes convergence or divergence of Radio Frequency (RF) energy.

To model the impact of these effects on the propagating RF signal, the APM is utilized. APM is a hybrid model built by integrating the Radio Physical Optics (RPO) model, and the Terrain Parabolic Equation Model (TPEM). RPO is an over-water model capable of computing propagation loss coverage at all heights and ranges. TPEM is an integrated over-water and land model capable of computing propagation loss coverage at only low angles and heights. APM is thus an EM propagation model that can compute propagation effects from the following environmental inputs/mechanisms: (i) Range-dependent refractivity environments;(ii) Variable terrain consisting with unlimited range-height pairs; (iii) Range-varying dielectric ground constants for finite conductivity and vertical polarization calculations; and (iv) Troposcatter.

2.2 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. This leads to constructive or destructive interference at the receiving antenna. The phenomenon described is known as multipath propagation induced fading [8]. Fading results in zones of communication loss between transmitters and receivers. 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.

Evaporation ducts lead to significant bending of RF signals and 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. Evaporation ducts can also disrupt signal propagation [9] and lead to the occurrence of communications skip zones. At certain separation distances UxVs operating at sea may be faced with a situation where one UxV is able to communicate with another UxV at a farther distance than its nearest neighbor, when its nearest neighbor is operating in a communication skip zone [10]; As illustrated in Fig. 1. [3]
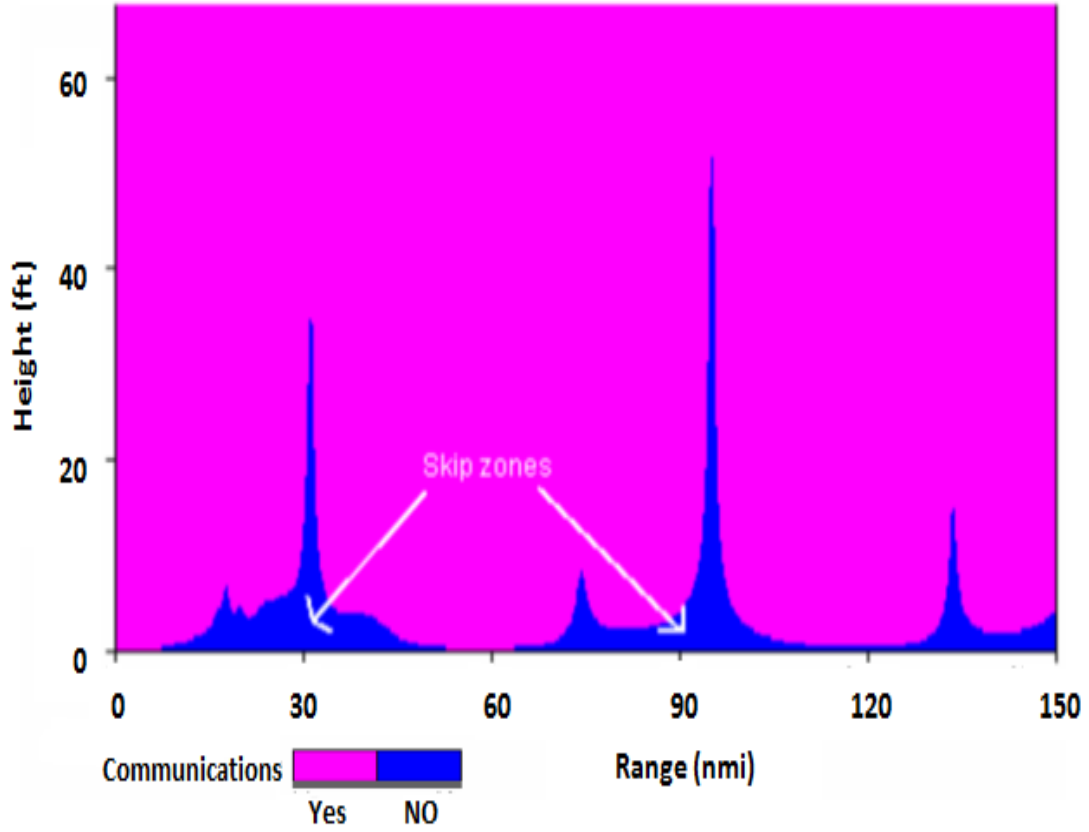
Figure. 1. UHF communication under surface ducting conditions

2.3 Propagation Loss

Propagation loss is the amount of signal lost in an EM wave with respect to distance during transmission between a transmitting and receiving radio antenna. The fundamental quantity in the radio wave propagation model is the propagation factor F, defined as the ratio of the electric field E at a point, to the ratio of the electric field strength E0 which occurs at a point under free space conditions [1]; F = |E/E0|. Propagation loss in decibels (db) as a function of F is given by

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

Where *20log(4πr/λ)* is the Free-space-loss parameter, r = range, and λ = wavelength. APM is capable of computing threshold propagation loss which is the maximum attenuation or power loss a signal can absorb without dropping the communications link, shown in Fig. 2. It is computed as a function of range, or distance between the transmitter and receiver.
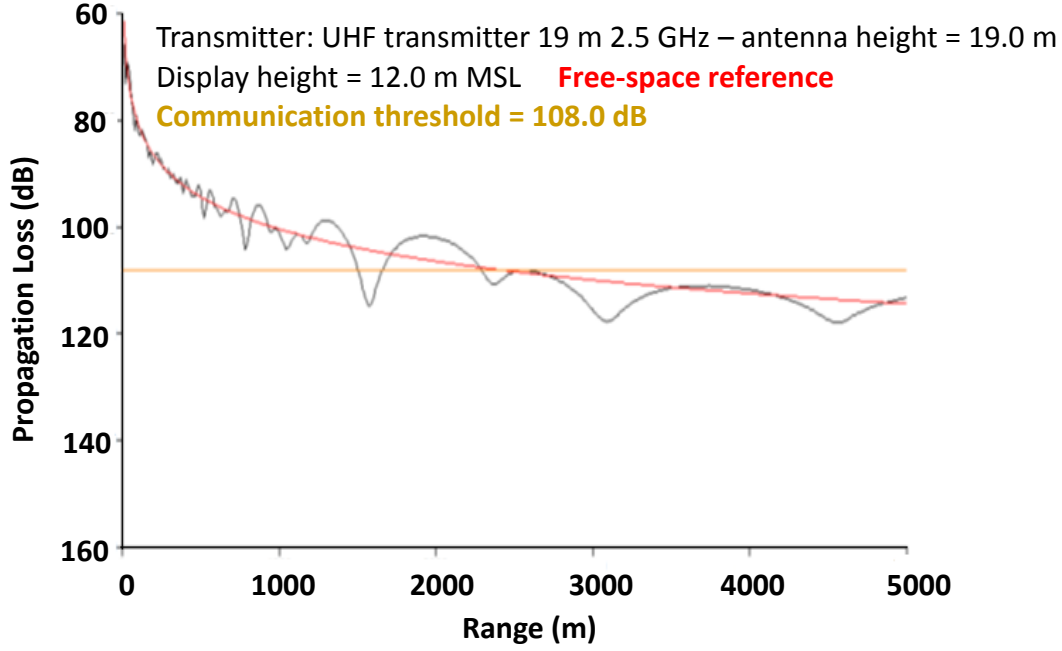
Figure. 2. Communications threshold propagation loss vs. Range for a fixed radio transmitter and receiver height

3. FINITE STATE MARKOV CHANNEL

The propagation loss profile computed by APM represents a snap shot in time used to generate an iterative propagation loss profile. A Finite State Markov Channel (FSMC) scheme is used to model the APM-characterized physical fading channel. Based on the Gilbert-Elliot channel model [4, 5], and demonstrated to be effective in the modeling of fading channels [6], FSMC is a probabilistic state transition model implemented in ACF-UV by partitioning the range of the received signal-to-noise ratio into a finite number of intervals, for which each state is represented as an application-defined communications channel quality [6]. The APM and FSMC models are integrated within ACF-UV to create communications awareness picture; analogous to a communication aide for each maritime UxV. To summarize, APM is used to generate UxV-to-UxV signal transmission profiles, and the FSMC to predict continuous transmission link quality and signal stability as the UxVs traverse their mission paths.

In the FSMC each state represents a defined channel quality. The Gilbert-Elliot channel model represents the special case in which there are two states. Each of these states is represented by a crossover probability which identifies the quality of each channel.

Let $S = \{s_0, s_1, s_2, ..., s_{k-1}\}$ denote a set of K FSMC states, illustrated in Fig. 3(a), which are finite [7]. Let S_t be the state at time index $t \in \{1, 2, 3, ...\}$, which can be defined as envelope power values as shown in Fig. 3. The state of the channel represents the output of the Markov chain. Hence, the channel state transition probability can be defined as a $K \times K$ matrix with elements which represent the probability of transitioning from state s_j to state s_k.

3.1 Fading Channel and State Definition

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 [7]. 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 is Rayleigh distributed. This multi-path fading channel is typically called a Rayleigh fading channel. Combined with AWGN, the received SNR is proportional to the square of the

signal envelop and is distributed exponentially. The probability density function (pdf) and cumulative density function (cdf) of the SNR respectively are:

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

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

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; we can also assume that $\Omega = \sigma^2(N_0/2)$ without loss of generality. The cdf, expressed in eqn. 3, by definition expresses the ratio of bit packets contained within the signal envelope x, that have a reception power less than Ω. The states are defined as threshold SNR values in decibels, expressed as follows:

$$SNR = P_R - P_N \tag{4}$$

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:

$$P_R = P_T + G_T + G_R - L_{APM} - L_{sys} - L_{cp} \tag{5}$$

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_{APM} is the propagation loss calculated by APM (in dB), L_{sys} is assumed system losses (in dB), and L_{cp} is cross polarization loss (in dB). The SNR range can be split into a discrete number of states, equally or unequally spaced depending on the signal and receiver capabilities.

Figure 3 provides a representative picture of the signal envelope and its relationship to the states, and demonstrates how the amplitude of the signal varies within time. Signal strength (dB) is plotted on the ordinate axis and a direct linkage of the amplitudes corresponding to differing states is shown with the vertical axis plotted on the right.
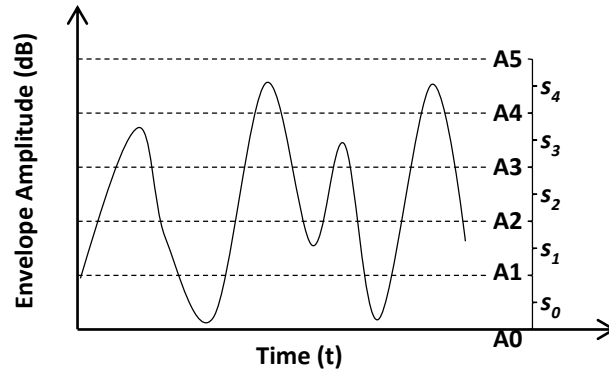

Figure. 3. Example of signal envelope and defined states;

3.2 FSMC Nakagami-m Fading Channel Model

The FSMC model presented in [6] follows a level crossing rate approach and does not address non-adjacent state transitions and non-Rayleigh fading distributions. In order to develop a more robust and practical framework the fading channel is modeled using a Nakagami-m fading distribution. The m parameter of the Nakagami model describes the channel fading effects and can be used to capture a wide range of fluctuation intensities. As a result, the m parameter of the Nakagami

model can also be used to approximate Rician and Lognormal distributions [11]. The Nakagami model is thus able to account for certain environmental conditions and their impact on the RF signal power [12]. It also offers greater flexibility for fitting empirical data making it an ideal candidate for use for modeling intermittent communications under maritime conditions. The Nakagami distribution probability density function is given as a function of reception power (signal amplitude square) with respect to distance *(d)*:

$$P_{Nakagami}(x(d); m(d)) = \left(\frac{2m^m x^{2m-1}}{\Gamma(m)\,\Omega^m} \right) exp\left(-\frac{mx^2}{\Omega} \right), x \geq 0 \tag{6}$$

The Nakagami model is defined by the Ω(d) and m(d). 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.

3.2.1 State Transition Probability

In this section, the procedure for determining the transition probabilities for a Markov model of a Nakagami-*m* fading model is presented based on approached outlined in [11, 12, 13, 14]. The transition probability of the Nakagami-*m* fading channel can be computed using the conditional probability, *p(x/y)* (eqn. 7)*, that the fading channel is in state *x* at time *t+1* given that it was in state *y* at time *t* .

$$P_{x|y}(x|y) = \frac{P(x,y)}{P_y(y)} \tag{7}$$

Consider two samples of the Nakagami-*m* fading envelope $x = X(t_1)$ and $y = Y(t_2)$. The corresponding instantaneous power levels for the fading envelope are $W_x = X^2$ and $W_y = Y^2$. The joint probability density function of the non-negative random variables x and y can be computed using the derivation provided in [11] as:

$$P(x,y) = \frac{4(xy)^m exp\left[-\frac{m}{\Omega}\frac{x^2 + y^2}{1-\rho} \right]}{\Gamma(m)(1-\rho)(\sqrt{\rho})^{m-1}} \times \left(\frac{m}{\Omega} \right)^{m+1} \cdot I_{m-1}\left\{ \frac{2mxy\sqrt{\rho}}{\Omega(1-\rho)} \right\}, x \geq 0 \tag{8}$$

Where ρ is the correlation coefficient given by:

$$\rho = \frac{Cov(x^2, y^2)}{\sqrt{Var(x^2)Var(y^2)}} \tag{9}$$

When the samples *X* and *Y* are taken T_s seconds apart due to the movements of the UxVs, then the correlation coefficient is given by:

$$\rho = J_0^2(2\pi f_d T_s) \tag{10}$$

Where J_0 is the Bessel function of the first kind of zero order, and f_d is the maximum Doppler frequency. Substituting the joint pdf, $P(x, y)$, into eqn. 7 an expression for the conditional probability can be generated as follows

$$P_{x|y}(x|y) = \left[\frac{2\mathbf{\Omega}^{m-1}x^m exp^{-\left(\frac{\rho y^2 + \rho x^2)}{(1-\rho)\mathbf{\Omega}}\right)}}{y^{m-1}\mathbf{\Omega}(1-\rho)(\mathbf{\Omega}^2\rho)^{\left(\frac{m-1}{2}\right)}} \right] \cdot I_{m-1}\left\{ \frac{2xy\sqrt{\rho}}{\mathbf{\Omega}(1-\rho)} \right\} \tag{11}$$

Let us now define two states k and j for which the conditional probability of eqn. 11 is the probability that the received average SNR power x_k is in state k at time t_k, having just been y_j in state j at time t_j. We are now able to compute both adjacent and non-adjacent state transition probabilities by integrating the conditional probability density function:

$$p(k|j) = \frac{\int_{\sqrt{S_j}}^{\sqrt{S_{j+1}}} \int_{\sqrt{S_k}}^{\sqrt{S_{k+1}}} P(x,y)\,dxdy}{\int_{S_j}^{S_{j+1}} P(y)\,dy} \tag{12}$$

Where $S_j = (\alpha_j, \alpha_{j+1}]$ and α represents the boundaries of the state. This then enables us to compute the probability that it is in state k given that it was previously in state j.

3.3 SIMULATION RESULTS

Provided in this section are preliminary results using the FSMC approach outlined in the preceding sections. To simulate the Nakagami-m fading channel, an ACF-UV integrated MATLAB simulator is used. The parameters of the simulator are as follows: Expected avg SNR (Ω) = -129 dB, $f_d T_s$ = 0.05 and partitioned the following way S_0 = (-∞ dB, 133 dB], S_1 = (-133 dB, 131 dB], S_2 = (-129 dB, -127 dB], S_3 = (-127 dB, -125 dB], S_4 = (-125 dB, 0 dB]. Results here were initially validated against results from [6].

As the UxVs traverse their paths they pass through a series of good and bad communications zones. At each distance on their motion path ACF-UV computes the threshold propagation loss parameter of the transmitting signal. Using this threshold parameter, the FSMC model is then used to predict the probability of the data packets contained within the signal envelope x, that have a reception power less than the computed threshold propagation loss value. The results of the simulation are presented in Tables I & II.

TABLE I. AT -129 DECIBEL LOSS, M = 1

States j→k	J = 0	J = 1	J= 2	J = 3	J = 4
K = 0	0.8393	0.3052	0.0596	0.0024	0
K = 1	0.1297	0.3898	0.2280	0.0311	0.0002
K = 2	0.0298	0.2683	0.4663	0.2360	0.0095
K = 3	0.0012	0.0363	0.2342	0.5453	0.1472
K = 4	0	0.0003	0.0119	0.1852	0.8431

TABLE II. AT -129 DECIBEL LOSS, M = 2

States j→k	J = 0	J = 1	J= 2	J = 3	J = 4
K = 0	0.7909	0.2133	0.0148	0	0
K = 1	0.1908	0.5128	0.1919	0.0066	0
K = 2	0.0183	0.2649	0.5961	0.1988	0.0018
K = 3	0	0.009	0.1958	0.6680	0.1667
K = 4	0	0	0.0014	0.1265	0.8315

4. ADAPTIVE COMMUNICATIONS FRAMEWORK FOR UNMANNED VEHICLES ACF-UV

4.1 Framework Development

The purpose of developing the physics based representation of a vehicle to vehicle communications, described above, is to provide a better integrated picture of the global network. ACF-UV is an on-going developmental architecture for studying and analyzing communications networks among UxVs from a SoS perspective. ACF-UV 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 UxVs. With these capabilities, the framework provides a high level common operational picture of expected communications network quality in an operational scenario.
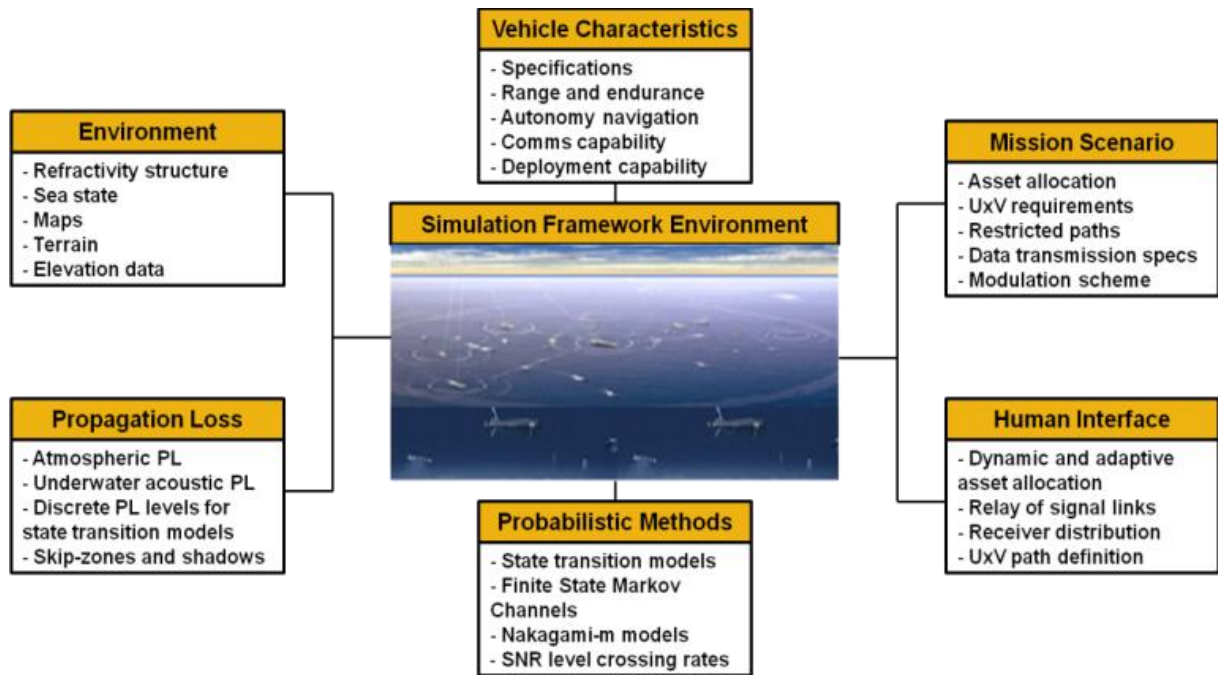

Figure. 4. ACF-UV Flow of Information Schematic

An essential element of the ACF-UV is a data driven visual simulation environment which integrates the outputs of independent modules into a common operational picture that provides a representation of the quality of the network. The value in this data driven modular approach is that it allows for an estimation of connectivity such that the elements can be adapted to fit specific purposes. For an example use case, ACF-UV can be used as an analytical component within the autonomy package of the robotic platform, which allows it to maintain its own connectivity to the C2 station while plotting its own route through an environment. In this situation, the modules that provide a predicative estimation of the communication link based on the robotic system and C2 station, as a function of atmospheric conditions and emitter characteristics are left unchanged, while the modules within the ACF-UV framework concerning vehicle location and behavior are substituted for the AI control software. In this way, the ACF-UV provides a predictive estimation of the connectivity for that vehicle as it moves through the environment that can be used by the AI to optimize the route taken. An alternative set of substitutions can allow for the framework to be applied to a different use case where a system designer executes the described analysis in setting requirements for a robotic system's emitter. If an operational perspective is desired, the ACF-UV can be used to refine the operational layout of a system of robotic systems which maintains connectivity.

From a developmental perspective, the modular approach provides two benefits: (1) the problem is broken down into manageable projects that can be worked out separately and integrated in the end by the flow of data in the form of inputs or outputs; (2) the framework can serve to integrate third party tools into a comprehensive SoS communications framework. Fig. 4 shows a schematic of the different modules and the flow of information. The prototyping environment for the framework is available as a graphical user interface (GUI) in MATLAB. In the GUI, a central map depicting the connectivity of the SoS network is presented where the connectivity is driven by the data provided by the modules illustrated in Fig. 5.
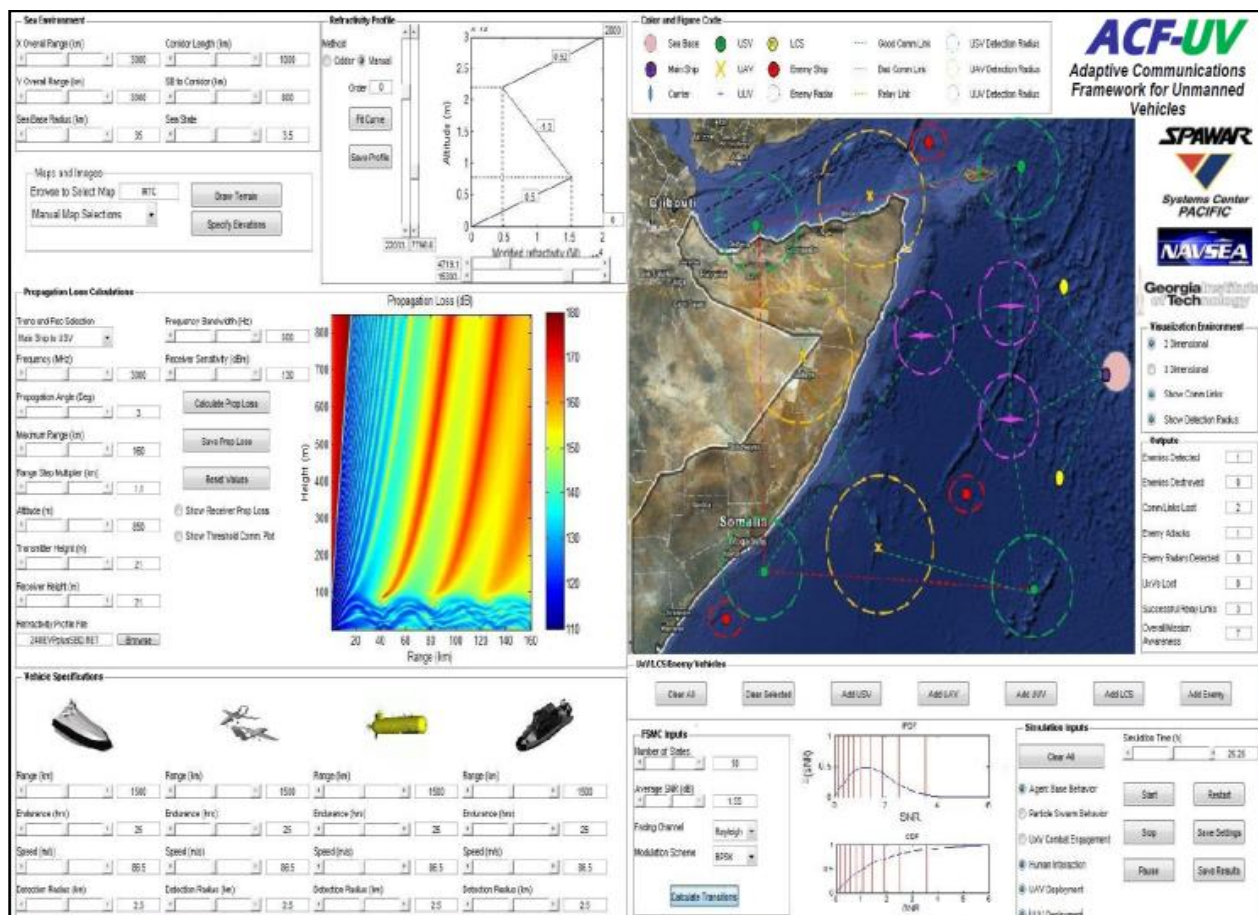

Figure. 5. ACF-UV GUI in MATLAB

The following sub-sections describe the implementation modules integrated in the framework to enhance its prediction and simulation capabilities.

4.2 ACF-UV Model Considerations

The communications system performance is impacted by many factors which ACF-UV takes into account, they include:

- The effect of the channel (or channels) between nodes.

- The channel as a function of both the mean propagation loss and statistics of the variation about the mean (Fading).

- The propagation loss and fading characteristics as a function of (a) Signal frequency, amplitude (gain), and implemented modulation scheme, (b) Atmospheric refractivity structure, and (c) Node positions and their time dependence.

- The ability of UxV radios to adapt their transmissions in response to channel changes in order to maintain high throughput.

These factors are taken into account in the ACF-UV by the integration of models that define the environment, vehicle specifications and capabilities, and predict the transmission channel between nodes. The models to estimate propagation losses and predict the transmission channel between nodes were presented in Section 3. The following three models help define the atmospheric environment, and UxV specifications and capabilities within the simulation environment. And simulation modules capabilities are presented next.

4.2.1 Refractivity Structure

The environment is characterized as a function of atmospheric refractivity. This is done by creating a refractivity profile with range and altitude from the transmitter outwards into space. From the refractivity profile, the Modified Refractivity (M) gradient information is used for the propagation loss calculations using the Parabolic Equation method. The refractivity profiles of major interest for maritime intermittent communications are those that cause trapping layers in which the radio signal is trapped due to its refraction from the boundary of these layers. These trapping layers can be surface-based ducts, elevated ducts, or evaporation ducts. Fig. 6 shows typical refractivity profiles and their corresponding trapping layers.
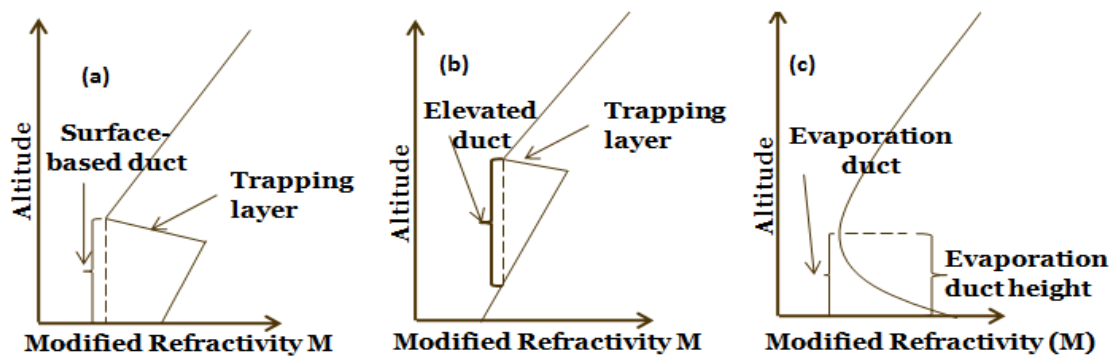

Figure. 6. Typical surface-based duct (a), elevated duct (b), and evaporation duct (c)

Effects of these refractivity structures on radio signals depend on transmitting height, propagation angle, radio signal strength, frequency, and modulation. Multipath fading leads to skip-zones, absorption will lead to shadowing, and long range will be mostly affected by free-space loss.

4.2.2 Vehicle and Asset Specifications

In keeping with the idea of a modular and data driven tool, UxVs and manned vehicles are initially modeled through the use of top level specifications. These specifications included range, endurance, speed, payload capacity, and overall dimensions (e.g. antenna height). These high level performance and capability specifications can be loaded from a library developed from open source reference, and combined with a model of the basic movement dynamics in the simulation environment to understand the behavior of the UxVs

4.2.3 Simulation Environment Inputs and Outputs

In order to assess the impact of UxV requirements and communications quality on the overall mission, a developmental simulator was implemented in MATLAB using an object-oriented approach. A 2-dimensional world is currently used with plans to extend it to a full geographic coordinate system to model any portion of the globe. A UxV, Littoral Combat Ship (LCS), or other platform is defined by a vehicle class with its corresponding performance and capability specifications. The vehicle classes also have turn, and detect methods which may be called by the main simulation. These UxV and LCS assets are represented by points with their corresponding detection radius. Vehicle motions are governed by discretized constant-speed kinematics; the motion methods implement the necessary corrections to deal with the discrete nature of this simulation. The communication network is represented by communication links, modele between UxVs and LCS during the simulation. A simulation proceeds by initializing the world and all assets in their desired locations and running the simulation for a given amount of time or until some operational condition is met, e.g., perimeter patrol completed.

Inputs for the simulation environment include: atmospheric environment characteristics (refractivity profile), radio signal specifications, UxV and LCS performance and capabilities, UxV and LCS initial locations, UxV and LCS paths and agent based behavior, and stopping criterion (time or a set goal). An Agent Based Modeling (ABM) and Emergent Behavior approach is also being developed to enable UxVs to autonomously position themselves to optimize area coverage while maintaining constant communication with all UxVs and LCS. Outputs of the simulation are measures of performance with emphasis on the communication network which include: enemies detected, enemy radars detected, communication links lost, successful relay links, and overall mission awareness.

5. CONCLUSION

In this paper, the Adaptive Communications Framework for Unmanned Vehicles (ACF-UV) for evaluating intermittent communications in maritime environments is presented and demonstrated. The integrated APM module is used to compute maritime signal propagation loss. A Finite-state Markov channel (FSMC) model for which fading channel states, represented by different intervals of propagation loss amplitudes, are used to differentiate the dynamic amplitude variations of time-varying multipath fading channels, is also presented. The fading channel states are partitioned into a finite number of intervals which represent application-specific communications states. Ultimately, all of these elements are combined to provide a comprehensive network picture in the ACF-UV.

6. ACKNOWLEDGMENT

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