Unmanned Aerial System Performance in Airborne Communication Relay

The Application of Border Gateway Protocol to Connect Airborne Navy Networks

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To my wife, Teresa, and my son, Benjamin
Your support and love is all I need. I am truly blessed.

The Program Executive Office for Unmanned Aviation and Strike Weapons
Common Standards and Interoperability Team
Thank you for tolerating my quirks and always supporting my effort

Executive Summary

Naval aircraft communication terminals have been developed through "stovepipe" architectures that result in a lack of interoperability between aircraft. The lack of end-to-end information sharing between naval systems is due to a lack of robust, system-of-systems design to achieve interoperability beyond system boundaries.

The Navy may operate many aircraft in a region tasked to achieve a single mission objective. Each aircraft is designed to perform a set of mission tasks and each aircraft must share the information it has gathered with the other aircraft in the region so that the entire system of aircrafts in the mission region can achieve mission success. A number of network capability gaps have been identified that obstruct the flow of information into a common operational tactical picture. Intelligence, Surveillance, and Reconnaissance (ISR) platforms that develop or create the tactical picture in the mission must be able to provide intelligence to platforms that continue the mission in later phases of the mission. Military Operations Research studies have generally assumed that the communications architectures required to support a Common Operational Tactical Picture exist in the region (mission area). In this study I will analyze the existing communication network capability in order to find an optimal network architecture that will fully connect all aircraft in a mission region. Then conduct an analysis of the effectiveness of the existing network architecture of the aircraft in the mission region against the application of

Border Gateway Protocol. The Border Gateway Protocol (BGP) can be used to create a fully connected network of networks in a mission area.

Multiple heterogeneous networks must operate as if it were a single homogeneous network in order to send and receive data between many different types of aircraft in the mission region. Can this be accomplished without additional requirements to existing aircraft program management?

This study was conducted in three phases. Those phases were Scenario Development, Communications Link Analysis, and Interoperability Analysis. The purpose of the Scenario Development phase was to define the problem in an operational context and scope the problem. The completion of this phase resulted in the creation of an operational view, scenario timeline, and a definition of the existing communications architecture. The scenario development phase identifies the Navy's interoperability needs through analysis of the existing communication architecture (constraints) and connections required from source to destination objects in the region (objectives). Broad aircraft to aircraft interoperability gaps that are identified in the scenario development phase are analyzed in detail in the Interoperability Analysis phase of this study.

The purpose of the Communication Link Analysis phase was to evaluate the data link terminals on the air vehicles in the scenario. The data link terminals must be able to send and receive data sufficiently in order to maintain connections between dis-joined users in the mission area. The purpose of the Interoperability Analysis phase was to further analyze the

results of the scenario development and communications link analysis in order to understand the risks of implementing Border Gateway Protocol onboard current aircraft and quantify the tradespace of input variables that make proposed solutions viable investments for the Navy, and understand the underlying complexity of proposed technologies.

The application of Border Gateway Protocol can be used to connect the multiple heterogeneous networks in a mission region in order to increase interoperability across the operational battlespace. There are many different Navy aircraft and ships managed by many different program elements and network administrations. The host ship and aircrafts in the mission region can be split in to separate groups defined by their single and clearly defined routing policy. Using the BGP protocol is not a new requirement for Navy programs. The requirement to use BGP exists in current program documentation. Although the application of Border Gateway Protocol to an existing program is not a new requirement, the addition of technology on the aircraft will be required to support the application of BGP on Navy airborne networks.

Through Scenario Development, this analysis had identified a need to create a communications relay node in order to connect the networks. The aircraft identified as the relay aircraft would be an unmanned air vehicle with high endurance. The relay aircraft that currently operates with a Common Data Link terminal would require an additional mesh network data link terminal. Using an aircraft as a relay node also removes the beyond line-of-

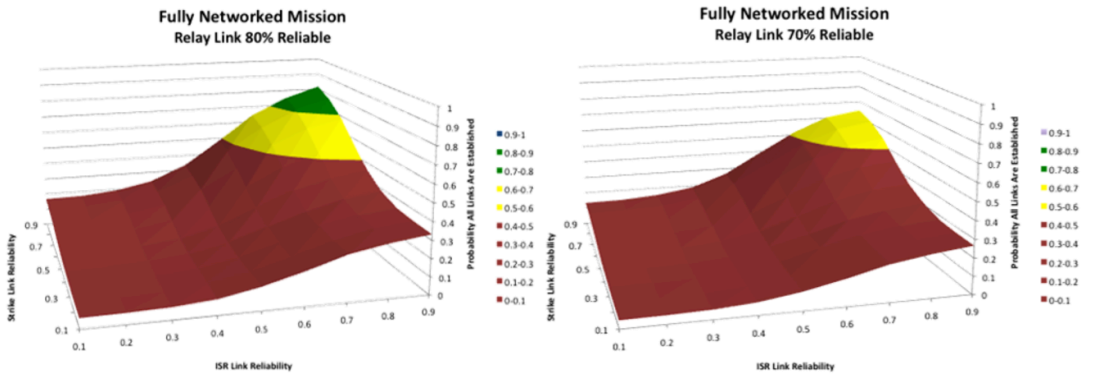
sight data paths, the very costly data paths, as a primary data path. Simply adding the mesh network data link terminal does not, in itself, give the relay aircraft the ability to forward datagrams to any host computer in the mission region. The Scenario Development phase, conducted in collaboration with the warfighter, identifies the aircraft to use as a relay node, outlines a high-level concept of operations, and defines the network architecture. Scenario Development alone does not fully answer the question, Can Border Gateway Protocol increase interoperability and therefore increase the mission effectiveness of our aircrafts and ships in an operational battlespace?
The Communication Link Analysis part of this analysis evaluates the performance or ability of the data link terminals to support interoperability in the mission scenario. The bottom line metric of goodness for data links in the scenario is probability of successfully recovering a message sent from a data link terminal on the host ship or aircraft on station and recovered at the intended destination. The performance of data link terminals in the mission area is degraded by a number of factors. Degradation of a transmitted signal will happen because of distance between terminals due free space path loss and other losses due to atmosphere, such as rain fade attenuation. The transmitted signal will also experience small scale fading, which is modeled as a rice fading channel in this analysis because of the terminals are within line of sight at all times. The aircraft in the scenario are moving at speeds up to 124 nautical miles per hour and are operating at different altitudes. There is a fair

amount of Doppler shift between the transmitting and receiving terminals in the scenario.

The simulation quantifies bit error rate by calculating the received energy per bit to noise density ratio at the receiving terminal, taking into account power at the transmitter and degradation of the signal due to free space path loss and rain fade. Randomly generated data is simulated through the channel faded by Rician distributed data and the effects of Doppler shift. The generated data further complicated by additional noise which has been scaled due to the received energy per bit to noise ratio. The data points are then evaluated by a threshold detector and recovered, either correctly or incorrectly. The received data is compared against the original data sent over the channel and the number of incorrectly received bits divided by the total number of bits sent is the bit error rate. The bit error rate is then used to evaluate a packet error rate based upon the average size of packets sent through the channel. The results of this analysis are presented in the following table. There is a 70% probability of recovering message from the ISR aircraft to the unmanned air vehicle executing the relay communications mission. There is an 80% probability of recovering a message sent from the communication relay aircraft to the host ship. These results are used in the Interoperability Analysis section of this study.

	ISR to Relay	Relay to Ship	Ship to Relay	Relay to ISR
Average Ground Range(nm)	25.17	20.34	20.34	25.04
Average Slant Range (nm)	22.22	20.92	20.92	25.33
Average C/N (dB)	9.90	12.77	4.28	9.06
Average C/N0 (dB)	96.43	95.78	90.82	92.07
Average Eb/N0 (dB)	23.12	22.47	37.81	39.06
Average BER (%)	7.347E-05	1.769E-05	8.416E-08	1.136E-07
Average Message Success Probability (%)	70.69%	82.51%	99.95%	99.94%

The Interoperability Analysis phase quantifies the tradespace of data link reliability required to support the addition of new technology and the application of Border Gateway Protocol. The new technologies on the platforms are the addition of a mesh network data terminal on the relay node and BGP Speakers on all of the autonomous systems. The simulation of the application of BGP shows that there is a tradeoff of data link reliability, but there is a minimum threshold where there is full network connectivity for over 50% of the mission scenario. That tradespace is depicted in the figure below.



The probability that any host computer can send data to any host computer in the mission region is never greater than the probability that all BGP Speakers are in the ESTABLISHED state. Full network connectivity in the mission region is only as strong as the most unreliable link. The probability that all BGP Speakers are in the ESTABLISHED state for greater than 50% of the mission scenario is shown in yellow and greater than 70% is shown in green.

This study will be used to inform several efforts being conducted by different groups throughout Naval Air Systems Command. Specifically, this analysis will inform operational demonstrations conducted by the Program Executive Office of Unmanned Aviation and Strike Weapons (PEO (U&W)) Common Standards and Interoperability, the creation of battlespace simulations by the Navy's Warfare Analysis and Integration Department, and support the creation of a Navy-wide Data Transport Strategy.

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Introduction

Naval aircraft communication terminals have been developed through "stovepipe" architectures that result in a lack of interoperability between aircraft. The lack of end-to-end information sharing between naval systems is due to a lack of robust, system-of-systems design to achieve interoperability beyond system boundaries.

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results of the scenario development and communications link analysis in order to understand the risks of implementing Border Gateway Protocol onboard current aircraft and quantify the tradespace of input variables that make proposed solutions viable investments for the Navy, and understand the underlying complexity of proposed technologies.

Scenario Development

The scenario around which this study is conducted is a generic mission. The purpose of defining a scenario is to give the analysis an operational context upon which technical solutions can be applied to existing Naval programs.

Operational View

In the scenario there is a manned intelligence gathering aircraft (M1), a number of manned aircraft on a strike network (M2), a number of manned aircraft dedicated to supporting the intelligence and strike aircraft (M3), an number of unmanned aircraft(U1 and U2), and the host ship.

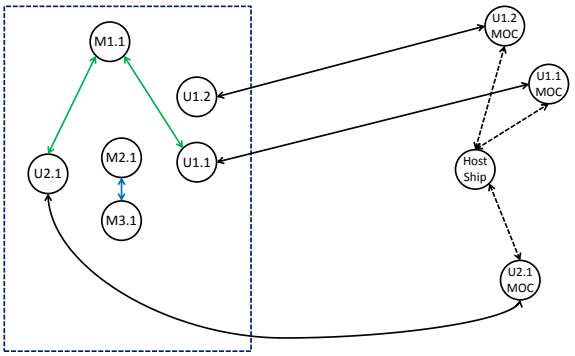


Figure 1) As-is communication architecture

		Receive									
		Host Ship	U1.1	U1.2	M3.1	M2.1	M1.1	U2.1	U1.1 MOC	U1.2 MOC	U2.1 MOC
Transmit	Host Ship								NB BLOS	NB BLOS	NB BLOS
	U1.1						CDL		WB BLOS		
	U1.2						CDL			WB BLOS	
	M3.1					Mesh Network					
	M2.1				Mesh Network						
	M1.1		CDL	CDL							
	U2.1										WB BLOS
	U1.1 MOC	NB BLOS	NB BLOS								
	U1.2 MOC	NB BLOS		NB BLOS							
	U2.1 MOC	NB BLOS						NB BLOS			

Figure 2) As-is communication matrix

Figure 1 and figure 2 depict the current communications architecture and the type of communications link between the two objects. The communication types in the scenario are the Common Data Link, Mesh Network, Wide Band Beyond Line-of-Sight, and Narrow Band Beyond Line-of-Sight. In this scenario, the users believe that there are many communication gaps. Information is not adequately shared between platforms in order to achieve mission success. Figure 3 and Figure 4 depict the notional communication architecture that the users believe will fully connect the platforms in the mission area. The warfighters believe that this communication architecture is adequate to achieve mission success.

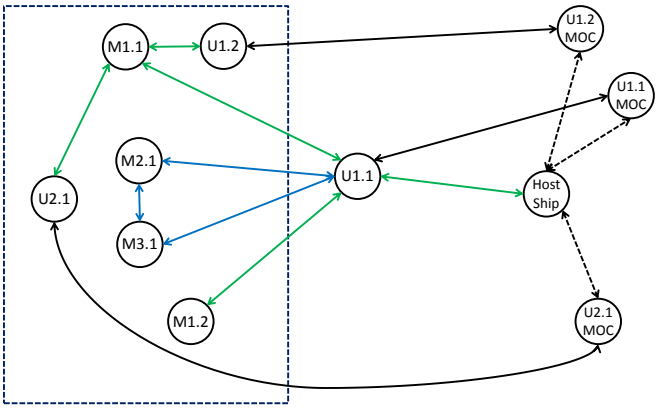


Figure 3) To-be communication architecture

		Receive										
		Host Ship	U1.1	U1.2	M3.1	M2.1	M1.1	M1.2	U2.1	U1.1 MOC	U1.2 MOC	U2.1 MOC
Transmit	Host Ship		CDL							NB BLOS	NB BLOS	NB BLOS
	U1.1	CDL			Mesh Network	Mesh Network	CDL	CDL		WB BLOS		
	U1.2						CDL				WB BLOS	
	M3.1		Mesh Network			Mesh Network						
	M2.1		Mesh Network		Mesh Network							
	M1.1		CDL	CDL					CDL			
	M1.2		CDL									
	U2.1						CDL					WB BLOS
	U1.1 MOC	NB BLOS	NB BLOS									
	U1.2 MOC	NB BLOS		NB BLOS								
	U2.1 MOC	NB BLOS							NB BLOS			

Figure 4) To-be communication matrix

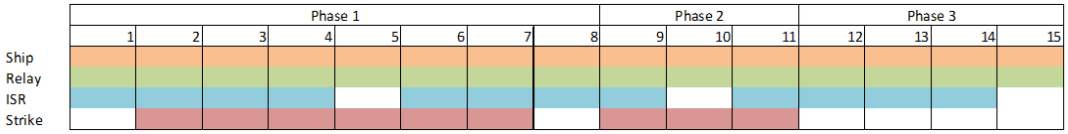


Figure 5) Aircraft on-station scheduling

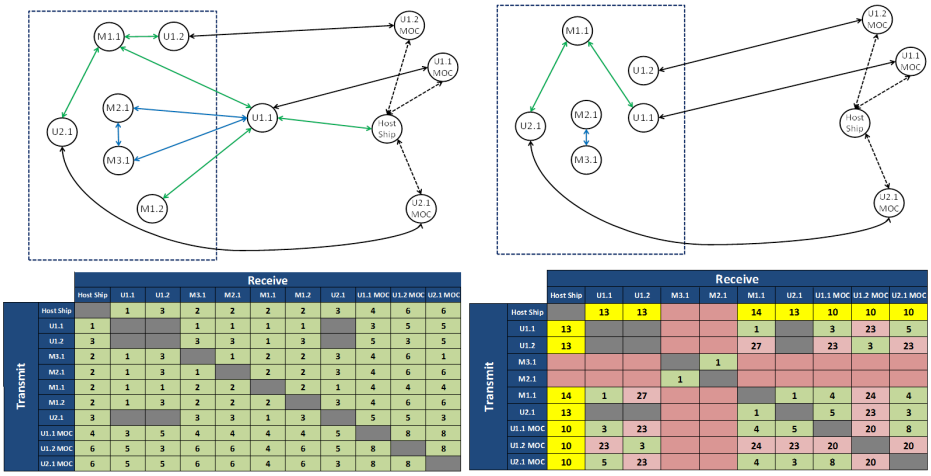
The mission timeline is detailed in figure 5. The mission is a 15 hour mission with an intelligence gathering phase (phase 1), a strike phase (phase 2), and an assess phase (phase 3). The intelligence gathering aircraft develops the tactical picture for the surface warfare commander located on the host ship. The intelligence is developed through the analysis of data obtained through the onboard sensors of the intelligence gathering aircraft. The intelligence that results from processing raw sensor data must be shared with all other aircraft in the scenario. The only communications terminals on the intelligence aircraft are point to point data links (CDL).

The strike network is comprised of many aircraft that communicate on a mobile ad-hoc network (mesh network). The mesh network is currently a future network defined by the capabilities of an aircraft to join the network in

an ad-hoc manner, the network is self-forming, the network is self-healing, and the data link terminals can forward datagrams within its own network.

In phase 1, the intelligence gathering aircraft (aircraft M1.1) in figure 1 is must send sensor data to the host ship. Aircraft M1.1 is not the only intelligence gathering aircraft in the mission. Aircraft M3.1 is also has intelligence gathering capabilities and will be used to support the operations of aircraft M1.1. The scenario timeline, shown in figure 2, has the intelligence gathering aircraft in operations for four hour blocks with an hour in between each block. The strike network is in operations, which means that a number of M2 or M3 platforms are in the mission region area, for most of phase 1 and all of phase 2. The relay aircraft and host ship are active throughout the entire scenario.

OSPF Analysis of Communications Architecture



Transmit \ Receive	Host Ship	U1.1	U1.2	M3.1	M2.1	M1.1	M1.2	U2.1	U1.1 MOC	U1.2 MOC	U2.1 MOC
Host Ship		1	3	2	2	2	2	3	4	6	6
U1.1	1			1	1	1	1		3	5	5
U1.2	3			3	3	1	3		5	3	5
M3.1	2	1	3		1	2	2	3	4	6	1
M2.1	2	1	3	1		2	2	3	4	6	6
M1.1	2	1	1	2	2		2	1	4	4	4
M1.2	2	1	3	2	2	2		3	4	6	6
U2.1	3			3	3	1	3		5	5	3
U1.1 MOC	4	3	5	4	4	4	4	5		8	8
U1.2 MOC	6	5	3	6	6	4	6	5	8		8
U2.1 MOC	6	5	5	6	6	4	6	3	8	8	

Transmit \ Receive	Host Ship	U1.1	U1.2	M3.1	M2.1	M1.1	U2.1	U1.1 MOC	U1.2 MOC	U2.1 MOC
Host Ship		13	13			14	13	10	10	10
U1.1	13					1		3	23	5
U1.2	13					27		23	3	23
M3.1					1					
M2.1				1						
M1.1	14	1	27				1	4	24	4
U2.1	13					1		5	23	3
U1.1 MOC	10	3	23			4	5		20	8
U1.2 MOC	10	23	3			24	23	20		20
U2.1 MOC	10	5	23			4	3	8	20	

Figure 6) Comparison of connectivity

The “to-be” communications architecture (figure 3) is what the warfighters believe is the solution to the disjoined communications problem of the “as-is” communications architecture depicted in figure 1. An Open Shortest Path First (OSPF) analysis was conducted against the architecture in both figure 1 and figure 3.

The OSPF analysis requires weighting the links for both “as-is” and “to-be” networks. The line-of-sight links (cdl and mesh network) are set to one, the beyond line of sight links to the unmanned system control stations (MOCs) are weighted at three because of the higher cost to operate due to the use of satellite, and the narrow band links connecting the unmanned system control stations to the ship are weighted at 10 because they have limited applications and require the use of satellites.

There are two separate networks in the “as-is” network configuration. The mesh network aircraft are not connected to the rest of the mission. Also, a high bandwidth path from any node in the mission area to the host ship does not exist because the narrow band satellite link is always in the path to and from the host ship. When a mesh network capability is added to an unmanned system and the unmanned system is moved out of the mission area to conduct a relay communications mission (the “to-be” network configuration), there is a significant increase in connectivity between all of the nodes in the mission region. Along with increased connectivity, the quality of the data paths is also more reliable.

The changes to the mission network configuration are an unmanned aircraft is moved out of the mission area to perform communication relay, a Common Data Link between the host ship and the relay aircraft is added, and a mesh network data link terminal is added to the relay aircraft. Open Shortest Path First analysis of the changes indicates that there could be increased connectivity and quality from any node sending data to any receiver. This analysis quantifies the effectiveness of creating new links in the scenario and further defines mission operations. The Scenario Development phase does not define the technical implementation of using an unmanned aircraft to connect the mesh network and the Common Data Link. The Interoperability Analysis Phase of this study will quantify the tradespace of data link reliability required to apply the Border Gateway Protocol in order to create the network of networks required to connect all aircraft in the mission area.

Communication Link Analysis

The overall objective of Communication Link Analysis is to analyze the performance of the communications infrastructure over which the Border Gateway Protocol must operate. Therefore the existing communication terminals onboard the aircraft in the mission area, the relay communication aircraft, and the host ship are studied through modeling, simulation, and analysis in order to quantify the bit error rate (BER) of each communication terminal in the scenario and quantify an overall probability that an entire Ethernet framed IP Packet over Generic Frame Procedure is transmitted, received, and correctly interpreted by the systems (aircrafts and host ship) in the scenario. The packet error rate is derived from the bit error rate. The analysis in this section consists of free space path loss, rain attenuation, rice fading, and Doppler shift effect.

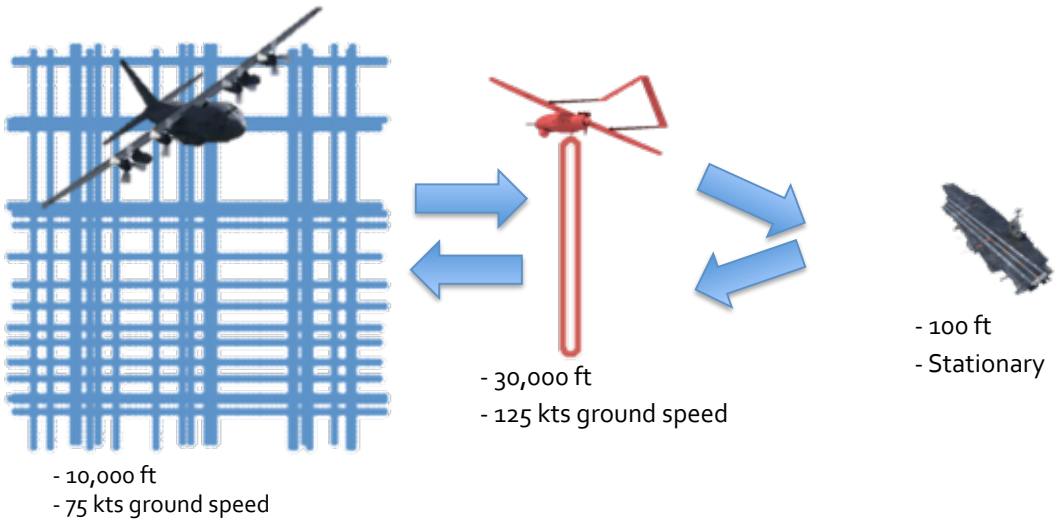


Figure 7) Aircraft communication terminal geometry

Both Free Space Path Loss and Rain Attenuation are based upon the distance between the transmitter and receiver. The distances between the aircraft in the mission area and the relay aircraft are constantly changing. The on station aircraft moves laterally and longitudinally at 10,00o feet altitude above sea level with respect to the relay aircraft which moves along a racetrack pattern at 30,000 feet above sea level. The host ship is stationary with the antenna at 100 feet above sea level. High speeds and relative higher speeds between the ISR aircraft and the communications relay aircraft can result in Doppler shifts of the communication center frequency. Along with Doppler shift, we can also assume that there is always line of sight between the two aircraft and the communication relay aircraft and the host ship. The non line of sight components can be statistically described by the Rice distribution.

Large Scale Path Loss

The free space path loss in the simulation is defined by equation 1.

$$L_{FS}(dB) = 20\log(f) + 20\log(r) + 32.44 \qquad \text{(eq. 1)}$$

The frequency (f) is in GHz and the distance (r) is in meters. In order to quantify the distance between the objects in the scenario, the Pythagorean theorem is used between the ISR aircraft and the communications relay aircraft and also between the communications relay aircraft and the host ship. This

quantifies, at the initial timestep, the ground distance, slant distance, and elevation angle between two objects. With slant range, we are able to calculate free space path loss at every timestep of the simulation. Figure 8 shows L_{FS} as a function of range in the operating frequencies for this analysis.

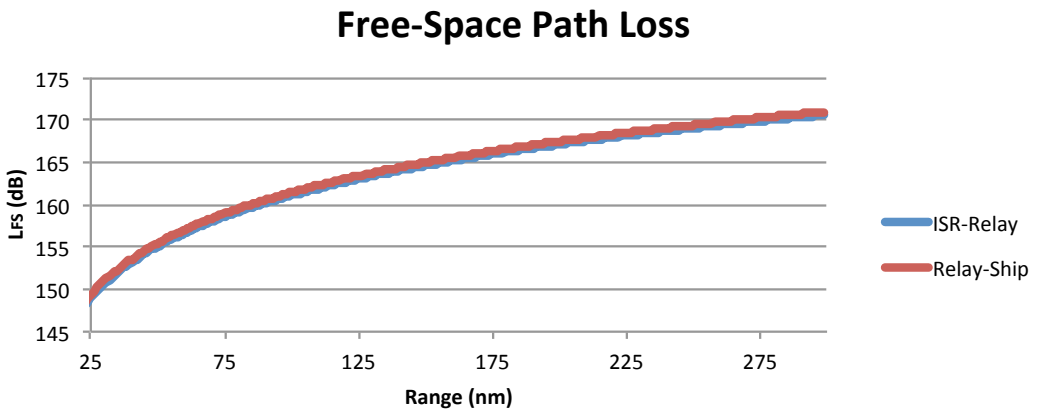


Figure 8) Free Space Path Loss

This analysis utilizes the International Telecommunications Union (ITU) Rain Attenuation Model. This model is described in detail in Recommendation ITU-R P.618-11, Propagation data and prediction methods required for the design of Earth-space telecommunication systems. Satellite Communication Systems Engineering byLouis J. Ippolito Jr. describes the steps used to quantify rain fade attenuation in this analysis. These steps are listed below.

1. Determine the rain height
2. Calculate slant path and horizontal projection
3. Determine the rain rate for 0.01% of an average year

4. Calculate specific attenuation
5. Calculate the horizontal reduction factor
6. Calculate the vertical adjustment factor
7. Determine the effective path length
8. Calculate the attenuation exceeded for 0.01% of an average year

The rain height is the average annual zero degree (C) isotherm height (h_O) plus 0.36 kilometers. The 0^OC isotherm height is available via look up tables provided by the ITU. Also sourced from maps and tables provided by the ITU were the inputs for rain rate (step 3) and the inputs required to generate attenuation coefficients k and a required in step 4.

$$hr = ho + 0.36km \qquad \text{(eq. 2)}$$

At each time step in the simulation the aircraft on station moves based upon the speed (75 kts) and direction. The communication relay platform also moves based upon speed (125 kts) and direction. Based upon the positions between the aircrafts and ship in the simulation, the slant path and horizontal projection is calculated with equation 3 and equation 4.

$$L_S = \begin{cases} \dfrac{h_r - h_s}{\sin\theta} & \text{for } \theta \geq 5 \\ \dfrac{2(h_r - h_s)}{\left[\sin^2\theta + \dfrac{2(h_r - h_s)}{R_e}\right]^{\frac{1}{2}} + \sin\theta} & \text{for } \theta < 5 \end{cases} \qquad \text{(eq 3)}$$

The calculation of specific attenuation, g_r, requires the calculation of attenuation coefficients k and a. Equations 4, 5, and 6 are used to calculate g_r. The variables kh, kv, ah, and av are dependent upon carrier frequency. The variables kh, kv, ah, and av can either be calculated given known matrices provided by the ITU or via lookup table. This model uses the inputs and equations detailed in Recommendation ITU-R P.838-3.

$$k = \frac{1}{2}\left[k_h + k_v + (k_h - k_v)\cos^2\theta\cos(2\tau)\right] \qquad \text{(eq 4)}$$

$$\alpha = \frac{1}{2k}\left[k_h\alpha_h + k_v\alpha_v + (k_h\alpha_h - k_v\alpha_v)\cos^2\theta\cos(2\tau)\right] \qquad \text{(eq 5)}$$

$$\gamma_R = kR_{0.01}^{\alpha} \qquad \text{(eq 6)}$$

The rain model used in this analysis calculates the vertical reduction factor $u_{0.01}$ with the following equations

$$\zeta = \tan^{-1}\left(\frac{h_r - h_s}{L_G r_{0.01}}\right) \qquad \text{(eq 7)}$$

$$\chi = \begin{cases} 36 - |\varphi| & \text{for } \varphi < 36 \\ 0 & \text{for } \varphi \geq 36 \end{cases} \qquad \text{(eq 8)}$$

$$LR = \begin{cases} \dfrac{L_G r_{0.01}}{\cos\theta} & \text{for } \zeta > \theta \\ \dfrac{h_r - h_s}{\sin\theta} & \text{for } \zeta \leq \theta \end{cases} \qquad \text{(eq 9)}$$

$$\upsilon_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left[31\left(1 - e^{-\left(\frac{\theta}{1+\chi}\right)}\right)\frac{\sqrt{L_R \gamma_R}}{f^2} - 0.45\right]} \qquad \text{(eq 10)}$$

Determine the effective path length (L_E), step 7, and calculate the attenuation exceeded for an average year in the range from 0.001 percent to 5 percent, step 8.

$$LE = L_R \upsilon_{0.01} \qquad \text{(eq 11)}$$

$$A_{0.01} = \gamma_R L_E \qquad \text{(eq 12)}$$

$$\beta = \begin{cases} 0 & \text{for p} \geq 1\% \text{ or } |\varphi| \geq 36 \\ -0.005(|\varphi| - 36) & \text{for p<1\% and } |\varphi| \geq 36 \text{ and } \theta \geq 25 \\ -0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta & \textit{otherwise} \end{cases} \quad \text{(eq 13)}$$

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-[0.655+0.033\ln(p)-0.045\ln(A_{0.01}-\beta(1-p)\sin\theta]} \quad \text{(eq 14)}$$

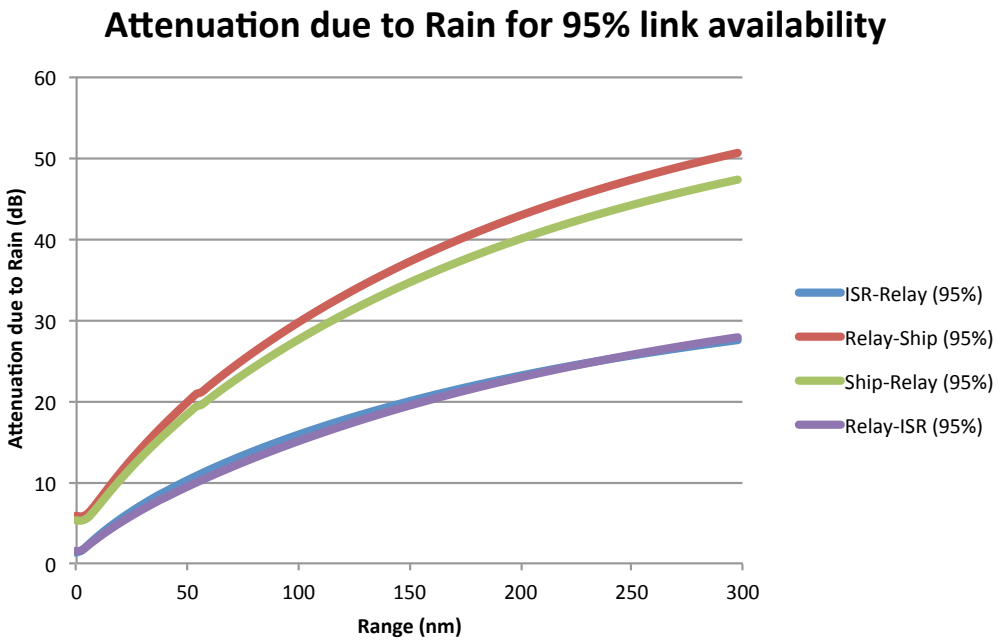


Figure 9) Rain Attenuation

The rain attenuation for system design for 95% link availability is shown in figure 9. There is a much larger effect on the link between the host ship and the relay communication aircraft. This is because of the difference in altitude between the ISR aircraft and the relay aircraft (32,000 ft.) and the difference

in altitude between the relay aircraft and the host ship (41,950 ft.). There is also a smaller effect due to frequency.

There is also a relationship between link availability to attenuation due to rain shown in figure 10. A communication terminal designer would need to account for higher attenuation due to rain if a more reliable link is necessary. For this analysis we use the attenuation calculated for each range and altitude difference for each transmitter and receiver in the simulation and account for rain attenuation in the overall link budget between transmitters and receivers in the scenario. Rain attenuation is added to free space path loss.

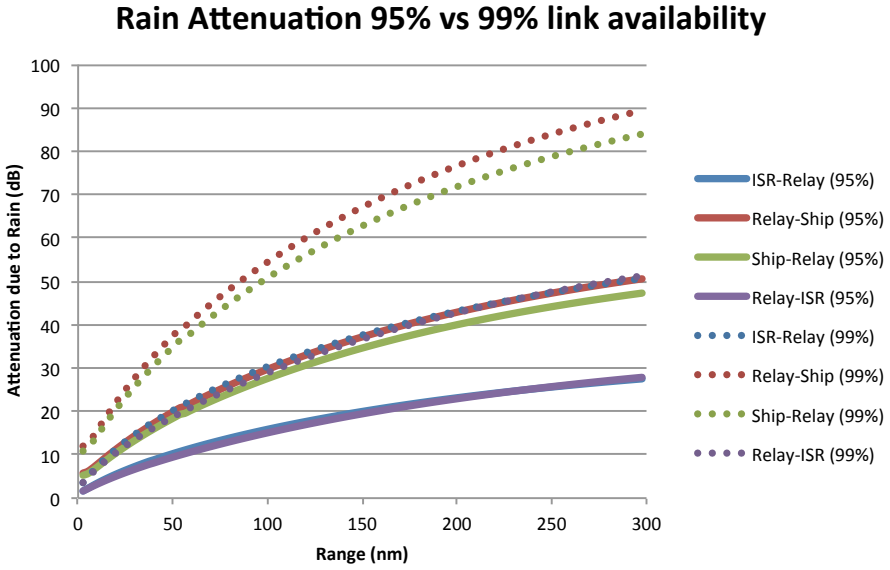


Figure 10) Rain Attenuation Link Availability

The receiver figure of merit, $\frac{G}{T}$, is calculated by subtracting receiver system noise temperature from receiver system gain (equation 15)

$$\frac{G}{T} = G_R - T_S \qquad \text{(eq 15)}$$

Data link terminal system noise was provided in the system descriptions for this analysis. Total system noise (T_S) is adjusted by the calculation of sky noise (t_r) due to rain from equation 16.

$$tr = tm\left(1 - 10^{-\frac{A_r(dB)}{10}}\right), \quad tm = 275K \qquad \text{(eq 16)}$$

The resulting carrier to noise ratio $\left(\frac{C}{N}\right)$, carrier to noise density $\left(\frac{C}{N_0}\right)$, and energy per bit to noise density $\frac{E_b}{N_0}$, ratio are calculated with the following equations where K is Boltzmann's constant, B_N is bandwidth, Rb is bit rate in bits per second, and EIRP is the power of the transmitter in dB plus the transmitter gain.

$$\frac{C}{N} = EIRP - \frac{G}{T} - L_{FS} - A_{RAIN} + K - B_N \qquad \text{(eq 17)}$$

$$\frac{C}{N_0} = \frac{C}{N} + B_N \qquad \text{(eq 18)}$$

$$\frac{E_B}{N_0} = \frac{C}{N} + B_N - R_b \qquad \text{(eq 19)}$$

The resulting $\frac{E_b}{N_0}$ is then used to scale noise in the Monte Carlo simulation in which the model compares randomly generated transmitted data to received data through over a Rice Fading channel.

This section, regarding Link Budget, quantifies the effect of range with respect to carrier to noise ratio in a situation where both the transmitter and receiver are moving at hundreds of miles per hour. This is modeled by simulating the movement of aircraft in the mission scenario in order to understand the distances under which these systems must operate effectively in order to maintain a fully connected network. A histogram of distances is shown in figure 11 for the ranges between the aircraft on station and the communication relay aircraft and figure 12 is the histogram of the distances between the communication relay aircraft and the host ship.

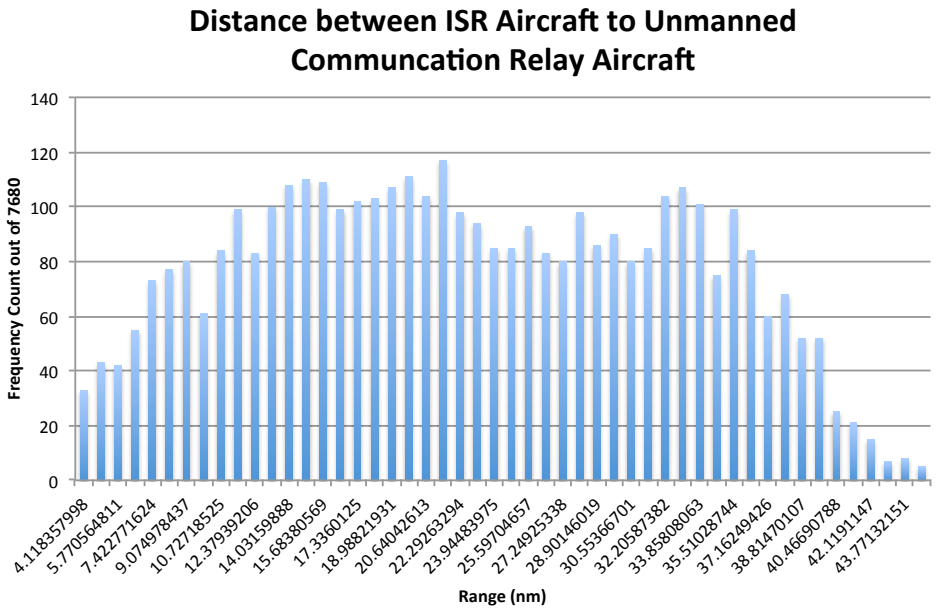


Figure 11) ISR to relay aircraft distance histogram

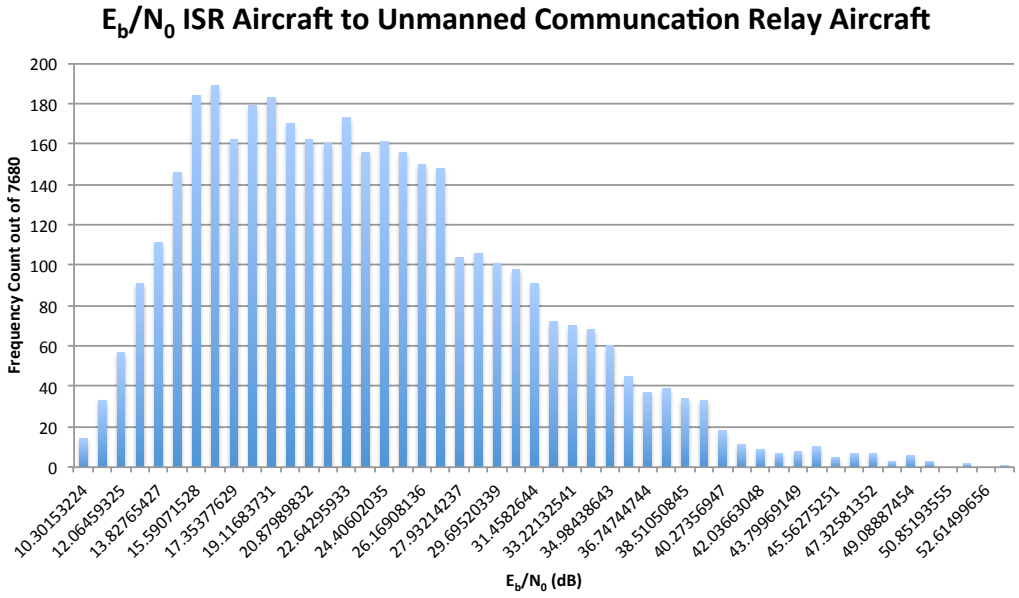


Figure 12) Relay aircraft to host ship distance histogram

Figure 11 shows that the average distance between the aircraft on station and the communication relay aircraft is approximately 25 nautical miles

and is associated with an average $\frac{E_b}{N_0}$ of 18.1 dB, shown in figure 12, from the ISR aircraft to the relay aircraft. Table 1 shows that the average distance between the communication relay aircraft and the host ship is approximately 20 nautical miles and is associated with an average $\frac{E_b}{N_0}$ of 22.5 dB.

	ISR to Relay	Relay to Ship	Ship to Relay	Relay to ISR
Average Ground Range (nm)	72.76	24.27	24.27	73.52
Average Slant Range (nm)	72.87	24.75	24.75	73.63
Average C/N (dB)	17.83	23.75	27.27	17.45
Average C/No (dB)	104.36	106.76	113.80	100.47
Average Eb/No (dB)	31.05	33.45	60.79	47.45

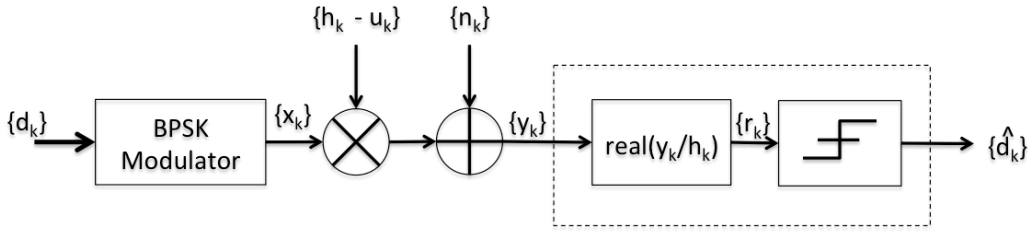
Table 1) Object distances and average energy per bit to noise density

The average ranges and, based upon range, the resulting carrier to noise ratio that takes into account free space path loss, rain fade attenuation, sky noise based upon the resulting rain attenuation, and system noise are shown in table 1. Carrier to noise power density is the bandwidth of the channel added to the carrier to noise ratio, higher bandwidths are associated with better performance. The desired bit rate (dB) is then subtracted from the received carrier to noise power density to obtain the energy per bit to noise density. In order to quantify overall bit error rate and essentially, the probability that the receiving data link terminal can recover IP packets, the energy per bit to noise density at the receiving data link terminal must be known. In the next section we will analyze $\frac{E_b}{N_0}$ to bit error rate (BER) and probability of message recovery

in order to define the overall quality of the both the link between the aircraft on station and the communication relay aircraft and the link between the communication relay aircraft and the host ship.

Small Scale Path Loss

The Budget Link section analyzes and quantifies the relationship between range and energy per bit to noise density. In this section we will use the resulting energy per bit to noise density resulting from path loss and other losses in order to scale the noise added to the received signal. This section also describes how Doppler shifting effects the received signal. The overall architecture of this portion of the simulation is shown in figure 13. The analysis of this section will quantify bit error rate and probability of recovering packets at the receive terminals.



- d_k – randomly generated data {0, 1}
- x_k – BPSK data {0,1} = {-1,1}
- h_k – rician fading
- u_k – doppler filter (h_k is shaped to zero with respect to normalized frequency f/f_{max})
- n_k – noise
- y_k – received signal yk = xk*(hk-uk)+nk
- r_k – real part of the received signal divided
- Decision d_k – if the real part of r_k is greater than 0, received bit is one and zero otherwise

Figure 13) Simulation Model

The simulation will generate evenly distributed ones and zeros (d_k). The generated data set at the output of the BPSK modulater will be represented by the data set x_k where d_k={0,1,0,0,1…} would be represented by the set x_k={-1,1,-1,-1,1…}. Rice distributed data, h_k, that is shaped by Doppler shift fading factors, u_k, will fade x_k. Noise factored by $\frac{E_b}{N_0}$ is added to the signal and the signal that arrives at the receiving terminal, y_k, is represented by equation 17.

$$y_k = x_k(h_k - u_k) + n_k \qquad \text{(eq 20)}$$

The resulting data set, $\hat{d}_k$, is compared to original data set, d_k, and the number bits received in error divided by the number of total bits sent is the resulting bit error rate that accounts for fading due to the channel, fading due to Doppler shifts, and the noise of the channel factored by $\frac{E_b}{N_0}$.

Rician Small Scale Fading

In the line of sight situation, the received line of sight component dominates the received multipath components. The level to which this component overshadows the multipath components is represented by a parameter, *k*, known as the Rice factor. The rice probability density used in the simulation is represented in equation 18.

$$p_R(r) = \frac{2kr}{s^2} e^{-\frac{kr^2}{s^2}} e^{-k} I_0\left(\frac{2kr}{s}\right) \qquad \text{(eq 21)}$$

$$s = \sqrt{\frac{k}{k+1}} \qquad \text{(eq 22)}$$

The parameter, s, is the power in the constant part of the signal.

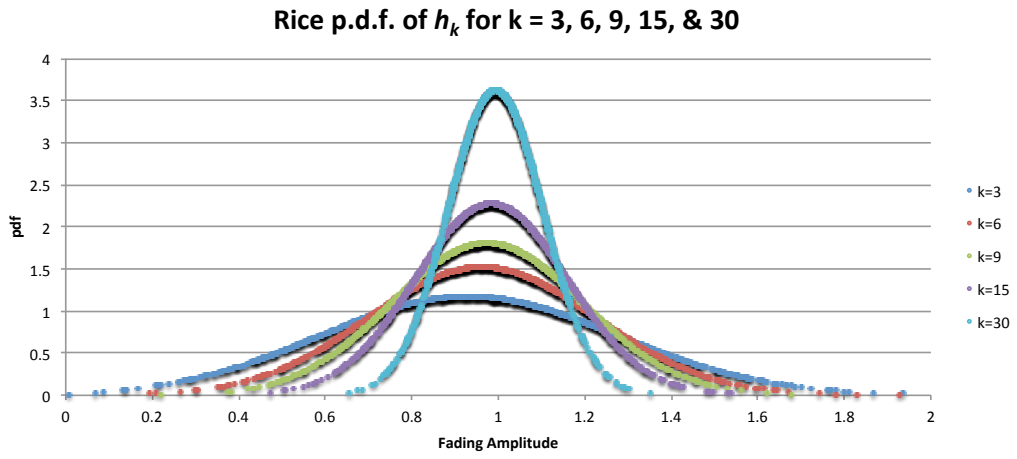


Figure 14) Rician pdf for k=3, 6, 9, 15, and 30

Figure 14 shows the distribution of Rice fading signals used to modify the transmitted data x_k as it is sent from transmitter to receiver. The result of simulations where only the value of *k* is changed between simulations is shown in figure 15.

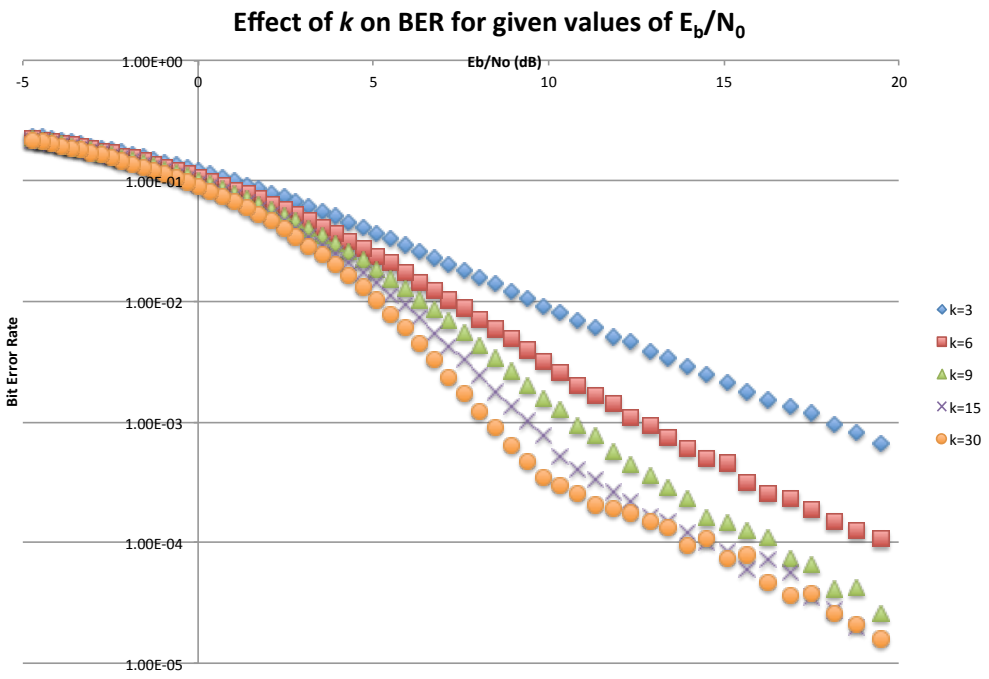


Figure 15) Bit Error Rates for Rician k=3, 6, 9, 15, and 30

Figure 15 illustrates that when k increases, the bit error rate decreases, as expected. In future analysis this can be used to show the difference between directional and omni-directional antennas in similar mission simulations.

Doppler Effect

The aircraft on station is moving throughout the scenario at 75 nautical miles per hour and the communication aircraft is moving along its racetrack pattern at 125 nautical miles per hour. These speeds can relationally be very fast. When there is a difference in path lengths between the transmitter and receiver over time, there is a phase change in the received signal. Equation 23. Where Dl is the change in path length in meters and l is wavelength (speed of light divided by frequency). The change in path length between the objects in the scenario at each timestep are known throughout the scenario, which means that f_d can be calculated using equasions 23 and 24. Figure 16 depicts the Doppler shifts that are present in this scenario between the aircraft on station and the communication relay aircraft.

$$\Delta\phi = \frac{2\pi\Delta l}{\lambda} \qquad \text{(eq 23)}$$

$$f_d = \frac{\Delta\phi}{2\pi\Delta t} \qquad \text{(eq 24)}$$

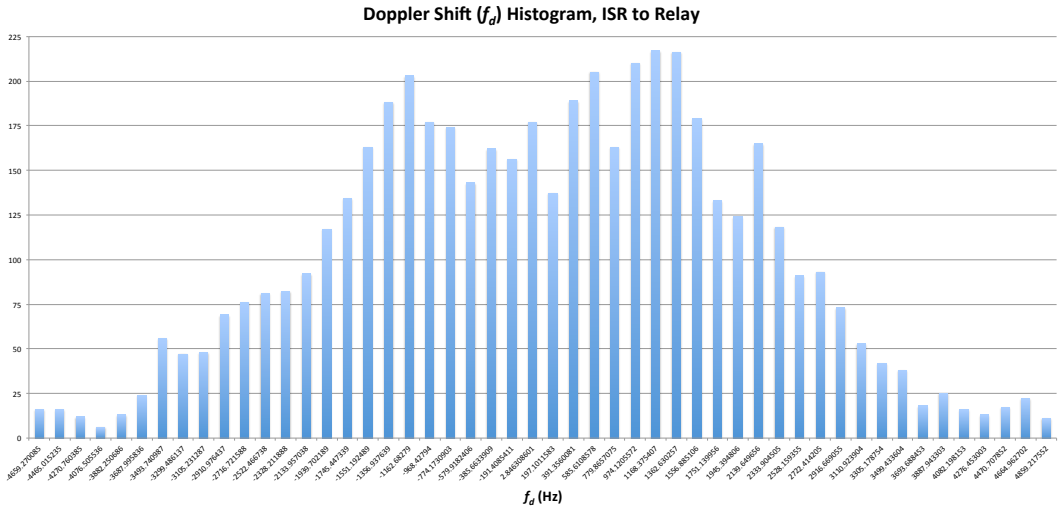


Figure 16) ISR to relay aircraft frequency shift histogram

In order to account for Doppler shifts in the simulation, equation 25 was used to create the data points shown in figure 17. Equation 5 is described in section 4 of the paper, "On the Generation of Correlated Rayleigh Random Variates by Inverse Discrete Fourier Transform," by David J Young and Norman C. Beaulieu. The filter F(s) is equation 16 in Young's paper.

$$F_S[k] = \begin{cases} 0 & k = 0 \\ \sqrt{\dfrac{1}{2\sqrt{1-\left(\dfrac{k}{Nf_m}\right)2}}} & k = 1,2,\ldots,k_m - 1 \\ \sqrt{\dfrac{k_m}{2}\left[\dfrac{\pi}{2} - \arctan\left(\dfrac{k_m - 1}{\sqrt{2k_m - 1}}\right)\right]} & k = k_m \\ 0 & elsewhere \end{cases} \qquad \text{(eq 25)}$$

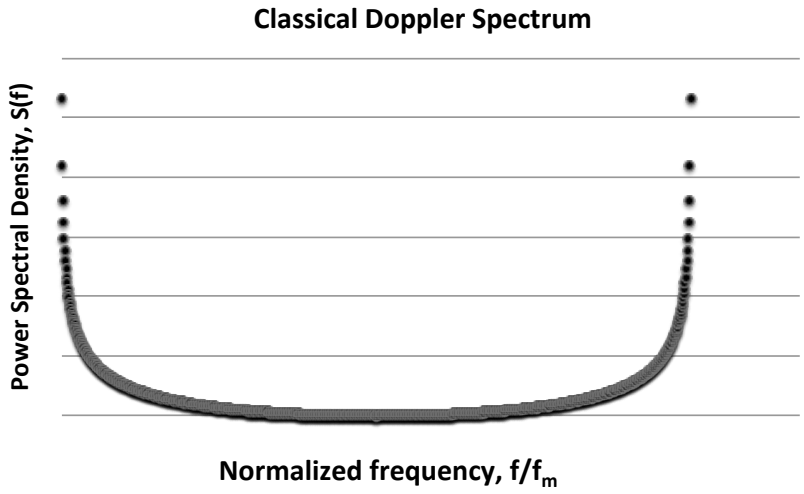


Figure 17) Classical Doppler Spectrum

Figure 18 depicts a sample set of Rice distributed data points. The probability density function is depicted in figure 14 for k=9. These data points are multiplied by the data points generated by the function $F_s[k]$. The result u_k is depicted in figure 19.

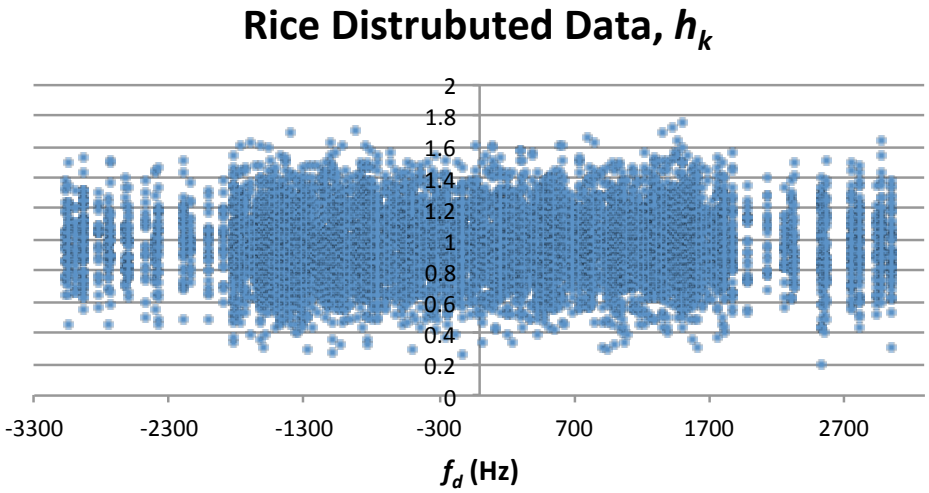


Figure 18: Rice Distributed Data

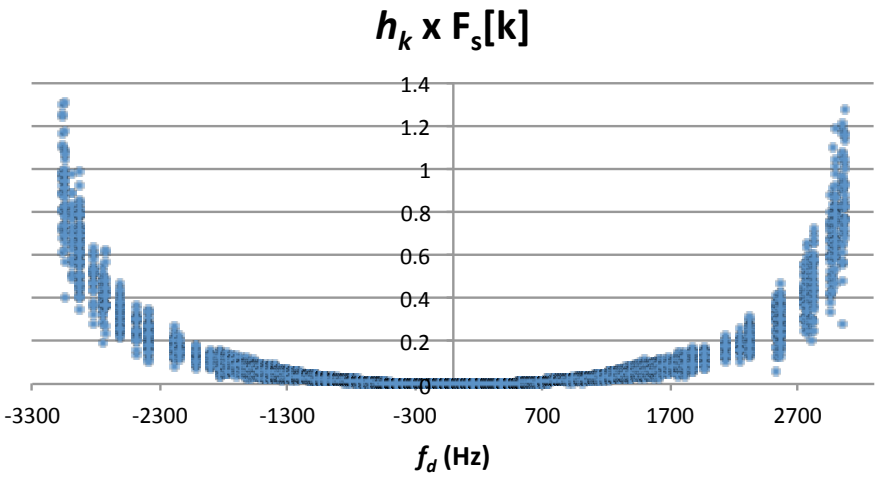


Figure 19: Rician data affected by Doppler filter

Figure 19, u_k, is h_k data scaled so that when it is added back onto h_k, data points at the ends, represent data points that are close to f_m and data points in the center are representative of data points that are close to the center frequency.

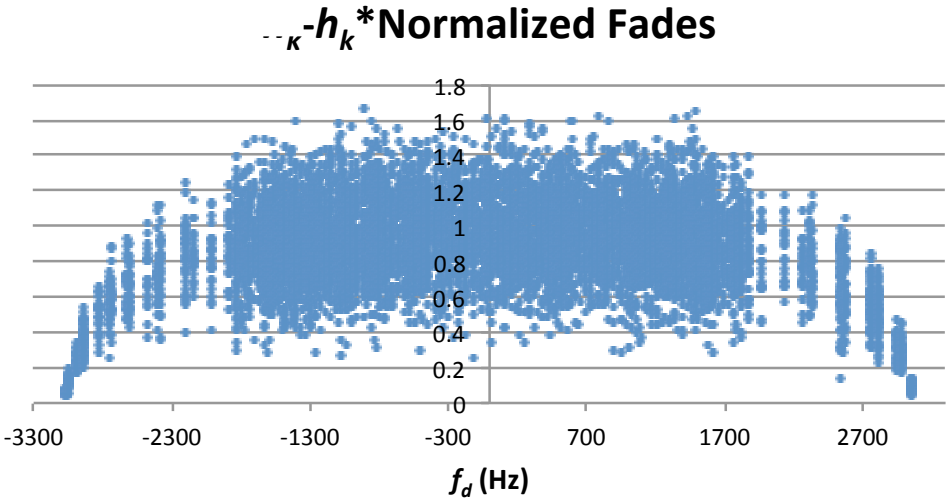


Figure 20: Doppler filtered data points

The resulting data that shapes the original data x_k, is shown in figure 20. The resulting data is then summed with noise data generated by equation 26.

$$n_k = \frac{1}{\sqrt{2}} \times \Big((0,1) + i(0,1)\Big) \times 10^{-\frac{\left(\frac{E_b}{N_0}\right)}{20}} \qquad \text{(eq 26)}$$

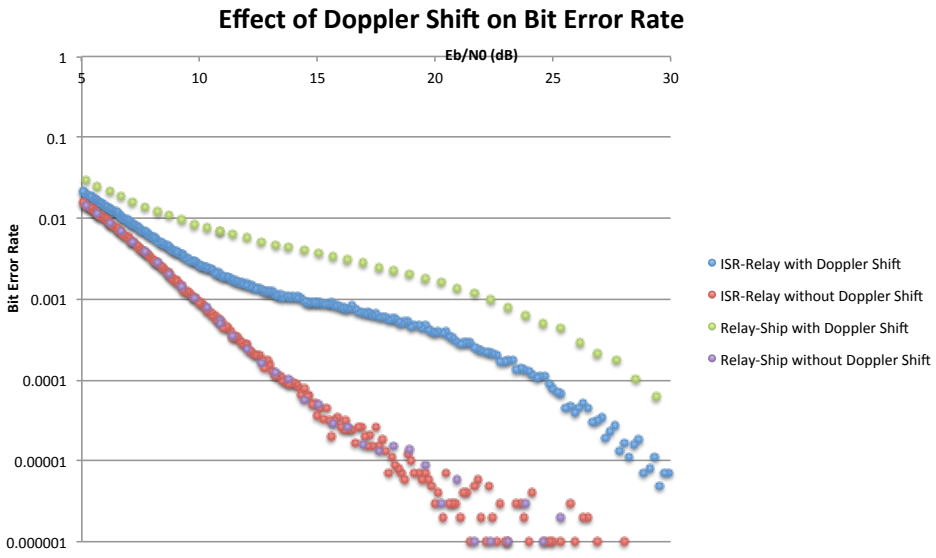


Figure 21) Effect of Doppler shift on bit error rate

The resulting effect that Doppler shifts have on bit error rate in the simulation is shown in figure 21. When F[k] always equals zero, h_k, is left untouched and the data at the receiver is only faded by Rician generated data in both links where there is no Doppler shift. There are much larger effects on bit error rate with respect to EbN0 received when Doppler shift is present. Figure 21 also shows that there is more Doppler effect between the communications relay aircraft and the host ship.

At each timestep of the simulation a large number of data points are randomly generated. The data points are faded by the Rician distributed data points and the Doppler spread frequency filter; then random noise, which is scaled by $\frac{E_b}{N_0}$, is added to the received signal; and the resulting signal, $y_k = x_k(h_k - u_k) + n_k$, is received and interpreted by the threshold detector. The threshold detector evaluates each data point and the number of incorrect detections divided by the number of data points that were generated in order to compute the bit error rate. The bit error rate and the packet sizes are used to generate a packet error rate or a message success probability. The receiving systems utilize the generic frame procedure as described in ITU-T recommendation G.7041/Y1303 which can correct single bit errors and detect multiple bit errors. Packet error probability is calculated with equation 27, where *p* is the bit error probability and N is the size of the packet.

$$P(message\ success) = (1-p)^N + Np(1-p)^{N-1} \qquad \text{(eq 27)}$$

Communications Link Analysis Summary

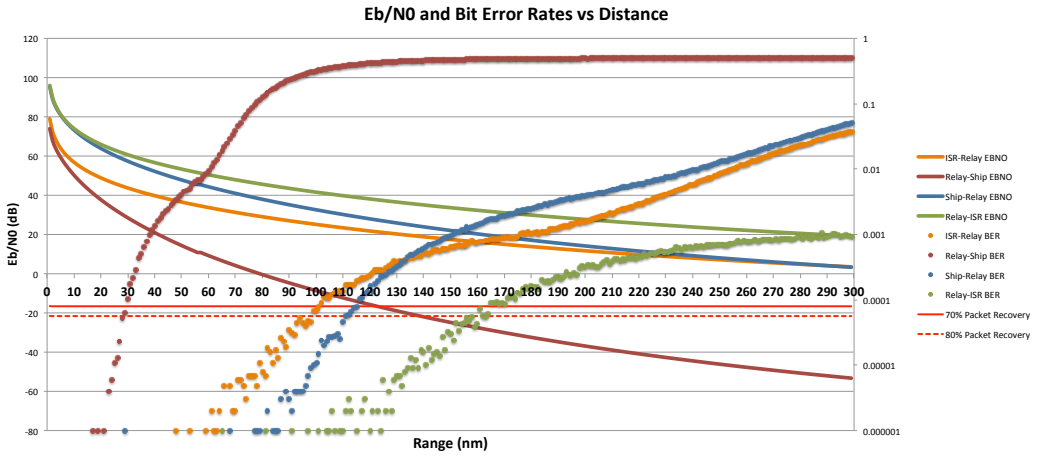


Figure 22) Communications Analysis Results

	ISR to Relay	Relay to Ship	Ship to Relay	Relay to ISR
Average Ground Range (nm)	72.76	24.27	24.27	73.52
Average Slant Range (nm)	72.87	24.75	24.75	73.63
Average C/N (dB)	17.83	23.75	27.27	17.45
Average C/No (dB)	104.36	106.76	113.80	100.47
Average Eb/No (dB)	31.05	33.45	60.79	47.45
Average BER (%)	3.54E-05	2.00E-05	4.07E-09	5.90E-08
Average Packet	71.10%	81.76%	100.00%	99.97%

Table 2) Average range, bit error rate, and probability of packet recovery

Refer back to figure 13 and equation 20 to see that the received signal, y_k, is then sent through a coherent detector and evaluated as either a one, if the real part of y_k is greater than zero. If the real part of y_k is not greater than zero, it is evaluated as a zero. The received data is then compared against the transmitted data to generate the bit error rate of the channel. The bit error rate is then used to evaluate packet error rate, or probability of message success. Results of the individual links in this scenario are presented in Table

2. The ISR aircraft to communications relay link is capable of recovering seven of 10 messages transmitted and the link between the communication relay unmanned system to host ship is capable of sending and recovering eight of 10 messages. These results are used in the next part of this analysis to quantify the overall network reliability when the Border Gateway Protocol is used to facilitate interoperability in the scenario.

Interoperability Analysis

Border Gateway Protocol

Each aircraft in the region contains one or more IP based networks. An Autonomous System is a connected group of one or more IP prefixes run by or more network operators that have a SINGLE and CLEARLY DEFINED routing policy (RFC 1930).

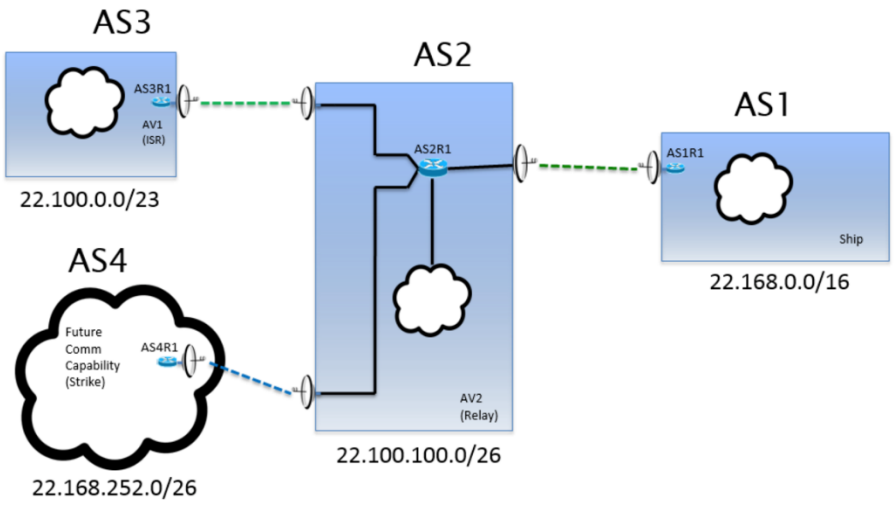


Figure 23) Autonomous System network architecture

Figure 23 depicts the network architecture of the aircraft to support connecting the aircraft in the mission region. The Intelligence gathering aircraft (AS3), relay aircraft (AS2), and ship (AS1) are Autonomous Systems and the group of aircraft on the mesh network (AS4) is an Autonomous System. A major problem in the operational mission area (the region) is that, currently,

all of the Autonomous Systems (aircraft and ships) may not be able to route packets between Autonomous Systems.

The Internet utilizes the Border Gateway Protocol version 4 (BGP) as described in RFC4271 in order to route IP packets between Autonomous Systems. This analysis will quantify the tradespace of data link reliability required in order to make the application of BGP in Navy aircraft networks a feasible solution inter-AS routing in the region.

The Border Gateway Protocol (BGP) is a protocol that allows Autonomous Systems to share IP address prefixes and route information about the IP prefixes between Autonomous Systems. BGP allows each aircraft in the region to advertise its existence to the rest of the aircraft in the region. The application of BGP to aircraft networks in a region for this analysis works as follows. In reference to figure 23, AS3 exchanges messages with AS2 with regard to the IP prefixes managed within AS3. The relay aircraft (AS2) updates its local routing table to include the IP prefixes learned from AS3 and advertises the learned IP prefixes to AS1 and AS4.

In order to quantify the tradespace of data link reliability, BGPv4 was modeled as described in RFC4271; the probability that a message sent by one BGP router was correctly recovered by the peer BGP router in the BGP session was varied; and in each timestep of the simulation, the link between both BGP Speakers in a BGP session were verified on whether the BGP Speakers were in the ESTABLISHED state or not in the ESTABLISHED state. The results are reported by the probability that the link between BGP Speakers in a BGP

session is established for a given percent of time in the simulation. For example, there is a 95% probability that the link between the relay aircraft and the host ship will be established for 69% of scenario given 8 of 10 messages sent between the BGP router on relay aircraft and BGP router on the host ship is received and recovered correctly. In other words, there is high confidence that the relay aircraft can correctly route IP packets from the host ship during 70% of the mission when the data link reliability between the relay aircraft and host ship is 80%.

Border Gateway Protocol Modeling

BGP Modeling Introduction

This section describes the modeling and simulation of the BGP Protocol in the network identified in the Scenario Development phase of this analysis. This is an event step, monte-carlo driven simulation. The model objects in the simulation are BGP Speaker, BGP Session, & BGP Simulation. BGP Speaker describes the attributes that define a BGP Speaker. Two of these attributes are identifier and autonomous system number. The BGP Session consists of two BGP Speakers and based upon the events that have occurred during the simulation, holds the state of each BGP Speaker in a BGP Session. The BGP Simulation defines each BGP Session and assigns BGP Speakers to each BGP Session. The BGP Simulation also tracks the input variables and quantifies the measures of effectiveness related to network reachability during the simulation.

BGP Speaker

The BGP Speaker in the model is defined by a unique identifier (an IP address) and the Autonomous System Number, which is a unique identifier of the Autonomous System. The BGP Speaker also holds three routing table databases. The names of routing table databases are the ADJ-RIB-IN, ADJ-RIB-OUT, and LOC-RIB.

The ADJ-RIB-IN holds all the IP address prefixes and routes learned from other BGP Speakers. When a BGP Speaker learns an IP address prefix and associated route from a BGP Peer in a BGP Session, the BGP Speaker puts that information into its ADJ-RIB-IN. Then the BGP Speaker chooses the best possible routes for the IP address prefixes in its ADJ-RIB-IN. Multiple routes may exist in the ADJ-RIB-IN for the same IP address prefix because a BGP Speaker may learn that different routes for the same IP prefixes from different sources. After the BGP Speaker has chosen a route for an IP address prefix, the BGP Speaker places that route in its LOC-RIB.

The LOC-RIB holds the routing information for all IP address prefixes and routes that the BGP Speaker is actively using. The LOC-RIB is created by choosing the best routes for the IP address prefixes in the ADJ-RIB-IN. The BGP Speaker will also aggregate IP prefixes to reduce the size of the LOC-RIB. For example if the BGP Speaker is already using a path for 22.100.0/17 and learns the prefix 22.100.128/17 and a shorter path with the same destination Autonomous System, the BGP Speaker can aggregate the IP address prefixes

(22.100/16) and use the shorter Autonomous System path of the two learned IP address prefixes.

The ADJ-RIB-OUT database holds all the IP address prefixes and routes that should be advertised to the BGP Speaker's BGP Peers. When a BGP Speaker learns a route and prefix from a peer, the BGP Speaker can be certain that the peer is actively using the route. When the BGP Speaker advertises a prefix and route, it will append its own Autonomous System number to the beginning of the route. For example, if the BGP Speaker in AS 65534 is using an autonomous system path of {64515, 65001, 64912} to reach prefix 22.168/16, then the BGP Speaker will advertise an autonomous system path of {65534, 64515, 65001, 64912} for the prefix 22.168/16 to the other BGP Peers to which the BGP Speaker is connected.

BGP Session Description (BGP Finite State Machine)

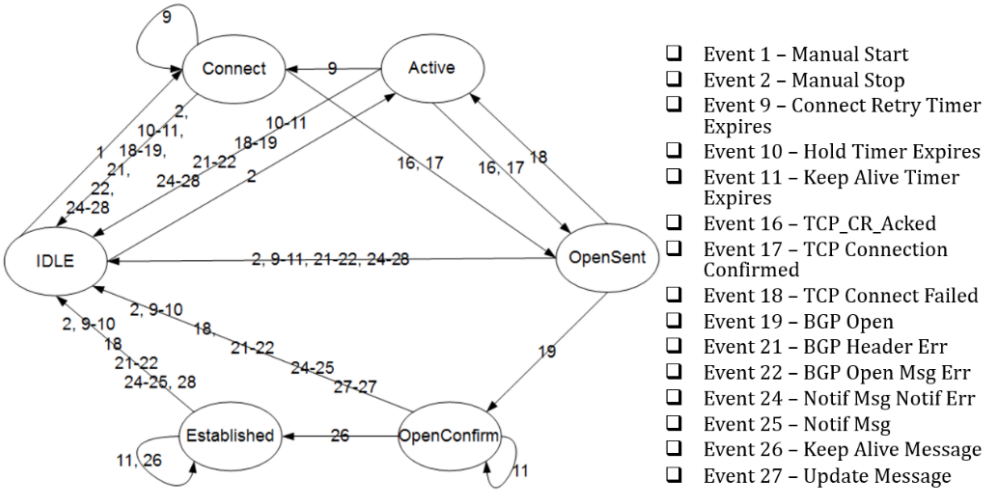


Figure 24) BGP Finite State Machine

Each BGP Session holds the status of both BGP Speakers connected to each other with the intent of sharing IP address prefixes and routes to increase internetwork connectivity. The status of a speaker in a session is specified by the state that the speaker is in. There are 6 states. These states are IDLE, CONNECT, ACTIVE, OPENSENT, OPENCONFIRM, and ESTABLISHED. When two speakers in a session are in the ESTABLISHED state, the speakers share the information in their ADJ-RIB-OUT databases. Then each speaker makes its own decisions on how to use each learned prefix and route. Once each speaker has updated its own LOC-RIB database, the speaker can correctly and efficiently route IP datagrams throughout the network of aircraft in the region. The state of each speaker is driven by the events that take place during the simulation. Each event is shown in Figure 24. There are 15 mandatory events specified in the BGP version 4 protocol. These events are listed in Figure 24 and are explained in detail in RFC 4271. The events and states together make up the Finite State Machine.

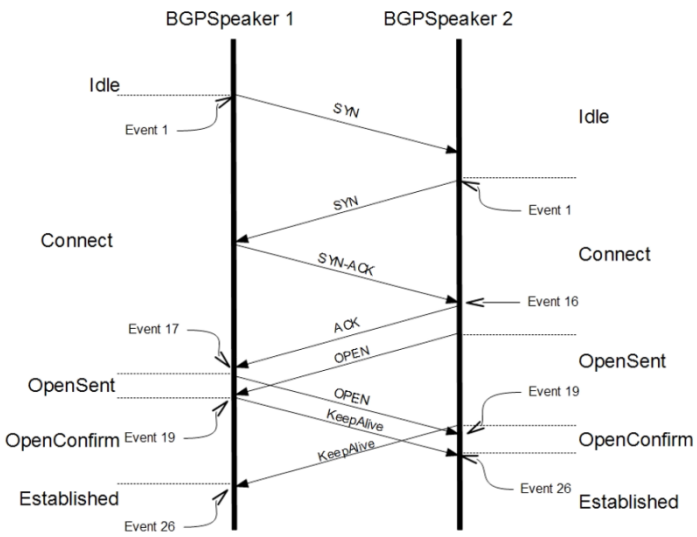


Figure 25) Session establishment sequence of events

Every BGP Session maintains a separate Finite State Machine for both BGP Speakers in each session. At the beginning of the simulation each BGP Speaker in the scenario is in the IDLE state. A BGP Speaker will attempt to establish a TCP connection to the other BGP Speaker in the BGP Session by initiating a Manual Start (Event 1). Establishing a TCP connection consists of one BGP Speaker sending a TCP SYN messages, the other BGP Speaker in the session replies with a SYN-ACK message, and finally the BGP Speaker that sent the initiating SYN message sends a TCP ACK message. This is called the SYN-SYN-ACK sequence described in the TCP protocol. The BGP Speakers then send OPEN messages and start keepalive timers as described in the BGP version 4 protocol and move into the ESTABLISHED state where the two BGP Speakers are able to share network reachability information. The sequence of events and states of two BGP Speakers in a BGP Session are shown in Figure 25.

Data Link Reliability is the Measure of Performance (input variable) that has the most effect against the percent of the simulation where two BGP Speakers in a BGP Session are both in the ESTABLISHED state. Data Link Reliability means that a percentage of packets sent by one BGP Speaker will be received correctly by the other BGP Speaker in a BGP Session. A 70% data link reliability between two BGP Speakers in a BGP Session means that 3 out of 10 messages sent between the two BGP Speakers will be dropped. When a BGP Speaker sends a message, with the eventual goal of establishing the link between itself and the other BGP Speaker in the session, the BGP Speaker sets the Connect Retry Timer. When the Connect Retry Timer expires (Event 9) the BGP Speaker will return to the IDLE state, wait for a Manual Start (Event 1), and then try to re-establish the link between the two speakers in a session. When the Connect Retry Timer is running, under the TCP Protocol, the BGP Speaker will continue to resend a message until there is an acknowledgment of receipt by the other BGP Speaker in the session. As Data Link Reliability drops, the probability that the Connect Retry Timer expires increases. Low Data Link Reliability means that there are more messages are sent in trying to establish the link than messages with respect to network reachability.

BGP Simulation

The BGP Simulation sets up the network for analysis by creating the BGP Speakers, defining which BGP Speakers are in BGP Sessions, and defines which events take place based upon the scenario.

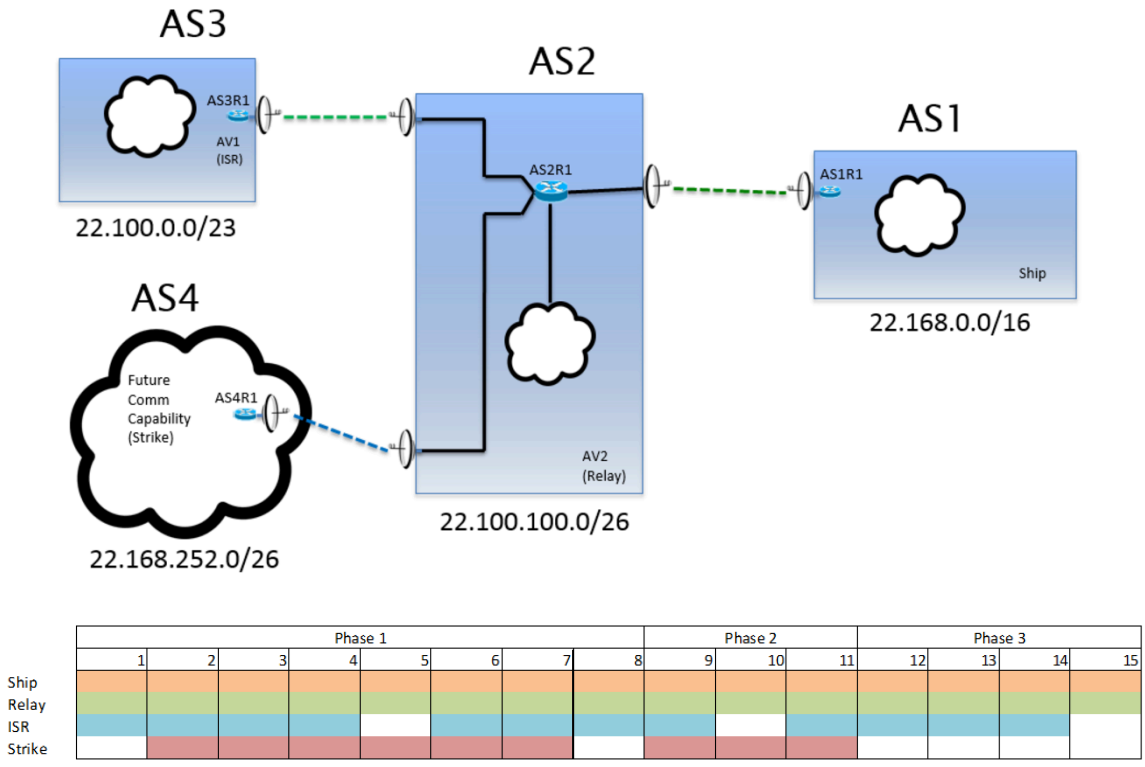


Figure 26) AS network architecture and aircraft on-station schedule

The BGP Simulation is driven by the timeline and network architecture shown in Figure 26. The ship and relay objects are present through the entire scenario; the Intelligence gathering aircraft is present in the scenario during hours 1-4, 6-10, and 11-14; and there are aircraft belonging to the Strike (mesh) network during hours 2-7 and during hours 8-11. The BGP simulations triggers events based upon the network architecture and the scenario timeline. During the entire scenario when AS2R1 or AS1R1 is not in the ESTABLISHED state, a Manual Start event is applied to the BGP Speaker that is not in the ESTABLISHED state. The flow of events that follow the Manual Start are driven

by the Finite State Machine that is managed in the BGP Session between BGP Speakers AS2R1 and AS1R1.

The BGP Simulation tracks the status of the links at every time step in order to quantify the effect of data link reliability on network reachability. At every second, when two BGP Speakers are in a BGP Session are both in the ESTABLISHED state, the BGP Simulation increases a counter for the link associated with the BGP Session. The results are reported as a probability that the links are established when they need to be established. For example, given the link reliability between the mesh network and the relay aircraft is 70%, there is a 95% probability that the link between the relay aircraft and the mesh network is established for 80% of the scenario. In other words, there is high confidence in the mesh network being connected to the rest of the network for 80% of the scenario when seven out of ten messages are successfully sent and received between mesh network aircraft and the relay aircraft.

BGP Modeling Summary

The three model objects BGP Speaker, BGP Session, and BGP Simulation create the structure for which to quantify the tradespace of data link reliability required to maintain network connectivity between the four Autonomous Systems that represent the intelligence gathering aircraft, relay aircraft, host ship, and the strike network of aircraft in the scenario. BGP Speakers hold the databases of learned IP address prefixes and routes, choose which routes to use, aggregate routes when appropriate, and advertise the routes that the BGP

Speaker is using to other BGP Speakers. The BGP Session manages the Finite State Machine of both BGP Speakers in a BGP Session and controls the flow of events that happen during the simulation. The BGP Simulation drives the simulation by creating the BGP Speakers, putting pairs of BGP Speakers into BGP Sessions, defining the data link reliability between the two speakers in a session, and tracks the percentage of simulation time that both speakers in every session are in the ESTABLISHED state.

Analysis Results

The link between the host ship and the relay aircraft is called the relay link and has a data link reliability of 80%. In figure 23, the relay link is the link between AS2 and AS1. The reliability of the relay link was determined based upon existing program requirements and documentation for the data link systems. The link between the relay aircraft and the intelligence gathering aircraft is called the ISR Link and has a data link reliability of 70%. In figure 9, the relay link is the link between AS2 and AS3. The ISR link and the relay link both currently exist and are in use on Navy aircraft and ships today. The relay link is an air-to-ground link where the host ship (ground terminal) is stationary and the aircraft is always moving. The ISR link is an air-to-air link where both aircraft are moving at various speeds and altitudes throughout the region. The 10% degradation of the ISR link from the relay link is due to the air-to-air vs air-to-ground motion of the objects. The link between the relay aircraft and the strike network of aircraft is called the strike link and is a future capability that

requires integration into the current existing network. The future capability is expected to have a data link reliability of 90%.

The existing capabilities of data links is such that data can be passed between platforms over the current point-to-point data link, but not forward that data on to another destination. If the intelligence gathering aircraft (AS3) would like to pass data to the host ship (AS1). There must be a direct connection between AS3 and AS1. Although the network architecture exists where AS2 (the relay aircraft) can simultaneously be connected to AS3 and AS1, the AS2 cannot receive packets from AS3 and forward the packet on to AS1. As a potential solution, each individual aircraft is considered an autonomous system. This means that the application of the Border Gateway Protocol as described in the Border Gateway Protocol Modeling section gives every platform in the scenario the ability to share IP address prefix reachability information and routing information to the other platforms in the mission region. BGP Speakers are able to forward datagrams correctly within the network when both BGP Speakers in a BGP Session are in an ESTABLISHED state.

Individual Link Performance

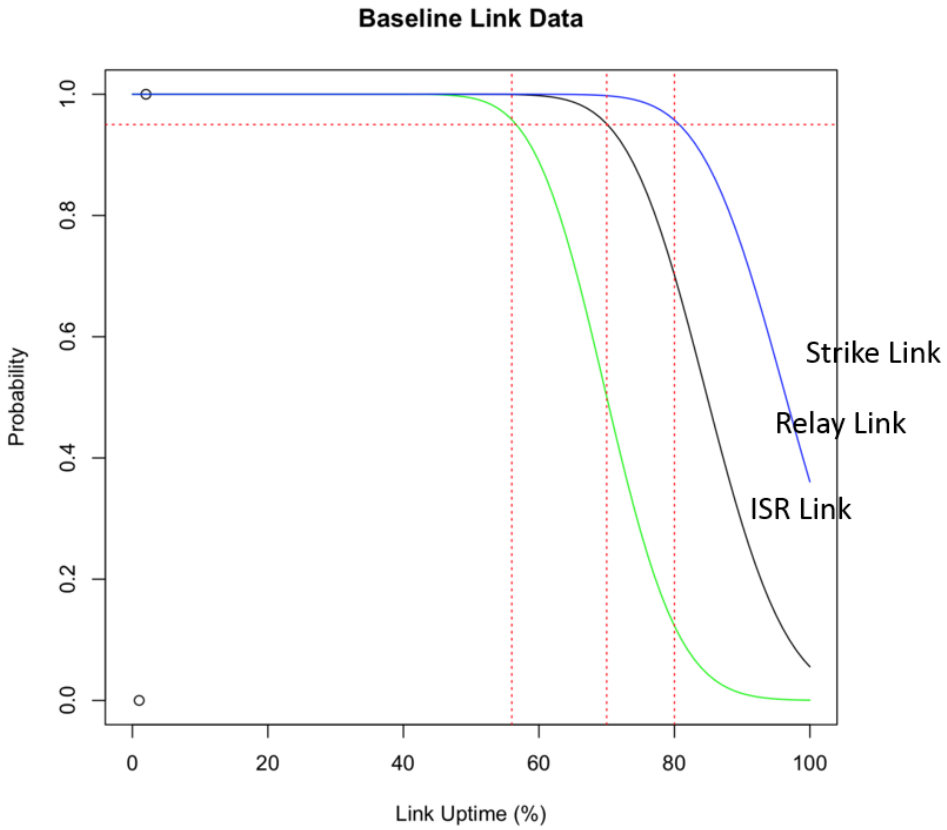


Figure 27) Data link reliability results

The data link reliability of the strike link is 90%, the reliability of the relay link is 80% and the reliability of the ISR link is 70%. Figure 27 is the poisson cumulative distribution function of the probability of link establishment vs. the percent of time the link is established throughout the simulation. Figure 27 shows the probability that both BGP Speakers in a BGP Session (y-axis) will be in the ESTABLISHED state for the percentage of the scenario (x-axis). Given that nine of ten messages between the relay aircraft and aircraft in the mesh network are correctly recovered by the receiving BGP Speaker, there is a 95% probability that relay aircraft can forward datagrams into the mesh network

correctly for 80% of the scenario. Given that seven of ten messages between the relay aircraft and the intelligence gathering aircraft are correctly recovered by the receiving BGP Speaker, there is a 95% probability that relay aircraft can forward datagrams to the intelligence gathering aircraft correctly for 56% of the scenario. Given that eight of ten messages between the relay aircraft and the host ship are correctly recovered by the receiving BGP Speaker, there is a 95% probability that relay aircraft can forward datagrams to the host ship correctly for 69% of the scenario. These results show that (1) percent of time that BGP Speakers in a BGP Session are ESTABLISHED is lower than the data link reliability and (2) the probability that both BGP Speakers in a BGP Session are in the ESTABLISHED state drops as the percent of link establishment during the simulation increase

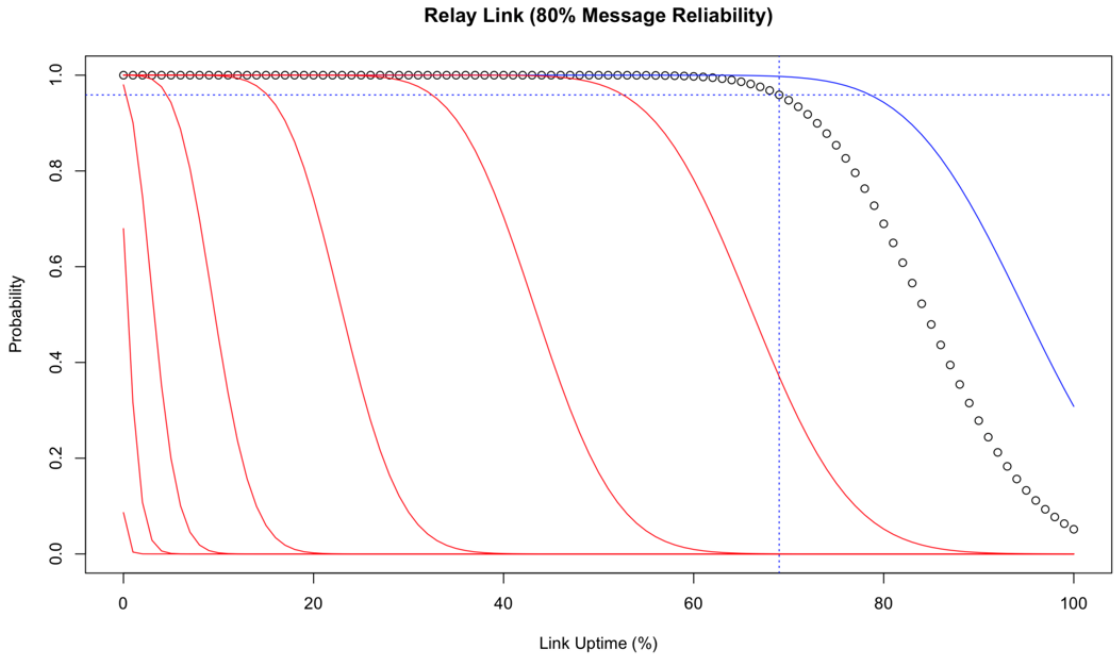


Figure 28) Relay Link message reliability

The effect of data link reliability against link establishment is shown in Figure 28. The graph shows data link reliability from 10% (far left) to 90% (far right) on probability of link establishment vs. percentage of scenario time that the link is established. As stated before, the data link reliability between the relay aircraft and the host ship is 80% and there is a 95% probability that the link between the two platforms will be established for 69% of the simulation. Figure 28 shows that when data link reliability drops, the percent of time during the simulation that the BGP Speakers connecting AS2 (the relay aircraft) and AS1 (the host ship) are both in the ESTABLISHED state also declines. The relationship between data link reliability and link establishment is also not linear. There is a larger increase in link establishment between 50% and 60% data link reliability than the increase between 80% and 90% data link reliability or 10% and 20% data link reliability. The ISR link and the strike link show the same results and effects.

Overall Network Connectivity Results

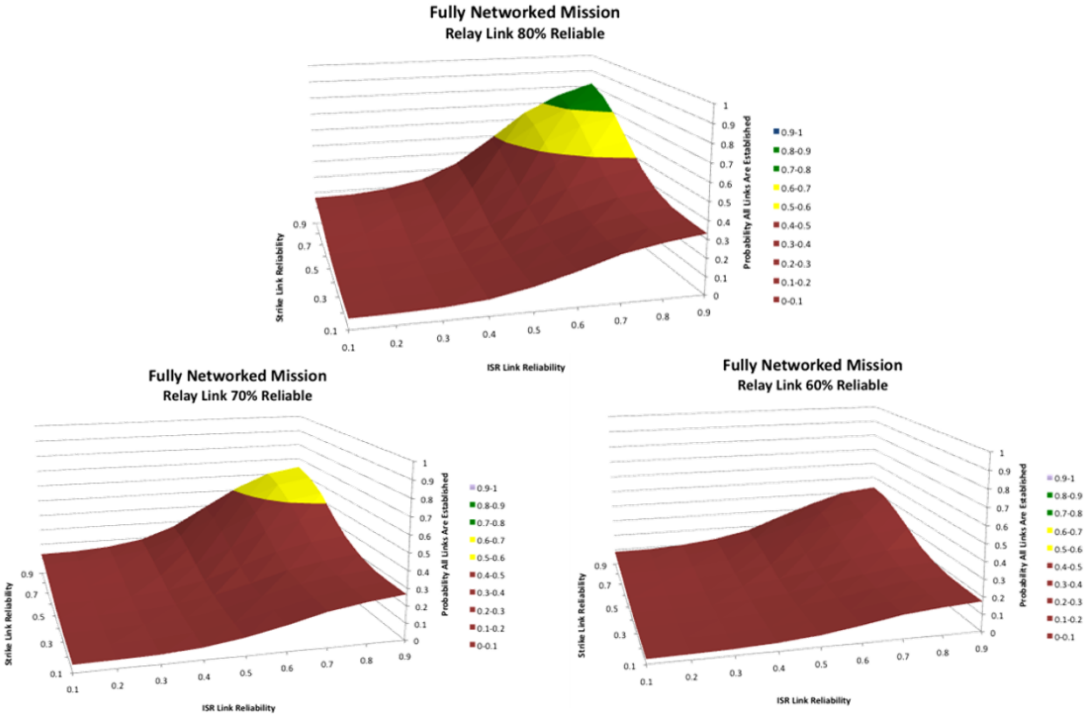


Figure 29) Interoperability Analysis results

Our goal, in this analysis, is to answer the following question. Can we integrate multiple networks onboard aircrafts and ships in a mission area? Yes. When each platform is viewed as an autonomous system, the addition of BGP Speakers to each platform behind the data link terminals gives each platform the capability to share enough information to correctly forward datagrams throughout the network of networks. Existing air-to-air and air-to-ground data links are not 100% reliable. Some percentage of messages sent by one data link terminal onboard a platform will not reach the intended receiving data link terminal for a number of reasons. Therefore, the connections between BGP Speakers must be reliable enough to support the application of BGP in airborne

networks. This means that when links are unreliable, BGP Speakers are not able to stay in the ESTABLISHED state. BGP Speakers often return to the IDLE state when their keepalive timers expire. The resulting effect is that many more messages related to re-establishing the link are sent in order to drive both BGP Speakers in a BGP Session back into the ESTABLISHED state rather than actual mission related information. The quantified tradespace of data link reliability required to connect all platforms in the region is shown in figure 29. The set of graphs shows the tradespace of data link reliability for all three data links in the simulation where the Navy will have full network connectivity in the mission area above a certain percentage of the mission. A fully connected network in the mission area, where any platform can send a datagram to any platform in the region as shown in figure 29, does not currently exist. A minimum standard for connectivity in the region is defined as 50% (yellow), with an objective requirement for having a fully connected network for 70% (green) of the scenario. There is a tradeoff between the three links where if one link is underperforming, increasing the data link reliability of the other two data links will increase overall network connectivity. The mesh network (strike data link) link is not a currently fielded capability. This analysis helps us set the program requirement for this future network data link reliability. Under the assumptions that the relay link message reliability is 80% and the ISR link message reliability is 70%, the minimum data link reliability for the strike data link must be 70% in order to achieve full network connectivity for greater than 50% of the simulation. Applying an objective requirement of 90% on the future

strike network data link would increase network connectivity to 64% given the current data link reliability of the air-to-ground and air-to-air data links. In order to bring full network connectivity up to 70% over the timeframe of the mission scenario, existing links must also be upgraded achieve better data link reliability. If data link reliability of the air-to-air data link between the intelligence gathering aircraft and the relay aircraft is increased to 80% and the future strike network data link set to 80%, leaving the current 80% data link reliability between the relay aircraft and the host ship unchanged, there is a fully connected network between all platforms in the mission region for over 70% of the scenario.

Study Summary

The application of Border Gateway Protocol can be used to connect the multiple heterogeneous networks in a mission region in order to increase interoperability across the operational battlespace. There are many different Navy aircraft and ships managed by many different program elements and network administrations. The host ship and aircrafts in the mission region can be split in to separate groups defined by their single and clearly defined routing policy. Using the BGP protocol is not a new requirement for Navy programs. The requirement to use BGP exists in current program documentation. Although the application of Border Gateway Protocol to an existing program is not a new requirement, the addition of technology on the aircraft will be required to support the application of BGP on Navy airborne networks.

Through Scenario Development, this analysis had identified a need to create a communications relay node in order to connect the networks. The aircraft identified as the relay aircraft would be an unmanned air vehicle with high endurance. The relay aircraft that currently operates with a Common Data Link terminal would require an additional mesh network data link terminal. Using an aircraft as a relay node also removes the beyond line-of-sight data paths, the very costly data paths, as a primary data path. Simply adding the mesh network data link terminal does not, in itself, give the relay aircraft the ability to forward datagrams to any host computer in the mission region. The Scenario Development phase, conducted in collaboration with the

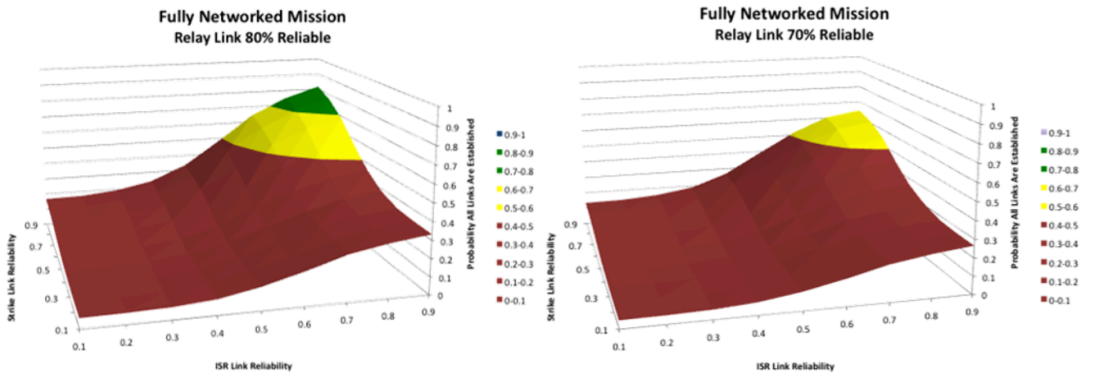
warfighter, identifies the aircraft to use as a relay node, outlines a high-level concept of operations, and defines the network architecture. Scenario Development alone does not fully answer the question, Can Border Gateway Protocol increase interoperability and therefore increase the mission effectiveness of our aircrafts and ships in an operational battlespace?
The Communication Link Analysis part of this analysis evaluates the performance or ability of the data link terminals to support interoperability in the mission scenario. The bottom line metric of goodness for data links in the scenario is probability of successfully recovering a message sent from a data link terminal on the host ship or aircraft on station and recovered at the intended destination. The performance of data link terminals in the mission area is degraded by a number of factors. Degradation of a transmitted signal will happen because of distance between terminals due free space path loss and other losses due to atmosphere, such as rain fade attenuation. The transmitted signal will also experience small scale fading, which is modeled as a rice fading channel in this analysis because of the terminals are within line of sight at all times. The aircraft in the scenario are moving at speeds up to 124 nautical miles per hour and are operating at different altitudes. There is a fair amount of Doppler shift between the transmitting and receiving terminals in the scenario.

The simulation quantifies bit error rate by calculating the received energy per bit to noise density ratio at the receiving terminal, taking into account power at the transmitter and degradation of the signal due to free

space path loss and rain fade. Randomly generated data is simulated through the channel faded by Rician distributed data and the effects of Doppler shift. The generated data further complicated by additional noise which has been scaled due to the received energy per bit to noise ratio. The data points are then evaluated by a threshold detector and recovered, either correctly or incorrectly. The received data is compared against the original data sent over the channel and the number of incorrectly received bits divided by the total number of bits sent is the bit error rate. The bit error rate is then used to evaluate a packet error rate based upon the average size of packets sent through the channel. The results of this analysis are presented in the following table. There is a 70% probability of recovering message from the ISR aircraft to the unmanned air vehicle executing the relay communications mission. There is an 80% probability of recovering a message sent from the communication relay aircraft to the host ship. These results are used in the Interoperability Analysis section of this study.

	ISR to Relay	Relay to Ship	Ship to Relay	Relay to ISR
Average Ground Range(nm)	25.17	20.34	20.34	25.04
Average Slant Range (nm)	22.22	20.92	20.92	25.33
Average C/N (dB)	9.90	12.77	4.28	9.06
Average C/N0 (dB)	96.43	95.78	90.82	92.07
Average Eb/N0 (dB)	23.12	22.47	37.81	39.06
Average BER (%)	7.347E-05	1.769E-05	8.416E-08	1.136E-07
Average Message Success Probability (%)	70.69%	82.51%	99.95%	99.94%

The Interoperability Analysis phase quantifies the tradespace of data link reliability required to support the addition of new technology and the application of Border Gateway Protocol. The new technologies on the platforms are the addition of a mesh network data terminal on the relay node and BGP Speakers on all of the autonomous systems. The simulation of the application of BGP shows that there is a tradeoff of data link reliability, but there is a minimum threshold where there is full network connectivity for over 50% of the mission scenario. That tradespace is depicted in the figure below.



The probability that any host computer can send data to any host computer in the mission region is never greater than the probability that all BGP Speakers are in the ESTABLISHED state. Full network connectivity in the mission region is only as strong as the most unreliable link. The probability that all BGP Speakers are in the ESTABLISHED state for greater than 50% of the mission scenario is shown in yellow and greater than 70% is shown in green.

This study will be used to inform several efforts being conducted by different groups throughout Naval Air Systems Command. Specifically, this analysis will inform operational demonstrations conducted by the Program Executive Office of Unmanned Aviation and Strike Weapons (PEO (U&W)) Common Standards and Interoperability, the creation of battlespace simulations by the Navy's Warfare Analysis and Integration Department, and support the creation of a Navy-wide Data Transport Strategy.

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