An Adjustable Budget-Based Detection Toolbox for Contested Spectrum Environments

By 1st LT Nolan Pearce and Joe Rottner

Electromagnetic Spectrum (EMS) operations in contested environments require battlefield assumptions based on mission dependent factors and complex electronic warfare (EW) concepts. To Soldiers unfamiliar with antenna theory and radio propagation, it can be difficult to visualize the impact of Electromagnetic signatures and the tactical benefit of Electronic Protection (EP) or Electronic Support (ES) operations.

The cyberspace domain, especially the EMS, is a complicated gray space with friendly, adversary, and non-state actors competing for limited spectrum resources. Variables in equipment, terrain, and mission requirements endlessly complicate the following two simple questions:

1. Will friendly forces successfully receive my communications?
2. Will enemy forces be able to intercept my communications?

An input-based toolbox, leveraging foundational wireless communication principles and calculations, allows for instant approximation to the above questions. By abstracting propagation calculations behind a mission-relevant toolbox, Soldiers can stay mission-focused with relevant information about the EMS environment. Current systems regarding EMS operations require operation by a skilled technician and produce more output than decipherable or necessary for a ground Soldier.

Our toolbox, available at https://www.github.com/jrottner/detection_toolbox, uses a series of user inputs and python functions to create EW-based mapping tools. Users can select their waveform, frequency, transmitter power, and link distance under a given detection probability. After calculations are performed, the users are met with a simple "GO/NO-GO" on the success of their communication and the probability of detection from enemy EW equipment along a two-dimensional (2D) map.

The toolbox is endlessly customizable for the addition of new features. While the initial design gives a definitive answer to the probability of success, more waveforms and environmental details may be added for specialized cases. This toolbox will allow its users to gain an understanding of the EMS through experimentation in training and allow for quick solutions in live scenarios.

Background

This toolbox is essentially an endless customizable link budget. Just like a financial budget, factors in the user's communication link debit or credit the signal strength. If the user finds that their link is unsuccessful between friendly locations, more than just the transmitter power may be changed to achieve mission success.

Link budgets are generally dependent on the following factors:

1. Transmitter power
2. Antennas at both the transmitter and receiver locations
3. Relative locations of the transmitter and receiver
4. Transmission frequency
5. Transmission mode
6. Random or intentional impediments in the environment (vegetation, jamming, etc.)

Design of the toolbox required some design liberty with user input, toolbox-designated specifications, and output. For example, while the user will often change parameters such as frequency, link distance, power, and modulation scheme, it is assumed that the ability of an enemy detector will remain constant. Similarly, it is assumed that a successful communication link – meaning, the transmitted signal received above a certain signal-to-noise ratio (SNR) – will stay the same for each mode regardless of implementation.

For this initial toolbox, frequencies were customizable within the very-high/ultra-high frequency (VHF/UHF) range. This range is the most closely comparable for point-to-point communication links and involves the simplest forms of wireless channel effects. In HF links below the VHF range (less than 30 MHz), wireless signals potentially bounce multiple times between the earth's surface and the ionosphere. Links in the UHF range (300MHz-3 GHz) are often used for satellite links with greater range and greater antenna array performance at a similar physical size. The penalty paid for these higher frequencies is more atmospheric absorption or other phenomena. These links may require weather-dependent factors unnecessary for a simple line-of-sight (LOS) link. Therefore, the toolbox will focus on the more operationally relevant VHF/UHF frequency bands for LOS operation predictions.

Currently, many industry standards exist for wireless propagation modeling over certain terrain. As more cellular networks come online, telecommunication companies often need to identify possible weaknesses in cell tower locations or in indoor wireless environments. The Free-Space Path Loss model primarily uses the distance between transmitter and receiver to identify the power lost over this link but relies on free space assumption that there is no terrain, vegetation, or buildings between the two points. However, the Hata model accounts for these scenarios and the Hata adjusted model allows for customization in rural and suburban environments. The Hata and Hata adjusted model appear to track real-world path loss more closely than the simplistic Free Space Path Loss model. We proceed with these more descriptive models to balance more predictive performance while simplifying the amount of descriptive input information needed by the operator.

To define success in the toolbox environment, a user must achieve a higher received SNR than the minimum viable SNR at the receiver's location. This means a signal will be received with more than enough power to be successfully decoded. The received SNR is calculated using a link budget approach with options to select various modeling algorithms for the distance-based path loss from the transmitter to the receiver. The minimum SNR, however, is calculated as an assumption based on the Shannon-Hartley Theorem. This theorem states that a communication environment has a maximum capacity for transmission (in bits / second) for a given SNR and signal bandwidth; by using a given data rate and bandwidth for common military signals, the minimum viable SNR can be found.

Users cannot change the minimum viable SNR. However, the SNR determined by the link budget calculation will be updated if the user changes their test parameters – for example, the user can move their radio locations closer together and will see a higher SNR because of the decreased distance.

Calculation of enemy interception underwent a similar application. To find the maximum intercept distance, the minimum viable SNR was used as the receiver signal strength. From here, the maximum distance possible while still achieving a successful link could be found from the transmitter. This gives a likely area where other forces could intercept the transmission given the experimental variables.

These calculations only identify data points – the received SNRs – possible at given locations. However, geographic mapping tools allow for easily interpretable results. The SNRs are first converted to "GO" values if they are greater than the minimum viable SNR and "NO-GO" otherwise. These values, assigned to their relevant coordinate grid location, appear as a "heatmap" on a map of the link location. Overall, these outputs easily allow users to identify the strength of their communication link and see possible enemy intercept areas.

Application

A simple application for this toolbox is a point-to-point single-channel ground and airborne radio system (SINCGARS) VHF link between two whip antenna stations. In the toolbox, two arbitrarily selected points were used to test this link. The transmitter was placed at Barton Field in Fort Eisenhower, GA, and the receiver at the first tee of the Masters Course in Augusta, establishing a reasonable 13km link distance for VHF Line-of-Sight. The user selects omnidirectional antennas for both radios and uses the Free-Space Path Loss model due to the relatively unrestricted and flat terrain between the two points.

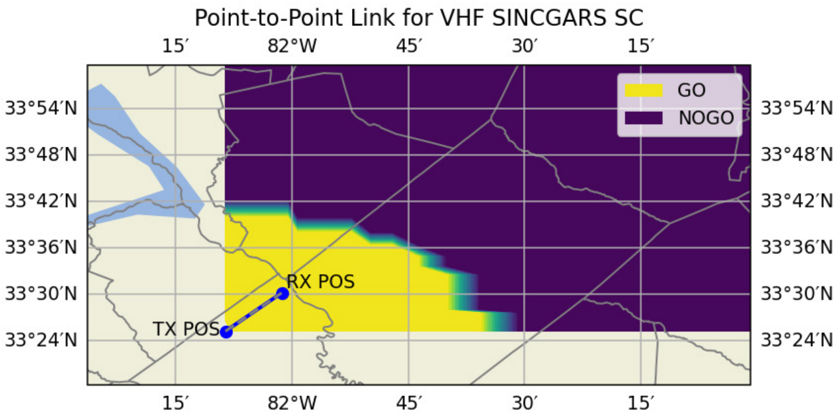

Figure 1: Toolbox output depicting a 25W SINCGARS Radio at 80 MHz in Fort Eisenhower, GA

After running the calculation, the user is presented with a "GO/NO-GO" on successful link establishment and a heatmap of the received SNR. Using the calculations previously mentioned, VHF SINCGARS requires around 4 dB minimum viable SNR. Based on the link, the path loss between the two points is around 9dB. Therefore, the user needs a transmission power of at least 13 dB or 20 watts.

Similarly, the user can see an approximate range of detection from their transmitter point. If the simulation started with 25W of transmitter power, the detection range extends a few kilometers outside of the receiver's range. This

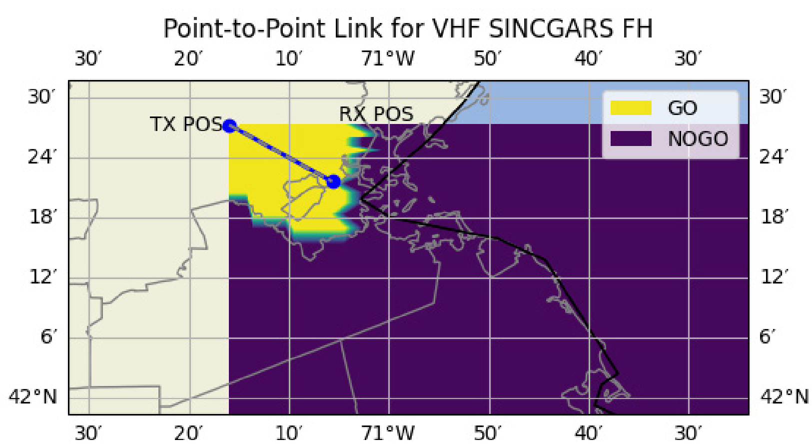

Figure 2: Toolbox output depicting a 20W SINCGARS FH Radio at 120 MHz in Lexington, MA.

may encourage the user to limit the transmitter's power for a lower probability of enemy detection or interception.

Users can test SINCGARS frequency hop (FH) with a directional Yagi-style antenna at the transmitter. Locations for these transmitters were set at MIT Lincoln Lab's Katahdin Hill and the MIT Library in Cambridge, MA. The main lobe of the Yagi antenna clearly allows for more selective communication towards the friendly receiver station. Similarly, the FH mode increases the effective range of the radio by allowing a lower minimum viable SNR at the receiver. Starting from the same 20W transmitter power, the minimum viable SNR is 4 dB along the axis of the main lobe of the directional antenna. Because the transmitter station is in an elevated position (roughly 100 meters), its effective range is similarly increased. Enemy detectors will generally need to stay in the main lobe of the antenna to successfully intercept friendly communications.

Given the option to tweak simulation parameters, Soldiers should be able to identify potential advantages and vulnerabilities in their EW arsenal. Even for a simple point-to-point radio check, the toolbox will allow for a broader understanding of EMS signatures and operations within congested environments.

Additional Research

The electromagnetic spectrum is a constant-changing battlefield. However, its backbone of theorems, algorithms, and assumptions remain constant. Open-source mapping functions and calculations, derived from common military EW assets, enabled the creation of a toolbox useful for testing link fidelity.

This toolbox can expand in several different research areas. First, more communication modes, frequency ranges, and radio profiles can always be added to suit each individual battlefield need. Modern communication modes often employ anti-jam and anti-detection methods that would enable successful communication much further than calculated using simple single-channel SINCGARS. For example, packet and digital FM amateur radio modes both occupy the same frequency range as FM voice, but can travel further distances due to their lower bandwidth. Automatic link establishment (ALE) would allow for communications over greater distances using the HF frequency range. Improvements in path loss modeling for frequency hop systems – namely, doppler fading and wideband scattering – would give a better picture to the EMS impacts towards transmitted signals. Likewise, recent advancements like the Trellis TSM® waveform and mobile ad-hoc network (MANET) systems require further analysis to determine a minimum viable SNR for the toolbox.

The toolbox currently calculates its received signal criteria based on input conditions. However, the inverse could also be calculated – the toolbox could suggest what optimal frequency modes, locations, and antennas should be implemented for a given set of environmental conditions.

Statistical modeling could improve the decision-making output from the simulation. Calculations with the probability density function will produce the outage probability, or the percent chance that a signal will fall below the minimum viable SNR. Instead of the produced "GO/NO-GO", the simulation could give a probability heatmap of expected outages.

The toolbox can also be implemented in any number of training environments due to its low complexity and simple python framework. Link budget calculations could be added to the Team Awareness Kit (TAK) suite for greater situational awareness in a congested spectrum environment.

Conclusion

The cyberspace domain is mired in uncertainty. Environmental and mission variables complicate whether or not a link exists between friendly radios. This toolbox would help to clearly and reliably inform Soldiers of the feasibility and possible risks of EMS operations, while enabling a greater tactical understanding of communication principles as it relates to the mission.

Author Bios

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Acknowledgements

The code for the toolbox can be found at https://www.github.com/jrottner/detection_toolbox/ under an MIT Open Use license. All information for wireless propagation was taken from Andrea Goldsmith's 2020 Wireless Communications textbook, freely available through the Stanford University website. We encourage any collaboration or suggestions for this toolbox.