Battlefield Command and Control Systems Resilience in an Electromagnetic-Contested Environment:

Modeling Electronic Warfare Impacts on Communications Networks as Dependent Hidden Markov Models

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1 Problem Statement

1.1 Background

Since the turn of the 20th century, electronic warfare (EW) has steadily become a critical tool across the entirety of modern combat. EW is used:

- At the tactical, operational, and strategic levels of war.
- In the land, air, sea, and electromagnetic domains.
- Across the entire spectrum of warfare:
  - Peacetime deterrence.
  - Information and influence operations.
  - Intelligence and counter-intelligence activities.
  - Kinetic and non-kinetic engagements.
  - Offensive and defensive operations.
  - Peer/near-peer warfare.
  - Irregular, asymmetric, and hybrid warfare.
  - Special operations.
  - Et cetera.

In the ongoing Russo-Ukrainian War, teams routinely employ EW to"jam" radio signals used for voice communications, counter-battery and air defense artillery radar, and unmanned vehicle control. After the United States-led invasion of Iraq in 2003, the use of improvised explosive devices (IEDs), and in particular remote-controlled IEDs (RCIEDs), led to a technology war between the U.S. Department of Defense (DoD) and insurgent bomb-makers to develop and evade radio-frequency (RF) jamming equipment meant to prevent RCIED detonation. In popular culture, *Top Gun* twice brought action-packed clips of firework-like flares and shimmering chaff into movie theaters and living rooms; flares and chaff are counter-infrared and counter-radar target acquisition systems that aircraft and helicopters routinely deploy against anti-air threats.

1.2 The Digitization of the Battlefield

The introduction of wired telephony in 1876, radiotelegraphy in 1897, and radiotelephony in 1900 set off a series of revolutions in battlefield communication. For thousands of years, senior commanders personally directed combat operations from the front lines, issuing orders through face-to-face communications, passing notes via runners, and using drums and horns to synchronize operations across vast battlefields. The U.S. Army maintained bugles and drums in combat formations through the start of World War I, when they were replaced by miles upon miles of hand-laid telephone cables connected trenches to command posts up and down western Europe. Vehicle and man-portable radios were introduced in World War II, enabling commanders to maintain communications while on the move. Satellites were used for analog communications during the Vietnam War, connecting the bureaucracy in Washington, D.C. with battlefield commanders in real time. Prior to the ground invasion in the 1990-1991 Persian Gulf War, a fully computerized and digitized Allied force hacked, jammed, and bombed the Iraqi Armed Forces from afar; the Iraqi Navy virtually ceased to exist, and the Iraqi Air Forces fled the country. Allied forces then easily overmatched the Iraqi Army during the 100-hour-long ground invasion with computerized weapons systems, encrypted communications, and satellite navigation.

1.3 Tomorrow's War, Today: Modeling EW Effects on C4 Systems

Given the deep integration of RF-based communication in Western military formations and the widespread and effective use of EW by the Armed Forces of the Russian Federation in Ukraine, there is an urgent need to develop accurate models integrating adversary EW systems; friendly command, control, communications, and computer (C4) systems; [1] and friendly C4 redundancy plans, commonly referred to as "PACE" (Primary, Alternate, Contingency, and Emergency) plans. For the purposes of this analysis, we will refer to the friendly force as the blue team and the adversary as the red team.

The meta-system of red EW systems and blue C4 systems and networks can be modeled as a dependent hidden Markov model (HMM), and the meta-system of C4 systems that constitute the blue team PACE plans forms a C4 network. The health of the network affects the flow of information from the front lines to the senior commander's headquarters and vice versa. An effective red team jamming mission might completely isolate a blue unit from communicating with the rest of the blue team. In this case, the blue unit would not be able to receive updated orders, coordinate operations, or submit requests for support such as fire missions (artillery or close air support (CAS)) or medical/casualty evacuation (MEDEVAC/CASEVAC). The degradation or disruption of the C4 network provides valuable information to planners so that communications plans can be modified or augmented to increase network reliability, or to develop contingency plans for when units experience the total disruption of communications with other elements. Analyzing the HMM provides the data needed to analyze the C4 network graph. By analyzing the steady state of the network graph during jamming operations, we can identify clusters of nodes that become isolated from the rest of the graph and evaluate possible changes to relevant PACE plans to improve the health of the network graph.

2 Data Source

We are using a previously-developed database owned by one of the authors. The blue team was developed using U.S. Army doctrine and the red team was developed using data from a U.S. Army training environment[1][2]. We will analyze a blue light infantry division fighting a red mechanized infantry division. The teams are deployed to static fighting positions on a two-dimensional plane. Because we are interested in EW effects on the blue team, only the necessary red EW emitter nodes are included in the cleaned dataset.

The blue team dataset consists of the major components of a single light infantry division:

- One (1) light infantry division main operations center.
- Four (4) subordinate brigades.
  - Three (3) subordinate line battalions per brigade, each with a tactical operations center.

[1] This project references both "command and control" (C2) and "command, control, communications, and computers" (C4) systems. While, by definition, one is subsumed by the other, the term "C4" is mainly confined to strategic doctrine and communications and procurement. The use of "C2" instead of "C4" is pervasive throughout the profession of arms. Any reference to a "C2 system" is a *de facto* reference to a 'C4 system".

        * Three (3) subordinate line companies per battalion.
            · Three (3) subordinate line platoons per company.
            · One (1) company command post per company.
        * One (1) tactical operations center per line battalion.
        * One (1) mortar platoon per line battalion.
    - One (1) reconnaissance, surveillance, and target acquisition (RSTA) squadron per brigade.
        * Two (2) subordinate RSTA troops per squadron.
            · Two (2) dismounted reconnaissance platoons per troop.
            · One (1) mobile gun system platoon per troop.
            · One (1) troop command post per troop.
        * One (1) squadron tactical operations center per squadron.
- One (1) artillery battalion per brigade.
    - One (1) battalion fire direction center.
    - Three (3) battery fire direction centers.
- One (1) main tactical operations center per brigade.

The red team dataset contains six (6) effectively identical EW emitters.

3 Methodology

3.1 The Networks

The red and blue teams were arranged on a $(-50, 50)$ by $(-50, 50)$ (X, Y) plane. The blue team was arrayed in a linear area offense formation and the red team was arrayed in a zone area defense (Figures 1 and 2). The blue team network nodes are the units and each element of the PACE plan between units is an edge (so there are four edges between any two connected nodes). The red team network nodes are the red units and the blue units that are within range (25 units or less) of a red unit. For each blue unit within range of a red unit, there is a one edge for each of the blue unit's communications systems.

3.2 The Markov Models

The meta-system of Markov models consists of the independent red team EW systems' jamming states, the blue team C4 systems' operational states (which are dependent on whether the red team is jamming them), and the blue team's observations of the operational states. This corresponds to four meta-Markov chains, each containing the states or observations for each system or red-blue edge.

- Each red team EW system moves between jamming states according to a Markov model, where each state is a radio-frequency band or the powered-off state.
- Each blue team C4 system moves between operating states according to a Markov model. The operating states are:

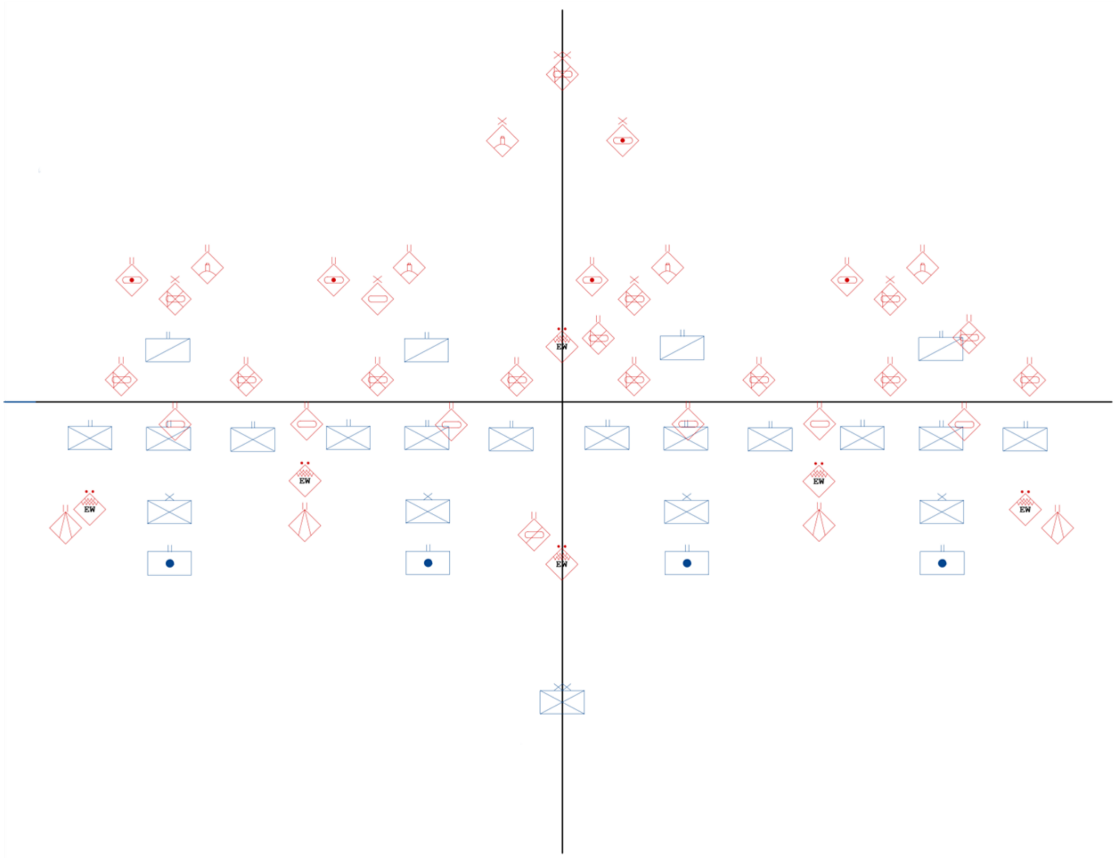

Figure 1: Red and blue team dispositions on the physical battlefield.

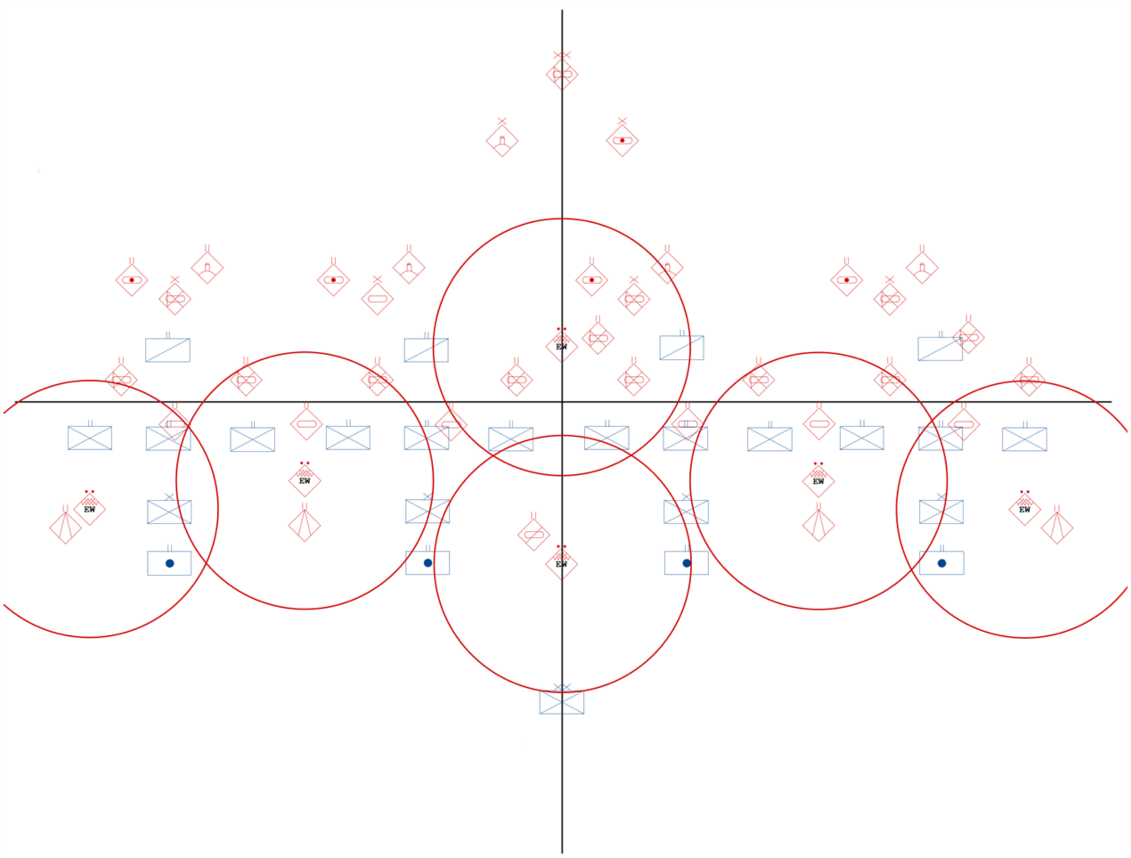

Figure 2: Red and blue team dispositions with overlaid EW range rings.

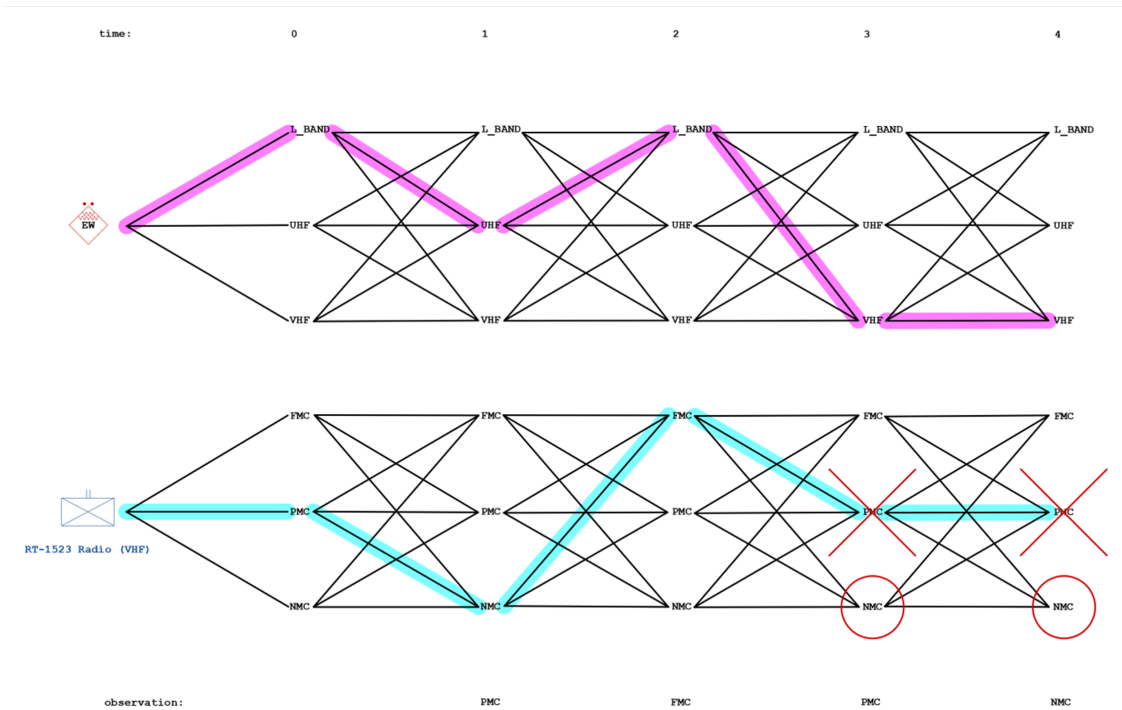

Figure 3: A state transition and observation diagram for a single red-blue dependent HMM system (red network edge).

  - Fully mission capable (FMC) (i.e., fully functional).
  - Partially mission capable (PMC) (i.e., partial functional or degraded functionality, but still usable).
  - Not mission capable (NMC) (i.e., not functional or broken).

- The blue C4 systems' operating states are dependent on whether they are or are not being jammed.
  - If the blue C4 system is within range of a red EW system, the red EW system is jamming on the blue C4 system's frequencies, and the power of the red EW system's jamming emissions successfully overpowers the strength of incoming transmissions to the blue C4 system, then the blue C4 system is forced into a *de facto* NMC state.
  - While the C4 system itself may be perfectly functional, the red jamming activity prevents the system from being used for its intended purpose.
- The blue team is unable to directly observe the operating states of their C4 systems. Instead, they are able to observe how they perceive the systems to be functioning (FMC, PMC, or NMC).

Figure 3 depicts the dependent HMM of a single red team EW system and a single blue team C4 system.

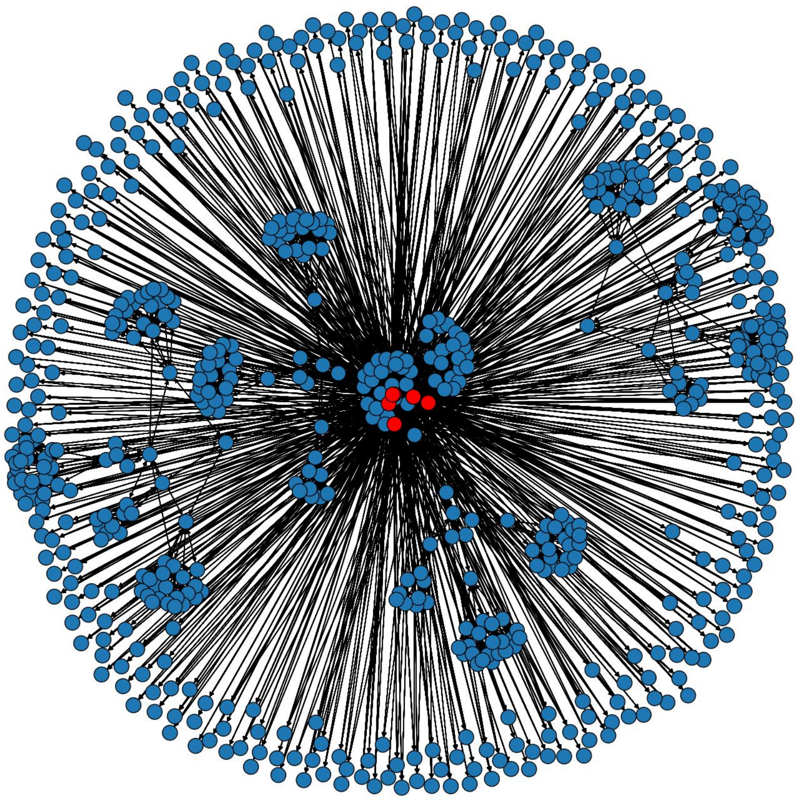

Figure 4: Combined blue and red graphs as visualized by `newtorkx`.

3.3 Markov Chain Monte Carlo Simulation

We created a Markov Chain Monte Carlo (MCMC) simulation to identify the steady-state distributions of the operating states and observed operating states of the blue team C4 systems ("ewNet"). Probability densities were estimated for blue and red state initialization and transitions, red jamming "hits" or successes, and blue state emissions or observations. The blue and red networks were created as graph objects using the Python library `networkx` for visualization and analysis purposes (Figure 4).

4 Evaluation & Results

We successfully developed the model and supporting MCMC simulation program and conducted a series of simulations for 100, 10,000, and 100,000 transitions. Numerical analysis of the 100-step Markov chains indicated that the program was not correctly calculating blue state transitions; most blue C4 systems spent most or all of their time in the NMC state in a manner not consistent with the red EW jamming "hit" rates or the state transition densities. We were unable to determine the root cause of this issue prior to submission and were forced to discard our results.

Despite lacking accurate simulation results, we developed an analytic approach to visualizing and

Status	Color
FMC	GREEN
PMC	AMBER
NMC	RED

Table 1: System function status and associated color code.

HQ State	HHQ State	Edge Health Value	Value Color
FMC	FMC	1	GREEN
FMC	PMC	0.75	AMBER
PMC	FMC	0.75	AMBER
PMC	PMC	0.5	RED
any	NMC	0	BLACK
NMC	any	0	BLACK

Table 2: Calculating the health of a communications edge.

understanding the steady-state distributions of the blue C4 system states and observations for decision-making purposes. For each element of a PACE plan between two blue team units (i.e., for each edge in the blue network), the health of that element is a function of the state of the corresponding C4 system at the corresponding nodes (Table 2). The overall health of the PACE plan (i.e., the aggregate of the four edges) is a function of the health of the components (Table 3).

Military units frequently use color-codes for easy visual or auditory identification of a system's status (Table 1 [2]). By visualizing the health of the network of blue units and their C4 connections to other units, commanders and planners are able to identify the effectiveness of a PACE plan for maintaining a connection between a headquarters and their higher and subordinate units. For example, if the health of tactical units is AMBER or worse, the PACE plan could be modified or replaced, or the unit could be given broader orders that permit local decisionmaking when isolated from its higher command. Or, if the health of the connection between brigade and division operation centers is AMBER or RED, the operations centers might need to be relocated or establish additional command posts to relay communications between the operations centers. Figure 5 depicts an example of the PACE plan aggregate health for the blue team after determining individual C4 system steady state distributions and their cascading impacts on the PACE edges between blue team units and Figure 6 depicts an example of the overall steady state of each PACE edge across the blue team's units.

In conclusion, we modeled the system-of-systems of electronic warfare jamming activity and command, control, communications, and computer systems and the connectivity of military unit headquarters and operations centers and developed a simulation program to estimate steady state distributions. While we were unable to generate reasonably accurate data, we developed an analytic framework for understanding the health of communications redundancy plans that will inform military commanders and planners when planning operations in an electromagnetic spectrum-contested environment.

[2] In addition to GREEN/AMBER/RED, "BLACK" is used when a system or resource's status is preventing further military activity/mission accomplishment.

HQ:HHQ Aggregate Health	Aggregate Health Value	Value Color
$P + A \geq 1$	1	GREEN
$P + A < 1 \&\& C \geq 0.75$	0.5	AMBER
$P + A + C \leq 1 \&\& E == 1$	0.25	RED
$P + A + C \leq 1 \&\& E < 1$	0	BLACK

Table 3: Calculating the health of the PACE plan between two blue nodes.

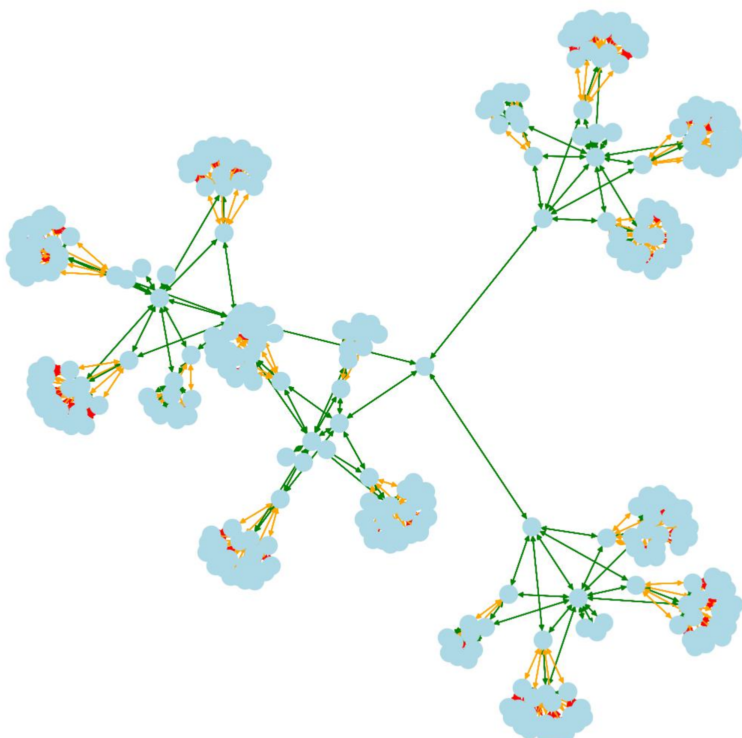

Figure 5: High-level visualization of PACE plan health of the blue team.

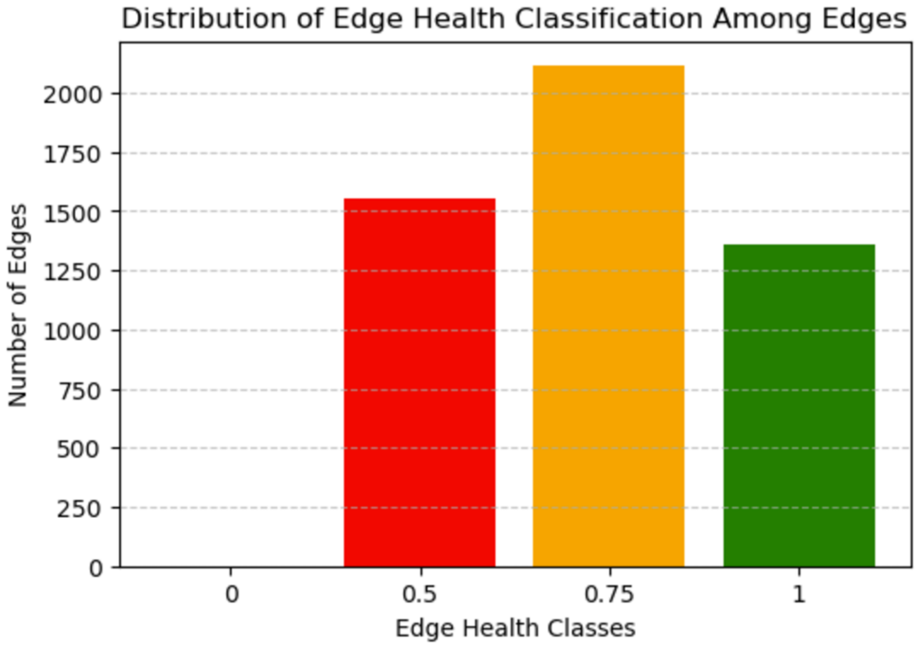

Figure 6: Example histogram of PACE element health across the entire blue network. In this example the most frequent edge health classification is 0.75 or AMBER as calculated using Table 2.

References

[1] United States Army. *Division Operations*. Army Techniques Publications No. 3-91. United States Army, Oct. 17, 2014.

[2] United States Army Training and Doctrine Command G-2. *Decisive Action Training Environment (DATE) World*. URL: `https://odin.tradoc.army.mil/DATEWORLD` (visited on 03/06/2024).