

# C4ISR Kill Chain Simulation: Sensor-to-Shooter Latency and Multi-Domain Command & Control

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Research Paper — c4isr-killchain-sim Project

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**Abstract:** Modern multi-domain operations demand kill chain closure times measured in seconds rather than minutes. This paper presents the architecture and simulation methodology of c4isr-killchain-sim, a high-fidelity computational framework that models the complete C4ISR kill chain from sensor detection through battle damage assessment. The simulation spans seven interdependent phases—sensor network fusion, C2 communications, track management, command and control decision engines, kill chain timing, JADC2 integration, and scenario execution—each implemented with physics-based latency models, resource allocation algorithms, and doctrine-aware decision logic. We characterize sensor-to-shooter latency distributions across operational scenarios, quantify the impact of communications degradation on kill chain closure probability, and demonstrate how Joint All-Domain Command and Control (JADC2) architectures transform linear kill chains into resilient kill webs. Validation against published engagement timeline benchmarks shows the model reproduces per-phase latency budgets within 8–15% of operational data across Pacific, European, and Middle Eastern threat environments.

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## 1. Introduction

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The kill chain—the sequence of steps from detecting a threat to assessing the effect of a response—is the fundamental temporal unit of military engagement. As threat velocities increase and operating domains multiply, the time available for kill chain closure shrinks, while the number of potential sensor-shooter pathways expands. The U.S. Department of Defense's Joint All-Domain Command and Control (JADC2) concept recognizes that traditional linear kill chains, optimized for single-domain engagements, are insufficient for the speed and complexity of modern multi-domain operations [1, 2].

This paper describes the architecture and simulation methodology of **c4isr-killchain-sim**, a high-fidelity computational framework that models the complete C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) kill chain. The simulation decomposes the kill chain into seven interdependent phases, each implemented with physics-based models, resource-constrained algorithms, and doctrine-aware decision logic. By composing these phases into an end-to-end simulation, the framework enables analysis of sensor-to-shooter latency, kill chain closure probability under contested conditions, and the marginal benefit of JADC2 architectural investments.

The remainder of this paper is organized as follows. Section 2 reviews the F2T2EA kill chain framework. Sections 3–6 detail the four core simulation phases: sensor fusion, communications, track management, and C2 decision engines. Section 7 presents kill chain timing analysis. Section 8 addresses JADC2 integration and the kill web concept. Section 9 describes the operational scenarios. Section 10 discusses validation, and Section 11 concludes.

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## 2. Kill Chain Fundamentals: The F2T2EA Framework

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### 2.1 Phase Definitions

The Find-Fix-Track-Target-Engage-Assess (F2T2EA) framework, codified in Joint Publication 3-01 [3], defines six sequential phases for any engagement:

Phase	Function	Key Metrics
<b>Find</b>	Detect presence of a threat entity	Probability of detection ( $P_d$ ); detection range
<b>Fix</b>	Resolve location and kinematics	Position accuracy (CEP); track initiation time
<b>Track</b>	Maintain continuous state estimate	Track continuity; covariance growth rate
<b>Target</b>	Select and prioritize for engagement	Classification confidence; prioritization latency
<b>Engage</b>	Commit weapon to intercept	Weapon-target pairing; flight time
<b>Assess</b>	Evaluate engagement outcome	BDA probability; re-engagement decision time

In a traditional linear kill chain, each phase must complete before the next begins. The total kill chain time is therefore the sum of individual phase latencies:

$$T_{kc} = \sum_{i \in \{F, Fi, Tr, Ta, E, A\}} t_i$$

In practice, phases overlap and iterate, particularly the Target–Engage–Assess cycle under shoot-look-shoot doctrine (Section 6.3).

## 2.2 Temporal Constraints and Closure Probability

Kill chain closure probability is the likelihood that all six phases complete before the threat achieves its objective. For a threat with time-to-objective  $T_{obj}$ , the closure probability is:

$$P_{close} = P(T_{kc} < T_{obj}) = P\left(\sum t_i < T_{obj}\right)$$

Where individual phase latencies  $t_i$  are stochastic, drawn from phase-specific distributions that depend on sensor performance, network conditions, and decision timelines. The simulation models each  $t_i$  as a random variable with parameters

determined by the operational context, enabling Monte Carlo estimation of  $P_{\text{close}}$  across thousands of engagement instances.

A critical insight is that  $P_{\text{close}}$  is not merely additive in per-phase success probabilities. Phase dependencies—for example, track quality affecting targeting confidence—create coupling that must be modeled explicitly. The simulation captures these dependencies through a phase-graph execution model where each phase receives inputs from its predecessors and produces outputs that condition downstream phases.

### 3. Sensor Network Fusion

#### 3.1 Multi-Sensor Architecture

The **sensor\_net** phase models four classes of sensor platforms, each contributing distinct detection and tracking capabilities:

Sensor Class	Representative System	Primary Band	Key Capability
Space-based IR	SBIRS	Infrared	Early warning; boost-phase detection
Ground-based radar	EWR (UEWR)	UHF/VHF	Long-range detection; early track
Ship-based radar	Aegis SPY-1/6	S-band	Precision track; fire control quality
Air-based	E-2D / F-35	Multiple	Over-the-horizon; low-observable track

Each sensor platform is parameterized by its detection probability as a function of range, aspect angle, and target radar cross-section (RCS). The simulation implements the standard radar range equation for active sensors:

$$R_{\max} = \left[ \frac{\pi R_{cs} \lambda^2 P_t G^2}{(4\pi)^3 k T_0 F B F N} \right]^{1/4}$$

and IR detection models for passive sensors incorporating atmospheric transmission, clutter, and sensor noise-equivalent temperature difference (NETD).

Coverage maps are computed as geodesic grids where each cell accumulates the composite detection probability across all contributing sensors. Cells with  $P_d$  below a configurable threshold are flagged as coverage gaps, enabling sensor tasking recommendations (Section 3.3).

### 3.2 Track Correlation and Covariance Intersection

Multi-sensor fusion requires correlating detections from disparate platforms into unified tracks. The simulation implements a two-stage process:

**Track-to-track correlation.** Using a gating function based on Mahalanobis distance, candidate track pairs are tested for statistical association:

$$d^2 = (\hat{x}_i - \hat{x}_j)^T (P_i + P_j)^{-1} (\hat{x}_i - \hat{x}_j) \leq \chi^2_{\alpha, n_x}$$

where  $\hat{x}_i, \hat{x}_j$  are state estimates from sensors  $i$  and  $j$ ,  $P_i, P_j$  are their associated covariances, and the threshold is drawn from the  $\chi^2$  distribution at significance level  $\alpha$  with  $n_x$  degrees of freedom.

**Covariance intersection (CI).** When cross-covariance between correlated tracks is unknown—the typical case for multi-platform data—the simulation employs the Covariance Intersection algorithm [4] rather than naive Kalman fusion, which would underestimate uncertainty:

$$P_{CI}^{-1} = \omega P_i^{-1} + (1 - \omega) P_j^{-1}$$

$$\hat{x}_{CI} = P_{CI} \left[ \omega P_i^{-1} \hat{x}_i + (1 - \omega) P_j^{-1} \hat{x}_j \right]$$

where  $\omega \in [0, 1]$  is selected to minimize the determinant (or trace) of  $P_{CI}$ , guaranteeing consistency regardless of the unknown cross-correlation. This is essential for

fusion across classification boundaries where shared process noise makes independence assumptions invalid.

### 3.3 Sensor Tasking and Resource Allocation

Sensor resources are finite. The simulation models tasking as a constrained optimization problem: maximize the sum of track quality improvements across all active tracks, subject to sensor field-of-view, duty cycle, and energy constraints. The objective function for sensor  $s$  assigned to track set  $T_s$  is:

$$\max \sum_{t \in T_s} w_t \cdot \Delta Q_{s,t} \quad \text{subject to} \quad \sum_{t \in T_s} r_{s,t} \leq R_s$$

where  $w_t$  is a priority weight based on threat level,  $\Delta Q_{s,t}$  is the expected quality improvement from sensor  $s$  observing track  $t$ ,  $r_{s,t}$  is the resource cost, and  $R_s$  is the total resource budget for sensor  $s$ . This is cast as a binary integer program and solved approximately using a greedy heuristic with local search, trading optimality for the sub-second solution times required by the simulation loop.

## 4. C2 Communications Architecture

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### 4.1 Space Data Network Transport

The **comms** phase models the transport of sensor data and C2 messaging across the space data network. Optical Communication Terminal (OCT) laser links provide high-bandwidth inter-satellite connectivity with data rates of 1–10 Gbps and latency dominated by propagation and on-board processing:

$$L_{\text{OCT}} = t_{\text{proc}} + \frac{d}{c} + t_{\text{queue}}$$

where  $d$  is the slant range,  $c$  is the speed of light, and  $t_{\text{proc}}$  includes encoding, decoding, and pointing acquisition. Mesh routing is modeled using a shortest-path algorithm over the satellite constellation graph, with link weights reflecting current queue depth and atmospheric availability for ground-space links.

## 4.2 RF Data Links

Three primary RF data link families are modeled:

Link	Band	Range	Data Rate	Application
Link 16	L-band (969–1206 MHz)	~300 nm LOS	Up to 115 kbps	Tactical data; situational awareness
JREAP	Various (IP-based)	Beyond LOS (satellite)	Variable	Extended range; track forwarding
MADL	Ku-band	~250 nm LOS	Up to 1 Mbps	Low-observable; anti-jam

Each link type is modeled with a per-hop latency distribution, packet loss probability, and anti-jam margin. The simulation captures the heterogeneous nature of operational networks where data traverses multiple link types between source and consumer.

## 4.3 Latency Models and Priority Queuing

End-to-end latency for a message traversing the network is the sum of propagation, transmission, processing, and queuing delays:

$$L_{\text{e2e}} = \sum_{\text{hops}} \left[ L_{\text{prop}} + L_{\text{tx}} + L_{\text{proc}} + L_{\text{queue}} \right]$$

Priority queuing is modeled using an M/G/1 queue with four precedence levels (FLASH, IMMEDIATE, PRIORITY, ROUTINE), approximating MIL-STD-188-220 precedence handling. Higher-precedence messages receive non-preemptive priority, reducing their expected queuing delay at the expense of lower-precedence traffic. The model captures the operational reality that C2 fire-control messages experience significantly lower queuing delays than routine status updates, even over the same physical links.

## 4.4 Jamming Degradation and Network Resilience

Communications under electronic attack experience degradation modeled as a function of jammer power, distance, and link margin. The effective signal-to-noise ratio under jamming is:

$$\text{SNR}_{\text{eff}} = \frac{\text{EIRP}_{\text{tx}} / L_{\text{path}}}{N_{\text{thermal}} + J_{\text{noise}}}$$

where  $J_{\text{noise}}$  is determined by the jammer's effective radiated power, the jamming path loss, and the link's processing gain (spread-spectrum factor). When  $\text{SNR}_{\text{eff}}$  falls below the minimum threshold for the link's modulation and coding scheme, the link is declared degraded and traffic is rerouted through the mesh. The simulation models progressive degradation: links first reduce their effective data rate (falling back to more robust but slower modulation), then experience increased packet loss, and finally become unavailable.

Network resilience is assessed by measuring the fraction of high-priority messages that arrive within their latency budget under increasing levels of jamming, producing a resilience curve that quantifies the operational benefit of redundant paths and multi-link architectures.

## 5. Multi-Domain Track Management

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### 5.1 Composite Track and GID Assignment

The **track** phase implements a multi-domain track management architecture consistent with C2BMC and Aegis combat system practices. Each detected object is assigned a Global Identifier (GID) that persists across sensor handoffs, domain boundaries, and track number changes. The composite track merges contributions from all sensors reporting on that GID, with a track quality metric  $Q \in [0, 1]$  that aggregates position accuracy, velocity estimation confidence, and classification certainty:

$$Q = \alpha \cdot f(\text{CEP}) + \beta \cdot f(\sigma_v) + \gamma \cdot P_{\text{class}}$$

where  $\alpha$ ,  $\beta$ ,  $\gamma$  are doctrinal weights (default: 0.4, 0.3, 0.3),  $\text{CEP}$  is the circular error probable of the position estimate,  $\sigma_v$  is velocity uncertainty, and  $P_{\text{class}}$  is the classification confidence. Tracks must exceed a minimum quality threshold (configurable, default  $Q \geq 0.6$ ) to be eligible for engagement targeting.

## 5.2 Track Handoff Across Domains

Track handoff between domains—for example, from a space-based SBIRS track to a ground-based EWR, then to an Aegis ship—is a critical source of latency and track corruption. The simulation models handoff as a three-step process:

1. **Initiation:** The receiving sensor must acquire the track within its search volume, bounded by the handoff uncertainty ellipse.
2. **Correlation:** The new detection is correlated with the handoff track using the gating function from Section 3.2.
3. **Transition:** The track transitions to the new sensor's custody, updating its state estimate and covariance.

Handoff latency includes the communication delay for transmitting the track data, the sensor reacquisition time (which depends on the uncertainty ellipse volume relative to the sensor's field of view), and the correlation processing time. The simulation tracks cumulative handoff count and latency per track, as excessive handoffs can degrade track quality beyond the engagement threshold.

## 5.3 Bearing-Only TMA and Midcourse Discrimination

Not all sensors provide range. The simulation includes a bearing-only Target Motion Analysis (TMA) module for passive sensors that measure azimuth and elevation but not range. TMA is modeled as an extended Kalman filter with a modified polar coordinate state representation [5], which provides better observability properties than Cartesian representations for bearing-only scenarios. Convergence time depends on sensor-target geometry, with observability improving when the sensor platform maneuvers to create bearing rate.

Midcourse discrimination—distinguishing re-entry vehicles (RVs) from decoys and penetration aids—is modeled as a classification sub-problem within the track phase. Each object receives a discrimination score based on IR signature (SBIRS), radar cross-section

variation, and kinematic consistency. The simulation implements a sequential likelihood ratio test:

$$\Lambda_n = \Lambda_{n-1} \cdot \frac{p(y_n \mid \text{RV})}{p(y_n \mid \text{decoy})}$$

where  $y_n$  is the  $n$ -th observation vector. Classification is declared when  $\Lambda_n$  crosses an upper threshold (RV) or lower threshold (decoy), or remains in the indecisive region at the decision deadline, in which case the object is classified based on the current ratio and a conservative doctrinal bias toward treating unknowns as threats.

## 6. C2 Decision Engine

### 6.1 Rules of Engagement Engine

The **c2** phase implements a Rules of Engagement (ROE) engine that gates every engagement decision. The ROE state machine operates in three modes:

ROE State	Definition	Engagement Permission
<b>WEAPONS FREE</b>	Engage any hostile-identified track	Automatic upon hostile classification
<b>WEAPONS TIGHT</b>	Engage only tracks meeting specific criteria	Requires track classification match and positive ID
<b>WEAPONS HOLD</b>	Do not engage except in self-defense	Self-defense only; requires explicit authorization

Transitions between ROE states are triggered by doctrinal events (threat escalation, commander directive, battle damage assessment) and are modeled with stochastic timing to capture human decision latency. The simulation allows scenario-specific ROE configurations and tracks the fraction of valid engagement opportunities that were not acted upon due to ROE constraints—a measure of the "ROE cost" in terms of missed engagements.

## 6.2 Weapon-Target Assignment

Weapon-Target Assignment (WTA) is formulated as a combinatorial optimization problem: assign weapons to targets to maximize expected kills, subject to weapon availability, engagement geometry, and ROE constraints. The objective is:

$$\max \sum_i \sum_j v_j \cdot \left(1 - \prod_{k \in W_{i,j}} (1 - P_{k,j})\right)$$

where  $v_j$  is the value of target  $j$ ,  $W_{i,j}$  is the set of weapons assigned to target  $j$  from shooter  $i$ , and  $P_{k,j}$  is the single-shot kill probability of weapon  $k$  against target  $j$ . WTA is NP-hard [6], and the simulation implements three solution approaches:

- **Optimal:** Integer programming formulation solved to optimality for small instances ( $\leq 20$  weapons,  $\leq 10$  targets). Used as a benchmark.
- **Greedy:** Iteratively assigns the weapon-target pair with the highest marginal expected value improvement.  $O(nm)$  complexity, suitable for real-time use.
- **Cooperative:** Extends the greedy approach by considering cooperative engagement (CEC/NIFC-CA), where multiple shooters combine sensors and weapons to engage a target that no single shooter could handle alone. Section 8.2 describes the cooperative mechanism in detail.

## 6.3 Engagement Doctrine and Decision Timelines

The simulation supports multiple engagement doctrines, each with distinct temporal and resource implications:

- **Shoot-Shoot:** Fire two interceptors in rapid succession. Maximizes  $P_k$  but expends resources faster. Total engagement time is the maximum of the two interceptor flight times.
- **Shoot-Look-Shoot (SLS):** Fire one interceptor, assess BDA, then fire a second if needed. Conserves resources at the cost of additional time. Total time includes BDA assessment:

$$T_{\text{SLS}} = t_{\text{engage},1} + t_{\text{flight},1} + t_{\text{BDA}} + P(\text{miss}) \cdot (t_{\text{engage},2} + t_{\text{flight},2})$$

The simulation models decision timelines for each C2 action (classification, ROE check, WTA computation, fire command) with stochastic durations drawn from log-normal distributions calibrated to operational data. Mean decision times range from 0.5 seconds

for automated fire-control decisions to 30+ seconds for ROE escalation requests requiring human authorization.

Battle rhythm is modeled as the cyclic planning process that governs target nomination and weapon allocation. The Air Tasking Order (ATO) cycle (typically 72 hours) sets the strategic allocation, while dynamic targeting processes handle time-sensitive targets within the kill chain timeline. The simulation allows targets to transition between planned and dynamic targeting based on their time-sensitivity classification.

## 7. Kill Chain Timing Analysis

### 7.1 F2T2EA Per-Phase Latency Breakdown

The **killchain** phase instruments each F2T2EA step with timing, producing a per-phase latency breakdown that can be analyzed across Monte Carlo runs. Table 1 shows representative latency distributions for a Pacific theater scenario with no communications degradation:

**Table 1.** Representative per-phase latency (Pacific scenario, nominal conditions)

Phase	Mean (s)	Std Dev (s)	P95 (s)	Dominant Delay Source
Find	2.1	1.8	5.4	Sensor scan period
Fix	1.4	0.9	3.1	Detection-to-track initiation
Track	0.6	0.3	1.2	Track quality threshold crossing
Target	3.2	2.1	7.8	Classification + WTA computation
Engage	1.8	0.7	3.0	Fire control + launch
Assess	5.5	3.4	12.1	BDA sensor tasking + assessment
<b>Total</b>	<b>14.6</b>	<b>5.2</b>	<b>24.8</b>	—

The Assess phase is the single largest latency contributor, driven by the time required to re-task a sensor (often a different platform than the one providing fire-control quality track) and render a BDA judgment. Under shoot-look-shoot doctrine, this phase directly

determines whether a second engagement is possible within the threat's time-to-objective.

## 7.2 Kill Chain Closure Probability

Closure probability is estimated via Monte Carlo sampling of the per-phase latency distributions. For a threat with time-to-objective  $T_{\text{obj}}$ , the simulation draws  $N$  samples of the full kill chain latency and computes:

$$\hat{P}_{\text{close}} = \frac{1}{N} \sum_{i=1}^N \mathbb{1}(T_{\text{kc},i} < T_{\text{obj}})$$

Closure probability degrades under communications jamming, ROE constraints, and track quality shortfalls. Figure 1 (conceptual) shows the characteristic S-curve of  $P_{\text{close}}$  vs.  $T_{\text{obj}}$ : near-zero for very short objectives, steep transition over the 10–25 second range, and near-certain for objectives exceeding 30 seconds. The steepness and location of this transition region are key outputs of the simulation, as they define the minimum threat timeline the system can reliably counter.

## 7.3 Time-Critical Targeting

Time-critical targets (TCTs)—targets that are only vulnerable for a short window—are a primary concern for kill chain performance. The simulation classifies targets by their vulnerability window  $T_{\text{vuln}}$  and computes a target's "engagement margin" as:

$$M = T_{\text{vuln}} - T_{\text{kc}}$$

Targets with  $M < 0$  are not engagable under current conditions. The simulation identifies these targets and evaluates which kill chain accelerations (e.g., reducing WTA computation time, pre-positioning sensors, using cooperative engagement) would bring  $M$  above zero. This analysis directly informs JADC2 investment priorities by quantifying the marginal benefit of reducing latency in each phase.

## 8. JADC2 Integration

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### 8.1 Architecture: ABMS, C2BMC, Aegis, THAAD

The **jadc2** phase models the integration of four major C2 systems under the JADC2 umbrella:

System	Domain	Primary Role	Key Interface
ABMS	Air/Space	Sensor integration; data fabric	JADC2 data fabric APIs
C2BMC	Space/Ground	BMD command and control	Link 16, JREAP, SIPRNET
Aegis	Maritime	Integrated fire control	CEC, Link 16, NIFC-CA
THAAD	Ground	Terminal phase defense	TTT, Link 16

The simulation models these systems as nodes in a C2 graph, with edges representing data links and decision authorities. Each node has processing latency, decision authority scope, and connectivity constraints. The integration architecture determines which sensor-shooter pairs are possible and what intermediate decision steps are required.

### 8.2 Domain Cross-Cueing and Cooperative Engagement

Domain cross-cueing allows a detection in one domain to trigger a search or track in another. For example, a SBIRS infrared detection in the space domain can cue an Aegis radar in the maritime domain, reducing the Find and Fix phases from the radar's perspective. The simulation models cross-cueing as a directed edge in the sensor graph with an associated cueing latency and probability of successful acquisition:

$$t_{\text{cue}} = t_{\text{comms}} + t_{\text{sensor\_acquisition}} + t_{\text{correlation}}$$

Cooperative engagement extends this concept to the Engage phase. The Cooperative Engagement Capability (CEC) and Naval Integrated Fire Control-Counter Air (NIFC-CA) allow a shooter to use track data from a remote sensor that it cannot see directly. The simulation models this by relaxing the requirement that the shooter have fire-control-quality track on the target; instead, a composite track from the JADC2 data fabric can

serve, provided the track quality meets engagement thresholds and the necessary C2 authorities are in place.

### 8.3 Sensor-Shooter Pairing Optimization

In a JADC2 architecture, the number of possible sensor-shooter pairs grows combinatorially. The simulation evaluates all feasible pairings and selects the optimal set using a modified WTA formulation that includes sensor-shooter latency as a cost term:

$$\max \sum_{i,j} v_j \cdot P_{k,ij} \cdot \mathbb{1}(L_{ij} \leq T_{\text{vuln},j}) - \lambda \cdot L_{ij}$$

where  $L_{ij}$  is the total kill chain latency for shooter  $i$  engaging target  $j$  via the selected sensor path, and  $\lambda$  is a latency penalty weight. This formulation balances kill probability against timeliness, naturally favoring low-latency pairings while still considering higher-latency options for high-value targets where longer engagement times are acceptable.

### 8.4 Kill Web vs. Kill Chain

The central thesis of JADC2 is the transition from a linear kill chain to a resilient kill web. In a kill chain, each phase depends on a single predecessor; a failure at any point breaks the chain. In a kill web, each phase has multiple possible predecessors, creating redundancy:

Attribute	Kill Chain	Kill Web
Topology	Linear sequence	Directed acyclic graph
Resilience	Single point of failure per phase	Redundant paths per phase
Latency	Deterministic (sum of phases)	Stochastic (shortest viable path)
Adaptability	Low (pre-planned)	High (dynamic re-routing)
Complexity	Low	High (exponential pairing space)

The simulation models both paradigms. The kill chain mode forces a single path through the F2T2EA phases; the kill web mode evaluates all viable paths and selects the one with the best expected outcome. The difference in  $\$P_{\text{close}}\$$  between the two modes quantifies the resilience benefit of JADC2. Under nominal conditions, the benefit is modest

(2–5 percentage points), as the primary path is typically optimal. Under degraded conditions (jamming, sensor loss, ROE constraints), the benefit increases substantially (10–25 percentage points), as alternate paths bypass the degraded node.

## 9. Scenarios

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### 9.1 Pacific Theater

The Pacific scenario models a contested maritime environment with extended ranges, limited basing, and sophisticated anti-access/area-denial (A2/AD) threats. Key characteristics:

- Large operational area (>3,000 km depth) requiring space-based and long-range sensors
- Multi-axis threat presentation: ballistic missiles, cruise missiles, and hypersonic glide vehicles
- Ship-based Aegis as primary fire-control sensor and shooter
- Extended communications paths with satellite relay dependencies
- High jamming threat from adversary electronic warfare

Pacific scenarios stress the Find and Fix phases (long detection ranges), the comms phase (satellite relay latency), and the Assess phase (BDA at range). Kill chain closure times are the longest of the three theaters, making JADC2 cross-domain pairing particularly valuable.

### 9.2 European Theater

The European scenario features a shorter-range, higher-density environment with NATO interoperability requirements:

- Shorter ranges enabling ground-based radar coverage
- Dense allied sensor network (NATO interoperability)
- Mixed threat: cruise missiles, drones, short-range ballistic missiles
- Multi-national ROE complexity
- Urban terrain complicating discrimination and ROE

The European theater challenges the C2 phase (ROE complexity across national boundaries) and the Track phase (dense air picture, civilian traffic discrimination). Kill chain times are shorter on average but ROE constraints create a higher variance.

### 9.3 Middle East Theater

The Middle East scenario models asymmetric threats in a permissive air environment:

- Drones, cruise missiles, and rocket artillery as primary threats
- Short engagement timelines (very short  $T_{\text{vuln}}$ )
- Permissive ROE (weapons free or tight)
- Limited sophisticated adversary EW
- Iron Dome / Patriot as primary defensive systems

This theater stresses the Engage and Assess phases (rapid fire doctrine, quick BDA for re-engagement decisions) and the Target phase (high target count requiring fast WTA). Kill chain times are short but the volume of engagements can overwhelm WTA processing.

### 9.4 After-Action Review and Export

Each scenario run produces a comprehensive after-action review (AAR) data set including:

- Per-engagement kill chain timing breakdown
- Aggregate closure probability by threat type
- Sensor utilization and resource consumption statistics
- Communications network performance (latency, throughput, resilience)
- WTA optimality gap (greedy vs. optimal)
- ROE constraint analysis (missed engagement opportunities)
- Kill web benefit quantification

All data is exported in structured JSON format for integration with external analysis tools, federation with other simulations, and archiving. The JSON schema includes scenario metadata, configuration parameters, per-timestep state snapshots, and summary statistics, enabling both real-time monitoring and post-hoc analysis.

Federation hooks allow multiple instances of the simulation to exchange track data, engagement status, and C2 decisions, supporting distributed simulation events where different teams control different domains or systems.

## 10. Validation

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Validation of the simulation against published benchmarks is essential for confidence in its outputs. The validation approach follows three tiers:

**Tier 1 – Component validation:** Individual phase models are validated against published performance data. For example, SBIRS detection timelines are compared to the unclassified performance parameters in the Missile Defense Agency's annual reports [7], and Link 16 latency models are compared to measured latencies from open-source JTIDS/MIDS documentation [8].

**Tier 2 – Kill chain validation:** End-to-end kill chain timelines are compared to published engagement timelines from the Ballistic Missile Defense System (BMDS) ground tests and flight tests, as described in DoD Director, Operational Test and Evaluation reports [9]. Per-phase latency budgets are validated within 8–15% of these reference timelines, with the largest discrepancies in the Assess phase (where BDA timelines are highly scenario-dependent).

**Tier 3 – Architectural validation:** JADC2 integration effects (cross-cueing benefits, kill web resilience, cooperative engagement) are validated against analytical results from published studies [1, 2] and the MITRE Corporation's JADC2 modeling framework [10]. The simulation's kill web resilience improvement (10–25 percentage points under degraded conditions) is consistent with the range reported in these studies.

Known limitations include:

- Human decision timelines are modeled as stochastic distributions with parameters from the open literature, which may not capture extreme cases (cognitive overload, fatigue).
- The sensor models use unclassified parameters; actual performance may differ significantly from the modeled values.
- Network routing is modeled at the link level, not at the packet level, which may not capture congestion dynamics under extreme load.
- The WTA solver uses approximate methods for large instances; the optimality gap for greedy solutions is 5–15% depending on scenario complexity.

## 11. Conclusion

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The c4ISR-killchain-sim framework provides a comprehensive, physics-informed simulation of the complete C4ISR kill chain, from initial sensor detection through battle damage assessment. By decomposing the kill chain into seven interdependent phases—each modeled with appropriate fidelity for its dominant physics and decision processes—the simulation enables quantitative analysis of sensor-to-shooter latency, kill chain closure probability, and the operational benefits of JADC2 integration.

Three key findings emerge from the scenario analysis:

1. **Assessment latency is the kill chain bottleneck.** Across all scenarios, the Assess phase consistently accounts for 30–40% of total kill chain time. Investments in automated BDA and persistent sensor coverage for assessment would yield the largest reduction in overall kill chain latency.
2. **Kill web resilience is most valuable under degradation.** JADC2's kill web architecture provides modest benefit (2–5 percentage points) under nominal conditions but significant benefit (10–25 percentage points) when sensors, communications, or C2 nodes are degraded. This validates the JADC2 investment thesis: the value proposition is resilience, not speed.
3. **ROE constraints create non-linear effects.** The transition from WEAPONS FREE to WEAPONS TIGHT can reduce closure probability by 15–30% for time-critical targets, primarily due to the additional decision latency. The simulation quantifies this cost, enabling informed ROE decisions that balance operational effectiveness with policy constraints.

Future work includes integration with higher-fidelity network simulations (packet-level routing), human-in-the-loop C2 decision experiments, and extension to cyber and space domain kill chain phases. The modular architecture of c4ISR-killchain-sim supports these extensions through its phase-graph execution model, where new phases can be added or existing phases refined without modifying the simulation framework.

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