Effects of Functional Allocations and Associated Communications on C2ISR Mission Effectiveness

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Abstract. Network-centric operations (NCO) hypothesize that shared awareness and coordinated actions will produce superior mission effectiveness at the force level. We have examined some simple cases of functional allocations in the area of Command, Control, and Intelligence, Surveillance, and Reconnaissance functions to investigate variations from some traditional architectures. Concurrently we have identified the associated communications performance necessary to ensure that the derived effectiveness is not compromised or limited by the communications. This approach quantitatively generates communications requirements for the links utilized in the NCO to support the defined architecture and mission.

We have developed and adapted operational models of time-sensitive targeting missions and some non-traditional airborne ISR architectures which use off-board sensors to provide an extension of the coverage area, using the Extend™ tool. These are being augmented with parametric descriptions of communications links between ISR, C2, and shooter nodes. By modeling the communications parametrically we can derive relevant communications performance requirements prior to invoking a specified communications system. The values of the communications parameters at which there is no degradation in mission performance can be interpreted as constituting the minimum requirements for the communication channel for the specified scenario.

Introduction

Network-centric operations (NCO) hypothesize that shared awareness and coordinated actions will produce superior mission effectiveness at the force level. We have examined some simple cases of functional allocations in the area of Command, Control, and Intelligence, Surveillance, and Reconnaissance functions to investigate variations from some traditional architectures. Concurrently we have identified the associated communications performance necessary to ensure that the derived effectiveness is not compromised or limited by the communications. This approach quantitatively generates communications requirements for the links utilized in the NCO.

The Boeing Phantom Works organization has developed operational models of time-sensitive-targeting mission execution using the Extend™ discrete-event simulation tool. Functional models, including human resource utilization and operational time-lines, have been developed in order to assess sensor-decider-shooter flow times and relate these to exposure times of time-sensitive targets (e.g., transport-erector/launchers that "hide-move-shoot-hide") and the overall probability of successful "kill". These models have been adapted to investigate the effects and any limitations of moving certain decision-related functions from an Air and Space Operations Center (AOC) to mobile platforms, such as AWACS. Such modeling activities have previously assumed near-perfect communications performance characteristics: infinite bandwidth, 100% reliability, and zero latency.

In the present work the TST models are being augmented with parametric descriptions of communications links between ISR, C2, and shooter nodes. Such parameters as communications channel data rate, reliability, protocol, and spatial delay are varied and their effects on mission performance (e.g., per cent kill) are assessed. The values of the communications parameters at which there is no degradation in mission performance constitute the minimum requirements for the communication channel for the specified scenario.

To assess these communications effects we have modeled simple system architectures of airborne C2-ISR platforms for traditional missions such as defensive counter-air. Scenarios have been created using simple target generation models. Air surveillance and data fusion models based on range vs. probability of detection have been incorporated in a non-traditional ISR network of forward-projected UAVs and fighters on combat air patrol along with the traditional AWACS. Thresholds of communications performance to maintain mission effectiveness are derived for each architecture and scenario.

By modeling the process parametrically we can investigate specific communications parameters, thus deriving relevant communications performance requirements prior to invoking a specified communications system. Different line-of-sight and beyond-LOS C2-ISR architectures have been investigated, along with different allocations of sensing and C2. Results from these analyses can be used in force- and system upgrade planning to justify the substantial investments required. Initial results indicate that, with sufficient communications performance linking the sensor data to the C2 and shooter tasks the C2 activities can be equally effective regardless of location (airborne/ground, theater/CONUS).

Functional Allocation Analysis Model

We have adapted models created by the Boeing Phantom Works Strategic Design and Analysis organization using the Extend™ tool running in a discrete-event simulation mode. The operational process is modeled using linked functions indicated in Figure 1. Figure 2 indicates the functional decomposition of the TST mission from the scenario architecture into the CAOC and the lower-level functionality.

Targets	Target Processing
• Target Generation	• Receive ID Data & Identify Target
• Target States	• Validate Target
• Search & detect targets	• Prioritize TST List
Track Processing	• Approve TST List
• Initiate New Track	• Develop Course of Action (COA)
• Update Existing Track	• Select & Approve COA
• Monitor Unknown Track	Manage Engagement
• Classify Tracks	• Task strike assets
Select & task reconnaissance assets	• Attack Aircraft
	• Battle Damage Assessment
	Intel Center

Figure 1. Functions included in Extend™ TST model.

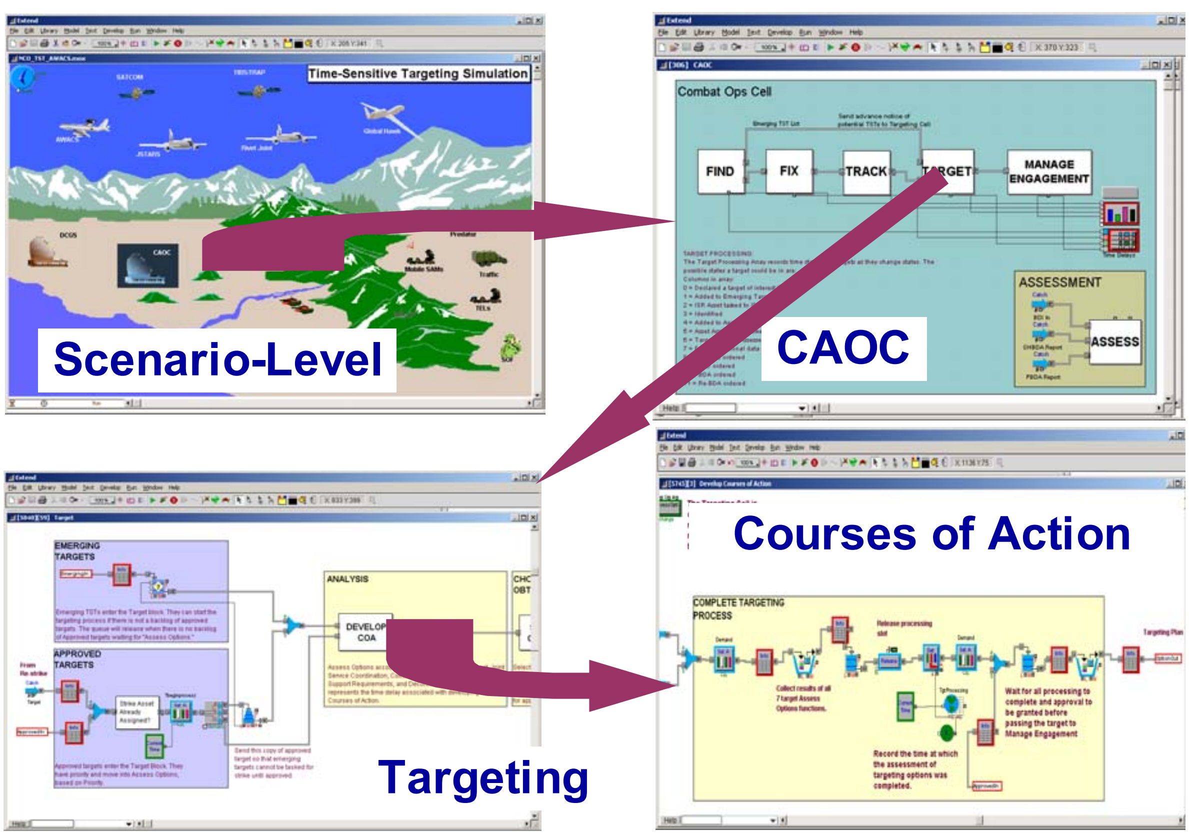


Figure 2. Example Functional Decomposition using Extend™. Functions are assigned to specific nodes and further decomposed into detailed processes.

Figure 3 shows the functions that may be located in either the AWACS or CAOC (left column) or shared between the two nodes (right column). The selection is controlled using the database which configures the architecture, including the communications connectivity. The ability to relocate functions quickly without either maintaining two separate models or “hard-wiring” the changes provides a high degree of flexibility.

The Extend™ model automatically displays the status of the relocatable functions (Figure 4), automatically indicating with a normal functional block that the function is active in the identified platform, and indicating with a “dot” that the function is inactive, as defined in the database which controls the model. Configuraton “truth” is defined in the database that drives the simulation, and represented graphically and automatically.

Relocatable Functions	Shared Functions between AWACS and CAOC
• Prioritize Targets Of Interest	• Develop Course Of Action
• Update Emerging TST List	• Determine Weapon Availability
• Assess Asset Availability	• Perform Threat Assessment
• Validate Target	• Joint Service Coordination
• Prioritize TST List	• Asses Collateral Damage
• Select Course of Action	• Perform Environmental Assessment
• Approve TST List	• Define Support Requirements
• Task Asset	• Define Deconfliction Requirement

Figure 3. Functions relocatable between AWACS and CAOC.

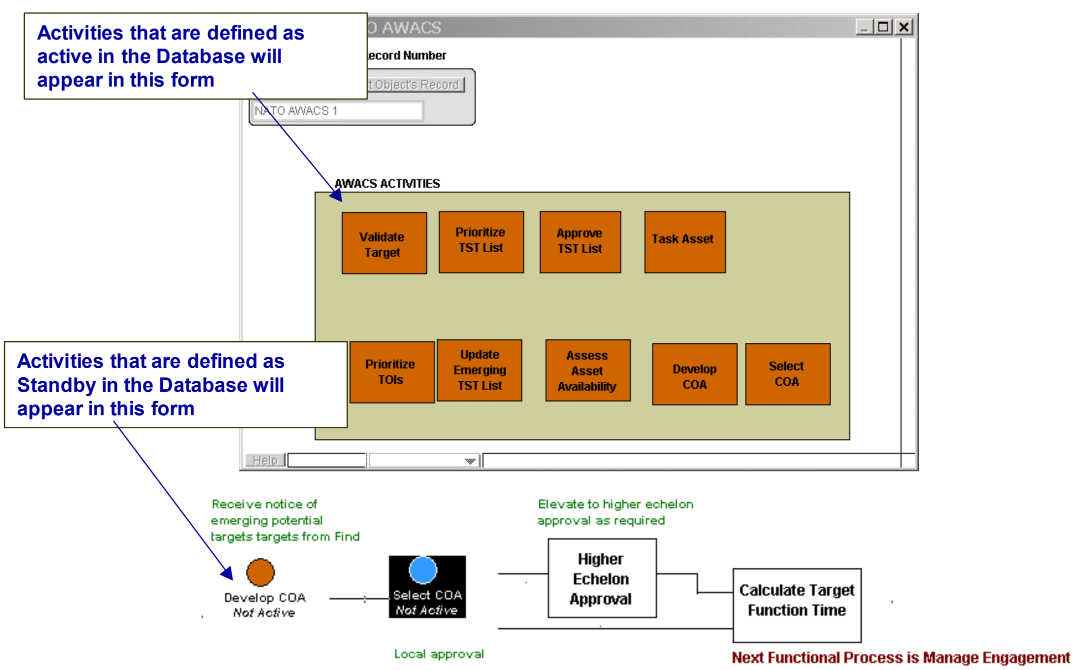


Figure 4. Representation of Active and Inactive Functions within Extend™ TST Model.

An analysis of possible functional architectures is in progress to consider what tasks could be performed on an AWACS or AEW&C given supporting battle management command and control decision aids. We are attempting to determine, given the number of personnel on such platforms and their other tasks, whether there are operations that could be conducted at a meaningful level that improve force-level flexibility. If so, what are the associated communication requirements between platforms?

We initially consider two architectures; in the first, all the ground moving-target indicator (GMTI) data is forwarded directly to an AWACS for initial processing and tasking of ISR assets for improved tracking and identification. C2 is exercised on AWACS rather than in a combined air & space operations center (CAOC) for the limited set of missions. Strike planning and execution is initiated. Battle hit-assessment and battle-damage assessment are commanded from the AWACS.

In the second architecture, AWACS works closely with the CAOC and other assets. Initial analysis and tasking comes from the CAOC. Detailed mission planning and strike assessment are managed from the AWACS.

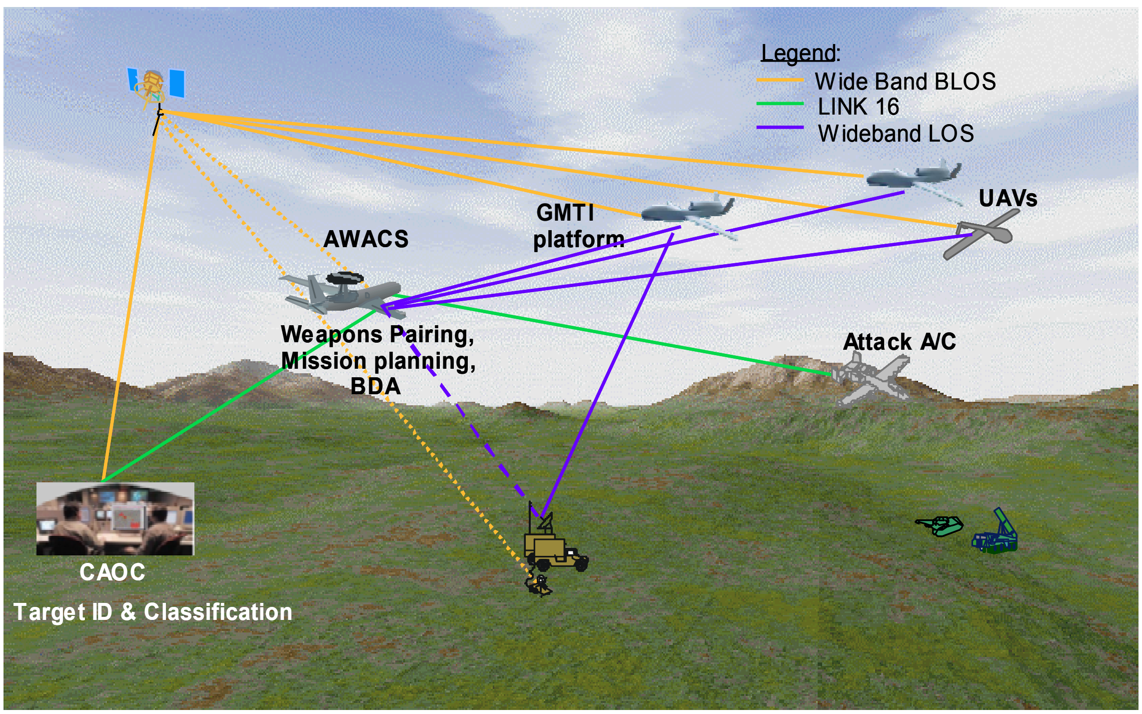


Figure 5. Scenario for functional allocation comparisons.

Figure 6 plots the number of time-sensitive targets that can be processed for the given scenario vs. the number of AWACS operator consoles allocated to that function. A low operational tempo is supportable. If additional air battle management capabilities are added to an "enhanced" platform with more automated battle-management decision aids, the number of TSTs that can be successfully processed can be increased (higher operational tempo). Working in combination with the CAOC provides the most effective force in terms of the number of TSTs that can be prosecuted, but would require better communications (analysis in work).

The modeling approach enables us to move or share many of the Battle-Management / Command & Control functions between the AWACS and CAOC. We are currently investigating the associated requirements for communications based on these different functional architectures.

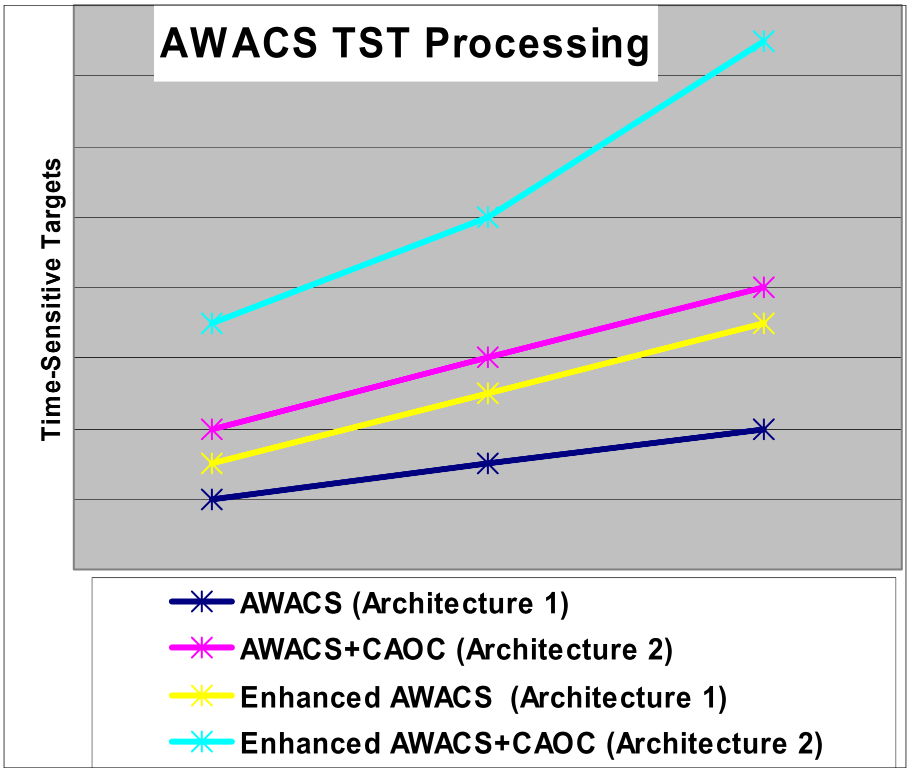


Figure 6. Number of TSTs effectively processed vs. number of AWACS workstations allocated (linear scales).

Communications Thresholds Analysis

In a companion analysis we are attempting to find and substantiate requirements for communications systems to support operational architectures in a network-centric environment. The possibility of linking many platforms together to share information and functionality of course demands a certain amount of communications performance (quantity and quality of service). The detailed question we are attempting to address is, "how good must it be"?

Once the architecture and functional allocations are defined, the information exchange requirements are established to determine the threshold communications performance necessary to ensure mission effectiveness as measured at the force level (more than just AWACS). In this example (Figure 7) we have postulated an architecture consisting of an AWACS C2-ISR platform, fighters providing both forward-deployed aerial surveillance using their radar and defensive counter air interdiction capability, and additional forward-deployed UAVs which perform additional aerial surveillance from locations beyond the forward edge of battle area (FEBA).

The DCA Targeting process, as modeled in Extend™, provides an operational perspective of the steps necessary to conduct DCA operations at an architectural level. The model accounts for sensor detection probabilities, communications logic and resource constraints, and requirements for tracking and tracking-error. The underlying sensor and tracking models were specifically developed for this effort. The communications model was adapted from earlier Boeing Internal Research & Development work. The analysis is based on a DCA vignette depicted in Figure 7, which also serves as the top page of the Extend™ model.

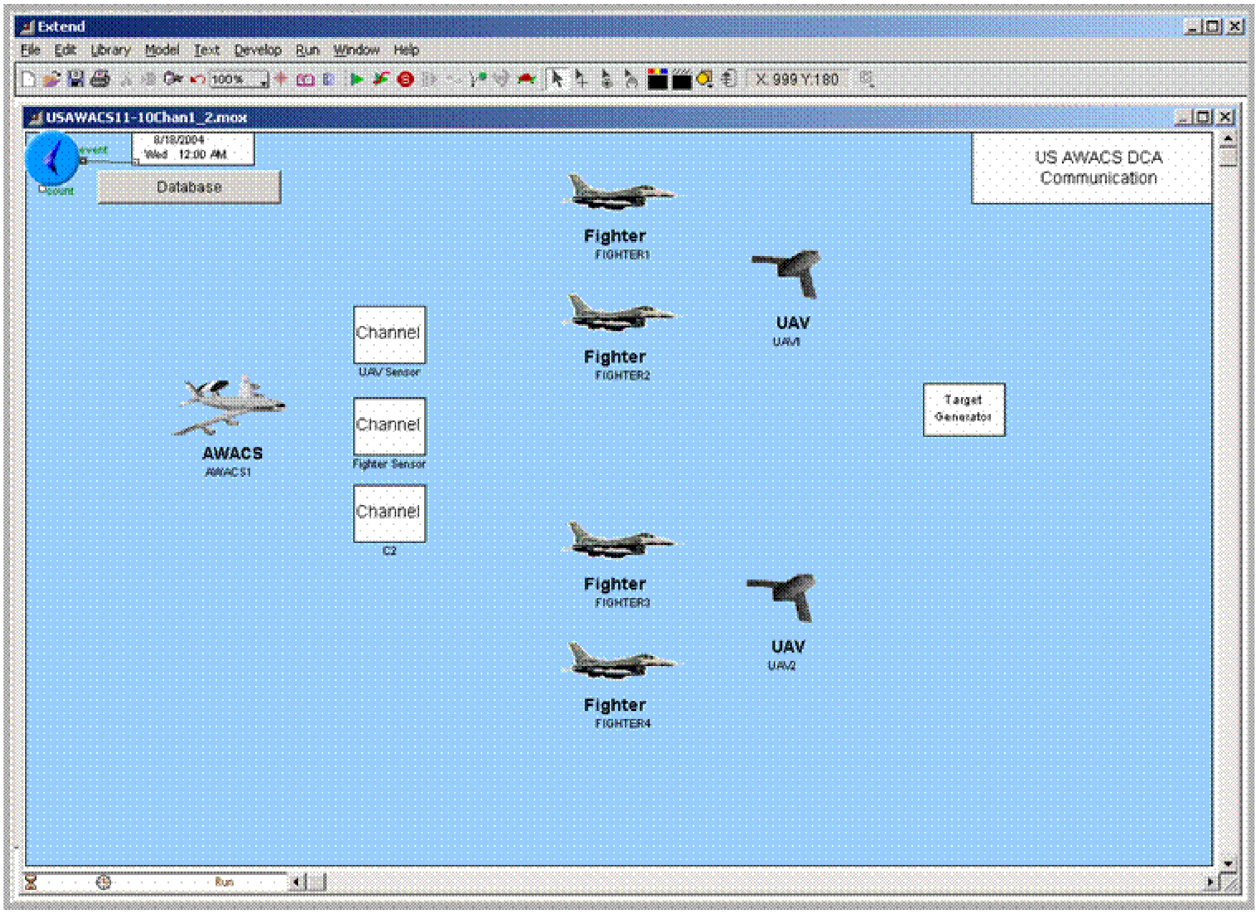


Figure 7. AWACS Defensive Counter-Air analysis architecture.

Sensor-C2 (AWACS)-Shooter Architecture

The basic architecture was Sensor-C2-Shooter Defensive Counter Air. The sensors are allocated to the UAVs, Fighters, and the AWACS. Targets were generated to approximate an enemy Special Operations Forces (SOF) insertion, an enemy Air-to-Ground Interdiction mission with Air-to-Air Escort, and an enemy High Value Asset Attack (in this case against the AWACS). The number of enemy assets and their timing were selected to demonstrate the ability of analysis to drive out requirements. The UAV and Fighter radar data (sensor reports) are fed to the AWACS over LOS or BLOS communication channels (depending on physical location in the scenario). The AWACS "track" function processes track data available from the UAVs and Fighters, as well as its internal track data. When sufficient quality track data was processed within time limits, a track was established ("Detection") and forwarded to the Fighters. The track data was reprocessed in the Fighters to confirm track quality. If the track data available to the Fighter met quality requirements, then an 'Engagement-Pairing' was recorded and the enemy target was considered engaged. No further modeling of the engagement was performed, and the issue of kill probability and weapon performance were not addressed. The focus is on the steps leading up to the distributed C2 engagement decision.

Variables

The AWACS DCA Extend™ model was developed using a database for inputs and outputs. Thus many inputs can be changed relatively easily to support desired analysis including:

- Target type / number / flight path / speed
- Channel data rate and other communications parameters

Extend™ utilizes a random number 'seed' to determine probabilities within individual runs. The 'seed' is repeatable, allowing comparison between runs with different inputs. Additionally, multiple runs utilizing random seeds can be made to establish mean and Standard Deviation within a single set of variables.

Measures of Effectiveness

The following measurements were collected:

- Detection / Engage-Pairing Position
- Mean total response time from Create to Engage-Pairing for various communication channel data rates and standard deviation
- Mean communication latency at the UAV and Fighter Communication Channels and standard deviation

The basic model was designed to establish communication bandwidth requirements needed to support a potential AWACS scenario. To avoid the additional complications of weapon selection and effectiveness, we modeled up through the 'Engagement-Pairing' call when the Fighter had sufficient target Track Quality. No account was made of Blue Force Fighter or weapon resources available to prosecute the scenario enemy targets, Fighter engagement tactics, nor weapons Probability of Kill (P_k).

Component Models

The AWACS Communications Extend™ Model involves three major component models (Sensor, Fusion, and Communications) fed by a Target Generation model with target tracking via a 'global array'. AWACS serves as the C2 node. Communications channels link the UAVs (sensor platforms) with fighters (sensor and shooter platforms) and AWACS. Threats are generated from a Target Generation model and enter the scenario. Sensors on the UAVs and/or Fighters detect the threats, and relay the information to the AWACS platform where the sensor data is fused to improve the Track Quality (TQ).

Once a threshold TQ is achieved, the threat location is relayed to the fighters for engagement. The "shooter" activity is limited in the analysis to an engagement decision based on the precision of track quality. This avoids the need to model weapons for P_k. Each of the model elements is described in detail below.

Communications Channel

The communications model is intended to cover a variety of possible implementations including Internet Protocol (IP), Link16, packetized, or message-oriented transmission. The blocks indicated in Figure 8 set up the correct attributes of the message for sending it to the correct destination (as defined in the database). Message and channel parameters are set prior to entering the transmission reliability and delay calculations. Priority is assigned based on the type of message. The priority helps control queuing during transmission, and can significantly affect the results for constrained, low-data-rate communications channels.

Each of the blocks which contribute to Communications Delays is described in the following sections.

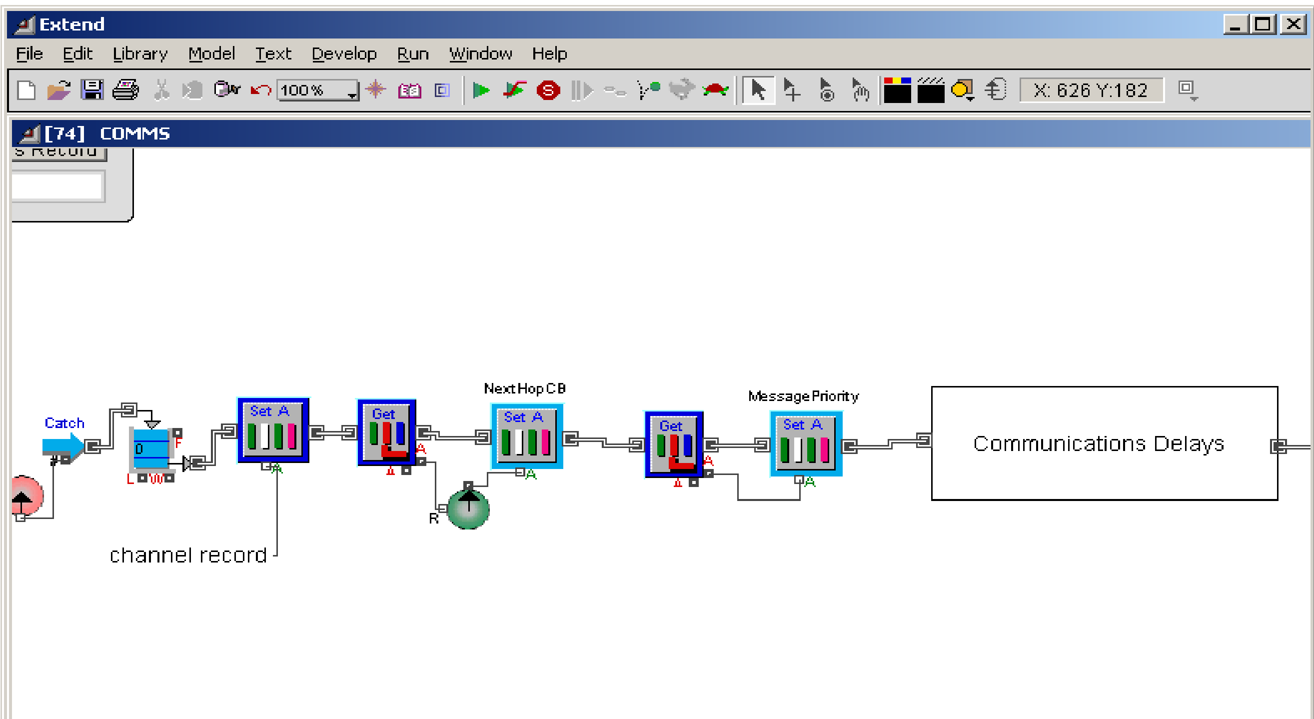


Figure 8. Communications model.

Communications Model Requirements

By modeling the communications channel parametrically and functionally we are able to simulate the performance of a variety of types of links, including time-division, multiple-access approaches as well as packetized, IP approaches. Because the goal is to determine threshold requirements for effective performance we need the ability to vary these individual parameters. We established an initial set of requirements for the communications channels. These are indicated in Figure 9.

Parameter	Use/Value
Message priority	Enables prioritization within queues to effectively manage limited communications throughput for highest-priority messages. Excessively “stale” messages can be deleted.
Protocol	Packetized (IP), Transmission Control Protocol (TCP; handshaking with packetized resending), UDP (User Datagram Protocol: broadcast mode, no transport-level resending); Message-oriented (non-packetized; the message is handled as a unit).
Availability	This calculation is based on %Area Coverage * %Time Available. The latter term is the probability of no-failure x (outage time)/(time between outages).
Compression	Compression enables a reduction in the number of bits transmitted at a “cost” of additional channel delay. Factors of 1-200x are possible. Decompression occurs at the receiving end and adds additional delay.
Encryption	Encryption/decryption add channel delay, but no other effects.
Latency	This is a calculation based on the actual time it takes to send a complete message through the channel. Latency = MessageSize/DataRate + CommunicationDistance/SpeedOfLight + EncryptionTime + DecryptionTime + CompressionDecompressionTime + (PacketLoss%*MaxTransmissionUnit/ DataRate). Packet loss can arise from such operational effects as jamming or low link margin at long distrances.
Effective Data Rate	This is a calculated as MessageSize/Latency
Message Reliability	This is calculated as Probability(message delivered within defined timeout).

Figure 9. Communications Channel Requirements.

Streaming data (e.g., ISR streaming video) is handled as a continuous sequence of message-oriented frames.

There is prioritized queue that holds the messages waiting to be transmitted. The messages go through a compression process, encryption process, packet process, the transmission process, and after successful transmission, the reverse of the first 3 processes (Figure 10).

Initially, message prioritization was as follows:

1. Sensor reports (first-in, first out, or FIFO)
2. Engagement pairing
3. Fighter acceptance (“engaged” accomplished)

This order was ultimately reversed to improve force-level performance, as discussed below.

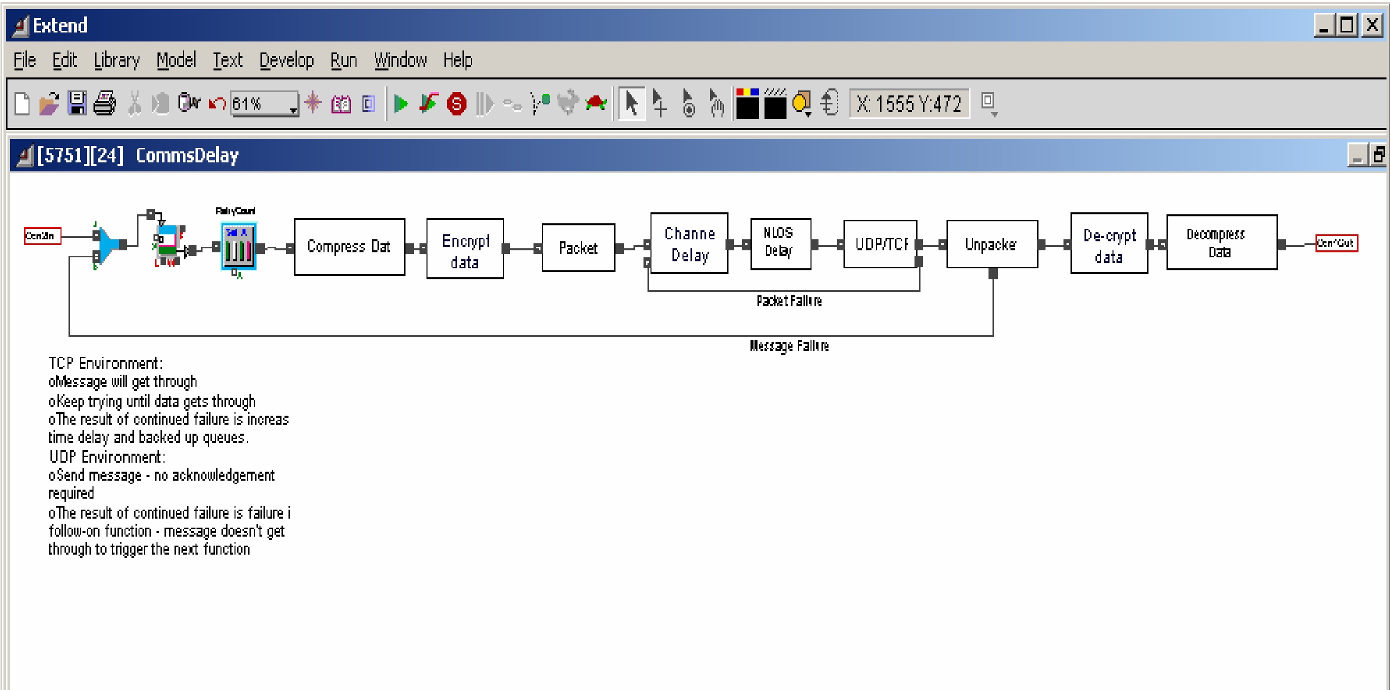


Figure 10. End-to-End Communications Model.

Target Generation

Target generation is controlled via the database. Large changes in the number and characteristics of enemy aircraft can be made relatively quickly. The hostile targets assumed in the analysis are indicated in Figure 11.

Figure 11. Target Types Data

Target Type	Route Record Number	Time of First Arrival	Arrival Interval	Max Number Packages	Target Speed	Package Size
AN-2	Route 1	2	0.25	4	100	4
Air-Ground	Route 2	9.6	1	4	480	4
Air-Air Support	Route 3	9.6	4	2	480	4
Air-Air	Route 4	29	0	1	1000	4

Sensor Model

The sensor model is a Monte Carlo, reference-range, scaling model using Swerling I target fluctuation statistics to calculate a single-scan probability-of-detection as follows:

$$P_{dss} = P_{fa}^{(1\,/\,(1+SNR))} \text{ (Swerling I, single pulse),}$$

where,

P_{dss} = Probability of detection single scan
P_{fa} = probability of false alarm
SNR = Signal-to-Noise Ratio (non-dB value for these equations), and
$SNR \propto (\text{Reference Range / target range})^4$.

Azimuth angle and range measurement errors are calculated for each report:

$$\text{Report Error} = (\text{Measurement Resolution}) / (2\ k \sqrt{(\text{SNR})}),$$

where,

Report Error = expected root-mean-squared 1-σ error in the measurement dimension;

Measurement Resolution = the measurement distance beyond which two targets can be resolved. Typically defined as the three-dB beamwidth in angle and one range gate in range;

k = error slope – a factor affecting beam splitting- dependent on system design, frequency, etc. Typically ranges between 1 and 2. (The denominator is limited to a maximum of 20 for a maximum beam splitting of 20:1.).

Finally, 2-D sensor report errors are translated to a Cartesian coordinate covariance for track fusion.

The radar simulation models first-order effects (report frequency) and second-order effects (report accuracy) impacting kinematic tracking performance.

Individual Sensors:

Each sensor platform has the opportunity to detect each target not removed by an 'Engaged-Pairing' call.

AWACS: In this analysis, AWACS is used both as a radar platform and for mission Command and Control (C2). As modeled, the tracking function is on-board the AWACS.

UAVs: UAVs are used as penetrating sensor platforms. No radar data processing is done on-board the UAV, but is sent via available communication links to AWACS.

Fighters: The fighters represent dedicated DCA assets capable of supplying raw radar data to AWACS, as well as confirming track data to effect 'Engagement-Pairing.' In this model the Fighters have a unique communication channel with the AWACS to support radar data and 'Engagement-Pairing' calls.

In this scenario, a target is considered "detected" when a sensor report is successfully received on AWACS. Sensor reports between platforms were allocated 25 bytes of data as indicated in Figure 12.

Data Item	Bytes Allocated
Header (1 byte)	1
Range and error (4)	4
Angle and error (4)	4
Altitude and error (4)	4
Time tag (2)	2
Doppler and error (4)	4
Own position (2)	2
Own speed (2)	2
Own Heading (2)	2
Total	25

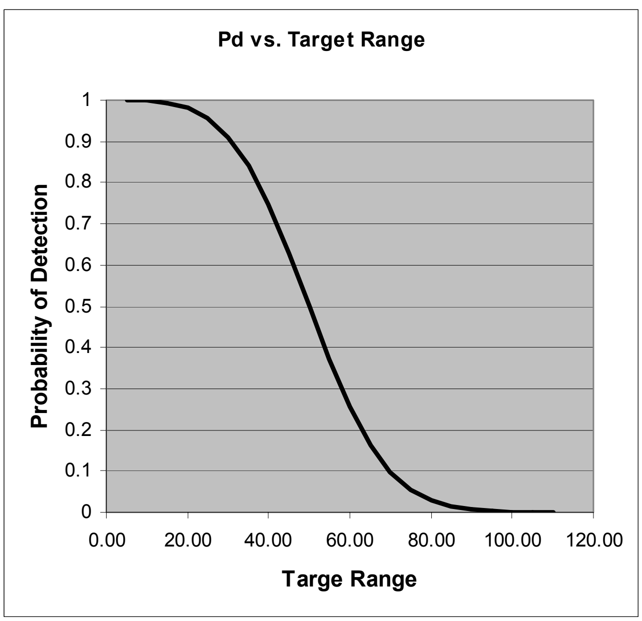
Figure 12. Message sizing for sensor reports.

The sensor model initiates the sensor scan and gathers information on both the sensor platform and all available target aircraft.

'P_d vs. Target Range' and 'Azimuth Angular Accuracy vs. Target Range' charts are included to help visualize the Swerling 1 single scan probability of detection and report error determination (

Figure 13). Since both detection probability and location accuracy are dependent on range, a simple model keeps track of the target locations and computes the distances from each (fixed) sensor platform to each target.

Using these curves the model determines the single-scan probability of detection. Those targets that are detected are recorded. Those targets that are not detected are ignored for the remainder of the cycle; in each frame all targets are evaluated for detection. Targets that meet the single-scan probability of detection have the detection time and target coordinates recorded in the global array. All targets continue to be kinematically propagated based on their characteristics at the beginning of the cycle (location, heading, speed).



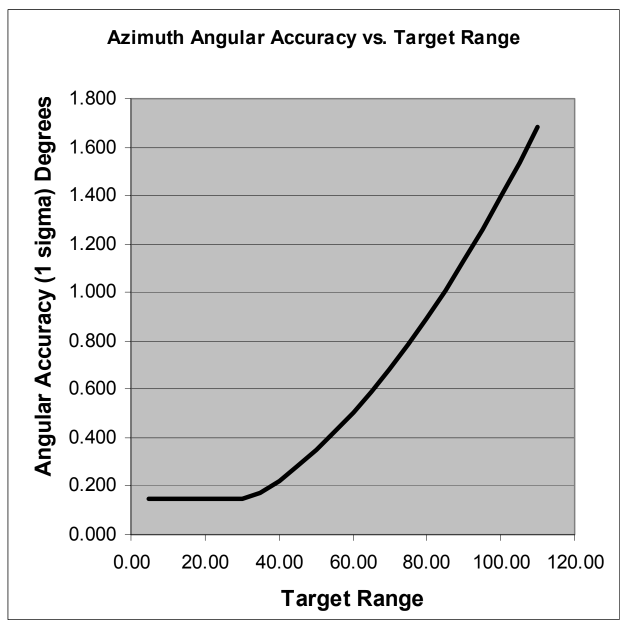


Figure 13. Sensor Model detection probability and accuracy depend only on the target range from the sensor.

Tracker Model

The Tracker model produces "theoretical best case" kinematic track fusion results given sensor updates, sensor accuracies, and communication latencies. The tracker measures radar detections (reports) in a 60 second sliding window for track initiation (requires 3 reports) and track maintenance (requires 1). It contains a three-state (position, velocity, acceleration) coupled linear Kalman filter used to fuse 2-D report error, and then predict and propagate 2-D track errors.

The model is based on the Singer target acceleration model used to estimate target process noise[1]. It uses open-loop fusion with no dynamic sensor tasking/management. The tracker is simplified and assumed to have perfect sensor report-to-track correlation, with no false alarms or false tracks. Only kinematic tracking is performed; track error is based only on estimates of report errors, process noise, and latencies (i.e. there is no report bias, gridlock error, time lock error, or explicit target maneuvers).

Coupled Tracker

The Coupled Tracker records the first Detection Time in the database, if not previously recorded, and updates the latest target information in the Report (Track) Table. Track association is perfect for the purposes of the model. Next, the Coupled Tracker checks to see if the current report is older than the last update. If it is older by more than one minute, the report is discarded. Otherwise, the covariance matrix is reset to the time of the oldest report less than one minute old and all subsequent reports are run through the tracker again. The reports are run through the tracker in order of the detection time, looking for three good reports within one minute to start a track or one good report to maintain track.

Covariance gating is done after the report passes through the tracker. The track is propagated from the time of detection of the report to the current time. If the area of the error ellipse (simplified area calculation) falls under a gating threshold and there have been three reports in the last minute, the report and subsequent track information is forwarded to the fighter. At the fighter, the gating process is repeated before an engagement pairing is accepted. The reports and the associated covariance matrix are aged in a sorted array for one minute then they are discarded.

Track Accuracy Requirement

Prior Boeing analysis[2] concluded that a Track Quality index 8 (per TADIL-J definition) was a goal for offboard tracks to be correctly correlated to onboard tracks. The probability statistics are indicated in

Figure 14, showing the correlation probability vs. Track Quality index and different sets of parameters (Horizontal (2-D), 3-D, and 2- and 3-D with Heading).

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[1] Singer, R.A., "Estimating Optimal Tracking Filter Performance for Manned Maneuvering Targets," ***IEEE Transaction on Aerospace and Electronic Systems***, AES-5, July 1970, pp. 473-483. (Benign – 1g maneuver, standard deviation, 10-second maneuver time constant).

[2] Internal Boeing Report, "Correlation Accuracy Requirements Study – Final Report", Enclosure (1) to D.V. Yates Memo, INT-98-034, (SL-98-0504)

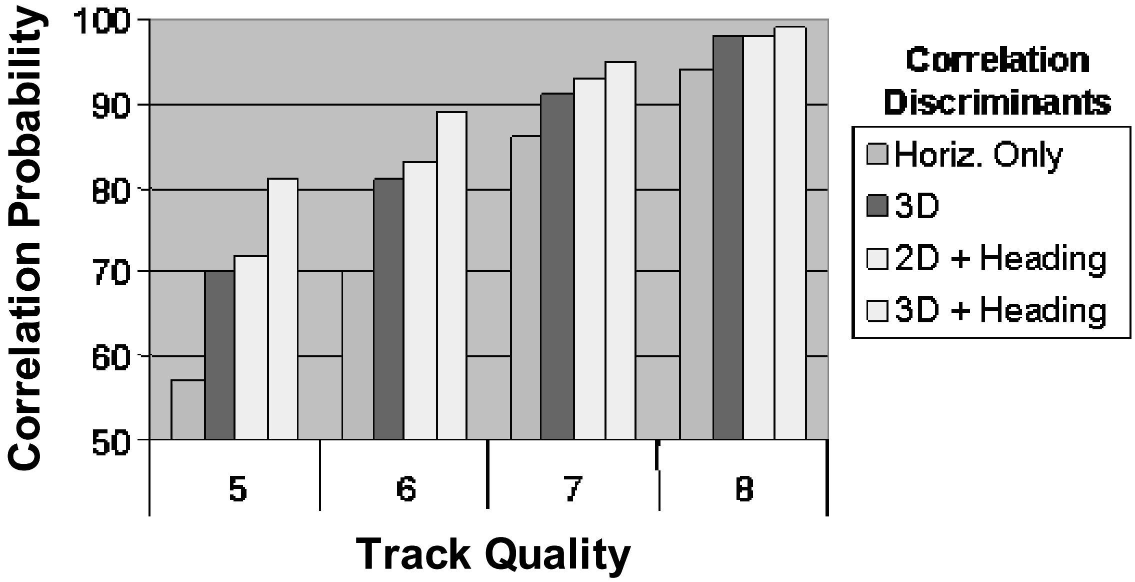

Figure 14. Track Correlation (%) vs. Track Quality.

Tracking and the Extend™ Global Array

Global arrays are used to store persistent information about each target in the model. Global arrays facilitate decision logic and the collection of statistics.

The 'targets' array documents the time and position when a target reaches a certain stage of processing. For example, when AWACS has been tasked to validate raw radar data on a target for the first time, a time stamp and 3-dimensional spatial (x, y, z) coordinates are placed in the global array in the row appropriate for that target. The other stages, listed below, are similarly documented.

For each target in the simulation, target information includes the information listed in Figure 15.

Target Type and Target Route	Time of Detection
Current target location (x, y, z)	Detection location (x, y, z)
Speed	Engaged (-Paired) Time
Heading	Engaged location (x, y, z)
Created location (x, y, z)	

Figure 15. Database Target Information

Scenario Definition

Blue air assets include an AWACS, with a common number of Weapons Controllers, set back from the Forward Edge of the Battle Area (FEBA) in deference to enemy Surface-to-Air Missiles (SAMs). Fighter support is placed between the AWACS and enemy attack, again set back from the FEBA and within line-of-sight (LOS) communication with AWACS. "Outrigger" UAVs are within LOS communication of the AWACS, but forward of the FEBA in an attempt to extend Air-to-Air radar coverage, especially for low flying aircraft utilizing terrain masking to delay detection as long as possible by Blue AISR assets.

Threat aircraft include a variety of target types: low, slow SOF insertion (AN-2 like); interdiction with escort (Air-to-Ground fighter-bombers with Air-to-Air escort fighters); and High Value Asset Attack (HVAA)). Threats appear in the scenario over a short period of time and in sufficient numbers to stress Airborne ISR assets and supporting communication.

SOF Insertion

Special Operation Forces (SOF) insertion is nominally simulated by AN-2 aircraft flying at 100 ft. altitude and 100 knots airspeed. The number is set to stress the communications to support the current notional number of Weapons Controllers. The SOF Insertion aircraft are placed in the simulation to 'Pop-up' where a nominal UAV would be able to detect very low flying aircraft in an area of significant vertical development (rugged terrain). This simulates sensor line-of-sight (LOS) restrictions.

'Enemy Air' Interdiction with Escort

Enemy Air Interdiction Fighter-Bombers and A-A Escort Fighter aircraft are inserted to 'fly' into nominal UAV radar coverage. The number is set to stress the communications to support an enhanced number of Weapons Controllers with additional enemy tracks to be monitored by surveillance personnel.

High Value Asset Attack (HVAA)

The third group of enemy aircraft would be a high altitude, high speed attack against High Value Assets like the AWACS. Although detected later because the attack is avoiding UAV Outriggers, the HVAA enemy aircraft arrive at the FEBA prior to the A-G Interdiction with A-A Escort. As communication channel speed is reduced, the overlapping arrival adds to the Weapons Controller/Surveillance Personnel workload as well as the communication traffic.

Analysis Results

Detection-to-Pairing Time Plots

"Detection" occurs when the sensor report regarding the object is received on AWACS.

Figure 16 indicates scenario-averaged response time from target creation to target engagement. The data presented are for single run cases with a common random number seed, which limits the variable to changes in ISR data rate. Although the UAV and Fighter Communication Channels are separate resources, the ISR data rate is the same for both.

In the limit as the data rate is reduced the system performance asymptotes as if there are no UAVs in the architecture. The steep drop at roughly 10 kbps indicates that the communications channel data rate is beginning to support early engagement based on the sensor reports from the forward deployed UAVs (this value is highly dependent on the analyzed scenario, especially the number of targets (44 aircraft). Such a performance curve, when derived from an approved scenario and architecture, could be the basis for establishing the minimum communications requirements for the specified information exchange requirement. The presence of such a steep threshold indicates a clear transition from "ineffective" to "effective" performance at the higher data rates.

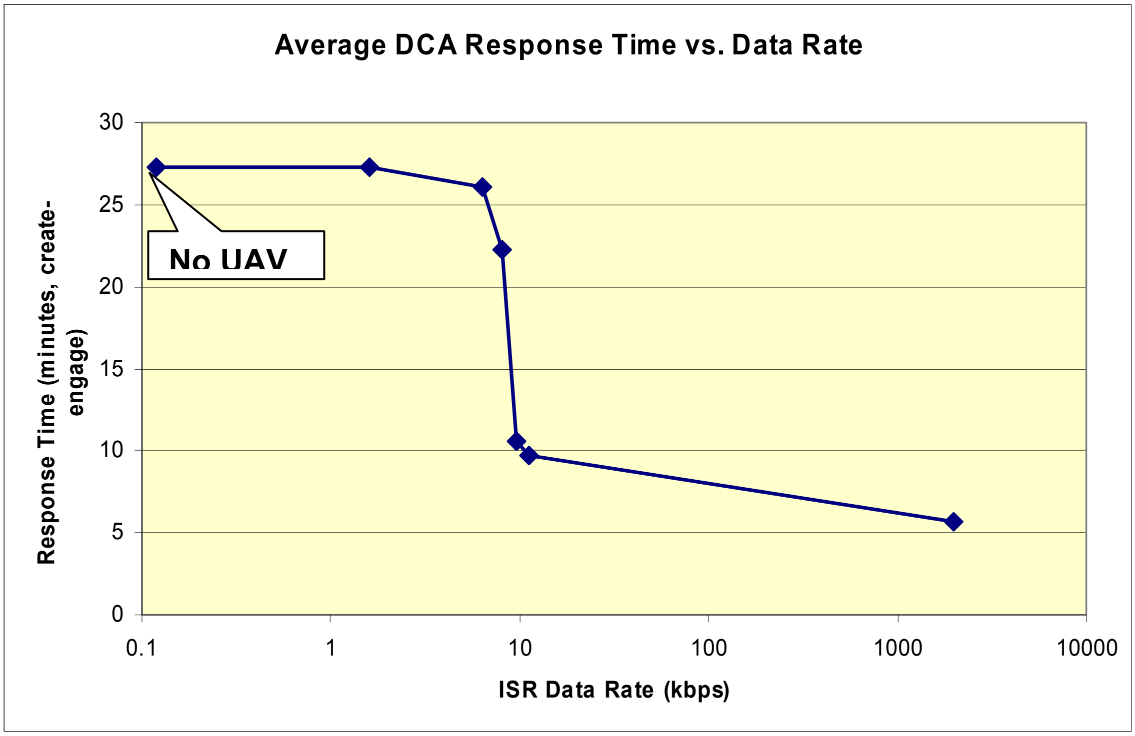

Figure 16. Scenario-average DCA Response Time vs. Data Rate.

Channel Latency

Maximum message latency is presented in Figure 17. Channel Latency is based on 45 minute runs, the approximate time the slowest enemy aircraft crosses the FEBA. The 'Fighter Channel Delay' line appears to reflect its use to transmit 'engagement pairing' radio traffic as well as fighter sensor reports. The local minimum in the Fighter Channel Delay indicates minimal engagement-pairings until the UAVs begin to report more targets. For the best case (2 Mbps), maximum channel latency drops to 1.25 seconds for the UAV channel, with an average latency of 95 milliseconds.

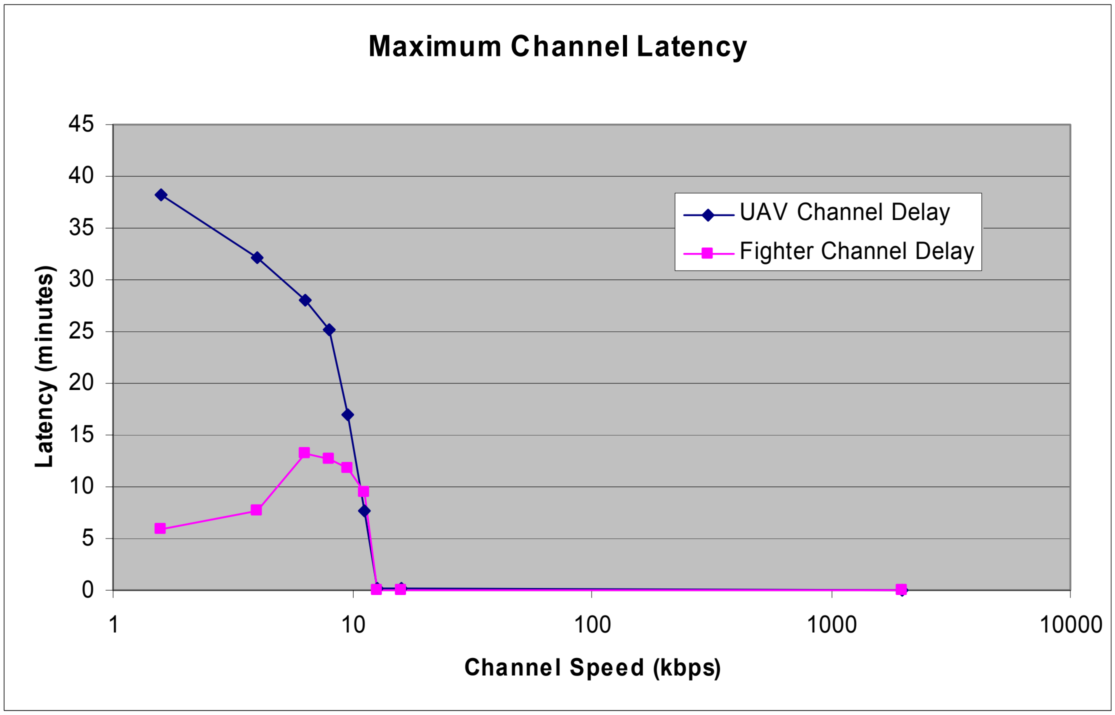

Figure 17. Maximum Channel Latency.

Other Findings – LIFO vs. FIFO

During the initial example runs when Communication Channel data rates were restricted, it was noted that at some point in the run, the communications queues would rapidly fill up. At the same time no more data would be processed (because of the staleness of the data) and all detections and engagement-pairings (except HVAA) would stop.

The analysis process had set the attribute queues to process the highest priority messages (sensor reports) on a First-In, First-Out (FIFO) basis. This meant that when the queue became loaded up, the older sensor reports would be transmitted first, but by the time they were transmitted they would have enough error so as not to be useable in the fusion model. Hence, as the 'through-put' of a channel was reduced, the queue would saturate at some point and no more targets would be processed.

By reversing the queue priority (processing engagement-pairing communications first), and changing to a Last-In, First-Out (LIFO) process, the most recent sensor reports would be processed first. At the break point of saturation for the FIFO runs, the LIFO runs were completed with approximately 240 kbps less communication data rate per channel. The use of LIFO ensures that the most accurate data is available for Tracker. This indicates that message processing for bandwidth-limited communications must carefully consider the operational impacts of prioritization schemes.

Discussion

These initial results for aerial sensor range extension using UAVs clearly indicate that inadequate data rate in the communications channel produces a force response time (from target creation to target engagement) virtually indistinguishable from an architecture which omits

UAVs for aerial surveillance range extension, completely nullifying the expected benefit of the forward-deployed UAVs (Figure 16).

In more general terms, the analysis provides a "theoretical best case" of integrated tracking accuracy, parametrically limited by communications-induced latencies: Adding fidelity (reality) to radar and tracking models will likely degrade these results. However, the analysis can be used to help derive communications requirements for application to specified architectures and scenarios.

Other parametric and model variations that can easily be pursued include:

- The effectiveness of data compression,
- The assigning of message types to different communications channels (e.g., C2 commands separate from fighter ISR),
- Scenario variation and the sensitivity of communications to the threat environment,
- Changes in sensor report update rate (freshness vs. communications load).

Summary

We are using analysis to help define communications requirements to support the development of C2-ISR force architectures. This can provide insight into the true requirements and benefits of network-centric operations by carefully defining the threshold performance, and without assuming nominal network performance of near-zero latency, perfect reliability, and infinite data rate.

The variant allocations of C2 functionality among various elements of the force architecture can be used to support life-cycle cost analyses and trade platform-based C2 vs. network-centric C2 with robust communications. The modeling of simple sensor-C2-shooter networks can be assessed for a variety of force architectures and missions.

By modeling the communications channel performance parametrically, we allow such parameters to be modified to identify performance thresholds based on force-level measures-of-effectiveness (e.g., time to engage, location of engagement, probability of kill). Once effective and "desirable" architectures are identified, the threshold communications requirements associated with the preferred architectures can provide the analytical basis for obtaining and integrating communications which satisfy the requirements.

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