Network-Centric Operations Case Study

Air-to-Air Combat With and Without Link 16

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Prepared for the Office of Force Transformation in the Office of the Secretary of Defense

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Preface

The Office of Force Transformation (OFT) and the Office of the Assistant Secretary of Defense for Networks and Information Integration (OASD [NII]) have developed a conceptual framework for conducting analyses and enhancing understanding of network-centric operations (NCO) capabilities. RAND is one of the supporting organizations that assisted the Office of the Secretary of Defense in developing the NCO Conceptual Framework (NCO CF). The NCO CF has several objectives: to provide a better understanding of key NCO attributes and their interrelationships; to provide metrics to measure progress in developing transformed, network-centric forces; and to help understand and articulate how NCO capabilities can be a source of combat power.

RAND has applied the NCO CF to the air-to-air combat mission. We used the framework to examine the results of the Joint Tactical Information Distribution System (JTIDS) Operational Special Project. This project examined the performance of tactical fighter aircraft (F-15s) equipped with Link 16 data communications terminals and found that F-15s equipped with Link 16 were significantly more effective in air combat than F-15s equipped with only voice communications.

This report describes the results of the case study that involved analyzing the capabilities of Link 16 data and voice communications networks, conducting interviews with experienced fighter pilots, and

building a quantitative model to calculate NCO CF metrics for mission capability packages designed for the air-to-air combat mission.

This case study provides useful insights into the application of the NCO CF and associated metrics. The report highlights the advantages NCO capabilities can potentially provide U.S. air forces in the air superiority mission. It also demonstrates the feasibility of applying the NCO CF in a quantitative fashion to the chain of inferences contained in the network-centric warfare hypothesis. This report should be of use as a starting point for those seeking to use the NCO CF to analyze the impact of NCO capabilities in more complicated military mission areas.

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Summary

In the mid-1990s, the U.S. Air Force at the request of Congress conducted the Joint Tactical Information Distribution System (JTIDS) Operational Special Project. In this exercise, the capabilities of F-15 air superiority aircraft equipped with voice-only communications were compared with F-15s equipped with voice and JTIDS Link 16 data link communications in tactical air-to-air combat. More than 12,000 sorties were flown in this special project. Blue offensive counterair packages composed of these F-15s ranged in size from two to eight aircraft. In all cases, the packages were controlled and cued by Airborne Warning and Control System (AWACS) aircraft. The size of the engagements ranged from two Blue fighters on two Red fighters to eight Blue fighters on 16 Red fighters. Engagements occurred during daylight and night conditions. The primary independent variable was whether the Blue F-15s were equipped with the Link 16 data link or with conventional voice communications only. The capability of the Red aircraft remained consistent during the project.

On average, Blue offensive counterair packages equipped with Link 16 achieved a two-and-a-half times improvement in kill ratio (Red aircraft to Blue aircraft "destroyed"), both during the day and at night. However, it was unclear how and why this significant improvement in force effectiveness arose. The aim of this study is to understand whether this increase in combat effectiveness stemmed from the network-centric capabilities of F-15 aircraft equipped with Link 16 and fighter pilots able to effectively use data link communications.

The original Network-Centric Warfare (NCW) hypothesis posits the following relationships between twenty-first century information technologies, information sharing, and warfighting capabilities:

- "A robustly networked force improves information sharing
- "Information sharing enhances the quality of information and shared situational awareness
- "Shared situational awareness enables self-synchronization, and enhances sustainability and speed of command
- "These, in turn, dramatically increase mission effectiveness." (Alberts and Garstka, 2001.)

The Network-Centric Operations Conceptual Framework (NCO CF), developed by Office of Force Transformation (OFT) and the Office of the Assistant Secretary of Defense for Networks and Information Integration (OASD [NII]), provides a more detailed and precise elaboration of the NCW hypotheses.[1] It includes NCO capability concepts (such as the degree of networking, degree of information sharing, and situational awareness) and hypotheses for how these concepts relate to and influence each other. The result is an interlinked set of NCO capabilities that describe how they in combination can lead to improvements in overall military force effectiveness. Importantly, the NCO CF describes subsidiary attributes and metrics for assessing NCO capability concepts, making it possible to determine whether and how possession of a particular NCO capability relates to improvements in force effectiveness. Figure S.1 shows a top-level view of the NCO CF, including its top-level NCO capability concepts and the hypothesized interactions between them.[2] All linkages reflect positive relationships; for example, it is hypothesized that

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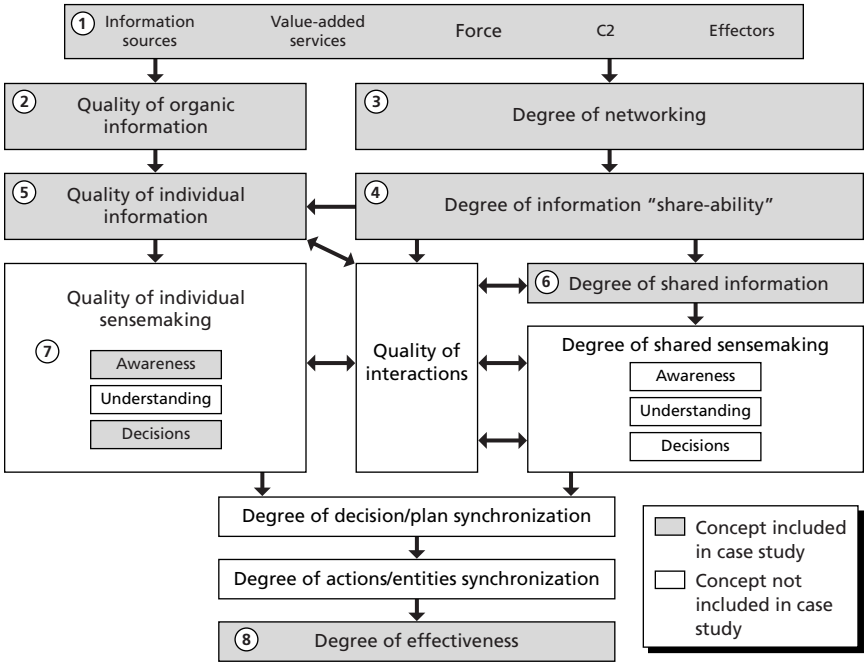
[1] Note that we use the terms NCO and NCW interchangeably in this report.

[2] The NCO CF is described in Signori et al. (2002); Evidence Based Research, Inc. (EBR) (2003); and Signori et al. (2004). Major concepts of NCO are described in Alberts, Garstka, and Stein (1999) and Alberts et al., (2001).

an improvement in the quality of information will improve the quality of situational awareness.

OFT and OASD (NII) tasked RAND to undertake a study to apply the NCO CF to the air-to-air combat mission. The primary objective of this case study is to understand whether the relationships between NCO capabilities hypothesized to exist in the NCO CF are valid for this particular military mission area and to determine how NCO capability improvements may lead to increases in military force effectiveness in air-to-air combat. In other words, our purpose was to "learn by doing" by applying the NCO conceptual framework to a specific mission.

Figure S.1
The NCO Conceptual Framework and Its Application to Air-to-Air Combat



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The air-to-air combat mission was chosen as an initial case study because it can involve relatively simple tactical engagement situations with a small number of aircraft. We anticipated it would be relatively easy to apply the NCO CF to simple tactical engagements. We were also fortunate that a source of quantitative force effectiveness data was available for this mission area. We were able to utilize data from the Joint Tactical Information Distribution System (JTIDS) Operational Special Project (Hq. USAF, 1997). Of particular interest is that the JTIDS project found that fighter aircraft in air-to-air engagements were significantly more effective when equipped with the Link 16 datalink than when equipped solely with voice communications. Specifically, Link 16–equipped fighters saw approximately a two-and-a-half times improvement in the kill ratio (Red aircraft to Blue aircraft shot down), both during daylight and nighttime conditions. This report examines whether the NCO CF can explain this major increase in mission effectiveness.

Figure S.1 showed the NCO CF top-level concepts that serve as the foundation for this case study, with the numbers indicating the order in which they are addressed in this report. The components of individual sense-making are shaded separately: we incorporate the quality of individual awareness and quality of decisions concepts but not the quality of individual understanding concept. Other concepts we focused on relate to physical NCO capabilities–notably the degree of networking and the resulting quality of information the pilots obtained from their organic sensors as well as from the network to which they are connected (see the various information concepts listed in Figure S.1). On the other hand, we did not employ the quality of interactions or sense-making concepts because we lacked data for these measures at the time the study was conducted. It is important to note that these concepts represent activities that take place in the cognitive domain (i.e., mental processes) and the social domain (i.e., interactions, such as conversations, between warfighters) and are difficult to evaluate directly.

Mission Capability Packages and Networking.

In the live flight operational exercises examined as part of the JTIDS Operational Special Project, F-15 fighter packages of two to eight aircraft flew against equal size or larger packages of enemy aircraft. We shall designate these fighter aircraft packages mission capability packages (MCPs).

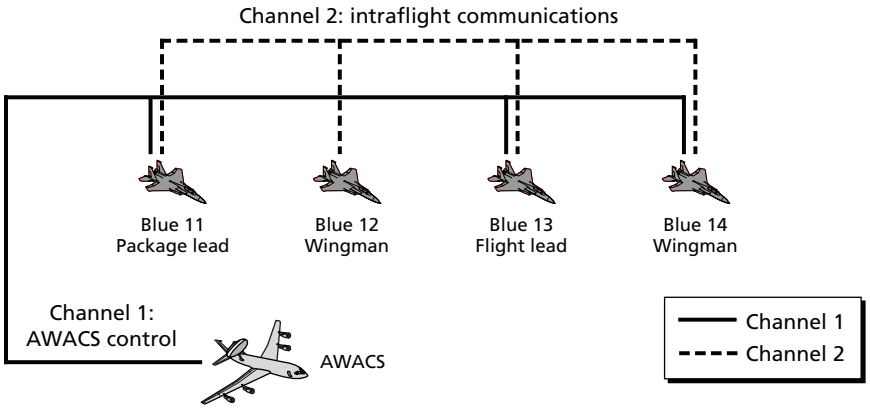
Two alternative Blue MCPs flew against the same Red MCPs in these live flight exercises. The Blue MCPs had different networking capabilities but were otherwise identical. One Blue MCP was equipped with the Link 16 digital data communications network, while the other had only voice communications. The Red fighters that participated in these live flight operational exercises had voice only communications.

Voice Networks

Figure S.2 illustrates the voice channel structure typically employed by Air Force fighters, in this case for an MCP with four fighters. Pilots each monitor two separate voice channels. AWACS broadcasts aircraft track information on Channel 1 to the Blue aircraft. The four fighter aircraft communicate among themselves on Channel 2. Each fighter pilot listens to two channels at a time, and only one aircraft pilot can speak on a channel at a time.

Air Force pilots have developed a voice coding scheme that allows pilots and AWACS flight controllers to transmit approximately one aircraft track about three times every ten seconds. We use ten seconds as the air picture track update cycle time because this is the rate at which the AWACS radar antenna rotates or performs one complete surveillance cycle of the battlespace. So, in principle, F-15 fighter pilots can receive updated air track information from AWACS every ten seconds, if AWACS flight controllers have the time to verbally transmit this information over the voice network every radar sweep and if there is “time available” to transmit the information over

Figure S.2
Typical Voice Channel Connectivity



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the voice channel (i.e., if there is no contention for the voice channel).

The pilots must interpret the spoken information they receive on their voice radios and build a mental three-dimensional "picture" of the positions and velocities of reported aircraft. This is known as developing situational awareness of the battlespace and is a persistent activity because of the dynamic nature of air combat. While fighter pilots generally have the mental ability to keep air track information in their minds for long periods, the utility of this information decreases as an air track "age" grows. An air track with an age of ten seconds or more has little utility because the pilot will have only a vague idea where the fast-moving jet fighter may be (the object that corresponds to the air track), especially at close ranges. We approximate the process of removing old information from a fighter pilot's mental map or "common operational picture" of the battlespace in the following way: air tracks older than the AWACS update rate are "dropped" on the grounds that the tracked plane will have moved far enough in ten seconds to make the pilot's mental air track position

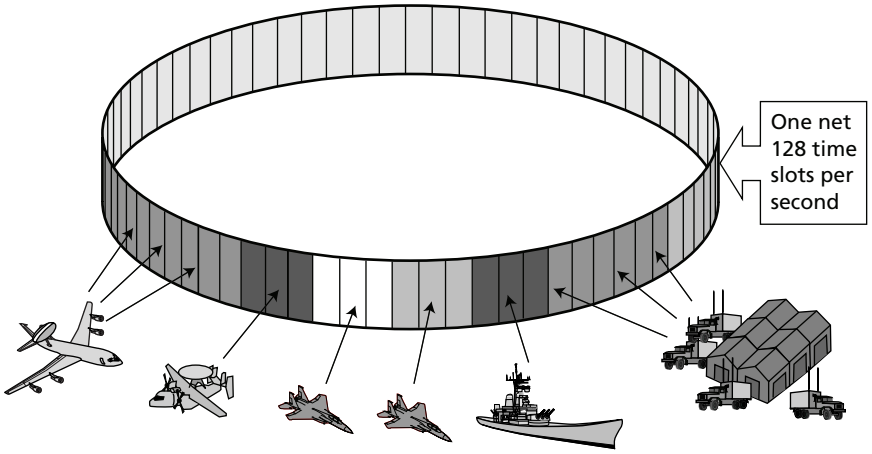
and velocity estimate too inaccurate to be useful in a high-speed tactical air combat engagement.

Link 16 Data Communications Network

Link 16 is a wireless data communications system that provides air track and other information to fighter aircraft, other weapons platforms, and command and control (C2) nodes equipped with JTIDS and Multifunctional Information Distribution System (MIDS) communications terminals. Link 16 uses a time-division multiple access (TDMA) wireless network structure and a jam-resistant, frequency-hopping waveform. This networking structure is illustrated in Figure S.3. In this type of network, each participant (or network node) can receive all transmissions made by other network participants.

Fighters equipped with Link 16 can receive air track information from other neighboring fighter aircraft and from AWACS (if AWACS is within a line of sight of the fighter). A Link 16 network is composed of 128 time slots per second, with each slot capable of

Figure S.3
Link 16 Network Connectivity



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describing a single airplane track to a high degree of accuracy. Link 16 air tracks received by a particular fighter from other aircraft are shown on a display screen in the cockpit along with air tracks detected by the aircraft's organic sensors. Therefore, each fighter pilot in a Link 16–equipped MCP can display nearly the same air track information or the same picture of the battlespace.

Information "Share-Ability" and Quality of Information

The "degree of information share-ability" concept describes how well individual pieces of information can be shared through use of the MCP's networking capabilities. In comparison to voice-only communications, the Link 16 network acts as an information multiplier; what is detected by one aircraft (either by AWACS or by a fighter) is immediately shared with all other fighters in the MCP precisely and in near real time. In contrast, voice transmissions are relatively slow (maximum of three track updates every ten seconds across an MCP voice channel), meaning that only a small fraction of the detected information can be shared. Further, voice communications introduce errors, either in the verbal communications themselves or because of radio noise or interference.

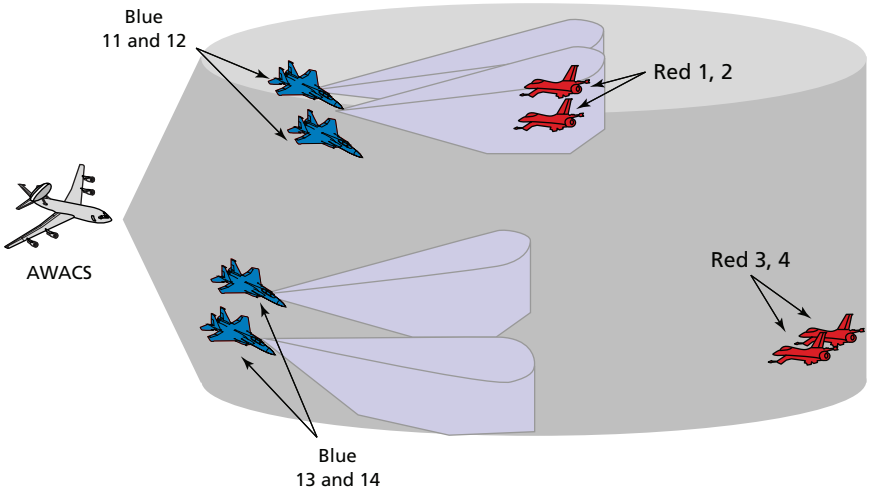
Consider the early stages of an air-to-air combat engagement shown in Figure S.4. In the tactical engagement, four Blue fighters engage four Red fighters. The four Blue fighters are provided threat warning information by AWACS and may be vectored by AWACS to engage particular threat aircraft. The figure illustrates the "opening gambit," or early stages of the engagement, which is a key part of the engagement recognized as strongly influencing the final outcome, as the Blue aircraft have an opportunity to maneuver for highly advantageous positions prior to engaging the Red aircraft directly. Here, the AWACS aircraft has radar coverage of the entire battlespace. Two of the Blue fighters (Blue 11 and Blue 12) have radar locks on two of the Red fighters (Red 1 and 2). Two of the Red aircraft (Red 3 and 4)

are out of radar range for any of the Blue fighters and are on the very edge of the battlespace but are approaching their attack positions rapidly and are detected by AWACS.

We calculated the quality of information across the MCP for the engagement geometry shown in Figure S.4, for both an MCP with Link 16 and an MCP with voice-only communications. Note the use of the term "information" to indicate that it includes information available to the pilot of a particular aircraft from both organic sensors and the network. Figure S.5 compares quality of information scores for each Blue aircraft in both the voice-only and Link 16–equipped MCPs along four metrics (all normalized between zero and one):

- Completeness (Detection) is the percentage of all air tracks in the engagement (four Red and five Blue aircraft) that the Blue

Figure S.4
Early Stages of a Tactical Engagement



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aircraft either detects directly or has reported to it in the last ten seconds;

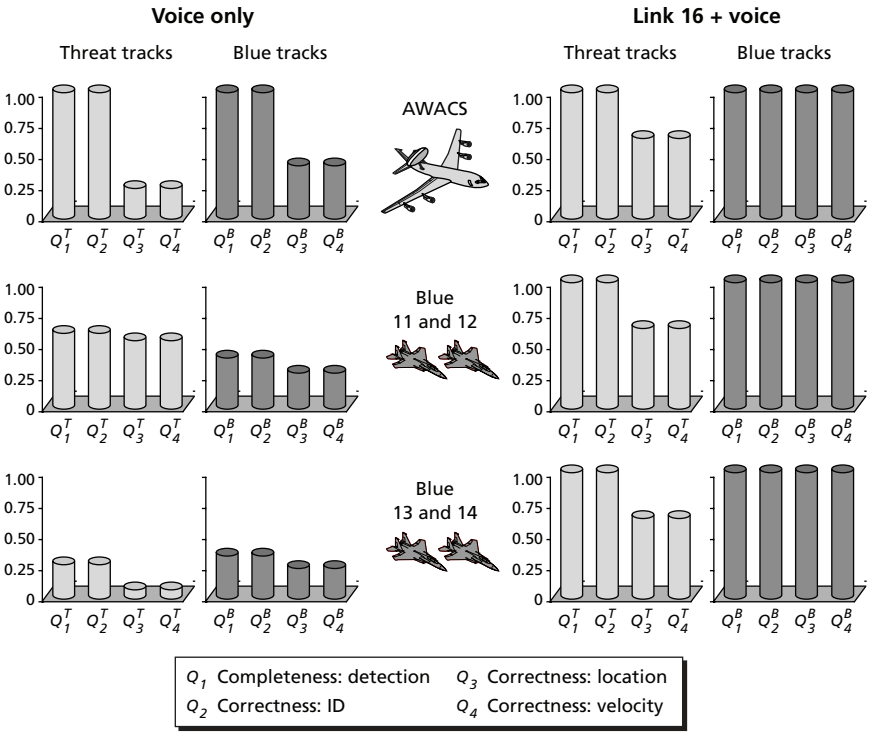
- Correctness (Identification) is the percentage of the air tracks for which the Blue aircraft has correct combat identification (ID)—i.e., Red, Blue, or neutral/civilian aircraft. If the air track ID is correct, a score of 1.0 is given. If it is incorrect or designated as unknown, a score of zero is given.
- Correctness (Location) is the percentage of air tracks for which the Blue aircraft has a location report (either from direct detection or network communications links). If the location report is less than one second old, it is considered to be "near real time," allowing for precise maneuvering and cuing fire control systems, and has a value of 1.0. If the report is between one and ten seconds old, it is considered to be "non–real time," suitable only for general cuing, and has a value of 0.25. If the report is older than 10 seconds, it is give a value of 0, as described earlier.
- Correctness (Velocity): Velocity is the percentage of air tracks for which the aircraft has a velocity report. As with Correctness (Location), the velocity report has value 1.0 if it is less than one second old, 0.25 if it is between one and ten seconds old, and 0 if it is older than that.

As shown, Blue aircraft in the Link 16 equipped MCP had much higher quality of information scores than the voice-only MCP, especially for the Location and Velocity metrics (which rely heavily on precise, real-time air track updates).

Shared Awareness and Decisionmaking

Interviews with experienced pilots revealed that the improved quality of information under Link 16 improved situational awareness and subsequent decisionmaking in two ways. First, in general, the pilots

Figure S.5
Comparing Quality of Shared Individual Information Across MCPs



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with access to the Link 16 network reported spending less time building situational awareness (i.e., determining where the Red and Blue aircraft are) than pilots with access only to the voice-only network. In the voice-only network, pilots had to continually listen to voice traffic describing air tracks, mentally convert each description into a velocity and location, predict where the aircraft would likely be over time based on the last report, and perform these mental calculations while listening to further incoming reports. Formal interviews were conducted with two pilots who had experience with Link 16–equipped aircraft. One of these pilots was a key participant in the JTIDS operational special project. In addition, we have discussed the

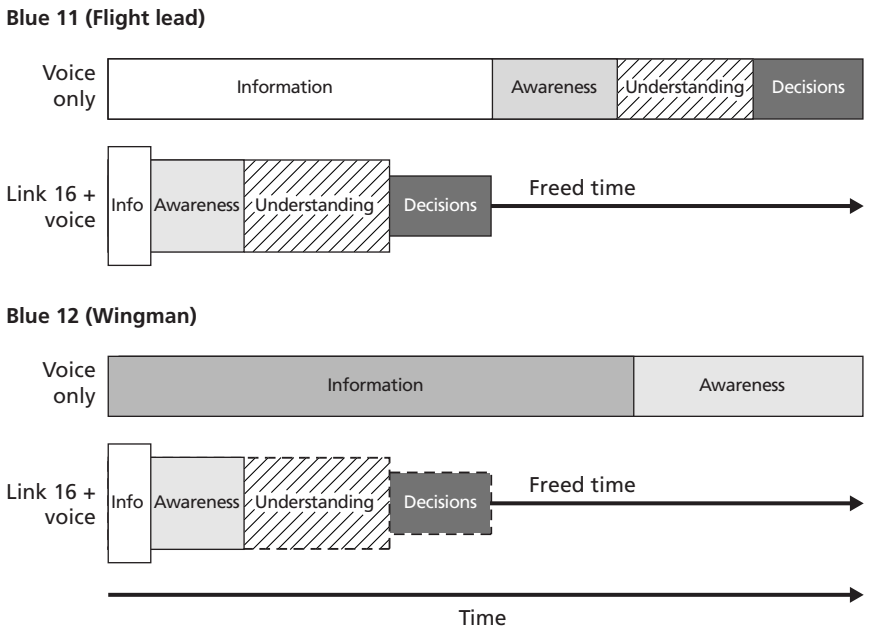
findings of this report with four other pilots who have had experience with Link 16–equipped aircraft and with the new tactics Link 16 enables. This process of gaining awareness was described as slow (restricted by voice transmissions), mentally taxing, and potentially error-prone. Further, because the manual mental process of building awareness is error-prone under the stressing conditions of combat, pilot situational awareness information likely will not be entirely common across the MCP. In other words, situational awareness is shared and interpreted imperfectly among pilots over voice channels.

In contrast, in the Link 16 network, pilots are presented with a continually updated image visually displaying the precise positions and velocities of all detected aircraft in the battlespace. The resulting process of gaining situational awareness was much faster, almost automatic (no mental calculations required), and accurate. The resulting time compression in obtaining information and awareness with Link 16 is shown in Figure S.6. This freed time could be used to consider more alternative courses of action, which will tend to lead to better decisions, and make more decisions in a given period of time, which (assuming the decisions are reasonable) should lead to more targets destroyed. Notably, the freed time also allows the wingman time for sense-making and making decisions to engage targets, as opposed to spending virtually all their time gathering and monitoring critical information as in conventional doctrine.

Second, the pilots were able to improve execution of air combat tactics that were enabled by taking advantage of their increased awareness as well as the increased time they had available for decision-making. From the interviews, we have identified four broad types of improved tactics for air-to-air combat. These tactics are illustrated in Figure S.7.

The first of these is simply an increased number of engagements in the same period. This tactic is possible because pilots with Link 16 can quickly recognize the most efficient attack trajectories. This is an important consideration because (according to the pilots) the fighters

Figure S.6
Decision Speed and Competitive Advantage with Link 16



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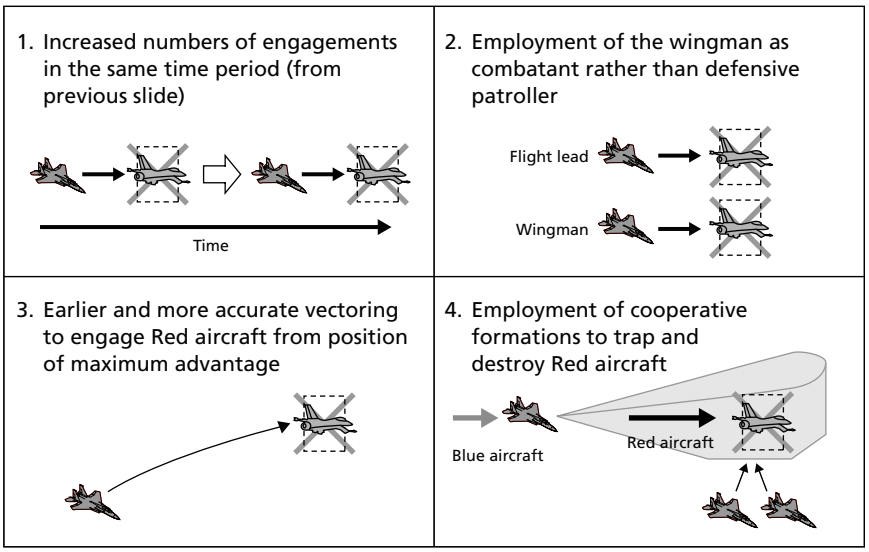
only have a limited time to engage before they run out of fuel and must return to base.

The second is the employment of the wingman as a combatant rather than as a defensive patroller. With Link 16 and good combat ID capabilities, the location and identity of threat aircraft are apparent to pilots of all Blue aircraft. The flight lead has more options for employing the wingman as a primary shooter because of the higher levels of individual and shared understanding of the engagement, effectively doubling the firepower. Wingmen do not have to take up defensive positions to hedge against possible attacks from threat aircraft advancing from unknown locations.

The third is the use of other planes' track information to vector earlier and more accurately, which allows a Blue fighter to enter an

Figure S.7
Improved Air-to-Air Tactics Execution Enabled by Improved Awareness



SOURCE: Interviews with fighter pilots experienced with Link 16.
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engagement from a position of maximum advantage, before the Blue fighter's radar (or the Red plane's radar, for that matter) can detect the engaging plane. This tactic takes maximum advantage of AWACS or other offboard sensor threat-reporting.

The fourth is the use of "ambush" combat air patrols (CAPs) and the use of terrain to trap and destroy Red aircraft. Because all Blue aircraft locations are known by all Blue fighter pilots—even if those aircraft are operating in voice communications or Identification, Friend or Foe (IFF), transponder silence—they have more options to engage targets. One example of an "ambush CAP" tactic is when a Blue fighter chases a Red fighter towards other Blue aircraft. The latter Blue aircraft have their radars turned off (or are hiding in a canyon) so the Red fighter is not likely to know that the latter Blue aircraft are present. Then, when the Red aircraft is chased into range, the other Blue fighters will suddenly engage the Red fighter, surpris-

ing the Red pilot and likely destroying the Red fighter with minimal risk to Blue aircraft. This latter tactic is an example of tactical self-synchronization enabled by the Link 16 network.

Mission Effectiveness

Loss exchange ratios (number of Red aircraft killed divided by the number of Blue aircraft killed) from the JTIDS Operational Special Project are shown in Table S.1. It is based on the results of 12,000 training sorties in tactical air-to-air combat. On average, Link 16 led to a two-and-half times improvement in the kill ratio (Red aircraft to Blue aircraft shot down), during both daylight and nighttime conditions.

The analysis presented above indicates in these tactical engagements the better decisionmaking and improved tactics execution by Blue fighter pilots were enabled by improved situational awareness provided by Link 16. This in turn led to the Link 16–equipped MCPs' improvements in kill ratios. This chain of inferences is verified by our interviews with experienced pilots. For some steps of the NCO inference chain, quantitative data were not available—e.g., data monitoring how pilots gained awareness and made decisions during the engagements. Nevertheless, pilot interviews substantiate the validity of the inference chain described in the NCO framework for this mission area.

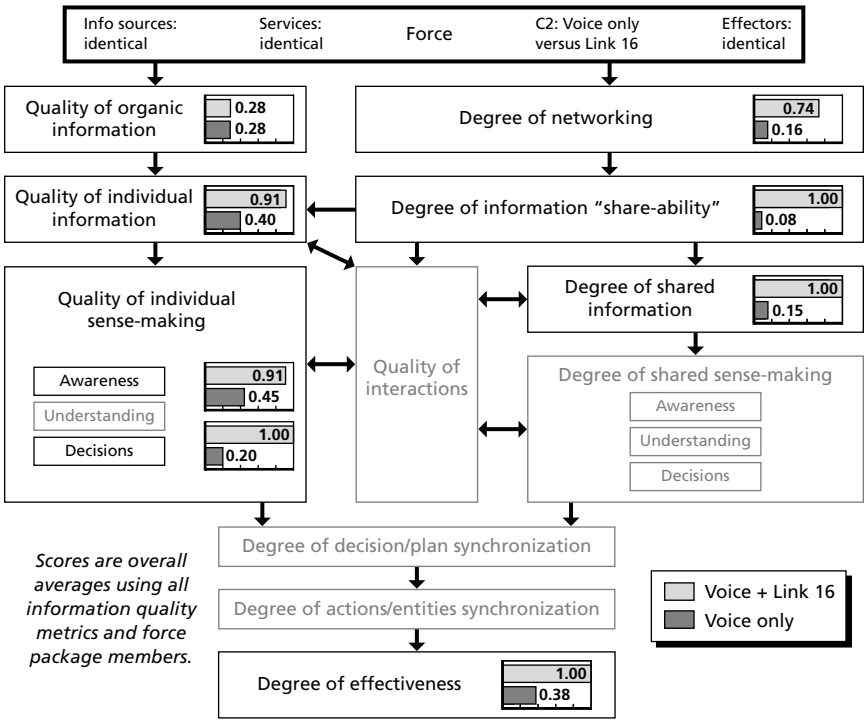
Table S.1
Results of the JTIDS Operational Special Project

	Kill Ratio	
	Voice Only (MCP 1)	Voice Plus Link 16 (MCP 2)
Day	3.10:1	8.11:1
Night	3.62:1	9.40:1

Conclusions

Figure S.8 presents averages of the NCO CF metric scores we calculated in this case study across the MCPs. As shown, despite starting with similar airframes, training, doctrine, and organic sensing capabilities, the Link 16–equipped MCP was able to take advantage of the information shared within the MCP through Link 16 and voice networks far more effectively than the voice-only MCP. As hypothesized by the NCO tenets, the robustly networked force enabled via Link 16 improved information sharing and the resulting quality of information, which enhanced shared situational awareness, which in turn

Figure S.8
Summary Comparison of MCPs Using Average Scores



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enabled self-synchronization (in this case study, as measured by the ability to make improved decisions and execute improved tactics) and which resulted in dramatically increased mission effectiveness as measured by the kill ratios.

We have applied the NCO CF and developed quantitative estimates for key NCO metrics within the framework. We have examined several inference chains that run through the NCO CF and have found them to be consistent with the results of a key air-to-air live flight experiment and with the observations of experienced combat pilots.

Finally, we recommend additional case studies be performed of more complex mission areas and that extend this analysis of the air-to-air mission area further to provide further understanding of NCW and the NCO CF, and particularly of the cognitive and social domain concepts, attributes and metrics covered in the framework (e.g., cognitive measures of sense-making and interactions).

Acknowledgments

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Finally, we owe a debt of gratitude to our RAND colleague Walt Perry and to Kimberly Holloman at EBR for their careful and thorough reviews of this work, and to Sarah Harting for expert assistance in the preparation of this document.

Abbreviations

AMTI	Airborne Moving-Target Indicator
ASD (NII)	Assistant Secretary of Defense for Networks and Information Integration
AWACS	Airborne Warning and Control System
C2	Command and control
CAP	Combat air patrol
CF	Conceptual framework
EBR	Evidence Based Research, Inc.
EEI	Essential Elements of Information
GPS	Global Positioning System
IFF	Identification, Friend or Foe
IFFN	Identification, Friend, Foe, or Neutral
JTIDS	Joint Tactical Information Distribution System
MCP	Mission Capability Package
MIDS	Multifunctional Information Distribution System
NCO	Network-centric operations
NCTR	Noncooperative Target Recognition
NCW	Network-centric warfare
OFT	Office of Force Transformation

SAM	Surface-to-air missile
SI	Shared Information
TDMA	Time Division Multiple Access
TTPs	Tactics, techniques, and procedures
USAF	U.S. Air Force

CHAPTER ONE

Introduction

Overview

The Joint Tactical Information Distribution System (JTIDS) Operational Special Project found that fighter aircraft in air-air engagements were significantly more effective when equipped with the Link 16 datalink than when only equipped with voice communications (Hq. USAF, 1997). The project has been cited as "compelling evidence" (Alberts et al., 2001, p. 244) in favor of the Network-Centric Warfare (NCW) "central hypothesis" that a robustly networked force (in this case, aircraft with Link 16), possessing capabilities and attributes fully exploiting its networking capabilities, will be able to generate increased combat power (Alberts et al., 2001, pp. 57–58).

However, there was only limited understanding of how and why these improvements arose. The Office of Force Transformation (OFT) and the Office of the Assistant Secretary of Defense for Networks and Information Integration (OASD [NII]) sponsored RAND to undertake a study using the Network-Centric Operations Conceptual Framework (NCO CF)[1] to understand why these improvements occurred. A key purpose of the case study was to determine whether the explanation for these improvements provided support for the tenets of NCW:

[1] The NCO CF is described in Signori et al. (2002); EBR (2003); and Signori et al. (2004). Major concepts of NCO are described in Alberts, Garstka, and Stein (1999) and Alberts and Garstka (2001).

- "A robustly networked force improves information sharing
- "Information sharing enhances the quality of information and shared situational awareness
- "Shared situational awareness enables self-synchronization, and enhances sustainability and speed of command
- "These, in turn, dramatically increase mission effectiveness." (Alberts and Garstka, 2001.)

The NCW tenets form a chain of hypotheses leading from improvements in networking capabilities to eventual mission effectiveness. The NCO CF expands and formalizes these hypotheses. It provides a detailed framework of NCW-related force attributes (such as networking, information sharing, and situational awareness) and hypotheses for how these attributes influence each other. The result is a detailed and interlinked set of hypotheses for how networking improvements—and procedures taking advantage of the networking improvements—might lead to improved combat effectiveness. Importantly, the NCO CF describes metrics for assessing a force's possession of these attributes, making it possible to test whether and how attribute possession relates to improved combat effectiveness.

In this report, the NCO CF is applied to an example air-to-air combat mission, typical of those observed in the JTIDS study. The resulting analysis compares assigning two air combat mission capability packages (MCPs) to the example mission, identical in every way except for one of them being equipped with Link 16 and the other equipped with traditional radio communications. While not fully conclusive because of lack of data, the main conclusions of the analysis were that the observed improvements in combat effectiveness likely were consistent with both the NCW tenets and the more detailed hypotheses of NCO CF. In brief, Link 16's networking capabilities dramatically improved the quality and distribution of information to the pilots in the example mission, resulting in an increase to both individual and shared information. This is believed to be associated with an increase in awareness, which resulted in the ability to employ

advanced tactics depending on enhanced awareness. Finally, the use of advanced tactics is believed to have led to the improved effectiveness observed in the JTIDS Special Operations Project.

The NCO Conceptual Framework

At the top level, the NCO CF comprises a set of concepts corresponding to the major NCW-related capabilities of interest and hypothesized dependencies between them.[2] Each dependency is a hypothesis of the form that "improvement for one concept leads to improvements in its dependent concepts." Figure 1.1 shows the top level of the NCO CF.

The top-level concepts and their hypothesized dependencies are described below.

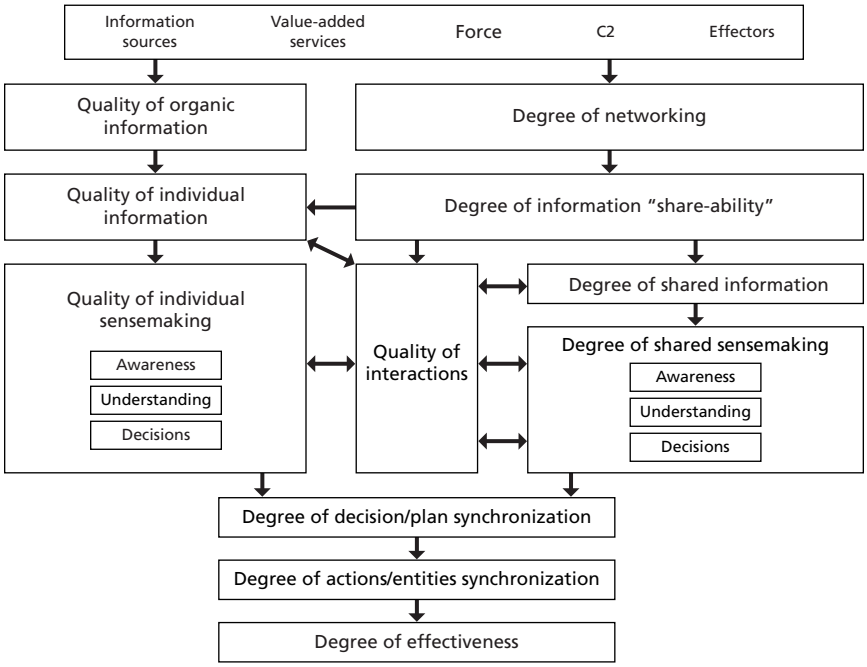
Force comprises the elements of a military force, including the resources and processes assigned, utilized, or deployed in support of a mission. These include information sources (such as sensors), value-added services that process and distribute the information, command and control (C2) elements, and effectors—the warfighters, weapons, and other systems that physically can destroy adversaries or affect other elements in the battlespace. The force collectively generates a set of organic information and a networking capability for processing and sharing that information.

Quality of organic information assesses the quality of information at its source (i.e., when it is first collected). Here, "quality" results from several contributing factors, including the completeness, correctness, timeliness, and relevance of the information.

Degree of networking measures the extent to which force entities are interconnected and the quality (speed, accuracy, reliability, and

[2] The NCO concepts found in the NCO CF allow us to measure the extent to which a given concept is present or is instantiated in the force.

Figure 1.1
Top Level of the NCO Conceptual Framework



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assurance) of those connections in exchanging data under a variety of possible scenarios.

Degree of information "share-ability" applies the degree of networking to the force's organic information. It measures the degree and quality to which force entities can share the information in their possession with other force entities.

Quality of interactions assesses the degree to which force members interact with each other and the quality of those interactions. This concept applies to all interactions between force members, not just technical network-supported data exchanges. It is concerned with interactions between force members at multiple levels, ranging from basic information sharing to detailed characterizations of how

effectively an organization's members work together to accomplish mission objectives. Consequently, this concept has many influences throughout the NCO CF, starting with contributing to the quality of information an individual receives from across the force.

Quality of individual information assesses the quality of the information each individual in the force has in his or her possession from all sources, whether generated organically, transmitted over the technical network, or heard in a conversation.

Degree of shared information assesses the quality of the information held in common by groups of force members. In addition to assessing quality, this concept assesses the extent to which the information is shared across the group and to what degree of consistency.

The *sense-making* concepts jointly describe how well an individual or group "makes sense" of the information in their possession, and determines what to do in response.

Quality of individual awareness describes how well an individual can interpret the information in their possession into a mental view of the battlespace that includes mission constraints, environmental factors, time-space relationships, and the capabilities and intentions of Red, Blue, and neutral forces, along with attendant uncertainties.

Quality of individual understanding describes how effectively the individual can infer meaning from their mental view of the battlespace, including recognition of patterns, cause-effect relationships, dynamic futures, and opportunities and risks.

Quality of individual decisions measures how well an individual's choices build on his or her awareness and understanding and how appropriate those choices are for the situation.

The shared sense-making concepts are similar to the individual sense-making concepts. Like the shared information concept, they address the degree and consistency of awareness, understanding, and decisions shared across the group, in addition to quality.

Degree of decision/plan synchronization assesses whether the complete set of decisions made by the force are synchronized with each other (i.e., mutually reinforcing) or at least deconflicted.

Degree of actions/entities synchronization assesses the execution of the decisions. It examines the actions of the force, determining whether those actions are synchronized.

Finally, *degree of effectiveness* assesses the force's actions by evaluating the force's achievement of mission objectives and avoidance of costs. Of additional interest is the force's *degree of agility,* which measures the force's ability to operate effectively and efficiently in an uncertain environment.

The NCO CF associates each top-level concept with subsidiary attributes. For example, Chapter Two notes that the case study analysis focuses on assessing the quality of air tracks known to the fighter pilots. The NCO CF assesses the quality of information elements (whether organic, individual, or shared) through eight subsidiary attributes, shown in Table 1.1. As shown, the attributes are divided into *objective attributes* (which are independent of mission context) and *fitness for use attributes* (which are context-dependent).

Table 1.1
Subsidiary Attributes for Quality of Information

Subsidiary Attribute	Definition
Objective Attributes	Measure quality in reference to situation-independent criteria
Correctness	Extent to which information is consistent with ground truth
Consistency	Extent to which information is consistent with prior information
Currency	Age of information
Precision	Level of measurement detail of information item
Fitness for Use Attributes	Measure quality in reference to situation-dependent criteria
Completeness	Extent to which information relevant to ground truth is collected
Accuracy	Appropriateness of precision of information to a particular use
Relevance	Proportion of information collected that is related to task at hand
Timeliness	Extent to which currency of information is suitable to its use

When applied, a subsidiary attribute is associated with one or more metrics that quantitatively assess the joint force with respect to the attribute.[3] The body of this report describes the calculation of a representative set of these metrics for a typical air-to-air combat mission. The report also describes modeling the attributes' dependencies through multidimensional quantitative relationships between the attributes' metrics.

The JTIDS Operational Special Project and an Example Air Combat Mission

The JTIDS Operational Special Project examined the results of 12,000 training sorties in tactical air-to-air combat (the sorties were carried out as part of the regular pilot training program). Each training sortie featured a Blue mission capability package (MCP), including an Airborne Warning and Control System (AWACS) aircraft plus fighter aircraft. The size of the engagements ranged from two Blue fighters on two Red fighters to eight Blue fighters on 16 Red fighters. Engagements occurred during the day and at night. Within the JTIDS project, the primary independent variable was whether or not the Blue MCP was equipped with the Link 16 data network. The capability of the Red aircraft remained consistent during the project.
The JTIDS Operational Special Project provided the kill ratios seen in Table 1.2. It is based on the results of 12,000 training sorties in tactical air-to-air combat. On average, Link 16 led to a two-and-half times improvement in the kill ratio (Red aircraft to Blue aircraft shot down), during both the daylight and nighttime conditions.

The analysis presented above indicates that in these tactical engagements the better decisionmaking and use of advanced tactics

[3] The NCO CF contains literally hundreds of subsidiary attributes and metrics, so they are not further identified here. This report lists a significant percentage of them in the process of applying the NCO CF's measures and metrics to an air combat mission.

Table 1.2
Results of the JTIDS Operational Special Project

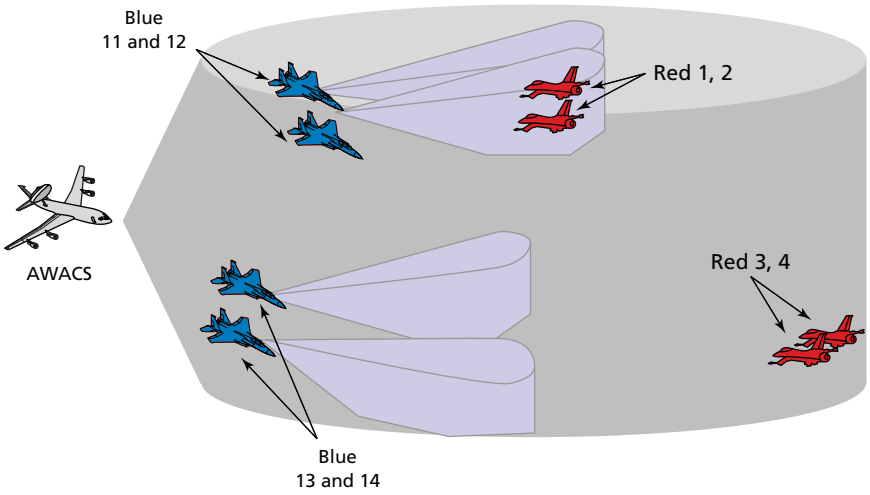
	Kill Ratio	
	Voice Only (MCP 1)	Voice Plus Link 16 (MCP 2)
Day	3.10:1	8.11:1
Night	3.62:1	9.40:1

employed by Blue fighter pilots were enabled by Link 16–driven improvements to situational awareness. This in turn led to the Link 16–equipped MCPs' improvements in kill ratios. This chain of inferences is verified qualitatively by our interviews with experienced pilots. For some steps of the NCO inference chain, quantitative data were not available—e.g., data monitoring how pilots gained awareness and made decisions during the engagements. Nevertheless, pilot interviews substantiate the validity of the inference chain described in the NCO framework for this mission area.

To provide insight into what might have occurred during the sorties, Figure 1.2 shows a typical combat mission. It is a four-on-four combat scenario, in which four Blue fighters battle four Red fighters, with the four Blue fighters directed by an AWACS aircraft.

Consider the early stages of an air-to-air combat engagement shown in Figure 1.2. In the tactical engagement, four Blue fighters engage four Red fighters. The four Blue fighters are provided threat-warning information by AWACS and may be vectored by AWACS to engage particular threat aircraft. The figure illustrates the "opening gambit," or early stages of the engagement, which is a key part of the engagement recognized as strongly influencing the final outcome because the Blue aircraft have an opportunity to maneuver for highly advantageous positions prior to engaging the Red aircraft directly. Here, the AWACS aircraft has radar coverage of the entire battlespace. Two of the Blue fighters (Blue 11 and Blue 12) have radar locks on two of the Red fighters (Red 1 and 2). Two of the Red aircraft (Red 3 and 4) are out of radar range for any of the Blue

Figure 1.2
Air-to-Air Scenario Exemplar



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fighters and are on the very edge of the battlespace but are approaching their attack positions rapidly and are detected by AWACS.

We calculated the quality of shared information across the MCP for the engagement geometry shown in Figure S.4, for both an MCP with Link 16 and an MCP with voice-only communications. Note that we use the term "shared information" to indicate that it includes the information available to the pilot of a particular aircraft from both organic sensors and from the network.

To gain insight into whether the observed improvements in air-to-air combat effectiveness occurred in a way consistent with the NCW hypotheses, we apply the NCO CF to the air-to-air combat mission, which is illustrated in Figure 1.2. Restricting the analysis to a single mission has important implications, both positive and negative. On the positive side, it limits and simplifies the analysis required to generate metrics. Thus, we can direct most of our attention to understanding the application of the NCO CF's metrics—important for a first application of the framework. Using an illustrative scenario

also permits use of the NCO CF despite not having a full set of scientifically captured data about what happened and how systems performed and were used during the JTIDS Operational Special Project. On the negative side, this analysis has certain gaps because quantitative data were unavailable to calculate certain metrics. The entire set of possible and important chains of influences articulated in the NCO CF have not been examined in this case study. Furthermore, the simple model does not incorporate the range of engagement sizes that took part during the experiments or the ways in which each of those experiments evolved.

Outline of the Report

Chapter Two of the paper describes the overall methodology for applying the NCO CF and calculating the resulting metrics for the air-to-air combat mission. The chapter describes the data available for the study and the resulting selection of concepts, subsidiary attributes, and metrics for analysis. It also describes the bases for calculating the metrics, and the relationships between the metrics.

Chapters Three to Ten describe the calculation of metrics for each selected concept. Each of these chapters first describes the factors contributing to that concept. Each chapter then describes the calculation of the corresponding metrics, presents the results, and concludes by presenting a figure providing an at-a-glance comparison between the performance of the Link 16–equipped MCP and the performance of the voice-only MCP.

Chapter Eleven presents research conclusions and areas for further research.

Finally, the appendix describes the details of the technical model that actually calculated the measurements, implemented in the software package Analytica.

CHAPTER TWO

Methodology

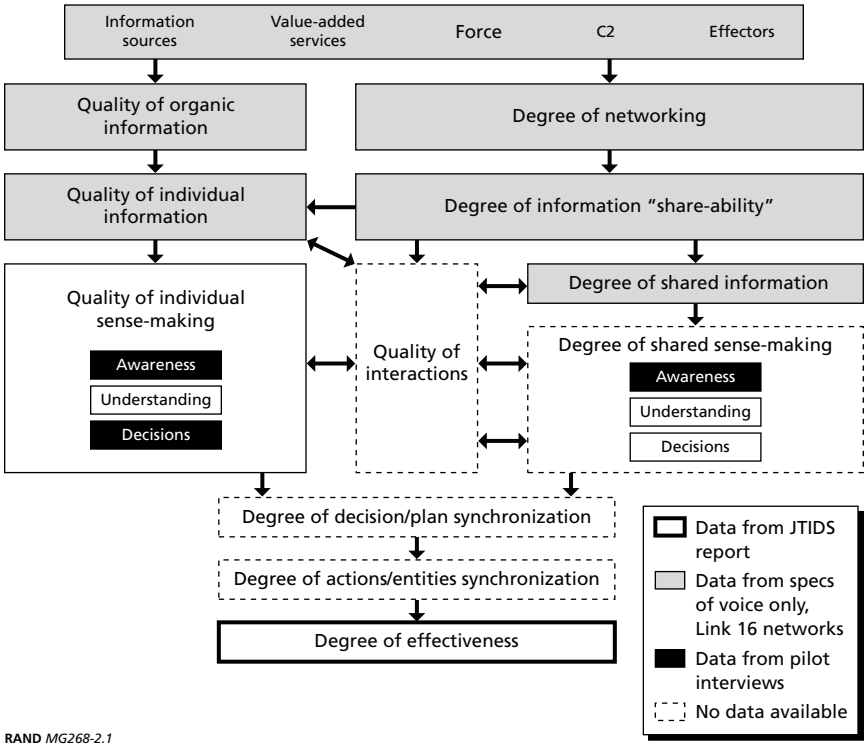
The methodology uses selected metrics from the NCO CF, which is described below and in the principal references that are source documents for this analysis.[1] The aggregation of the data, explained before the analysis associated with each area of the NCO CF, is also discussed below.

Application of the NCO CF

Figure 2.1 shows the data available for assessing each of the NCO CF top-level concepts. From the JTIDS Operational Special Project, we have the kill ratios shown in Table 1.1. We obtained information on the technical capabilities of the voice and Link 16 networks for combat aircraft and AWACS from a variety of sources, including those listed in the references. In addition to describing the characteristics of the network, we also used the information from these background references and from interviews with experienced combat pilots to construct the opening phases of an archetypal four-on-four air combat tactical engagement. We interviewed several pilots who partici-

[1] The NCO CF is described in David A. Signori et al. (2002); EBR (2003); and Signori et al. (2004). Major concepts of NCO are described in Alberts, Garstka, and Stein (1999) and Alberts et al. (2001).

Figure 2.1
The NCO Framework and Corresponding Data Available for the Case Study



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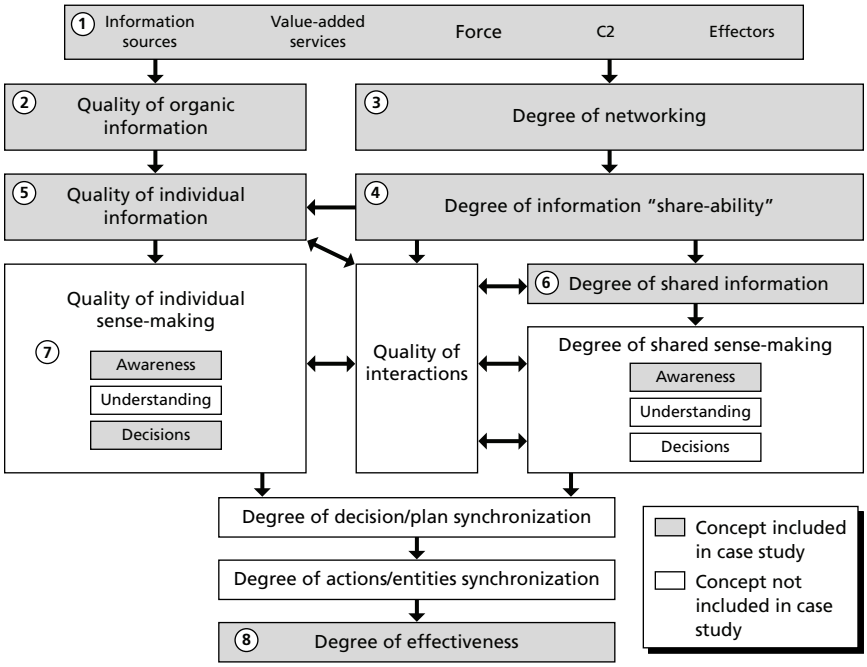
pated in the JTIDS experiments, which provided important data on the types of decisions they were able to make, and the situational awareness information they obtained with both the voice-only and Link 16 network architectures. We also used these interviews to verify that the tactical engagement geometry was reasonable and representative of real tactical engagements.

Figure 2.2 summarizes the concepts of the NCO CF addressed in this study. The concepts we incorporate are indicated on the legend. The numbers on the concepts indicate the order in which they are addressed in this report and are used to refer to this diagram later in this report.

Figure 2.2
Concepts Included in the Case Study



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Because of the limits of the data available from the JTIDS Operational Special Project, as well as the nature of the experiment (comparing the impacts of two different networking architectures), this case study does not cover all of the concepts in NCO CF. The subsidiary concepts of individual sense-making are colored separately: we incorporate the quality of individual awareness and quality of individual decisions concepts but not the quality of individual understanding concept. We were unable to gather quantitative data to estimate measurements for the quality of interactions, decision synchronization, and action/entity synchronization concepts in our analysis. We were, however, able to extrapolate shared awareness from the data available. For example, pilot interviews reveal that Link 16

significantly increases the level of individual and shared situational awareness available throughout the entire Blue fighter package. These interviews also reveal that the improvements in mission effectiveness that stemmed from increased situational awareness were a function of the level of training and the use of common tactics, techniques, and procedures. It is important to note that the sense-making and decision synchronization measures represent activities that take place in the cognitive domain (i.e., mental processes) and social domain (i.e., interactions between warfighters, such as conversations) and are difficult to evaluate quantitatively. For this reason and because of the lack of data, quantitative metrics for shared awareness, shared understanding, and shared decisionmaking were not evaluated.

Approach to Measurement in the Case Study

In the air-to-air example, the metrics constructed track the information or situational awareness positions of the Blue MCP. Each metric contains an array of subsidiary values, with array entries tracking either what each Blue aircraft pilot "knows" about other air tracks in the battlespace or what each Blue aircraft pilot is able to do as a result.

In this case study, what each pilot "knows" about a particular air track is characterized by three of the eight quality of information attributes discussed in Chapter One—completeness, correctness, and accuracy. These three attributes most directly characterize whether a pilot's knowledge of air tracks is sufficient to make tactical decisions to take appropriate actions. For the other five attributes, we do not examine relevance because all air tracks in the engagement battlespace are assumed to be relevant. We did not include consistency because we assume that the Blue aircraft's sensors reliably report the tracks they detect. Accuracy is used in place of precision; the latter simply describes the potential margin of error of the pilot's knowledge, whereas accuracy also reflects whether the margin of error is small

enough to meet the pilots' needs. As will be discussed, the currency and timeliness of the information implicitly impact the calculation of the correctness metrics and so are not considered separately.

We define one subsidiary metric to measure completeness, one to measure correctness, and two to measure accuracy of the air tracks.

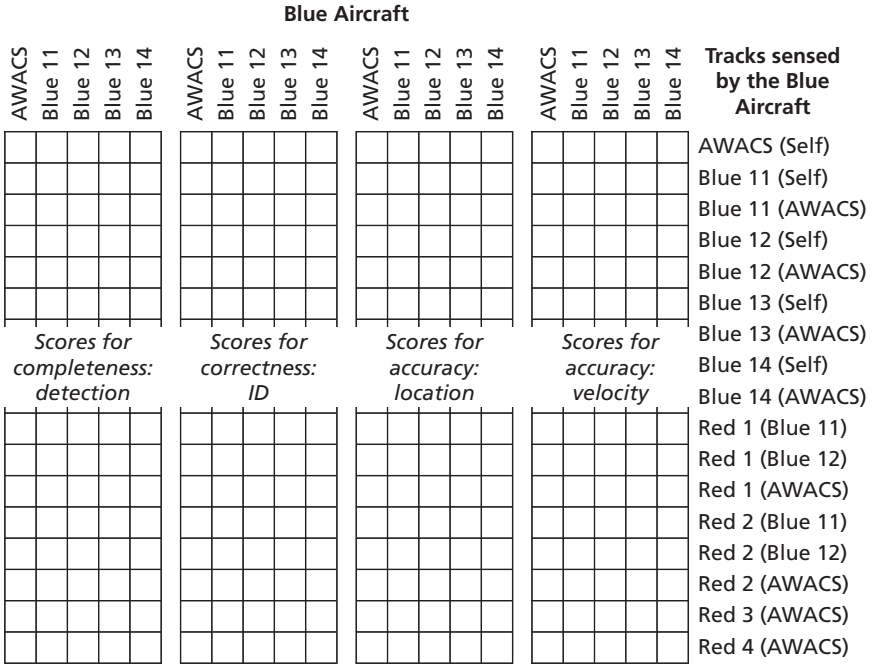
- Completeness: Detection, which tracks whether the Blue pilot is aware of the track at all. This metric has score 1 if the pilot is aware of a track and 0 if not.
- Correctness: ID, which tracks whether the Blue pilot correctly labels the air track as Red or Blue. This metric has score 1 if the pilot correctly labels the track and 0 if not.
- Accuracy: Location, which tracks the pilot's awareness of the aircraft's location. The scores of this metric are based on the pilots' needs for precision in track location. Thus, the metric has score 1 if the precision is sufficient for the pilot to make precision maneuver and targeting decisions, 0.25 if the precision is sufficient to make general cuing decisions, and 0 if the precision is insufficient even for general cuing decisions.
- Accuracy: Velocity, which tracks the pilot's awareness of the air track's velocity. Like Accuracy: Location, the scores of this metric are based on the pilots' needs for accuracy in track velocity, and it has the same 1, 0.25, and 0 scores.

These four metrics are the most important characterizations of an air track for an Air Force pilot. Note that air track currency, measured by the latency of the most recent track update reported to a pilot, affects the location and velocity metrics calculations. In particular, greater latencies in updates lead to uncertainty in the true position and velocity of the tracked aircraft, increasing the potential margin of error and reducing the location and velocity scores. Chapter Four presents the specific formulas incorporating air track currency.

The case study uses two major types of arrays tracking knowledge of air tracks. The first assesses knowledge of the raw data ele-

ments in the case study—the 17 sensed air tracks in the battlespace described in Figure 1.2. To generate the 17 tracks, note that each Blue aircraft detects itself (five), Blue 11 and Blue 12 each detect Red 1 and Red 2 (four), and AWACS detects every other aircraft in the battlespace with its radar (eight). This array type is used in assessing what raw data each aircraft senses organically (quality of organic information) and how well the voice-only and Link 16–equipped MCPs share the raw data elements across the Blue aircraft (degree of information share-ability). Figure 2.3 shows an example array. As shown, each entry assesses a pilot's knowledge of one of the sensed air tracks, as measured by one of the four quality metrics.

Figure 2.3
An Array Tracking Pilots' Knowledge of Sensed Air Tracks



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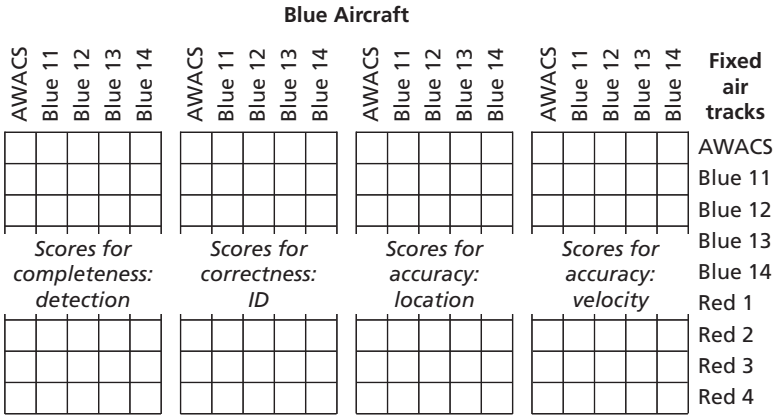
The second type assesses knowledge of the essential elements of information (EEIs) in the case study—the nine unique, or "fixed," air tracks in the battlespace (AWACS, four Blue fighters, and four Red fighters). A Blue aircraft generates its knowledge of an EEI by fusing the multiple sensed tracks corresponding to that EEI; our analysis includes a simple representation of the fusion process. The EEIs are the "refined" elements of information used by pilots to generate awareness and make decisions, so this second array type is used to compute quality of individual information and degree of shared information metrics. This second array type is used to compute quality of individual awareness metrics, as well; we develop a simple model mapping EEIs to "elements of awareness," which assess what the Blue pilots cognitively know about aircraft tracks in the battlespace. Figure 2.4 shows an example array. As shown, it is identical to Figure 2.3 except for the change to fixed tracks rather than sensed tracks.

What pilots can do as a result of their air track knowledge is assessed by arrays tracking whether pilots are able to make and exe-

Figure 2.4
An Array Tracking Pilots' Knowledge of Fixed Air Tracks



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cute certain types of decisions referred to as "advanced tactics." We will discuss the advanced tactics in detail later in the briefing. They are based on interviews with pilots who participated in the JTIDS experiments (Hq. USAF, 1997). Importantly, the ability to perform these advanced tactics is associated with significant improvements in combat effectiveness. In this case study, we model quality of individual decisionmaking strictly on whether pilots have sufficient awareness to run the advanced tactics. Thus, this case study effectively considers only the roles of information and situational awareness and does not explicitly consider other factors that can have major impacts on decisionmaking (and hence, effectiveness)—combat training, C2 structures, team interaction factors, and so on. However, we believe these additional factors are similar for the two alternative MCPs considered in this case study.

CHAPTER THREE

Force Characteristics

The NCO CF force metrics describe information- and collaboration-related components of the joint force under consideration. In this case study, the force metrics comprise descriptions of the modeled air superiority force packages or MCPs and their information sensors, voice communications systems, and data communications systems.

The Blue force packages are identical except for the presence or absence of the Link 16 data communications network. Each MCP includes one AWACS aircraft and four Blue F-15s, and each F-15 has similar Airborne Moving-Target Indicator (AMTI) radar, noncooperative target recognition (NCTR) sensors, an identification, friend-or-foe (IFF), transponder, and similar weapon systems. The four are divided into two-ship flights, each with a flight lead and a wingman.

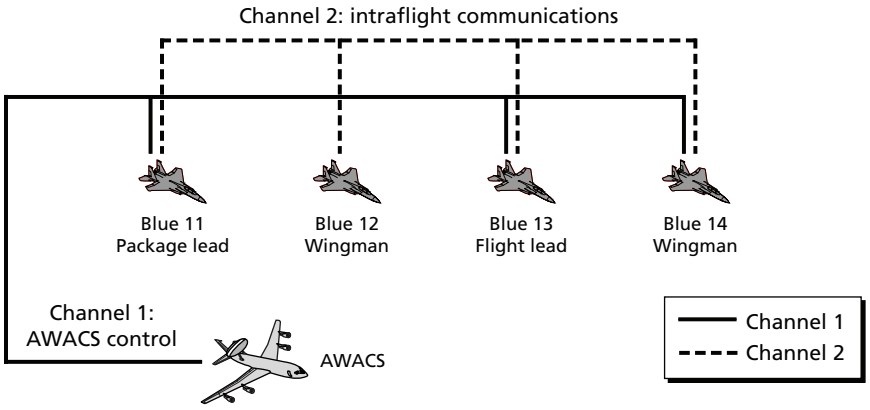
MCP 1: Voice Communications Only

The first MCP (MCP 1) is equipped with only voice communications between aircraft. Figure 3.1 describes a typical channel structure for voice communications used by Air Force fighters, in this case for an MCP with four fighters. Each pilot monitors two separate voice channels. AWACS broadcasts aircraft track information on Channel 1 to the Blue aircraft. The four fighter aircraft communicate among themselves on Channel 2. Each fighter can listen to two channels at a time, but only one aircraft can speak on a channel at a time.

The Air Force has developed a voice-coding scheme that allows pilots and AWACS flight controllers to transmit approximately one aircraft track about three times every ten seconds. We use ten seconds as the air picture track update cycle time because this is the rate at which the AWACS radar antenna rotates or performs one complete surveillance cycle of the battlespace. So, in principle, F-15 fighter pilots can receive updated air track information from AWACS every ten seconds, if AWACS flight controllers have the time to verbally transmit this information over the voice network every radar sweep and if there is "time available" to transmit the information over the voice channel (i.e., if there is no contention for the voice channel). By convention, tracks transmitted later than ten seconds ago are considered to be invalid or "expired," on the grounds that the tracked plane may have moved far enough in ten seconds to make the transmitted information inaccurate.

The pilots must interpret the spoken information they receive on their voice radios and build a mental "picture" of the positions

Figure 3.1
Voice Channel Networks for MCP 1



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and velocities of reported aircraft. While fighter pilots generally have the mental ability to keep air track information in their mind for long periods, the utility of this information decreases as an air track "age" grows. An air track with an age of ten seconds or more has little utility because the pilot will have only a vague idea where the fast-moving jet fighter may be (the object that corresponds to the air track), especially at close ranges. We approximate the process of removing old information from a fighter pilot's mental map or "common operational picture" of the battlespace in the following way: air tracks older than the AWACS update rate are "dropped" on the grounds that the tracked plane will have moved far enough in ten seconds to make the pilot's mental air track position and velocity estimate too inaccurate to be useful in a high-speed tactical air combat engagement.

The interpretation (and mental updating) of voice-delivered air track information places a significant cognitive load on the pilot. This cognitive load must be handled effectively by the pilot while he or she simultaneously performs other high-priority mission-related tasks. For example, in addition to listening to and interpreting voice channel traffic, the wingman must also maintain visual contact with the flight leader's aircraft, fly in formation, conduct visual surveillance of the battlespace—i.e., "check six"—and monitor his or her own radar instruments. Needless to say, fighter pilots must be highly trained to effectively conduct all these tasks simultaneously or in rapid succession.

For the sake of simplicity, we approximate this two-channel scheme with a single channel in which one pilot is allowed to speak at a time and all other aircraft listen. We assume that AWACS, on average, uses half the airtime, and that the four fighter aircraft use one-eighth of the airtime each. While not optimal (the AWACS broadcasting all the time is near-optimal because it has all tracks and the time delay in transmission negates any benefit that might be obtained by transmitting more timely tracks), the results of the calculations vary by less than 0.02 for all summary metrics. (Further optimization

to increase the metrics is possible, such as giving priority to transmitting the locations of the Red aircraft that are only held by the AWACS, but again the benefits are limited). This approach has limitations near the performance boundary for the system, particularly when the system is agile (for example, if operators could chose to give up their time slot). However, it was used in the case study because it is relatively independent of the MCP, thus enabling later comparisons with other MCPs. Furthermore, this approximation still overestimates the performance of the voice network because it ignores the impact of the heavy cognitive loading of the pilot arising from the heavy voice channel loading. For example, it ignores the impact of pilots frequently having to listen to SAM warning information.

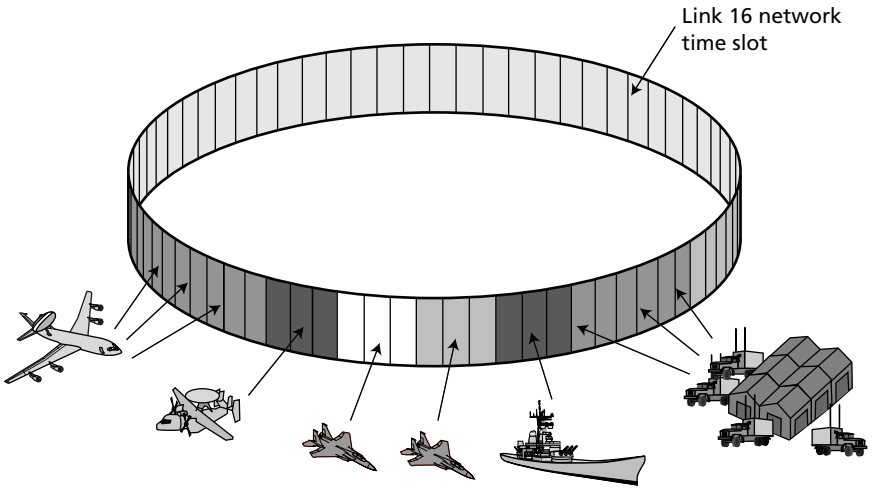
MCP 2: Link 16 Networking

MCP 2 is identical to MCP 1 except for the addition of the Link 16 network. Link 16 is a wireless data communications system that provides air track and other information to fighter aircraft, other weapons platforms, and C2 nodes equipped with JTIDS and Multifunctional Information Distribution System (MIDS) communications terminals. Link 16 employs a time-division multiple-access (TDMA) wireless network structure and a jam-resistant frequency-hopping waveform. The Link 16 networking structure is illustrated Figure 3.2. As shown, the topology of a Link 16 network is entirely different from that of voice networks. In this type of network, each participant (or network node) can receive all transmissions made by other network participants in the same broadcast region.

Fighters equipped with Link 16 can receive air track information from neighboring fighter aircraft and from AWACS (if AWACS is within a line of sight of the fighter). A Link 16 network is composed of 128 time slots per second, with each slot capable of describing a single airplane track to a high degree of accuracy. Each Blue plane (and other information sources, such as those broadcasting SAM

threats) is allocated one or more time slots during which they can transmit information. Link 16 air tracks received by a particular fighter from other aircraft are shown on a display screen in the cockpit along with air tracks detected by the aircraft's organic sensors. Therefore each fighter pilot in a Link 16 equipped MCP can display nearly the same air track information or the same picture of the battlespace.

Figure 3.2
The Link 16 Network for MCP 2



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CHAPTER FOUR

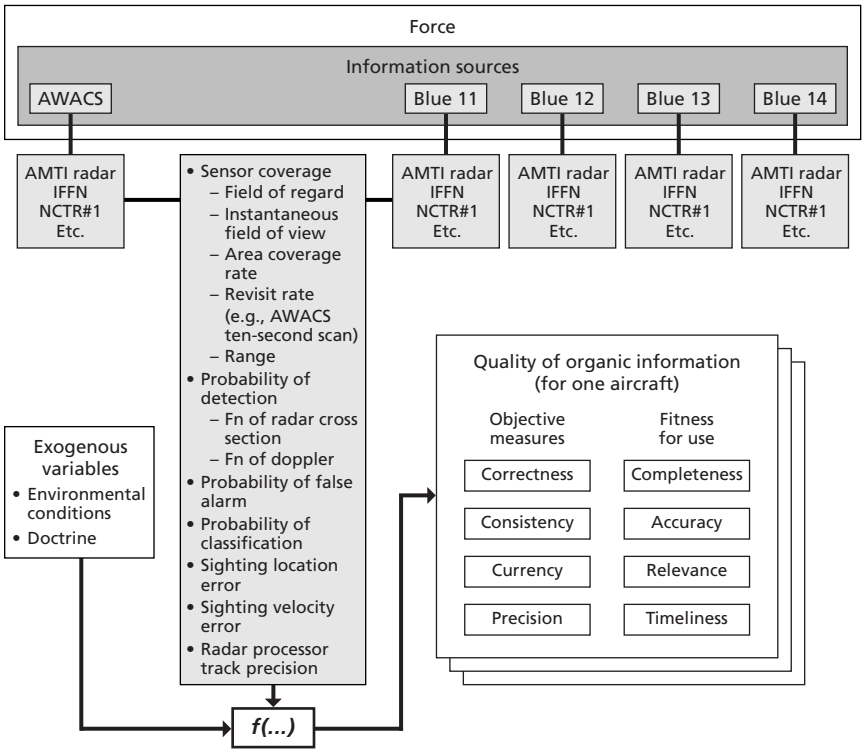
Quality of Organic Information

Input Factors and Specific Metrics

In general, the computation of quality of organic information (here, the aircraft track information detected by each plane's sensors) is complicated. Each Blue aircraft is equipped with multiple sensors, each with distinct capabilities, such AMTI radar, Identification, Friend, Foe, or Neutral (IFFN) transponders, NCTR systems, and so on. The computation of information quality could take into account a wide range of factors for each sensor, such as sensor coverage statistics (field of regard and revisit rate), probability of track detection within sensor field, probability of false alarms, probability of classification error, sighting location and velocity errors, and so on. Figure 4.1 provides a more complete list of sensor attributes that might be important to consider when calculating or estimating the quality of organic information for individual platforms.

However, because the purpose of this report is to compare voice-only and Link 16 air superiority MCPs, it is possible to simplify the analysis greatly. The sensors in each MCP are identical, and the scenarios for which the metrics are calculated are also the same. We simply declare an organic information position common to both MCPs (in terms of what each sensor reports) and conduct measurements from that position. We use the "threat information position" to compute partial scores for the four air-track quality metrics discussed in

Figure 4.1
Factors Potentially Involved in Computing Quality of Organic Information

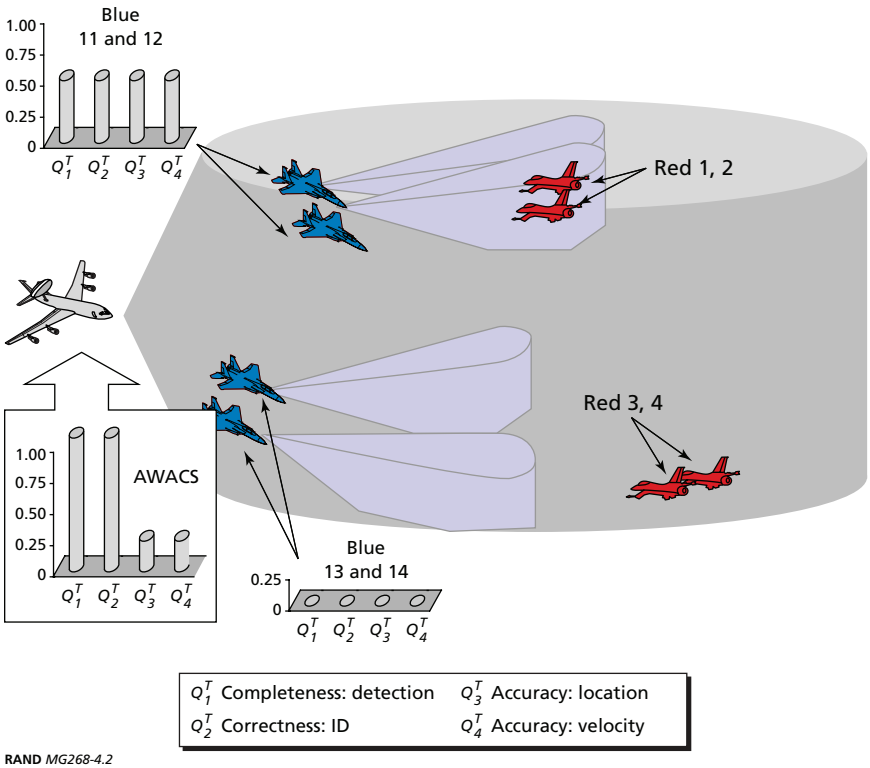


Chapter Two: Completeness: Detection (of air tracks), Correctness: ID, Accuracy: Location, and Accuracy: Velocity.

Inputs, Calculations, and Individual Platform Results

Figure 4.2 shows the organic information position of each Blue aircraft with respect to what they know about the positions of the Red aircraft (the "threat tracks"). From the figure, AWACS detects the

Figure 4.2
Quality of Organic Information for Threat (Red) Tracks



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position of all four Red aircraft within the battlespace. Two of the Blue fighters (Blue 11 and Blue 12) have detected two of the Red aircraft with their radar; the other two Blue fighters do not have any organic Red aircraft track information.

As noted in Chapter Two, the currency of track updates directly impacts the metric scores. Table 4.1 scores the organic track reports by the age of the report. Tracks with a latency of less than a second from sensor detection to pilot report are considered near real time. Because these tracks are sufficient for making precision maneuver and

Table 4.1
Table of Metric Scores by Track Latency

	Metric Score for a Track Updated Within a Given Time Range		
Metric	**Less Than One Second**	**One to Ten Seconds**	**More Than Ten Seconds**
Detection or ID	1.00	1.00	0
Location or velocity	1.00	0.25	0

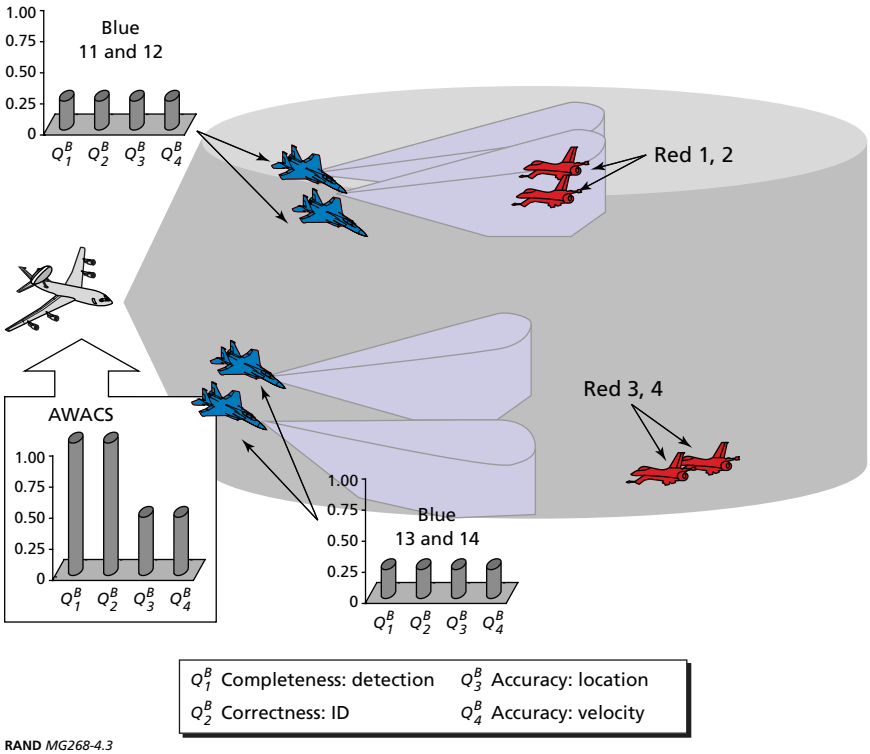
targeting decisions, they score the maximum value of 1.0 for all four metrics; we assume that the Blue force's radars and detection sensors are highly likely to be correct. Tracks with a latency of one to ten seconds are considered "cue only," suitable for general awareness and cuing, but not for precision maneuver or targeting. They score 1.0 for detection and ID correctness but only score 0.25 for location and velocity correctness. That is, because the measures of accuracy are assessed over time, a separate assessment of timeliness is not required. Tracks with a time-to-use of more than ten seconds score zero for all four metrics, because air tracks with this time latency are ascribed to have little utility for close in air-to-air combat.[1]

The small graphs on Figure 4.2 show the resulting quality of organic information for threat air tracks. Each graph shows the average metric score for all four Red aircraft as detected by each Blue plane. AWACS detects all four Red aircraft in the battlespace, but has a ten-second radar sweep delay. An aircraft will be detected once each sweep and then not detected again for another ten seconds (on average). That is, most of the time the AWACS track is more than one second old, meaning it scores 1.0 for detection completeness and ID correctness but only 0.25 for location and velocity correctness. Blue 11 and Blue 12 each detect two of the four Red aircraft with near–real time precision (provided by the F-15 sensors), so they each score 0.5 for all four metrics. Finally, Blue 13 and Blue 14 each detect none of the four Red aircraft, so they each score zero for all four metrics.

[1] Such high-latency air tracks may have some utility for general threat warning information, but more precise threat location and heading information is needed in air-to-air combat.

Figure 4.3 describes the quality of organic information with respect to each Blue aircraft's knowledge of the other Blue aircraft in the battlespace. Each graph now shows the average metric score for all five Blue aircraft as detected by each Blue plane. Thus, AWACS knows its own track exactly (via GPS) and knows the track of each Blue fighter within a ten-second sweep windows. It thus scores 1.0 for detection completeness and ID correctness, and 0.4 for location and velocity correctness. Each Blue fighter knows its own track exactly but does not know the track of any other Blue aircraft organically; each thus scores 0.2 for all four metrics.

Figure 4.3
Quality of Organic Information for Blue Tracks



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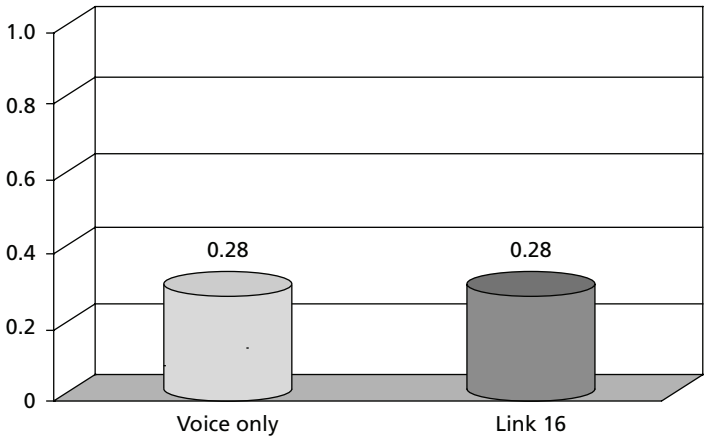
Overall Results

We average across all scores for all pilots' organic awareness of both Red and Blue tracks, to get an overall score of 0.28 for quality of organic information (also shown in Figure 4.4). This value applies to both the voice-only and Link 16 networks because both start with the same organic information position.

Figure 4.4
Overall MCP Scores for Quality of Individual Information



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CHAPTER FIVE

Degree of Networking

Specific Metrics

The NCO CF identifies four attributes associated with the top-level degree of networking concept: reach, quality of service, network assurance, and agility. The latter two, in turn, have subsidiary attributes; of these we selected availability, integrity/privacy, and network adaptation for this analysis. For each, we directly translate the functionalities of the voice-only and Link 16 networks, as given by their technical specifications, into metric scores.

Inputs, Calculations, and Individual Platform Results

Table 5.1 presents the resulting five degree of networking metrics for each of five communications modes for MCP 1 (voice only).

For the first MCP, voice only, voice is the only mode supported. The NCO CF defines "reach" as the degree to which nodes can connect and communicate, and the metric is the percentage of nodes that can communicate in the desired format. Because (in our single voice-channel scenario) each plane can transmit on, and each plane listens to, the channel, we define the value of reach for this mode to be 1.0.

The NCO CF defines "quality of service" as the ability to provide communications and storage services and a vector of metrics

Table 5.1
Degree of Networking Metrics for MCP 1 (Voice Only)

Attribute	Voice	Messaging	Data	Image	Video
Reach	1 Each plane can only listen to one message at a time	0 (none)	0 (none)	0 (none)	0 (none)
Quality of service	0.012 (2 MIL vocoder channels) (Rate: 0.3 tracks/sec.; 17 tracks/sec. max) (70% of tracks heard correctly)	0 (none)	0 (none)	0 (none)	0 (none)
Network assurance (availability)	~1	0 (none)	0 (none)	0 (none)	0 (none)
Network assurance (integrity/privacy)	~1 (jam-resistant, frequency-hopping military encryption)	0 (none)	0 (none)	0 (none)	0 (none)
Network adaptation	~1	0 (none)	0 (none)	0 (none)	0 (none)

NOTE: Average score (across five mission modes, five attributes) = 0.16. Metric scores of zero are assigned for some metrics in rows two through five because the voice network lacks messaging, data, image, or video capabilities.

including bandwidth, packet delay, delay jitter, and data loss. In this case study, we are only interested in communications and focus on bandwidth and data loss. Also, since we want metrics normalized between zero and one for this case study, quality of service equals the effective transmission rate of the network divided by the ideal transmission rate. The effective transmission rate is equal to the physical transmission rate multiplied by the probability that transmitted tracks are received correctly. We track both of these components in order to determine the metrics for information share-ability.

The Air Force has developed a scheme allowing speakers to transmit three tracks every ten seconds, which becomes 0.3 tracks per second. According to the pilots we interviewed, the standard military vocoder equipment can frequently be hard to hear, such that on average pilots hear only about 70 percent of the transmitted information (the rest is garbled). There are 17 sensed tracks in the scenario, and

ideally each should be updated at least once a second, making the ideal transmission rate 17 tracks per second. Performing the calculation yields a measurement of just 0.012 for quality of service.

For network assurance, we consider the availability, integrity, and privacy subattributes. Availability reflects the reliability of the network, even in the face of Red force jamming and environmental obstacles. Integrity and privacy reflect the protection of the network from Red force surveillance, so we combine these into a single metric. (The other assurance subattributes—authenticity and nonrepudiation—were not considered because in a broadcast network without data storage they are based on privacy and integrity.) Both assurance metrics are constants in this model, set at 1.0 because the AN/ARC-164 Have Quick radio and vocoder system are highly reliable in flight, and frequency-hopping and encryption are provided. We also, for simplicity's sake, assume a permissive environment without Red force jamming and surveillance and without environmental obstacles.

Network adaptability refers to the ability of the network (and associated concepts of operation) to support changes to the network, participants using the network, and processes during operation. The voice-only network is relatively adaptable during the mission (channel frequencies are preset in advance of the mission and can be changed during the mission to a preassigned backup frequency), so the score for adaptation is approximately one.

The average score for the voice-only MCP across all five attributes and five modes is 0.16.

Table 5.2 presents the five networking metrics scores for each of five communications modes for MCP 2 (voice plus Link 16).

In contrast to voice only, the Link 16 and voice MCP supports multiple communications formats: voice, messaging, data, and image transmission (only video is not currently supported). Thus, the Link 16 MCP scores a value of 1.0 for reach for all modes except video.

The Link 16 MCP scores a value of 1.0 for quality of service for messaging, data, and images. The Link 16 network has a data trans-

Table 5.2
Degree of Networking Metrics for MCP 2 (Link 16)

Attribute	Voice	Messaging	Data	Image	Video
Reach	1 (2 transmit, rest receive only)	1 (up to 30 nets, 128 participants per net)	1 (up to 30 nets, 128 participants per net	1 (most receive only)	0 (none)
Quality of service	0.012 2 MIL vocoder channels (3 tracks/10 sec.)	1 28.8 to 238 Kbps (128 tracks/sec.) JTIDS Waveform Tadil J[a] Depends on IA level, number of nodes	1 28.8 to 238 Kbps (128 tracks/sec.) JTIDS Waveform Limited Free text Depends on IA level, number of nodes	1 28.8 to 238 Kbps (128 tracks/sec.) JTIDS Waveform Depends on IA level, number of nodes	0 (none)
Network assurance (availability)	~1	1	1	1	NA
Network assurance (integrity/privacy)	~1 (basic military encryption)	1 (basic military encryption) AJ waveform	1 (basic military encryption) AJ waveform	1 (basic military encryption) AJ waveform	NA
Network adaptation	1	0.5 (depends on service)	0.5 (depends on service)	0.5 (depends on service and terminal)	NA

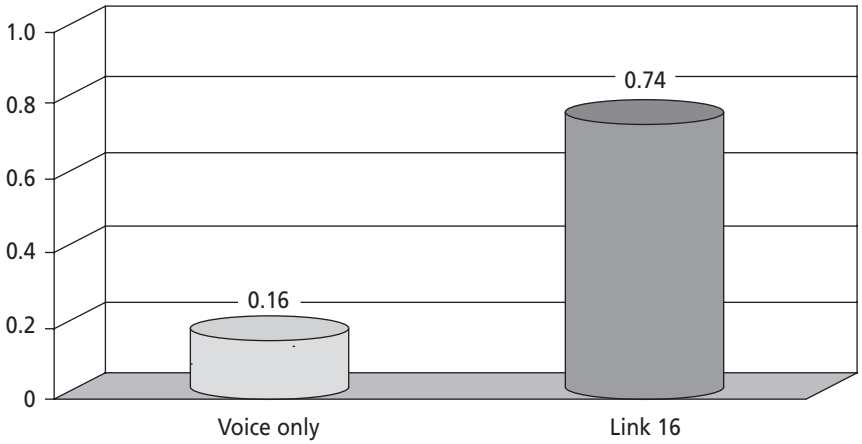
[a]Tactical Digital Information Link J (TADIL J) message catalog contains 256 message types. TADIL J messages are composed of one or more code words, each 7t bits (7- data, 5 parity).
NOTE: Average score (across five transmission modes, five attributes) = 0.74.

mission rate of 128 tracks per second, which exceeds the ideal transmission rate of 17 tracks per second. (More strictly, the bandwidth devoted to each plane—64 tracks per second for AWACS, 16 tracks per second for each Blue fighter—greatly exceeds the number of tracks each blue aircraft must transmit.) The Link 16 network also transmits these tracks with a high degree of accuracy, that is, with no data loss. Thus the quality of service for data, messaging, and image transmission is set to 1.0. The MCP scores a value of 0.012, though, for voice, since the Link 16 system retains the same type of vocoders and constraints as in the voice-only MCP if air track data are transmitted only by voice communications. The Link 16 MCP scores 1.0 for availability (network is highly reliable and also provides antijam capabilities because of its frequency-hopping wave form) and 1.0 for integrity and privacy (network is encrypted). (We note that the quantitative benefits and trade-offs that accrue from Link 16's use of frequency-hopping to prevent jamming are not assessed in this analysis.) Finally, there is some ability to customize the Link 16 network dynamically for the messaging, data and image modes, so we set the Network Adaptability scores for these modes at 0.5.

Overall Results

- The average score for degree of networking, across all metrics and modes for the voice-only MCP was 0.16.
- In comparison, the average score across all metrics and modes for the Link 16 MCP was 0.74. Figure 5.1 (next page) compares the two.

Figure 5.1
Overall MCP Scores for Degree of Networking



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CHAPTER SIX

Degree of Information "Share-Ability"

The computation of metrics that depend on other metrics is a complicated, multistage process. We describe this process for degree of information "share-ability" below, which depends on the subsidiary measurements for quality of organic information and degree of networking.

Specific Metrics

The NCO CF specific, subsidiary metric calculated for degree of information "share-ability" is quantity of retrievable information, which assesses the ability of aircraft to retrieve air track information from the MCPs' networks. For this case study, this metric is the array of probabilities providing, for each of the 17 sensed air tracks in the battlespace, the probability that a Blue aircraft has "retrieved" (received) an update on that track within a given time period (either less than one second or one to ten seconds; recall that these two latency bands directly impact the calculation of the quality of information measurements).

Ordinarily, to calculate the quantity of retrievable information, one would need to calculate another metric, the quantity of posted information (which assesses the ability of aircraft to post air track information to the MCPs' networks), first. However, in this report, we can simplify the analysis, as all air tracks "posted" (broadcasted) is

immediately "retrieved" (received) by the other aircraft in the MCPs' wireless networks. The only distinction is whether some of the broadcast data is lost during transmission. Thus, we need only calculate a single metric.

Inputs

Figure 6.1 summarizes the inputs contributing to the computation of the degree of information "share-ability" measurements. As shown, some of the inputs are derived from the earlier degree of networking measurements, while others are exogenous.

Figure 6.1
Factors Impacting Quality of Retrievable Information

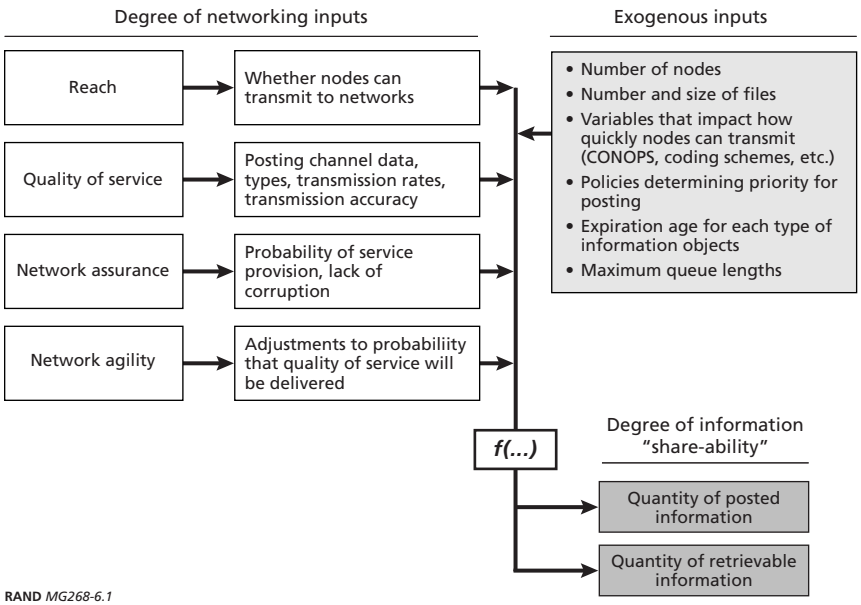

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Table 6.1 provides a fuller description of the inputs used to compute quantity of retrievable information as well as what those inputs are for both the voice-only and Link 16 MCPs.

Of interest in Table 6.1, for the voice-only MCP, is that the Air Force has standards through which three tracks can be transmitted over voice every ten seconds. This implies that all voice-transmitted posts will be at best in the one- to ten-second latency band. Second, note that pilots only "hear" about 70 percent of the transmitted tracks. For Link 16, the data transmission rate is up to 128 track updates per second, loss free (assuming, as the case study does, a permissive environment).

Calculations

Below, we describe the steps involved in calculating quantity of retrievable information and how these steps apply to the voice-only and Link 16 MCPs. We first compute maximum potential transmission rates for air tracks, then use these rates to compute the probabilities that particular sensed air tracks will be "retrieved." As might be expected, the resulting steps involve a series of product calculations. The steps occur in three phases.

Phase 1: calculate the maximum rate at which the Blue aircraft can share air tracks across the MCPs' wireless networks.

1. If nodes can transmit to the network, go to step 2. If not, the maximum rate is 0.
   a. All aircraft in both MCPs can transmit.
2. Multiply data transmission rate by accuracy to get maximum rate.
   a. For voice-only: have 3 tracks per 10 seconds times 70 percent accuracy, which equals 2.1 tracks per second.
   b. For Link 16: have 128 tracks per second, at 100 percent accuracy.

Table 6.1
Inputs to Quantity of Retrievable Information

Input	Input for Voice Only	Input for Link 16
	From Quality of Organic Information	
List of information elements to be retrieved from the network	17 sensed air tracks	Same as voice only
	From Degree of Networking	
Reach: whether and how nodes can transmit from and to the network	AWACS, fighters can transmit track info over voice	AWACS, fighters, can transmit track info digitally over Link 16
Quality of service: data transmission rates and accuracy	USAF standards for voice channels: maximum of three tracks every ten seconds. From pilot interviews, about 30% of track info is lost (not heard correctly) using voice-only channels.	Link 16 has 128 time slots per second; each can provide a track update. In assumed permissive environment, no track info is lost.
Network assurance: probability of service provision, lack of data corruption	Assume permissive environment, so service provision is 100% and data corruption is 0%	Same as voice only
Network agility: probability that quality of service will be delivered in variety of mission environments	Assume constant environment for case study (no change)	Same as voice only
	Exogenous Variables	
Number of network nodes attempting to retrieve	5 (AWACS, 4 Blue fighters)	Same as voice only
Number and size of data elements to be retrieved	17 sensed "air tracks"	Same as voice only
Policies determining priority for retrieval	AWACS has 50% of airtime; each Blue fighter has a 12.5% share of air time. Red tracks have two-thirds of air time; Blue tracks have one-third of air time.	AWACS has 50% of time slots; each Blue fighter has a 12.5% share of time slots. Red tracks have 2/3 of time slots; Blue tracks have 1/3 of time slots.
Lifespan: Length of time for which received tracks are considered "retrieved"	Top band: latency under 1 second Second band: latency between 1 and10 seconds	Same as voice only

Phase 2: calculate the maximum number of tracks of each type (Red or Blue, particular aircraft) that the Blue aircraft may have "retrieved" from the network at any time.

3. Multiply maximum rate by lifespan to get maximum number of "retrieved" tracks.
   a. For voice only: 0 tracks "retrieved" within one-second band; 2.1 tracks within one- to ten-second band.
   b. For Link 16: 128 tracks retrieved within one-second band; 1,280 tracks within one- to ten-second band.
4. Multiply maximum number of retrieved tracks by the percentage of airtime dedicated to each type of track and by the percentage of airtime devoted to each aircraft. This yields the expected number of tracks of each type that can be "retrieved" at any time.
   a. For voice-only: We look only at the 1-10 second band. (1) AWACS/Red tracks: (2.1 maximum tracks retrieved)(50 percent of airtime for AWACS)(two-thirds of airtime for Red tracks) = average of 0.7 tracks in one- to ten-second band. (2) Fighters/Red tracks: (2.1 tracks retrieved)(12.5 percent of airtime)(two-thirds of airtime for Red) = 0.175 tracks in one- to ten-second band. (3) AWACS/Blue tracks: using one-third of airtime for Blue tracks, get 0.35 tracks in one- to ten-second band. (4) Fighters/Blue tracks: 0.0875 tracks in one- to ten-second band.
   b. For Link 16: We look only at the less-than-one-second band because of the high transmission speed. (1) AWACS/Red tracks: (128 maximum tracks retrieved)(50 percent of airtime for AWACS)(two-thirds of airtime for Red tracks) = average of 42.67 tracks in less-than-one-second band. (2) Fighters/Red tracks: (2.1 tracks retrieved)(12.5 percent of airtime)(two-thirds of airtime for Red) = 10.67 tracks in less-than-one-second band. (3) AWACS/Blue tracks: using one-third of airtime for Blue tracks, get 21.33 tracks in one- to ten-second

band. (4) Fighters/Blue tracks: 5.33 tracks in less-than-one-second band.

Phase 3: calculate the probability that a given air track will be "retrieved" at any time.

5. Divide the expected "retrieved" tracks of each type by the number of air tracks of each type to retrieve. If this number is more than one, probability track has been retrieved is 100 percent. Otherwise, probability is this number. (For results for each of the 17 sensed air tracks by MCP, see below.)

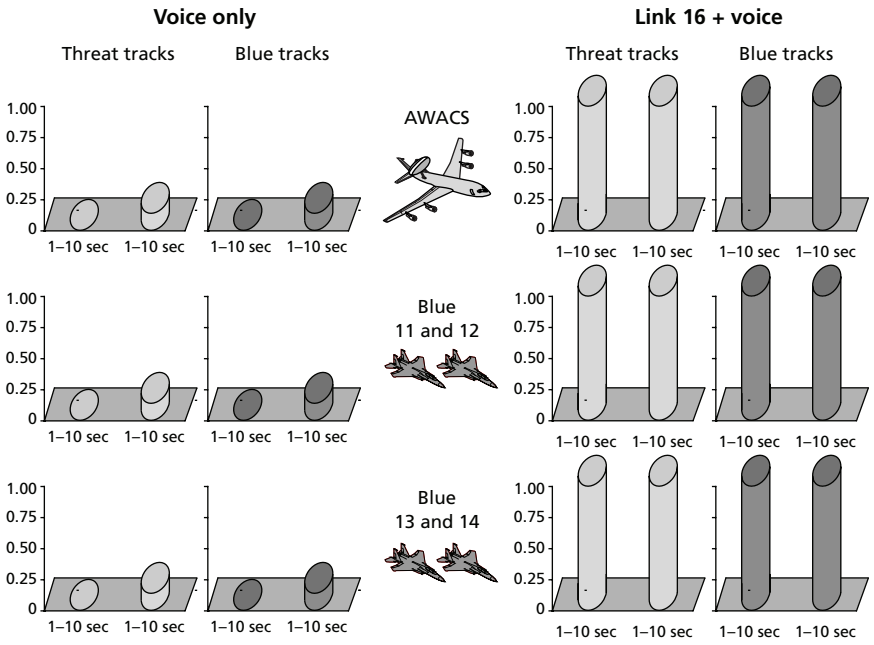
For the sake of simplicity, the calculations above did not include the input factors not directly included in the case study, such as network assurance and network agility. Had these factors been included, they would have been treated in a similar manner—for example, multiplying the track transmission rates by an additional factor representing the probability that tracks are not jammed or compromised.

Individual Platform Results

Figure 6.2 shows the total probabilities of retrieving air tracks for each plane in the Blue force, using the procedures discussed above. We represent the probabilities of retrieving tracks in the both less-than-one-second and one- to ten-second timeliness bands. We need this level of differentiation to properly compute the quality of information metrics.

For the voice-only network, a fairly small percentage of the total tracks are expected to be retrieved at any time in the one- to ten-second band (about 12 percent). No tracks are posted in the less-than-one-second band. Conversely, the Link 16 network posts 100 percent of the available track information within the less-than-one-

Figure 6.2
Percentage of Information Retrieved by Timeliness Band



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second latency band, although the AWACS tracks were only obtained within the one- to ten-second interval. Averaging the quantity of retrieved information across all Blue aircraft, the voice network manages only an overall score of 0.08 for degree of information "shareability," whereas the Link 16 network has a perfect score of 1.0.

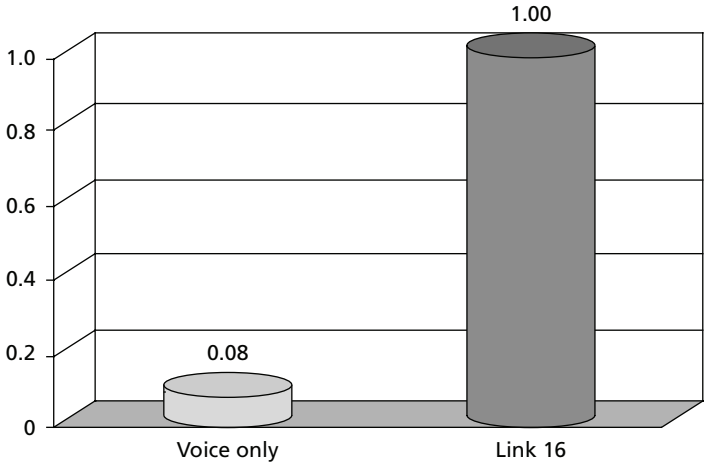
Overall Results

Averaging the quantity of retrieved information across all Blue aircraft yields:

- The voice-only MCP manages only an overall score of 0.08, because of the very limited number of track reports that can actually be carried over the voice channel.
- The Link 16 MCP has a perfect score of 1.0 because all sensed air tracks are immediately reported to the other Blue aircraft via the Link 16 network.

Figure 6.3 compares these two scores.

Figure 6.3
Comparing MCP Scores for Degree of Information "Share-Ability"



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CHAPTER SEVEN

Quality of Individual Information

Specific Metrics

In this case study, the quality of individual information comprises four subsidiary metrics about the air tracks: completeness of detection of air tracks, correctness of ID, accuracy of location, and accuracy of velocity. All four depend on the same inputs: the initial quality of the air tracks (quality of organic information), quality changes incurred when sharing the air tracks over the network (degree of information "share-ability"), and several other exogenous factors. All four have the same form. They are all arrays with each entry presenting the quality measurement on a Blue aircraft's knowledge of an air track. In particular, each measurement is the probability of "knowing" the unique track to within a particular latency and, weighted by the value of that knowledge. Recall that, for location and velocity metrics, knowing a track to within less than one second has value 1.0 and that knowing a track to within 1-10 seconds has value 0.25.

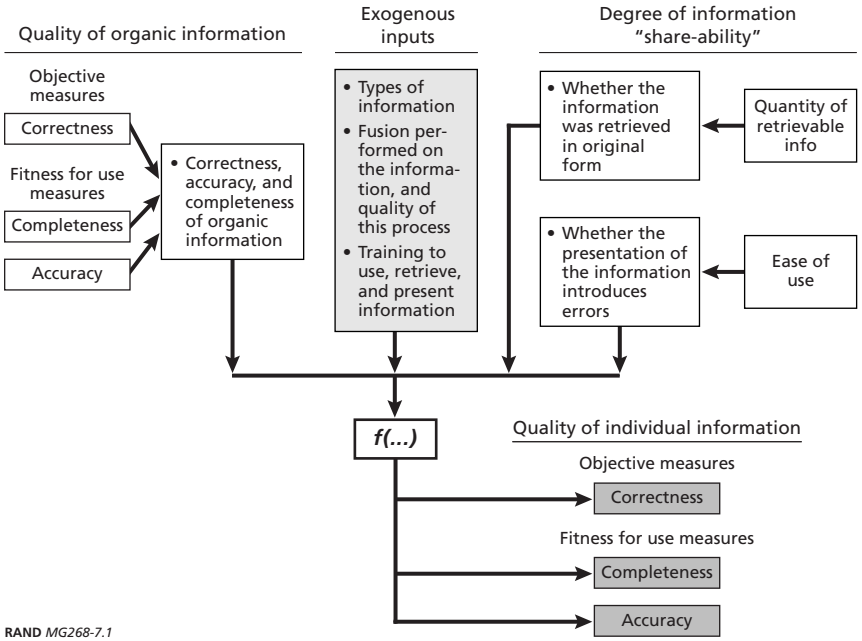
In comparison to degree of information "share-ability," however, of interest here is each aircraft's knowledge of the nine *unique* or *fixed tracks* in the battlespace (AWACS, four Blue fighters, four Red fighters), not the 17 sensed tracks. Thus, our calculations will account for the fusion of the sensed tracks into representations of the unique tracks.

Inputs

Figure 7.1 summarizes the inputs to quality of individual information, indicating which are derived from the quality of organic information measurements or the degree of information "share-ability" measurements and are exogenous.

Table 7.1 describes the inputs used to compute the quantity of individual information metrics, as well as what those inputs are for both the voice-only and Link 16 MCPs. Of interest in Table 7.1 are the fusion formulas. In this report, we assume that fusion is equivalent to selecting the best-known sensed track to represent the corresponding unique track. This tends to overestimate the quality of fusion for voice-only networks (as all fusion must be done mentally) and for Link 16 Red tracks (also requires mental fusion, although

Figure 7.1
Factors Affecting Quality of Organic Information



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graphical displays of tracks help greatly); it tends to underestimate the quality of fusion for Link 16 Blue tracks because it ignores the improvements in accuracy resulting from the ability to average multiple Blue aircraft tracks. However, we believe the formulas are reasonable approximations based on our pilot interviews, especially for an illustrative case study.

Table 7.1
Inputs to Quality of Individual Information Metrics

Input	Input for Voice Only	Input for Link 16
	From Quality of Organic Information	
Array providing organic quality measurements for the 17 sensed air tracks	See Chapter Four	See Chapter Four
	From Degree of Networking	
Array providing quantity of information retrieved measurements for the 17 sense air tracks	See Chapter Six	See Chapter Six
	Exogenous Variables	
Parameters describing the fusion of the sensed air tracks	No automated fusion performed; pilots must perform mental fusion (are trained to do so). Pilots trained to use organic information (visually displayed on radar screen) in preference to radio-reported information. Resulting formula: knowledge of a unique track is maximum of what is known about any corresponding sensed track (whether organic or over voice-only network).	Link 16 fuses Blue track positions automatically; does not fuse Red tracks. However, Red tracks of the same aircraft sensed by fighters (which have real-time tracking capabilities) will appear joined as a single dot; Red tracks sensed by AWACS have a different symbol, which pilots are trained to acknowledge. Resulting formula: knowledge of a unique track is maximum of what is known about any corresponding sensed track (whether organic or over Link 16 network).

Calculations

Calculating the quality of individual information measurements has two phases. The first represents fusion, in which we calculate the probability that each Blue aircraft has knowledge of one of the nine unique tracks in a particular latency band. The second uses the probabilities to calculate the four quality measurements for each track.

Phase 1: Calculate the probability of "knowing" a unique air track within a particular latency band (less than one second or one to ten seconds).

1. Create a new array whose entries reflect the best of source of information each Blue aircraft has on a particular sensed air track (organic or retrieved from the network).
   a. For voice only, best source of information each aircraft has on any sensed track is organic because the network does not do any refinement of the sensed track, and probability is high that the track will not be able to be retrieved over the voice-only network.
   b. For Link 16, best source of information each aircraft has on any sensed track is organic because the network does not do any refinement of the sensed track.
2. Compute the probability that the Blue aircraft has knowledge of each unique track within a latency band, by computing the probability that the aircraft has information on at least one of the corresponding sensed tracks within the latency band (either organic or retrieved from the network).
   a. For voice only, this gives rise to an array of probabilities. Note that tracks known within the less-than-one-second band result solely from organic sensing.
   b. For Link 16, this gives rise to an array of probabilities that tend to be much greater than for voice only. Notably, if one Blue fighter detects an aircraft (including itself) within the less-than-one-second band, all other Blue aircraft share the same knowledge.

Phase 2: Calculate the measurements for each of the four quality of individual information metrics.

3. For completeness of detection and correctness of ID, the measurement equals the maximum probability of "knowing" a unique air track from either the less-than-one-second or one- to ten-second latency bands. This stems from track detection and ID being insensitive to track latency (see results below).
4. For correctness of location and correctness of velocity, recall that tracks known within the less-than-one-second band have a weight of 1.0, and tracks known within the one- to ten-second band have weight 0.25. Then, to compute these metrics, select the maximum weighted probability of "knowing" the air track from either of the two latency bands (see results below).

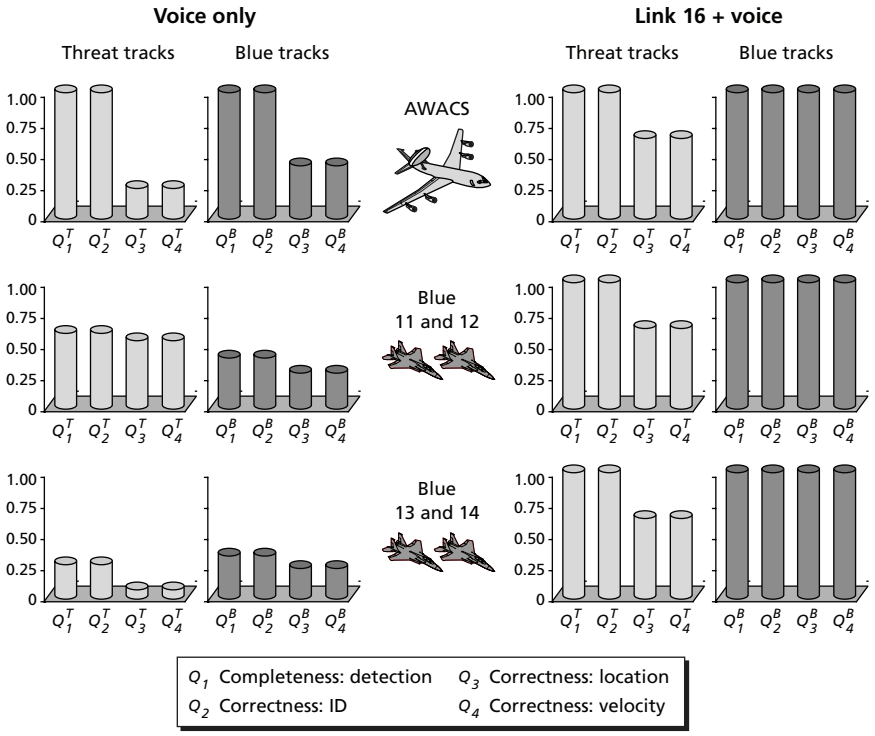
Individual Platform Results

Figure 7.2 compares quality of shared information scores for each Blue aircraft in both the voice-only and Link 16–equipped MCPs along four metrics (all normalized between 0 and 1). The voice-only positions are similar to the initial organic positions, with a slight boost resulting from tracks reported over the voice channel. The Link 16 positions equal the maximum of the initial organic positions. The only planes not known to a near-real time precision by all Blue aircraft are Red 3 and Red 4 (which are sensed only by AWACS).

Figure 7.2 summarizes and compares the individual information position for each Blue aircraft across each of the four major metrics, as follows:

- Completeness: Detection is the expected percentage of all air tracks in the engagement (four Red and five Blue aircraft) that

Figure 7.2
Comparing Quality of Individual Information Across MCPs



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the Blue aircraft either detects directly or has reported to it in the last ten seconds;

- Correctness: Identification is the expected percentage of the air tracks for which the Blue aircraft has correct combat ID—i.e., Red, Blue, or neutral/civilian aircraft. If the air track ID is correct a score of 1.0 is given. If it is incorrect or designated as unknown, a score of zero is given.
- Correctness: Location is the expected percentage of air tracks for which the Blue aircraft has a location report (either from direct detection or network communications links). If the location

report is less than one second old, it is considered to be "near real time," allowing for precise maneuvering and cuing fire control systems, and has a value of 1.0. If the report is one to ten seconds old, it is considered to be "non–real time," suitable only for general cuing, and has a value of 0.25. If the report is more than 10 seconds old, it is given a value of zero, as described earlier.

- Correctness: Velocity is the expected percentage of air tracks for which the aircraft has a velocity report. As with Correctness: Location, the velocity report has a value of 1.0 if it is less than one second old, 0.25 if it is one to ten seconds old, and zero if it is older than that.

As shown, Blue aircraft in the Link 16–equipped MCP had much higher quality of information scores than the voice-only MCP, especially for the location and velocity metrics (which rely heavily on precise, real-time air track updates).

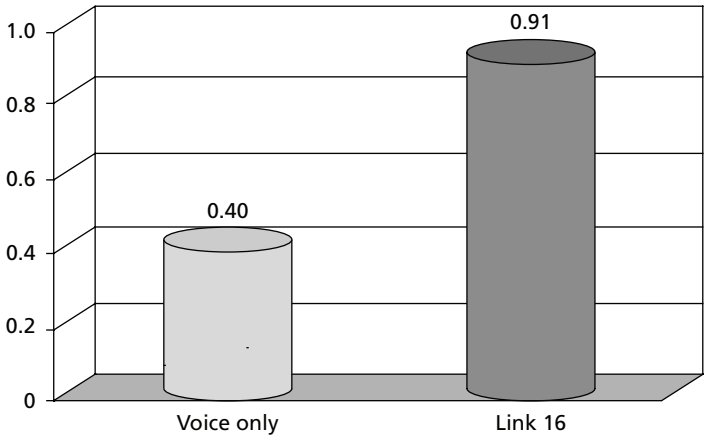
Overall Results

Averaging across all planes and all track quality metrics:

- The voice-only MCP has an overall quality of individual information score of 0.4.
- The Link 16 MCP has an overall score of 0.91.

Both of these scores were generated from the exact same quantity of organic information (average score of 0.28). The Link 16 network multiplies the utility of sensed information by allowing it to be shared across the entire Blue force. Figure 7.3 compares these two scores.

Figure 7.3
Overall MCP Scores for Quality of Individual Information



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CHAPTER EIGHT

Degree of Shared Information

Specific Metrics, Inputs, and Calculations

The subsidiary attributes that constitute the degree of shared information are largely identical to those for quality of individual information, and their metrics are largely calculated the same way. The primary difference is that the metrics are computed for sets of information shared across multiple individuals rather than computed for the information held by each individual. There is one additional attribute: the extent of sharing, which describes the information elements actually held in common across different force members. The attribute has two metrics: the proportion of information in common across force entities and the proportion of force entities that share an information element.

In our analysis of the degree of shared information, we focused on analogues of the information quality metrics, now applied to shared rather than individual track information (completeness of track detections, correctness of track identifications, correctness of location, and correctness of velocity). The new metrics have the same inputs and are calculated in a manner similar to those for quality of individual information, with a few changes:

- Only information transmitted across the networks is considered (i.e., organically known information is excluded from consideration). Thus, the new metric provides the weighted probability

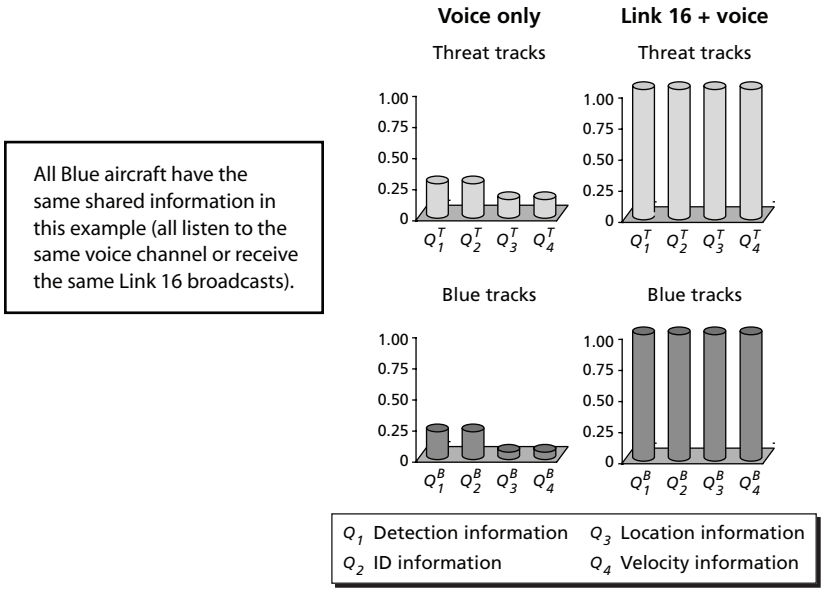
that a given Blue aircraft has retrieved information on a given unique track over the network (whether voice-only or Link 16).

- The metrics are calculated with respect to sharing the "available" track information across the Blue force. Therefore, the scores are not penalized for failing to share track information that is unknown organically. For example, in the case study, two Red aircraft tracks (Red 3 and Red 4) are not detected in near real time (in the less-than-one-second latency band) by any Blue aircraft and so are excluded from the measurement calculations.

Individual Platform Results

Figure 8.1 shows the quality of the available track information shared across the Blue aircraft. The charts in Figure 8.1 apply equally to

Figure 8.1
Comparing Degree of Shared Information Across MCPs



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every Blue aircraft in the force package because all of them are assumed to be listening to the same voice channel and/or receiving the same Link 16 broadcasts. In general, we see that the voice-only system manages to share around 25 percent (Red) and 20 percent (Blue) of the detection and ID information, and 12 percent (Red) and 6 percent (Blue) of the location and velocity information (taking into account the degradation involved in transmitting near–real time tracks over voice), whereas the Link 16 system shares all available information.

Overall Results

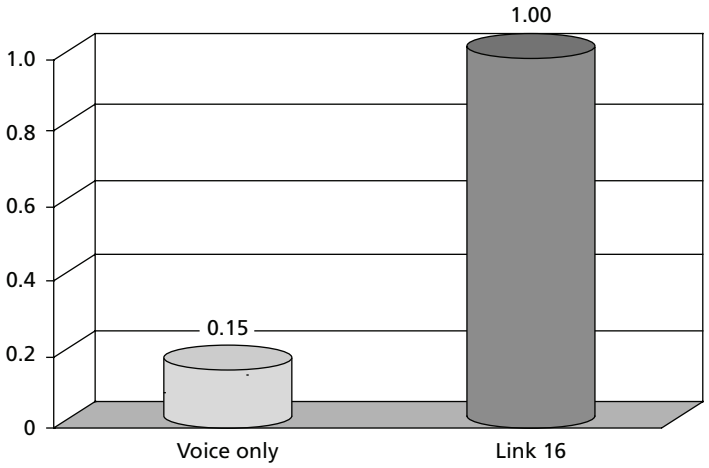
Averaging across all measurements:

- The voice-only MCP scores 0.15 for degree of shared information.
- The Link 16 MCP scores 1.0 because every available air track that could be shared was shared to the highest degree of accuracy in this case study.

Figure 8.2 compares the two MCP scores for quality of shared information.

These results clarify what was implied by the quality of individual information results—that the voice-only network provides only a marginal contribution to the Blue aircraft's information positions, whereas Link 16 largely ensures that what is known organically by one aircraft is known by all Blue aircraft.

Figure 8.2
Overall MCP Scores for Quality of Shared Information



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CHAPTER NINE

Quality of Individual Sense-Making: Awareness

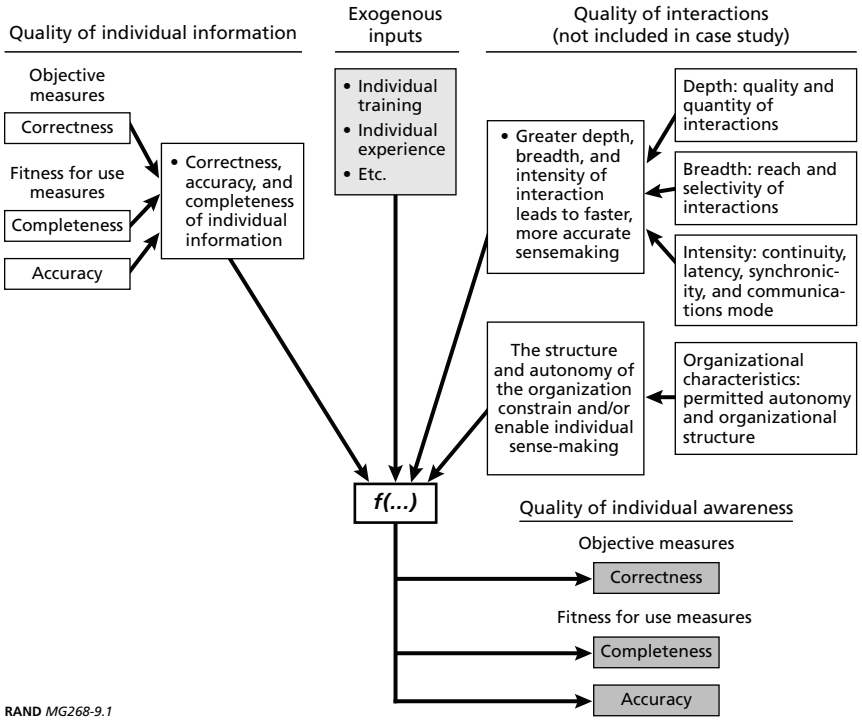
Major Factors Contributing to Individual Sense-Making

A number of major factors go into individual sense-making at the awareness, understanding, and decision levels, such as doctrinal impacts, organizational impacts, training, experience, and the quality of the interactions between force members. Figure 9.1 summarizes a number of these factors contributing just to individual awareness, showing which ones relate directly to the quality of information measurements, which relate to the NCO CF quality of interactions attributes (not included in this study) and are exogenous.

Understanding of these cognitive processes in the context of a military operation is limited because research into them is very recent. Unlike the previous concepts, which can be assessed through precise observation and assessment, the sense-making concepts must be assessed indirectly because it is impossible to view someone's knowledge and thought processes. Further, sense-making is known to depend on many factors that are not well understood and are assessed qualitatively and whose impacts on sense-making are even less well understood.

In this report, then, we rely on approximate models of awareness, understanding, and decisions. Awareness closely relates to a person's mental incorporation of the information they receive, so we model awareness as estimating how well the pilots know the aircraft track information they receive.

Figure 9.1
Major Factors Contributing to Individual Sense-Making



Understanding is more complicated, relating to how well a person can build on this awareness, determining what events will likely happen in the future and how they might be addressed (generating options and likely outcomes). Thus, in this report, understanding is modeled by estimating whether a person knows enough to make good decisions or at least has the potential to make good decisions. Therefore, we do not address understanding as a separate concept but rather address it in conjunction with decisionmaking later in this report.

Note that from the pilot interviews, we have made some useful observations on awareness and understanding from a qualitative perspective. With the voice-only network, most of the voice channel is

dedicated strictly to information sharing, which leaves little time for pilots to build more detailed understanding of the battlespace or to collaborate with others to assist in building such detailed understanding. In addition, the fact that the track information is auditory and on a time delay leaves pilots to create an approximate mental picture of each tracked plane's position. In contrast, with the Link 16 network, aircraft track information is immediately broadcast over the force visually, so pilots do not have to construct a time-delayed mental image—the Link 16 display does it for them. This leaves more time for pilots to gain a deeper understanding of the state of the battlespace and what to do about it. In addition, they also have unfettered access to the voice channel if they want to discuss what to do with the information or issue related commands.

Specific Metrics, Inputs, and Calculations

For this case study, we use a simple approximation to estimate quality of individual awareness metrics directly from the quality of information metrics (completeness of tracks; correctness of track ID, location, and velocity).

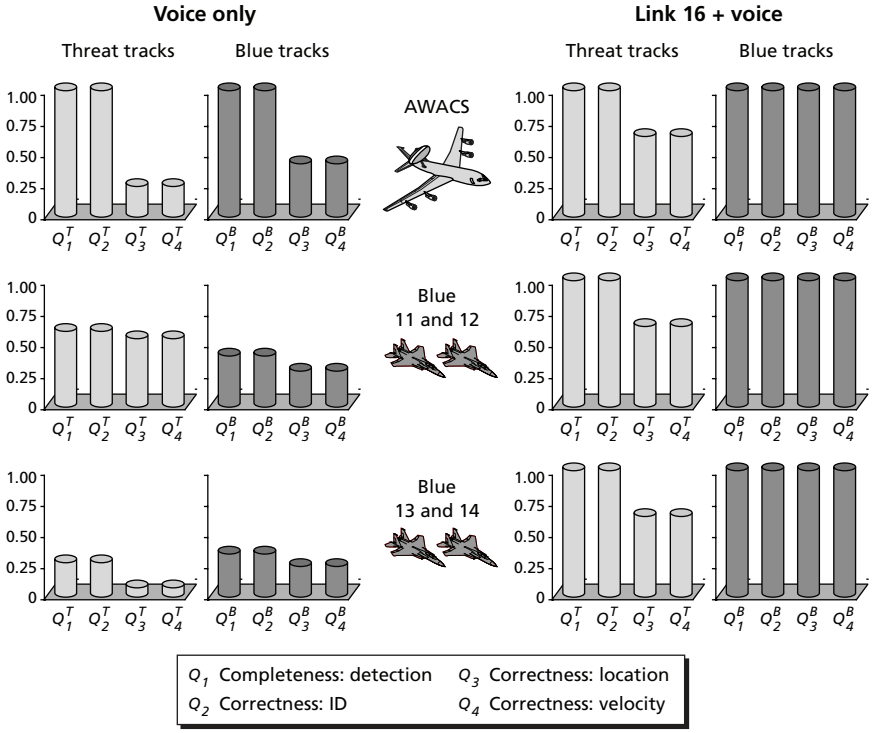
As with the quality of information metrics, we want to know whether a Blue aircraft pilot's awareness of the aircraft tracks is in near real time (mental image of aircraft track is within one second of its real position and velocity), or cue-only (mental image is within one to ten seconds of its real position and velocity), with a much greater weight placed on the former than the latter (1.0 versus 0.25 for the position and velocity metrics). Rather than simply copy the individual information metrics, however, we introduce the idea of "memory." For the track information in the one- to ten-second band, we assume a 50 percent chance that the information will be valid in the next ten-second window, on the grounds that the pilot may remember the information accurately enough and that the tracked plane has not deviated from its path far enough to make the pilot's

mental image of it invalid. Track information in the less-than-one-second band must be refreshed every second to remain valid.

Individual Platform Results

Figure 9.2 displays the resulting individual awareness scores for each Blue pilot. Note that the scores for the Link 16 MCP are exactly the same as for individual information because all track information is updated as frequently as it is obtained. That is, information obtained

Figure 9.2
Comparing Quality of Individual Awareness Across MCPs



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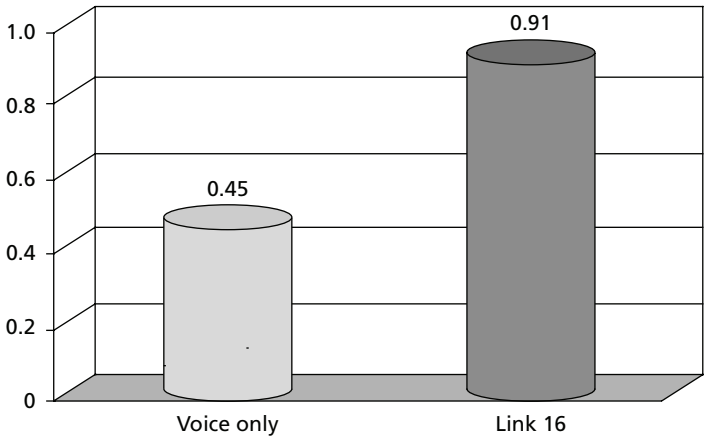
in less than one second is distributed for the pilots multiple times per second and information from the AWACS is updated every ten seconds, as it is obtained. The main differences in scores are for the voice-only MCP, where "memory" allows pilots to employ track information reported more than ten seconds ago.

Overall Results

Averaging across all quality of individual awareness scores for all Blue aircraft and tracks:

- The voice-only MCP pilots have an aggregate individual awareness score of 0.45, which is a slight improvement over the aggregate individual information score of 0.40.
- The Link 16 MCP pilots have an aggregate individual awareness score of 0.91, which equals the individual information score. Figure 9.3 compares the two MCP scores.

Figure 9.3
Overall MCP Scores for Quality of Individual Awareness



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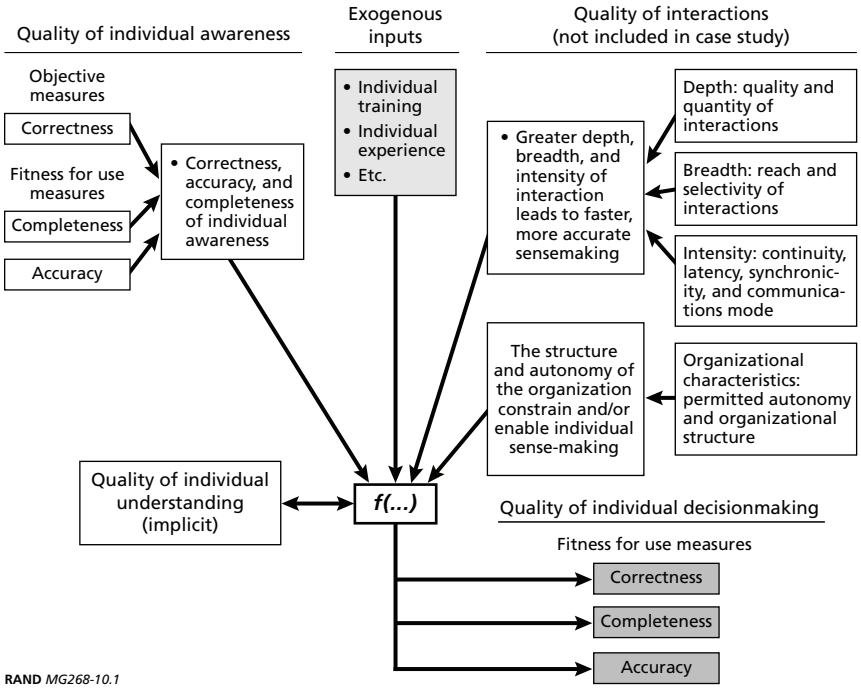
CHAPTER TEN

Quality of Individual Sense-Making: Decisionmaking

Major Factors Contributing to Individual Decisionmaking

We now consider the quality of individual decisionmaking (and individual understanding leading to decisionmaking). As with other aspects of individual sense-making, individual decisionmaking is complicated and not well understood because it takes place almost entirely in the cognitive realm. Figure 10.1 summarizes factors contributing to the decisionmaking measurements and shows whether these factors are derived from the quality of individual awareness scores, the NCO CF quality of interactions attributes, or other, exogenous factors. As shown on the figure, we do not model individual understanding directly in this case study, so its scores are implicitly included in the calculation of individual decisionmaking scores. Figure 10.1 also shows the three attributes for individual decisionmaking that are comparable to the completeness, correctness, and accuracy measures used to date—completeness of the decisions (whether the decisions encompass necessary depth, breadth, and time horizons), appropriateness (whether the decisions are consistent with existing understanding, command and intent and values—analogous to correctness), and accuracy (whether the decisions are sufficiently precise for a particular use). Note, however, that we do not use these three attributes to model individual decisionmaking in this case study.

Figure 10.1
Factors Contributing to Quality of Individual Decisionmaking



Interviews with experienced pilots revealed that the improved quality of information under Link 16 improved situational awareness and subsequent decisionmaking in two ways. First, in general, the pilots with access to the Link 16 network reported spending less time building situational awareness (i.e., determining where the Red and Blue aircraft are) than did pilots with access limited to the voice-only network. In the voice-only network, pilots had to continually listen to voice traffic describing air tracks, mentally convert each description into a velocity and location, predict where the aircraft would likely be based on the last report, and perform these mental calculations while listening to further incoming reports. This process of gaining awareness was described as slow (restricted by voice transmissions), mentally taxing, and potentially error-prone. Further, because the manual

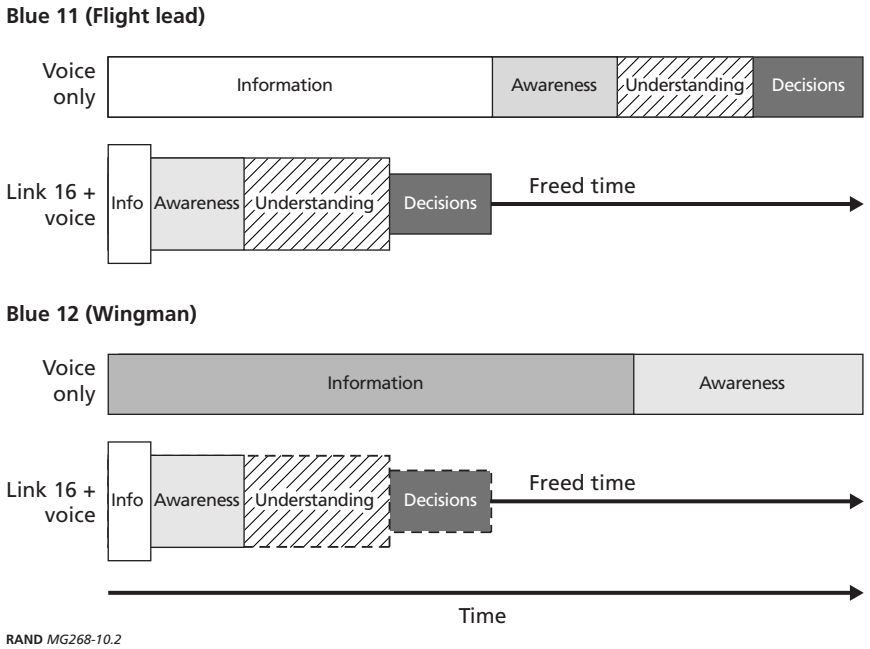
mental process of building awareness is error-prone under the stressing conditions of combat, it is likely that pilot situational awareness information is not entirely common across the MCP. In other words, situational awareness is shared and interpreted imperfectly among pilots over voice channels.

In contrast, in the Link 16 network, pilots are presented with a continually updated image visually displaying the precise positions and velocities of all detected aircraft in the battlespace; the resulting process of gaining situational awareness was much faster, almost automatic (no mental calculations required), and accurate. The resulting time compression in obtaining information and awareness with Link 16 is shown in Figure 10.2. This freed time could be used to both spend more time considering alternative courses of action, which will tend to lead to better decisions, and make more decisions in a given period of time, which (assuming the decisions are reasonable) should lead to more targets destroyed. Notably, the freed time also allows the wingman time for sense-making and making decisions to engage targets, as opposed to spending virtually all his time gathering and monitoring critical information, as in conventional doctrine. This is depicted graphically in Figure 10.2. It is important to note that the time line in the figure is qualitative in nature. The time needed by pilots to build their situational awareness could not be quantified in the case study even though the differences in this attribute were thought to be very significant according to pilots who had experience with Link 16.

The second influence factor is that the increased knowledge of both Red and Blue locations enables new tactics to be employed. We use this second influence factor, which builds on the first discovered in our analysis (and as depicted in Figure 10.1), and discuss its limitations after discussing the approach.

In conventional Air Force doctrine (with a voice-only network), half of the Blue fighters—the wingmen—are put on defensive patrol duty while the flight leads engage targets. Furthermore, the Blue air-

Figure 10.2
Decision Speed and Competitive Advantage with Link 16



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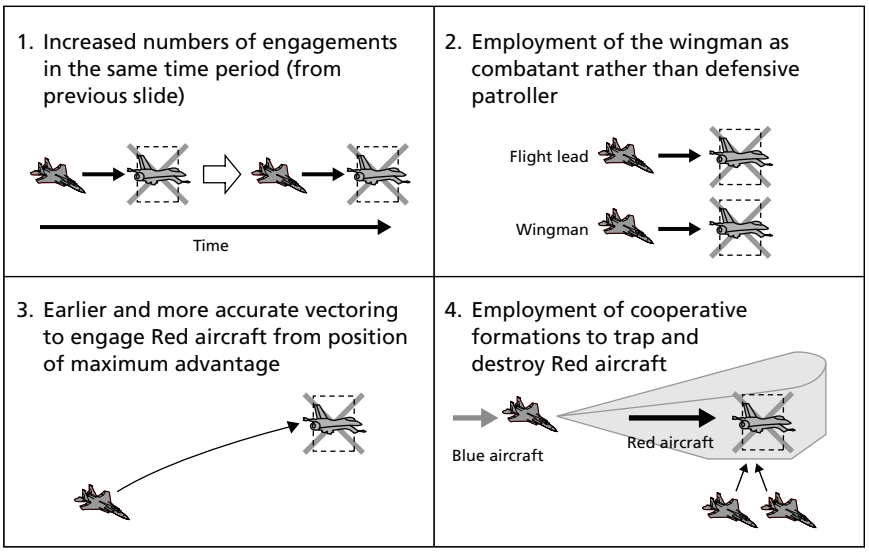
craft have limited awareness of the locations of the other Blue forces and so cannot act cooperatively.

From discussions with pilots who participated in the JTIDS Special Operations Project, we have identified four types of air-to-air combat tactics that were executed more effectively by the fighter pilots. This improvement in tactics execution was enabled by the increased information and decreased time required for information-gathering in Link 16-equipped force packages, as discussed on the last figure. The pilots were able to improve execution of air combat tactics by taking advantage of their increased awareness, as well as the increased time they had available for decisionmaking. These improved tactics are shown in Figure 10.3.

Figure 10.3
Improved Air-to-Air Tactics Execution Enabled by Improved Awareness



SOURCE: Interviews with fighter pilots experienced with Link 16.

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The first of these is simply an increased number of engagements in the same period. This tactic is possible because pilots with Link 16 can quickly recognize the most efficient attack trajectories. This is an important consideration because (according to the pilots) the fighters only have a limited time to engage before they run low on fuel and must return to base.

The second tactic is the employment of the wingman as a combatant rather than a defensive patroller. With Link 16, all threats are known by all Blue aircraft. The flight lead has more options for employing the wingman as a primary shooter because of the higher levels of individual and shared understanding of the engagement, effectively doubling the firepower of the fighter package.

The third advanced tactic is the use of other planes' track information to perform earlier and more accurate vectoring, which allows a Blue fighter to enter an engagement from a position of maximum

advantage, before the Blue fighter's radar (or the Red plane's radar, for that matter) can detect the engaging plane.

The fourth tactic is the use of "ambush CAP" tactics and the use of terrain to trap and destroy Red aircraft. Because all Blue locations are known by Blue aircraft—even if those aircraft are operating in radar or IFFN silence—they have more options to engage targets. One example of "ambush CAP" tactics is when a Blue fighter chases a Red fighter toward other Blue aircraft. The latter Blue aircraft have their radars turned off (or are hiding in a canyon) so the Red fighter is not likely to know that the latter Blue aircraft are present. Then, when the Red aircraft is chased into range, the other Blue fighters will suddenly engage the Red fighter, surprising it and likely destroying it with minimal damage to Blue aircraft.

Specific Metrics, Inputs, and Calculations

For this case study, the metric representing quality of individual decisionmaking is the probability that the Blue aircraft have an awareness of the battlespace sufficient to execute each of the advanced tactics described above. Note that many exogenous variables contribute to whether the Blue fighters can decide to, and correctly execute, the types of advanced tactics mentioned in the previous figure, ranging from individual training to the team hardness of the force package to whether Air Force C2 allows the advanced tactics. However, because this report's purpose is to compare the impacts of the Link 16 and voice-only architectures, we focus strictly on whether the quality of individual awareness (and hence the quality of individual information) is sufficient to allow the tactics to be employed. Table 10.1 presents a table of awareness requirements for each advanced tactic. Note that the table makes reference to an "immediate battle area." This is the space surrounding each Blue aircraft in which the fighter can actually engage another plane or be engaged by another plane; it is a

Table 10.1
Sense-Making Requirements to Employ Improved Tactics Execution (Notional)

Tactic	Near–Real Time Awareness (less-than-one-second band)	Cue-Only Awareness (one- to ten-second band)
Accelerated engagements	All aircraft in immediate battle area (to enable rapid target selection)	All aircraft in battlespace (eliminates the need to wait for cuing info and assists determination of engagement priorities)
Combatant wingman	All aircraft in immediate battle area, plus other Blue aircraft in flight (to meet protection role)	All Red aircraft in battlespace (prevents surprise)
Earlier and more accurate vectoring	All aircraft in immediate battle area	All aircraft in battlespace (provides info needed to vector on Red aircraft outside immediate battle area)
"Ambush CAPs"	All Blue aircraft in battlespace (needed to create precise formations); all Red aircraft in immediate battle area	All Red aircraft in battlespace (provides general cuing info for formations and avoidance of other aircraft)

small subset of the whole battlespace, which can be hundreds of miles in diameter (equivalent to the radar range of the AWACS aircraft).

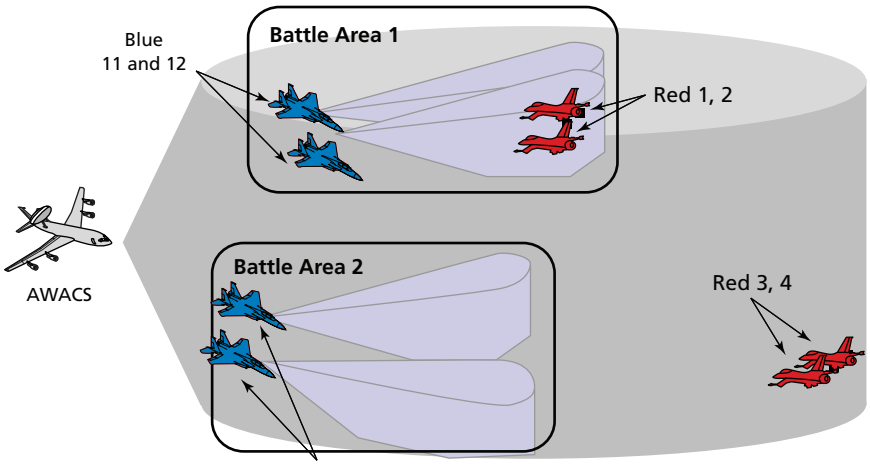
Results

Figure 10.4 compares the requirements for improved tactics execution to the state of the battlespace (in terms of which planes are in which battle areas), and the Blue fighters' quality of individual awareness. The quality of situational awareness within the Link 16 network is sufficient to enable the improved tactics, whereas the situational awareness within the voice-only network is insufficient to use these same tactics as effectively.

Weighting the potential to perform each tactic equally yields:

- The voice-only MCP has an overall quality of individual decisionmaking score of 0.2 because this MCP can perform the four tactics considered with only low to moderate effectiveness.

Figure 10.4
Sense-Making Requirements Met by the MCPs



	Voice only	Link 16
Accelerated engagements	No	Yes
Combatant wingman	No	Yes
Earlier and more accurate vectoring	No	Yes
Ambush CAPs	No	Yes

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- The Link 16 MCP has an overall score of 1.0 because this MCP showed significant improvement in executing all four tactics.

Figure 10.5 compares the two MCP scores.

Note that the values presented in Figures 10.4 and 10.5 are not based on data about the actual number or quality of the decisions made the pilots. They are simply based on Link 16's ability to effectively support all four types of tactics in Figure 10.4. We have chosen this approach because we do not have any data on the decisions made and because we believe that decisions embodied in the improved tactics execution generally are superior decisions (with the exact decisions

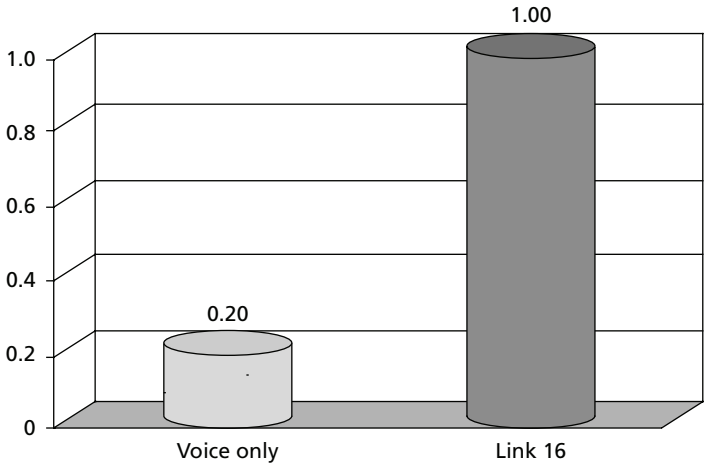
appropriate to make depending on the particulars of the engagement).

One limitation of this approach is that the values are based on subjective data determined through interviews with Link 16 pilots and not on objective measures of improved decisionmaking or the quality of decisions. The rankings of the two MCPs considered are therefore only relative and not absolute. Put another way, the rankings reflect only the perceived improvement in tactics execution. This is as much a measurement of agility as of the quality of the decisions (see Chapter Eleven). The precision of the numbers reported has been reduced to reflect the low-level of resolution that this analysis allows.

Linking Decisionmaking to Mission Effectiveness

The last step in applying the NCO CF is to link the decisionmaking scores to decision and action synchronization and hence to mission

Figure 10.5
Overall MCP Scores for Quality of Individual Decisionmaking



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effectiveness. Table 10.2 repeats the table of average loss exchange ratios from the JTIDS study. As shown, Link 16 increased the average force effectiveness by 160 percent.

We use this table to calculate overall MCP scores for mission effectiveness. Because we do not have sufficient data to define "perfect" kill ratios, we define the maximum observed kill ratios (in this case, for Link 16) to be 1.0, and score the voice-only MCP's mission effectiveness as its average kill ratios divided by the maximum observed kill ratios. Doing so, we find:

- By definition, the Link 16 MCP scores 1.0 for mission effectiveness
- The voice-only MCP scores only 0.38 for mission effectiveness.

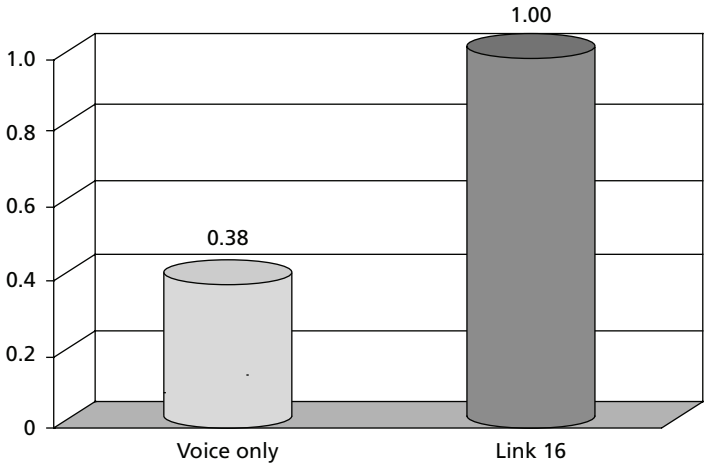
Figure 10.6 compares these two scores graphically.

The natural way to model the link between individual decisions and effectiveness would be to estimate the marginal impact of the ability to employ each of the advanced tactics previously discussed. However, we do not have enough data to attempt to compute the marginal impacts in this report.

Table 10.2
Results of the JTIDS Operational Special Project (Average Red-to-Blue Loss Exchange Ratios)

	Kill Ratio	
	Voice Only (MCP 1)	Voice Plus Link 16 (MCP 2)
Day	3.10:1	8.11:1
Night	3.62:1	9.40:1

Figure 10.6
Overall MCP Scores for Mission Effectiveness



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CHAPTER ELEVEN

Conclusions

In this chapter, we discuss the results from the analysis conducted in the air-to-air combat case study and the application of the NCO CF.

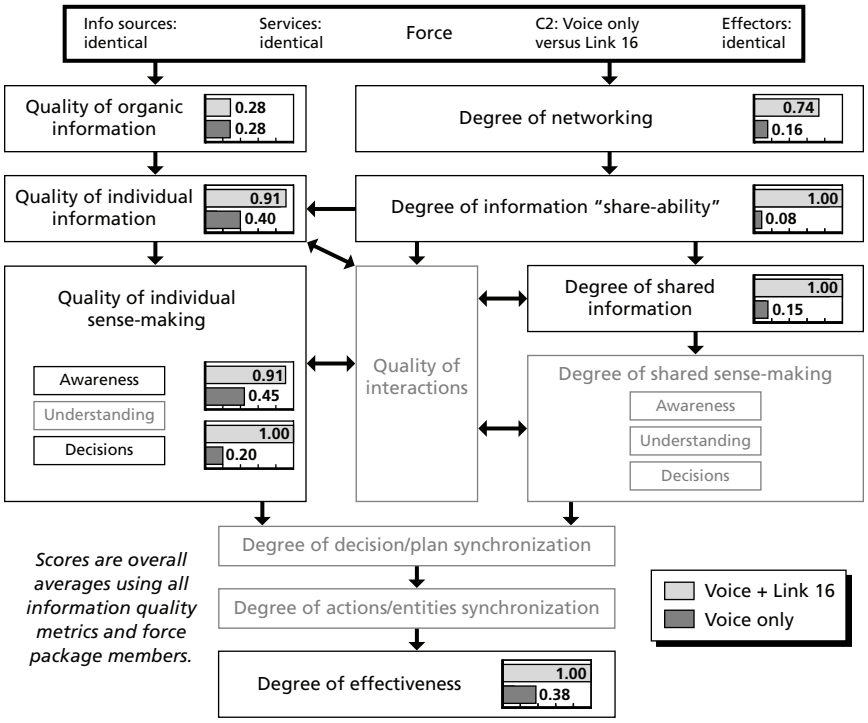
Summary

We can summarize the results of this case study by saying that the overall conclusions of the NCW hypothesis have been validated in this examination of the air-to-air combat mission. Despite starting with similar airframes, training, doctrine, and organic sensing capabilities, the Link 16–equipped MCP was able to take advantage of the information shared within the MCP through Link 16 and voice networks far more effectively than the voice-only MCP. Because of this, the quality of information available to individual fighter pilots was increased significantly. They did not have to spend as much time building their own picture of the battlespace or their own awareness of the battlespace. Instead, they have more time available for decisionmaking. While not proved conclusively in this case study, we believe on the basis of interviews with experienced pilots who have flown with Link 16 that they were on average able to make better decisions and make decisions earlier in the opening gambits of tactical air-to-air engagements. This resulted in greatly increased force effectiveness as measured in the landmark JTIDS experiments that were conducted several years ago.

To graphically show the improvements, Figure 11.1 traces the average scores of the Link 16 and voice-only MCPs all the way through the NCO CF, starting from quality of organic information and ending with improved mission effectiveness.

As hypothesized by the NCW tenets, the robustly networked force enabled by Link 16 improved information sharing and the resulting quality of information, which enhanced shared situational awareness, which in turn enabled self-synchronization (in this case study, as measured by the ability to make improved decisions and by improved tactics execution) and which resulted in dramatically increased mission effectiveness as measured by the kill ratios.

Figure 11.1
Complete Comparison of MCPs Using Summary Metrics



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The air-to-air combat case study provided quantitative data concerning the benefits of Link 16 to both information distribution and to lower levels of individual awareness. Furthermore, it showed that these increases in situational awareness likely enabled the improved execution of the four advanced tactics described in the previous chapter, which in turn led to the observed increases in kill rates.

Lessons Learned from Applying the NCO CF to the Air-to-Air Case Study

Below, we describe the lessons learned about the NCO CF from the air-to-air combat case study and the limitations of the study as an exploration of the NCO CF.

Applicability of the NCO CF. The case study provided valuable insights into the application of the NCO CF and associated metrics. In particular, we have shown that it is feasible to approximate the chains of influences through the NCO CF and do so in a highly meaningful manner. For example, rather than saying, "Link 16 was better than voice-only because its numerical scores were higher," it is possible to say, "Link 16 was better than voice-only because its data-handling, bandwidth, accuracy, and reach provided all Blue aircraft with the seven real-time, accurate tracks needed to improve tactics execution, which in turn greatly increased kill ratios in the JTIDS experiments."

Furthermore, this case study showed that an analysis using the NCO CF is possible, even in the absence of detailed information. In this instance, we had only knowledge of the capabilities employed and the kill ratio but were still able to develop a credible "story" about how improvements in the degree of networking led to an improved kill ratio.

We recommend that more complex case studies be conducted to further develop an understanding of NCW and the NCO CF.

Limitations of the NCO CF. In performing the analysis, we used many of the metrics and did not identify any major deficiencies at the lower levels of the NCO CF. However, we did not use traditional interpretations of the metrics for decision quality because we had no data on individual decisions. Instead, we analyzed the advanced tactics reportedly employed in air-to-air combat when using Link 16.

This analysis could be interpreted within the context of the NCO CF in several ways:

- Link 16 enabled the wingman to be used as a combatant, thus resulting in a more agile (flexible) decisionmaking process and more offensive firepower
- Link 16 enabled accelerated engagements and thus resulted in increased decision timeliness
- Link 16 enabled earlier and more accurate vectoring and "ambush CAP" tactics that resulted in more "appropriate" decisions.

However, the flexibility metrics of the NCO CF do not reflect the quality of the options, and decisions made without Link 16 could also be "appropriate"—particularly given the available information. Adding other metrics that reflect the "decisiveness" or "potential impact" of decisions and options to a greater degree may be necessary.

Another potential shortcoming in the NCO CF is that the degree of information share-ability should consider not only the quantity but also the quality of information posted and retrieved and whether the information is correct, incorrect, or irrelevant to the mission under consideration. That is, it should consider whether the information is degraded when it is posted and retrieved. While it did not play a role in this case study, it should be recognized that these quantities will depend on the quality of interactions measurements and whether people are willing to post and retrieve information.

We had to identify numerous relationships between the metrics, the underlying data, and exogenous variables. However, this was

expected, given the generic nature of the framework, and we did not identify any relationships that should clearly be added to the top-level NCO CF. We did note that the quantity of organic information (as opposed to its quality) affects the Degree of information "shareability" because more information leads to heavier bandwidth demands. Further, because we did not model interactions, the relationship between individual information and shared information was direct.

The exogenous variables needed for the analysis fall into two categories: those required to convert information about the force into data and ultimately metrics to evaluate the lowest-level capabilities—organic information and networking—and those required to evaluate the higher-level capabilities. It is reasonable to assume that the first set do not need to be captured in the framework. Other exogenous variables identified that may need to be explicitly considered for later versions of the framework included:

- Training, tactics, procedures
- Size of the network and quantity of organic information
- Information fusion processes.

Limitations of the Air-to-Air Case Study. While the air-to-air case study was successfully conducted, it did not stress the NCO CF in a number of areas that should be addressed in future studies.

First, the air-to-air scenario is relatively simple. It contained only nine force entities, five Blue and four Red, and we tracked only four pieces of relatively simple information: detection, identification (Blue/Red), location, and velocity as well as their relationships to four advanced tactics. Other scenarios with more force elements or information elements would stress the NCO CF more.

For example, it is not clear from this analysis if the NCO CF would satisfactorily handle such information elements as command intent and unit capabilities that may be generated from using large quantities of information.

Second, the analysis focused mainly on the easily quantifiable capabilities—namely, networking and information. Tracking the quality of interactions and cognitive artifacts is much more complex. For example, shared awareness and understanding may require additional assessment techniques to those required for individual awareness. Similarly, completing the chain from decisionmaking to mission effectiveness will require collecting data on the marginal impacts of deciding on different types of tactics under varying conditions.

Areas for Further Research

The Air-to-Air Case Study was a pilot study, and as such, several areas received limited treatment and would benefit from added attention.

First and foremost is the acquisition of data describing cognitive and social behavior. The current modeling of quality of sense-making and quality of Decisionmaking is highly approximate and based only on a small number of informal interviews.

Second, we would like to model the impact of nonmateriel changes to the force packages. These include more detailed analysis of the changes to the C2 concept, tactics, techniques, and procedures employed in the experiments. Similarly, it would be useful to model the impact of changes to the force mix beyond Link 16 versus voice-only, such as changes to the aircraft, sensors, and weapons involved as well as individual and organizational characteristics, such as team hardness. Together, modeling these sets of changes will help distinguish the impact of the network on mission effectiveness from the impact of other nonmaterial and force mix changes.

Third, we would like to expand the scenario used to compute the metrics beyond a single four-on-four engagement. This will mean both calculating metrics over a wide range of possible engagements, varying mission scales, force balances, and information positions (perhaps using Monte Carlo simulation) and having some ability to account for dynamics in information positions over time.

Finally, we would like to use the same overall approach in this case study to other combat areas. We believe that the detailed approach of identifying what information elements can be generated and shared through the use of different networks, what the subsequent situational awareness is across the joint force, and what types of "advanced" understanding and tactics are enabled as a result is broadly applicable. For example, the approach might be applied in disparate areas ranging from joint close air support to ground maneuver. Of particular interest would be an attempt to apply the approach to stability operations and missions other than war—environments that do not have the same clarity as traditional air-to-air combat.

APPENDIX

Analytica Model for the Air-to-Air Combat Example

Model Fundamentals

This appendix describes the Analytica model used to calculate the metrics in this report. Analytica uses a multidimensional-array notation and structure that is somewhat different from common mathematical and simulation modeling techniques, so we begin the appendix with a discussion of model fundamentals.

At the top level, Analytica models comprise a number of nodes and modules linked into an influence diagram. Each node in the diagram either calculates a portion of a metric or contains input parameters used in other nodes' calculations. A calculation normally depends on the output of other nodes; node A is dependent on node B if node A uses the output of node B to compute a metric. Analytica would show the former dependency with an arrow (link) from node B to node A. Modules consolidate a group of linked nodes into what appears as a single element in Analytica. Modules are also used to simplify and clarify the appearance of an influence diagram. A link appears between two modules if a node in one module is dependent on a node in the other module.

In the air-to-air example, each module comprises the nodes needed to compute a top-level metric. Figure A.1 shows the modules in the top level of the air-to-air model (and hence the metrics computed in the model). The figure also shows the overall dependencies between nodes in the modules (and hence the dependencies between

the metrics). The top-level diagram closely matches the top level of the NCO Conceptual Framework, with the exception that quality of interactions, shared sense-making, shared decisions, synchronization metrics, and degree of effectiveness are missing from the diagram. This set of metrics is not incorporated in the air-to-air case study, except for the degree of effectiveness, which is obtained from the JTIDS Special Operations Project results.

Each module contains a number of subsidiary nodes used to structure the subsidiary metrics for each top-level metric. Figure A.2 describes the types of nodes used in the Analytica model. The air-to-air model employed in this report uses decision, constant, variable, and objective nodes. The chance node is not used because we have

Figure A.1
Top Level of the Analytica Model

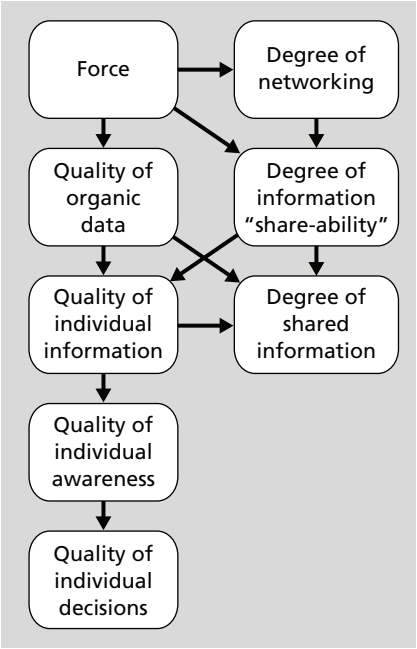

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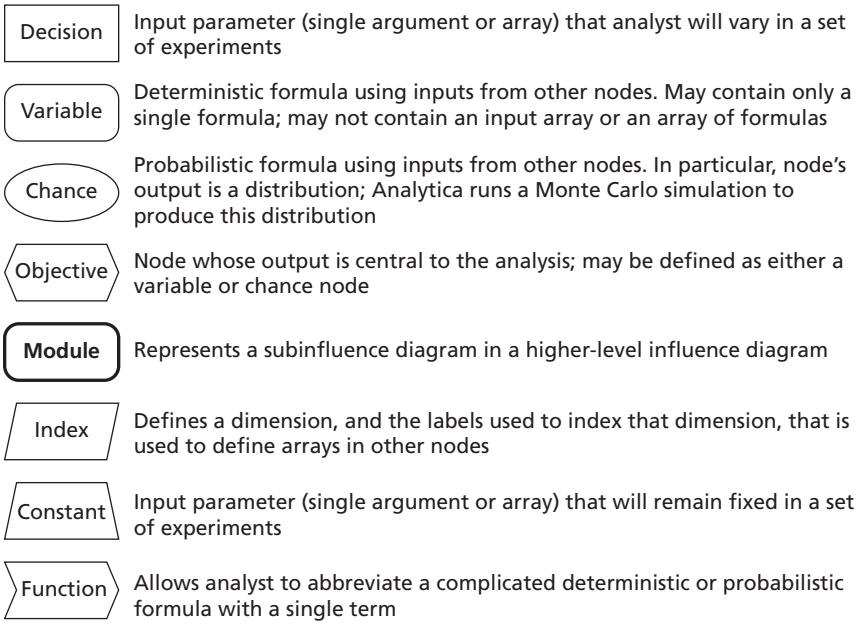
Figure A.2
Types of Nodes in Analytica



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chosen to use a deterministic model based on probabilities. The module nodes organize what would otherwise be a very complicated influence diagram into a manageable number of small subinfluence diagrams. The model uses index nodes to define the dimensions used in calculating the metrics.

A main theme with Analytica models, and the air-to-air example, is that each metric is a multidimensional array, not a single scalar. Each entry in the array gives a metric score for a set of dimensional indices. Array dimensions commonly used include the user/node (AWACS or one of the four F-15s), the information element received by the user, and the level of service used to receive the information item. For the latter, "level of service" can be either a network service

(e.g., data or voice), or a performance band (e.g., item received within less than one second or within one to ten seconds of its creation).

To compute the overall metrics shown in the body of the report, Analytica allows the user to average across the dimensions. Importantly, the dependencies between metrics are based on the full multidimensional arrays, not on the summary averages.

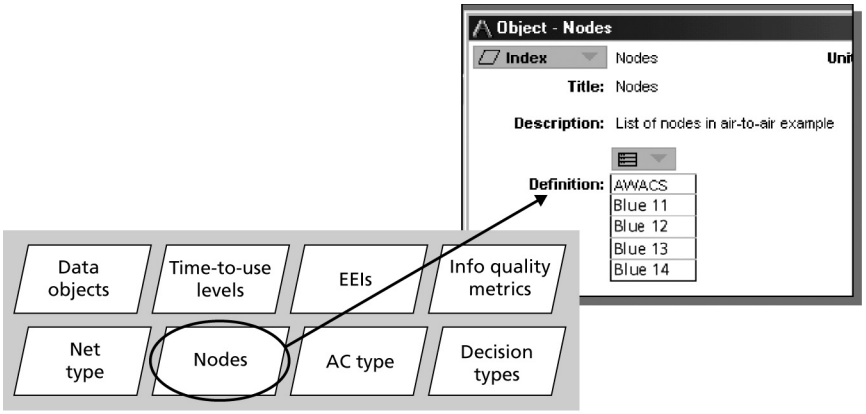
By convention, we use boldface to refer to an Analytica array and italics to refer to an array dimension.

As noted, the index nodes define the dimensions used in the arrays, as well as the entries used as index points for each dimension. The air-to-air model has eight dimensions that are commonly used in the Analytica arrays. Figure A.3 shows the corresponding index nodes and lists the entries for the "Nodes" dimension.

The dimensions (and their constituent entries) are as follows:

- *Data objects* refers to the 17 tracks (the sensed tracks) detected by the Blue aircraft in the model. It includes the eight tracks detected by AWACS (four Red fighters, four Blue fighters), the

Figure A.3
Air-to-Air Model Array Dimensions



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two Red tracks detected by Blue 11, the two Red tracks detected by Blue 12, and the track each Blue plane makes of itself (five total).

- *Net type* refers to the two types of networks tested in the air-to-air case study, voice only and Link 16.
- *Time-to-use levels* refers to the two timeliness performance bands used throughout the air-to-air case study. These include the less-than-one-second timeliness band (here referred to as "Targeting") and the one- to ten-second timeliness band (here referred to as "Cue Only").
- *Nodes*, as shown in Figure A.3, refers to the five Blue aircraft (the network "nodes" in this case study), including AWACS and the four Blue fighters.
- *Essential elements of information* (EEIs) refers to the nine unique tracks in the model, including AWACS, the four Blue fighters, and the four Red fighters.
- *Aircraft type* refers to whether an airplane is Red or Blue.
- *Information quality metrics* refers to the four common quality of information metrics used throughout the model (detection completeness, ID correctness, location correctness, and velocity correctness). To simplify the analysis, the Analytica dimension actually contains only two entries: "ID" and "location." This simplification is valid because, as noted in the briefing, detection completeness and ID correctness always have the same value and location correctness and velocity correctness always have the same value.
- *Decision types* refers to the four advanced types of tactical decisions enabled by individual awareness (accelerated engagements, combatant wingman, advance vectoring, and cooperative formations), plus a tactic to represent baseline decisions (those traditionally enabled by voice-only communications networks).

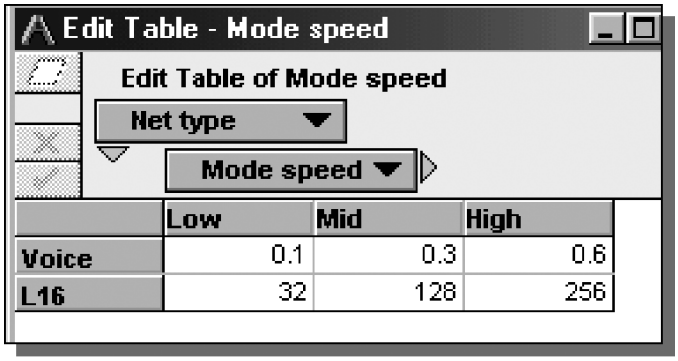
In Analytica, decision and constant nodes allow users to declare arrays of inputs. As suggested by the names, constant nodes allow

users to input an array that remains constant for all experiments in the model and decision nodes allow arrays that represent experimental choices—for example, whether voice-only or Link 16 is chosen.

Figure A.4, for example, shows the input array to the "mode speed" decision node (an input to the quality of service metric node). This is a two-dimensional array, consisting of the net type and mode speed dimensions. The former is one of the common dimensions shown in Figure A.3 and represents the choice between the voice-only and Link 16 architectures. The latter is a self-titled dimension that allows for sensitivity analysis. In this Analytica model, we have three sensitivity analysis settings, "low, mid, and high." The "mid" setting is used to compute the results shown in the paper and is based on real-world times to transmit tracks over voice-only and Link 16 channels. For comparison, the "low" setting describes networks in which the transmission speeds are much slower than in reality, and the "high" setting describes the reverse. The array entries show the number of tracks that can be transmitted per second, given a sensitivity setting and a network type (voice-only or Link 16).

Variable, chance, and objective nodes in Analytica contain a function that computes a new array using arrays from other nodes as

Figure A.4
An Example Input Array



	Low	Mid	High
Voice	0.1	0.3	0.6
L16	32	128	256

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arguments. Each node contains only a single function, resembling a function in a spreadsheet cell. However, the function can be a complicated set of nested conditional expressions, such as those allowed by Excel. There are several major conventions for array functions:

- Formulas use abbreviated notation to describe operations combining arrays, e.g. **Array3** = Op1 (**Array1**, **Array2** . . .).
- Some array operations are written as conventional mathematical expressions—e.g. **Array1***Array2.
- Special operations aggregate a matrix over one of its dimensions—e.g. sum(**Array1**, *index1*) replaces the *index1* dimension entries with the sums of the entries along that dimension.
- From a mathematical perspective, Analytica uses array operations, not matrix operations. Thus, if **Array1** and **Array2** have the same dimensions (and recall, by definition, each dimension has a unique set of entries associated with it), an array operation is performed on each corresponding pair of **Array1** and **Array2** entries—e.g., each entry in **Array1***Array2 is just the pairwise multiplication of the corresponding entries in **Array1** and **Array2**.
- Suppose Array1 and Array2 have different dimensions. Then, when computing the results of matrix operations, Analytica first expands the arrays so that each has the union of dimensions from Array1 and Array2. The expansion involves copying the existing array for each entry along an extra dimension. Thus, if Array1 has three unique dimensions, and Array2 has two unique dimensions, **Array1***Array2 will have five dimensions.

Force

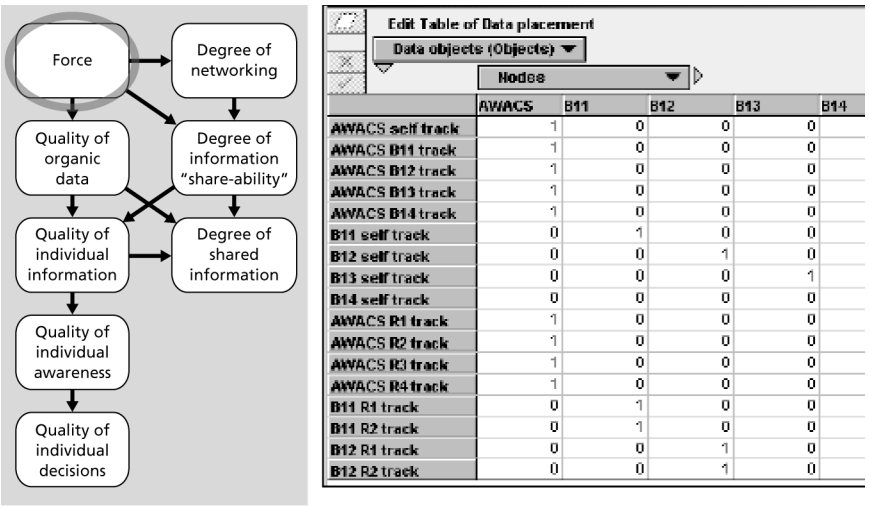
We now consider the specifics of the air-to-air Analytica model, beginning with the force module. This module contains a single node—the data placement constant node. This node is an input array

that indicates which Blue aircraft have which of the 17 sensed tracks in the model. Each sensed track is assigned uniquely to its corresponding Blue aircraft. The node's array has values of one if the corresponding Blue plane senses the track organically, and zero if not. It is used in a variety of the calculations to determine the information organic to each node. Figure A.5 shows the entries of the data placement node for this case study.

Quality of Organic Information

The quality of organic information subnetwork has two nodes, as shown in Figure A.6. Quality of organic data lists the initial quality of each of the seventeen sensed tracks, as measured by whether they fall into the less-than-one-second band or one- to ten-second band. (Information that falls in the less-than-one-second band is also placed

Figure A.5
Data Placement Node (Force Module)



	AWACS	B11	B12	B13	B14
AWACS self track	1	0	0	0	
AWACS B11 track	1	0	0	0	
AWACS B12 track	1	0	0	0	
AWACS B13 track	1	0	0	0	
AWACS B14 track	1	0	0	0	
B11 self track	0	1	0	0	
B12 self track	0	0	1	0	
B13 self track	0	0	0	1	
B14 self track	0	0	0	0	
AWACS R1 track	1	0	0	0	
AWACS R2 track	1	0	0	0	
AWACS R3 track	1	0	0	0	
AWACS R4 track	1	0	0	0	
B11 R1 track	0	1	0	0	
B11 R2 track	0	1	0	0	
B12 R1 track	0	0	1	0	
B12 R2 track	0	0	1	0	

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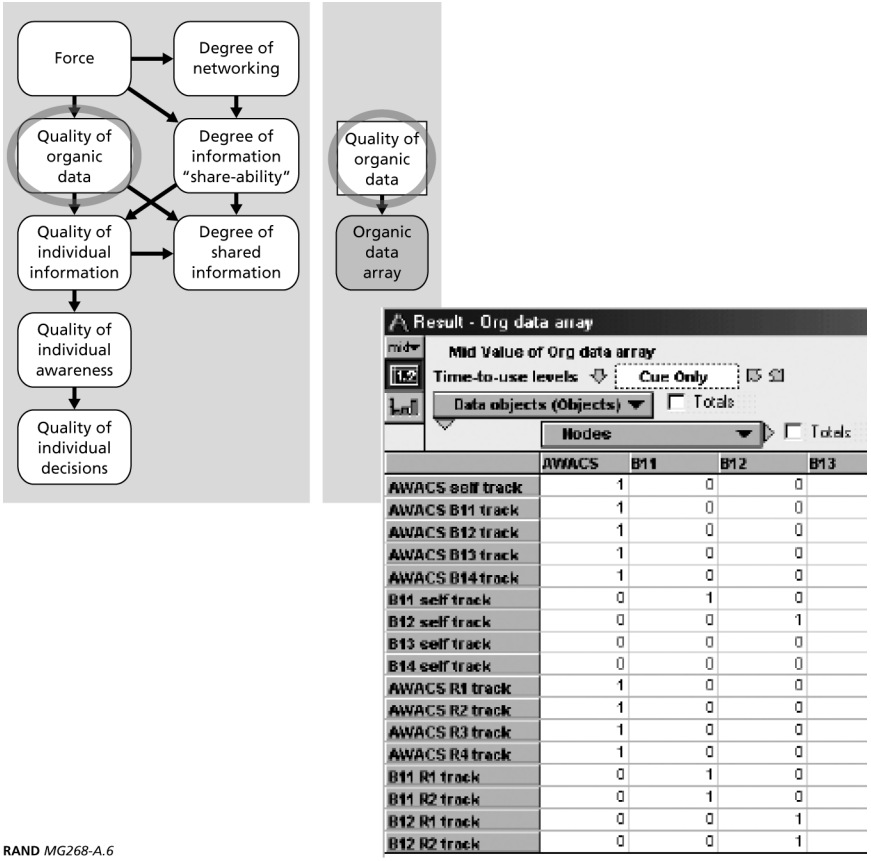
Figure A.6
Quality of Organic Information



	AWACS	B11	B12	B13
AWACS self track	1	0	0	
AWACS B11 track	1	0	0	
AWACS B12 track	1	0	0	
AWACS B13 track	1	0	0	
AWACS B14 track	1	0	0	
B11 self track	0	1	0	
B12 self track	0	0	1	
B13 self track	0	0	0	
B14 self track	0	0	0	
AWACS R1 track	1	0	0	
AWACS R2 track	1	0	0	
AWACS R3 track	1	0	0	
AWACS R4 track	1	0	0	
B11 R1 track	0	1	0	
B11 R2 track	0	1	0	
B12 R1 track	0	0	1	
B12 R2 track	0	0	1	

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in the one- to ten-second band to facilitate later analysis). As previously discussed, the probabilities that tracks fall into timeliness bands are the "premetrics" used in calculating the four quality of information metrics in the air-to-air case study. Thus, we input these probabilities rather than input scores for the four quality of information metrics directly.

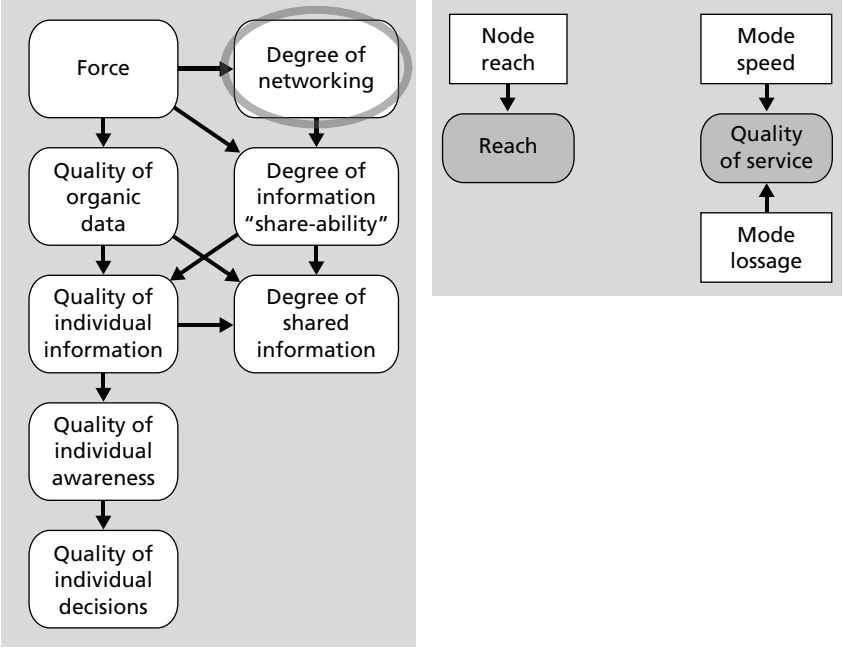
Organic data array, also shown in Figure A.6, adds an extra dimension, showing which nodes have which tracks and to what

timeliness band, organically. This extra dimension is needed for the calculation of the quality of individual information and quality of shared information metrics.

Degree of Networking

The degree of networking module contains five nodes, shown in Figure A.7. Node reach determines whether each node can connect to the "network" via voice-only or Link 16. Reach then uses the node reach and data placement inputs to determine whether each of the 17

Figure A.7
Degree of Networking



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sensed tracks can be posted to the network (either with voice-only or Link 16). In this case study, reach is a placebo, as all Blue aircraft can post to the network, even if via voice-only.

Mode speed determines the rate at each node can transmit sensed tracks via voice-only or Link 16. Three levels of speed for each mode ("low," "mid," "high") are used for sensitivity analysis; the "mid" speeds reflect the actual performance characteristics of voice transmission and Link 16. Mode Lossage is the average amount of data lost in attempting to transmit a track; this is set at 30 percent for voice-only and 0 percent for Link 16. Quality of service then uses the mode speed, mode lossage, and data placement inputs to determine the rate at which each sensed track will be posted and retrieved via voice-only or Link 16. The metric generated by the quality of service node is a three-dimensional array giving the posting-and-retrieval rate (in updates per second) along three dimensions: the sensed track, the network type, and the mode speed.

As noted earlier in this appendix, the Analytica model versions of reach and quality of service are a bit different than what was shown in the main body in the report. The metrics in the report directly represented the technical characteristics of the voice-only and Link 16 networks—these become the node reach, mode lossage, and mode speed input nodes in the Analytica Model. In the Analytica model, reach and quality of service actually calculate "premetrics" needed by degree of information share-ability, calculating whether each of the 17 sensed tracks can be posted to and retrieved from the network (reach) and the rate at which posting and retrieving occurs (quality of service).

Degree of Information "Share-Ability"

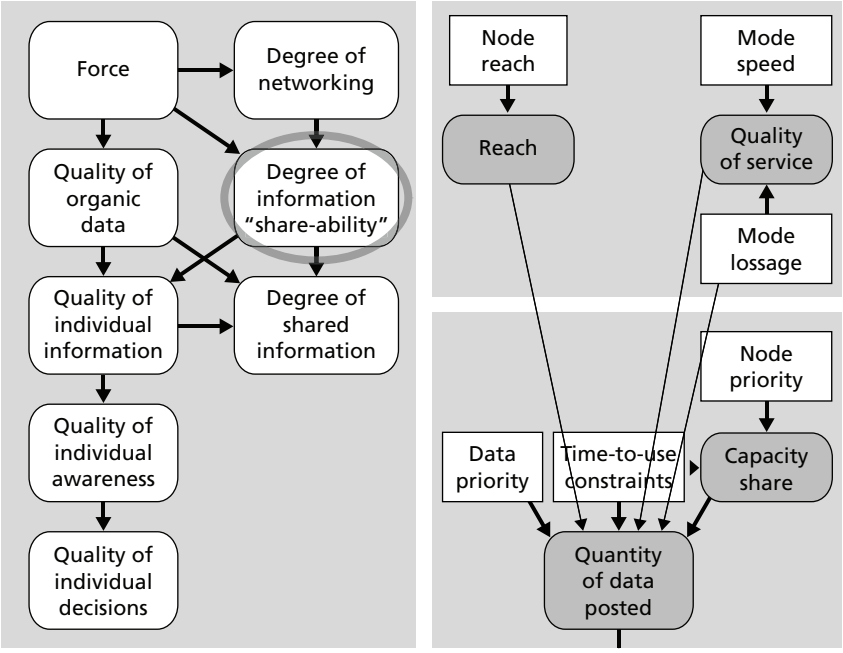
The degree of information share-ability subnetwork has two major submetrics that were used in the case study: quantity of data posted

and quantity of data retrieved. Figure A.8 describes the subtree computing quantity of data posted.

The metric node ("quantity of data posted") depends on the following input nodes:

- Reach determines whether each node can connect to the "network" via voice-only or Link 16.
- Quality of service determines the rate at which sensed tracks will be posted and retrieved via voice-only or Link 16. Because in this case we are only interested in the rate at which sensed tracks will be posted, we subtract the mode lossage input. Mode lossage only applies to retrieved information.

Figure A.8
Quantity of Data Posted



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- Node priority describes the percentage of the network's bandwidth (voice-only or Link 16) dedicated to each of the five Blue planes (nodes). In this model, we assume that AWACS has half the available bandwidth, and each of the four fighters has one-eighth of the bandwidth apiece.
- Capacity share is similar to node priority but with the percentage of bandwidth mapped to each of the 17 sensed tracks. The latter is an intermediate node needed to calculate the quantity of data posted; it does not add any new information to the model.
- Data priority lists the percentage of a node's allocated bandwidth devoted to updating each sensed track. In this model, Red tracks are assumed to have twice the allocation of Blue tracks. Within Red and Blue categories, each track gets equal allocation.
- Time-to-use constraints defines the maximum time allowed to transmit a track update in order for the update to quality for a certain timeliness performance band less than one second or one to ten seconds). Consistent with the bands, the maximum times are one second and ten seconds, respectively.

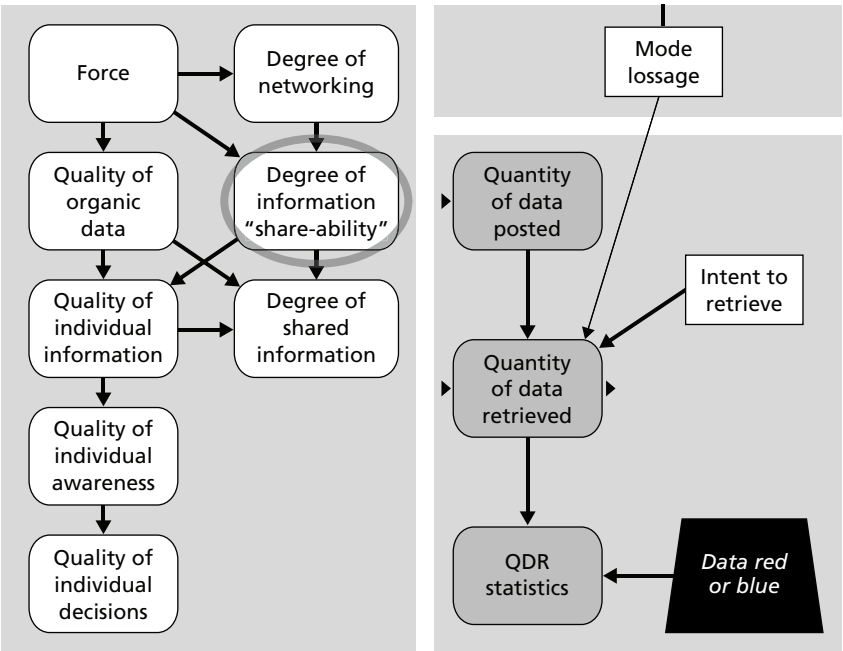
Quantity of data posted then computes the total expected fraction of sensed track updates that will be transmitted within the time-to-use levels. The final output of the computation is a four dimensional array that, given a sensed track, a type of network, a posting rate within that network type, and a timeliness performance band, gives the probability that the sensed track has been posted to the network within the specified timeliness band.

Figure A.9 describes the subtree used to calculate quantity of data retrieved.

This metric is a function of quantity of data posted plus several other nodes, including the following:

- Mode lossage is added back as an input. It lists the probability that a Blue aircraft received the sensed track update correctly,

Figure A.9
Quantity of Data Retrieved



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assuming it was properly posted to the network. As in the briefing, this probability is 100 percent for Link 16 and 70 percent for voice-only.

- Intent to retrieve lists the probability that the Blue aircraft does, in fact, attempt to retrieve the sensed track update. This is a placebo in the current case study because all planes are listening continually to the same voice channel (and receiving track data on the same Link 16 subnetwork, if applicable).

Quantity of data retrieved then computes a five-dimensional array, each entry of which describes the probability that a Blue aircraft has received one of the 17 tracks correctly within the most recent time-to-use constraint (less than one second or one to ten sec-

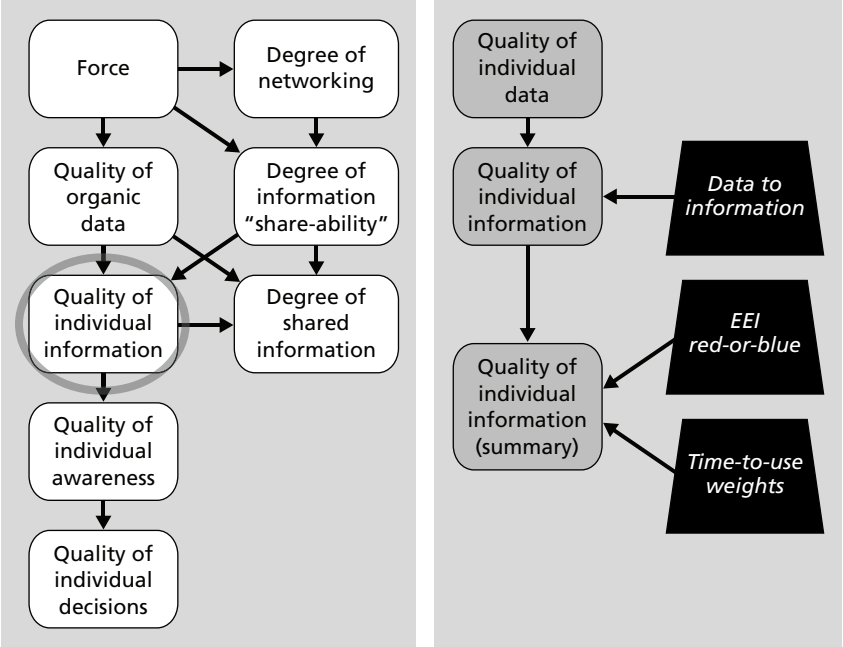
onds), given a type of installed network (voice-only or Link 16) and mode speed (low, medium, or high).

Quantity of data retrieved then provides input to quantity of data retrieved statistics, which computes the aggregate statistics seen on the figures. Note that quantity of data retrieved statistics do not provide inputs to other nodes.

Quality of Individual Information

Figure A.10 describes the subtree for quality of individual information.

Figure A.10
Quality of Individual Information



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The first node, quality of individual data, computes the total likelihood that a node (one of the Blue aircraft) has received one of the 17 sensed tracks within the less-than-one-second or one- to ten-second timeliness bands, either organically (from quality of organic data) or retrieved from the network (from quantity of retrieved data, either via voice-only or Link 16). It assumes the implicit fusion of organic network and network data sources. However, from our knowledge of the data networks and information requirements in question, this is a reasonable assumption for this case study.

Recall that 17 sensed tracks are in the model, but only nine unique tracks (the five Blue aircraft and the four Red aircraft) because several aircraft are tracked multiple times. These nine tracks are the EEIs for this report. The quality of individual information node calculates a five-dimensional array, with each entry giving the overall probability that a Blue aircraft has received a unique track in a particular timeliness band, by receiving at least one of the corresponding sensed tracks, given a particular network type and mode speed. The data-to-information constant aids this calculation by mapping each unique track to a corresponding sensed tracks. Figure A.11 provides a screenshot of a quality of individual information array, for the one- to ten-second timeliness band, voice-only, and medium-speed network.

The quality of individual information node assumes the implicit fusion of all the sensed tracks pertaining to the same unique track. This is a reasonable assumption because a single track on an airplane can provide all the required information. Note that we also assume that no difficulties crop up in converting this information into individual awareness. For example, we assume that pilots can distinguish between two tracks for one entity and tracks for multiple entities based on standard procedures, etc. For voice networks, pilots report giving first precedence to organically sensed tracks, then turn to voice-reported tracks. For Link 16 networks, Blue tracks are fused, and tracks of the same plane detected via F-15 radars will be superimposed. AWACS tracks, on a ten-second delay by definition, appear

Figure A.11
A Quality of Individual Information Array

Result - Quality of individual info

mid

Mid Value of Quality of individual info

Net type: Voice

Time-to-use levels: Cue Only

Mode speed: Mid

EEIs — Totals

Nodes — Totals

	AWACS	B11	B12	B13	B14
AWACS track	1	0.08077	0.08077	0.08077	0.08077
B11 track	1	1	0.129	0.129	0.129
B12 track	1	0.129	1	0.129	0.129
B13 track	1	0.3221	0.3221	1	0.3221
B14 track	1	0.3221	0.3221	0.3221	1
R1 track	1	1	1	0.3284	0.3284
R2 track	1	1	1	0.3284	0.3284
R3 track	1	0.1615	0.1615	0.1615	0.1615
R4 track	1	0.1615	0.1615	0.1615	0.1615

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as a different symbol, which pilots ignore if the AWACS-tracked planes are detected with an F-15 radar.

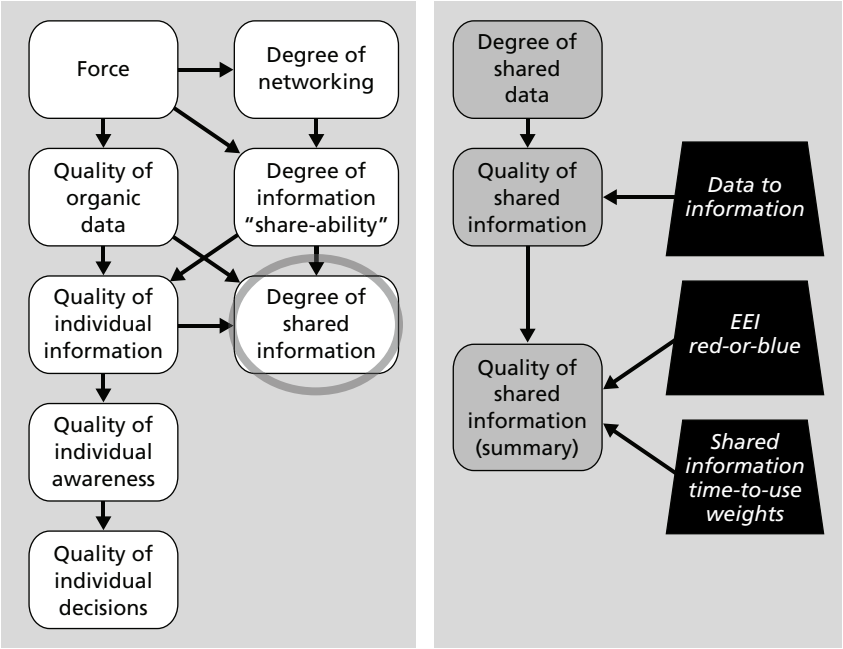
Quality of individual information summary converts quality of individual information's track receipt probabilities into the four quality of information metrics scores and then aggregates these scores into reflections of what each node receives on the Blue airplanes and Red airplanes as a whole. EEI-Red-or-Blue assists with the aggregation by declaring whether particular aircraft are Red or Blue. Time-to-use weights assists with the calculation by declaring the relative value of received tracks in the less-than-one-second band and one- to ten-second band for each of the four quality of information metrics. (Currently, information in the one- to ten-second band is declared to

have 25 percent of the value of information in the less-than-one-second band for the location and velocity correctness scores.)

Degree of Shared Information

Figure A.12 describes the subtree generating quality of shared information. In this report, we are interested in comparing what tracks can be shared over the voice-only and Link 16 networks, so we define "shared information" to be "information transmitted over the network (voice-only or Link 16)." Thus, the degree of shared information metrics are computed with respect to the organically collected information that could be shared over the network. In comparison,

Figure A.12
Degree of Shared Information



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the quality of individual information metrics were computed with respect to all the relevant information in the battlespace (all nine aircraft tracks, ideally in the less-than-one-second band).

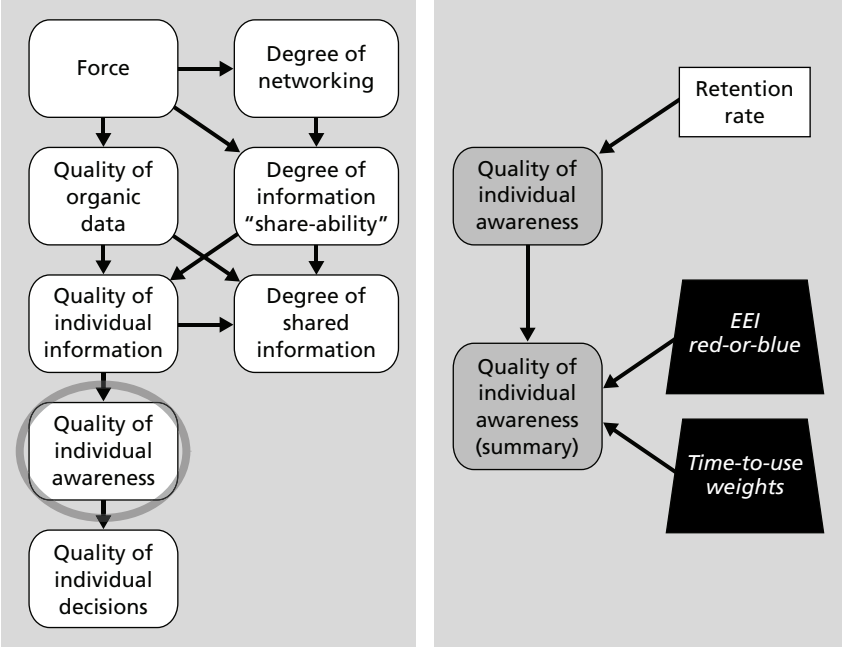
The nodes and node formulas in this subtree closely resemble those for quality of individual information. There are two differences. The first is in the quality of shared data variable; this node strictly computes the likelihood that a node has received one of the 17 sensed tracks within the less-than-one-second or one- to ten-second timeliness bands from the network (voice-only or Link 16), not organically.

The second is the shared information time-to-use weights constant, employed to compute the degree of shared information summary statistics. In comparison to the time-to-use weights constant in individual information, this constant compensates for the fact that some tracks (Red 3 and Red 4) are not tracked within the less-than-one-second timeliness band by any of the Blue planes. The compensated weights avoid mistakenly penalizing the degree of shared information for not sharing real-time information about Red 3 and Red 4 that does not exist organically.

Quality of Individual Awareness

Figure A.13 describes the subtree used to calculate quality of individual awareness. The first node, so named, models awareness by computing the likelihood that a particular pilot "remembers" a particular EEI based on previous updates. We assume a 50 percent chance of "forgetting" an EEI in each successive ten-second interval from the period when it was first received (the 50 percent is a parameter declared in retention rate). Here, "forgetting" means either that the pilot no longer remembers the update or that the tracked plane has moved far enough that the update is no longer valid. This "memory" model of awareness only applies to information items in the one- to ten-second band that are used for cuing purposes. It does not apply to

Figure A.13
Quality of Individual Awareness



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information items in the less-than-one-second timeliness band. (However, recall that, when a less-than-one-second track is received, it is modeled in both the less-than-one-second band and the one- to ten-second band). Information in the less-than-one-second timeliness bank is used for precision maneuver and targeting and must be updated constantly.

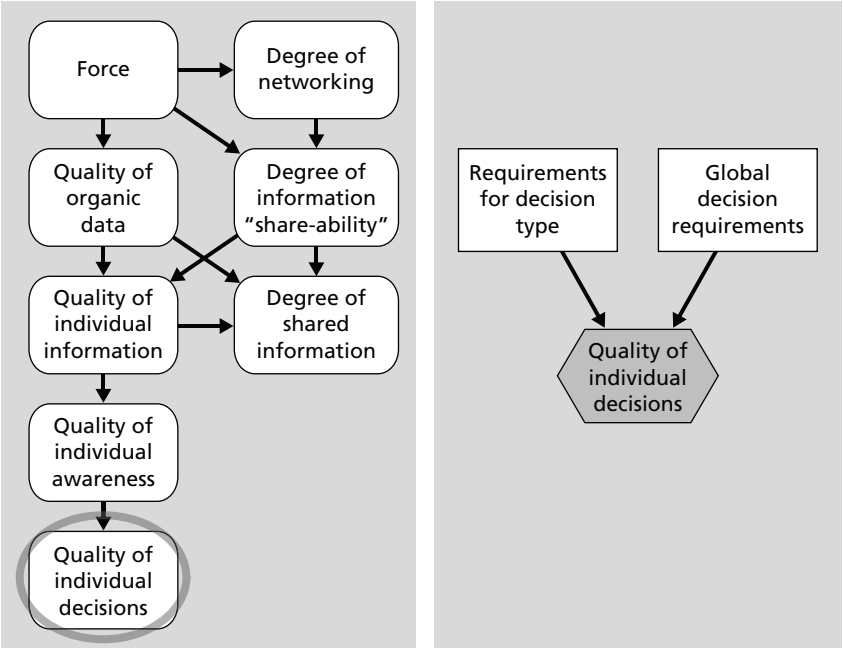
The node quality of individual awareness summary computes aggregate quality of awareness metrics. It is identical in nature to the previously discussed quality of individual information summary node.

Quality of Individual Decisionmaking

Finally, Figure A.14 describes the subtree used to calculate quality of individual decisionmaking, the penultimate metric in the air-to-air case study. (Recall that force effectiveness metrics come directly from the JTIDS Operational Special Project study.) The self-named node computes an array listing whether the quality of individual awareness is sufficient to use each of the four advanced tactics previously discussed in this report.

The two decision nodes declare the awareness requirements needed to use air-to-air tactics effectively. "Requirements for decision types" declares which EEIs need to be "known" and what timeliness

Figure A.14
Quality of Individual Decisions



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bands (less than one second or one to ten seconds) are needed to support improved tactics execution, in accordance with the requirements shown in Table 10.1. "Global decision requirements" sets the likelihood of awareness required for the EEI to be "known;" by default, this parameter is set at 90 percent. The quality of individual decisionmaking then computes an array of "1s" and "0s" by performing checks to see whether all the awareness conditions for a Blue aircraft to run an advanced tactic have been met.

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