



**NETWARS BASED STUDY OF A
JOINT STARS LINK-16 NETWORK**

THESIS

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AFIT/GCS/ENG/04-06

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Abstract

Both secure and anti-jam resistant, the Link-16 is the primary communications channel used by the Joint Surveillance Target Attack Radar System (Joint STARS) for the exchange of real-time tactical data among various ground, air, and sea platforms of the United States of America and North Atlantic Treaty Organization forces. This research explored the effect of increasing network traffic for imagery transfer to the mean delay when operating under different network topologies. Using Network Warfare Simulation (NETWARS), three different missions were simulated to run on five network topologies having a different number of participants, different assigned time slots, and stacked nets. As a result, this study determined that the Link-16 network is able to handle the increase in network traffic, from 30 kilobits per second to 50 kilobits per second, when using multiple stacked net configurations while assigning an adequate number of time slots. However, because each participant is limited to 128 time slots per second, the increased network traffic limits the communication ability of other participants.

NETWARS BASED STUDY OF A JOINT STARS LINK-16 NETWORK

I. Introduction

The Link-16 network was developed as a communication system for the exchange of real-time tactical data between aircraft, ships, and ground units to provide decision-makers the information necessary for mission success. Link-16 uses a Time Division Multiple Access (TDMA) protocol that divides time into discrete time slots to provide multiple and apparently simultaneous communication channels. The Link-16 network is limited to 128 time slots per second for transmission and reception. All communication is physically accomplished over a Joint Tactical Information Distribution System (JTIDS) data terminal. This type of network is very difficult to manage due to the static assignment of time slots and as a result, there are numerous Link-16 network designs for specific missions or areas of operation. Because of its static nature, addition of a participant into the mission requires modification and testing of the Link-16 network designs.

The Link-16 is a network of radio terminals using frequency hopping technique that transmits data on the available 51 different frequencies. This technique allows the network to have multiple nets that can be stacked. Using a predetermined pseudo-random pattern, the frequency is changed every 13 microseconds or approximately 600 times during each time slot. There are a total of 128 possible stacked nets numbered 0-127, (each assigned a particular hopping pattern) with the number 127 reserved to indicate a stacked net configuration [Nor94].

While the basic concepts of tactical data exchange served for many years by Link-11 and Link-4A are retained, Link-16 was developed to provide for technical and operational improvements to existing tactical data link capabilities. Because the Link-16 is not a replacement, interoperability with older links was maintained. The significant improvements, discussed further in Chapter 2, made to the Link-16 are: nodelessness, jam resistance, flexibility of communication operations, separate transmission and data security, increased number of participants, increased data capacity, network navigation features, and secure voice [Nor94].

The overall research goal is to study the effect of increasing the data transfer requirements on the Link-16 network. For example, how well can the Joint Surveillance Target Attack Radar System (Joint STARS) support transmitting images to fighters, Air Operations Centers, or other units.

This chapter provides a basic introduction and the overall research goal. Chapter II provides the background information on the Joint STARS Link-16 communication element to include Global Information Grid, Global Grid, force template concept, Link-16, Information Exchange Requirements, and doctrines. Chapter III includes the methodology this research used. Chapter IV contains the results of NETWARS simulations of the Link-16 network. Chapter V discusses research findings and future work.

II. Literature Review

2.1 Introduction

This chapter provides background on a NETWARS-based study of the Joint STARS Link-16 communication element. First, the Global Information Grid is defined. Then, a brief discussion of the Global Grid is presented as well as its seven-layer reference model. The concept of force templates is discussed followed by a description of Joint STARS and its capabilities and communications channels. Some features of Link-16, its hardware architecture and protocol are presented. Background about Information Exchange Requirements and how they are developed is discussed. Finally, the purpose of doctrines and the responsibilities of the Joint Forces Commander's Staff during a conflict is explored.

2.2 Global Information Grid

The Global Information Grid (GIG) is a globally interconnected, end-to-end set of information capabilities, associated processes, and personnel for collecting, processing, storing, disseminating, and managing information on demand to warfighters, policy makers, and support personnel. The GIG consists of all owned and leased communications and computing systems and services, software (including applications), data, security services, and other associated services necessary to achieve Information Superiority. It includes the National Security Systems (NSS) as defined in section 5142 of the Clinger-Cohen Act of 1996. The GIG supports all Department of Defense (DoD), National Security, and related Intelligence Community missions and functions (strategic, operational, tactical, and business) in war and in peace. It provides capabilities from all

operating locations (bases, posts, camps, stations, facilities, mobile platforms, and deployed sites) and interfaces to coalition, allied, and non-DoD users and systems [CRD01].

2.3 Global Grid

This section examines the Global Grid (GG), the communications infrastructure of the Global Information Grid [Whi01]. The seven-layer reference model consisting of Mission, Application, Service, Transport, Network, Link, and Physical Layers is also introduced.

The GG Reference Model is shown in Figure 1. The layered model provides a framework for all the communications-related functions and protocols, and facilitates communication upgrades as technology advances. The model is based upon the OSI and TCP/IP models but has some features that emphasize military communications.

Listed below are GG Reference Model Layer Definitions:

1. Mission Layer – The mission layer provides the specific aggregation of applications from the Application Layer necessary to perform a particular military mission. This layer was added to emphasize the concern for assuring uniquely military capabilities are provided to the warfighter. For example, most commercial Internet technology can be used in the GG but it has not yet solved all of the military's management, security, and mobile routing protocol needs. The GG incorporates this layer which has no corresponding layer in the other two models.

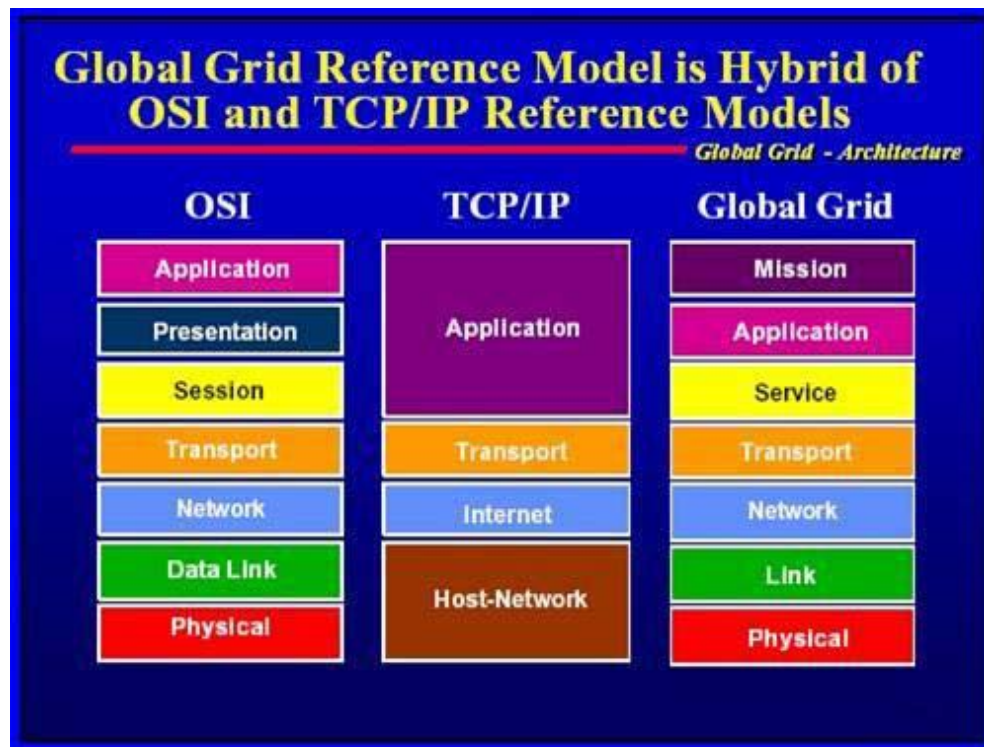


Figure 1. Global Grid Reference Model [Whi01]

2. Application Layer – This layer provides common and mission-specific applications that are employed as utilities by users or other programs at the Mission Layer. Applications are directly accessible by a user at this layer.
3. Service Layer – The service layer resolves differences in data format among applications and provides a control structure for connections and dialogues between applications. Applications are not directly accessible by a user at this layer.
4. Transport Layer – This layer provides reliable end-to-end data transfer, flow control, error recovery, and may include quality of service capabilities or the ability to optimize network resources.

5. Network Layer – The network layer consists of Internetwork and Subnetwork sublayers that transfer data across a network of networks or within a network respectively. This layer is the same as the OSI reference model layer of the same name and includes addressing, congestion control, and associated usage accounting functions.
6. Link Layer – This layer provides point-to-point data transfer.
7. Physical Layer – This layer is partitioned into five sublayers.
 - 7.1 Baseband Processing – This sublayer organizes/transmits/receives channel symbols at appropriate rates and converts between digital and analog signal representations.
 - 7.2 Baseband-Intermediate Frequency (IF) Processing – This sublayer performs frequency translation and analog processing.
 - 7.3 IF Processing – This sublayer performs filtering and amplification.
 - 7.4 IF-Radio Frequency (RF) Processing – This sublayer performs frequency translation and analog processing from IF to RF.
 - 7.5 RF Processing – This sublayer performs filtering, amplification, and transduction (conversion to signal) with the physical media.

The GG is a military internet with a military objective to provide total global connectivity for all information sources and information users. The idealized vision, Figure 2, for the GG is a “publish and subscribe”, “plug and play” network, in which any application can be plugged into the network anywhere, at any time, to help achieve warfighting objectives.

2.4 Force Template Concepts

A force template is an electronic description of an entity that enables it to be integrated into the Joint Battlespace Infosphere (JBI) with all the entities of its subcomponents [Mar02]. This section discusses why force templates are needed, how they model coalition units, and what information they provide to the JBI.

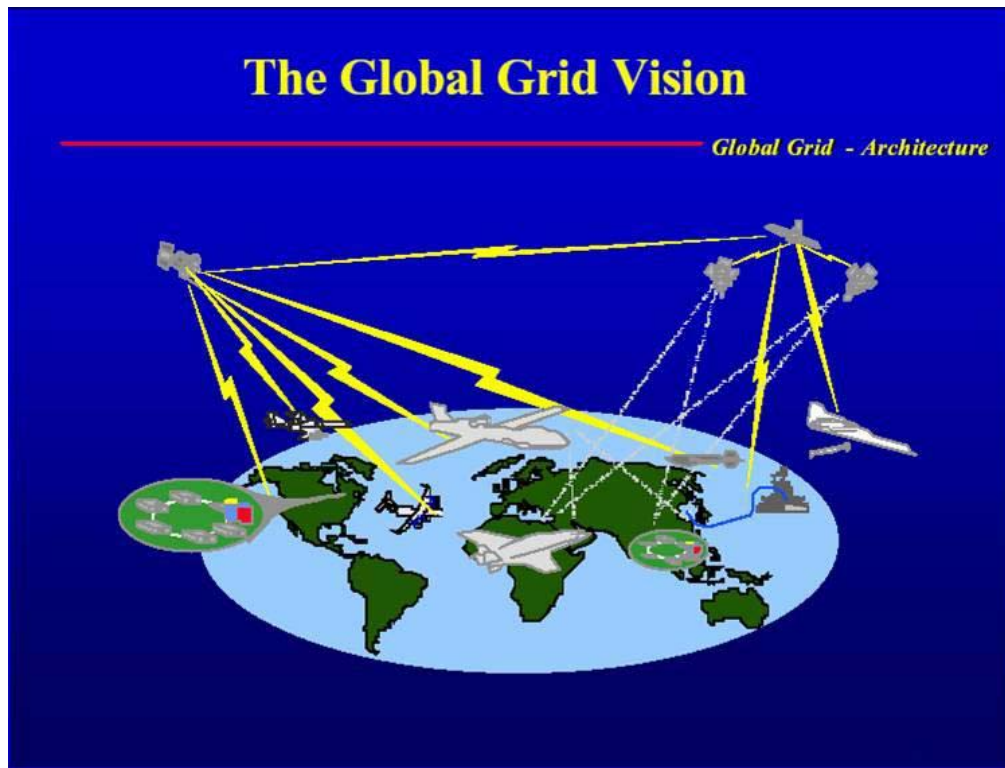


Figure 2. The Global Grid Vision [Whi01]

JBI provides the platform for information transfer while force templates contain information that enables operational entities within the battlespace (and their clients) to quickly interact with the JBI. In addition, a force template includes the context and policy that define an entity's contact with the JBI. Without the force template mechanism, it becomes extremely difficult to track and manage changes to JBI content resulting from the arrival and departure of coalition units.

An entity is an organization that decomposes into multiple components.

Components may be other entities (child entities) or clients. Entities typically correspond to operational military units and the organization that supports them. Both parent and child entities may each have their own force templates. These force templates may be separate, but linked based on their relationship. The level at which a force template is required reflects the modularity of the force (e.g., the level at which forces can be mixed, matched or tasked). Clients are owned by entities and correspond to specific individuals, systems, applications, repositories, or platforms. For example, an F-15 client may be owned by a fighter squadron entity. A client interfaces directly with the JBI on behalf of its owner. Unlike entities, clients do not connect to the JBI platform. Entities at any level may own a distinct set of clients [Mar02].

Three categories characterize the content of a force template: necessary, desired, and speculative. These categories are briefly described below [Mar02]:

1. Necessary Contents:
 - a. Information needed by the entity – information an entity needs to function within the theater.
 - b. Information provided by the entity – information an entity can provide within the theater.
 - c. The constraints associated with the above – examples are quality of service, pedigree, preferred sources, and required delivery windows.
 - d. Security Information – identity and security credentials for individuals occupying key unit positions. Public keys for specific clients (individuals,

platforms, or systems). Dissemination limitations on published information.

2. Desired Contents:

- a. Information Pedigree – indicators of the quality, reliability, and integrity of entity publications.
- b. Entity Description – the characteristics of the entity interfacing with the JBI. It also includes the child entities that compose the entity.
- c. Fuselets – are associated with either publications or subscriptions, i.e., XSLT, Excel spreadsheets, Active-X components, or Java beans. Fuselets are associated with specific publications within the JBI (but not necessarily by the providing entity). Fuselets are highly trusted, lightweight programs that helps accomplish transformations of sensitive data into a releasable form.

3. Speculative Contents:

- a. Ontologies and Ontology Mappings – Ontologies are the consistent set of terms that must be used to facilitate the information in order to achieve a successful coalition operation [AnB01]. As a result, it is essential to include ontologies specific to an entity, system, or related domain. These ontologies should come with mappings to common ontologies used within the JBI.
- b. Process Models, Rules, and Constraints – are items that describe how the entity does business (business rules) in the theater of operations.

- c. Available Services, or Agents – describes services provided by the entity for use by other (appropriate) JBI entities. For example, computation of look angles for satellites, requests for surveillance of certain areas, and agent services to determine unit personnel location and status.

2.5 Joint STARS

The Joint Surveillance Target Attack Radar System (Joint STARS) [Pik99] is a long-range, air-to-ground surveillance system designed to detect, locate, classify, and track ground targets in all weather conditions. The airborne platform of the Joint STARS is installed on an E-8 aircraft, a modified Boeing 707, with multi-mode radar system. The aircraft carries a phased-array radar antenna in a 26-foot canoe-shaped radome under the forward part of the fuselage.

The aircraft has a service ceiling of 42,000 feet and can fly non-stop for 11 hours (20 hours with in-flight refueling). The antenna is a multi-mode radar system capable of operating in the following modes: wide-area surveillance, fixed target indication, synthetic aperture radar, moving target indicator, and target classification.

The communications subsystem of the Joint STARS is composed of:

Digital Data Links:

- Surveillance and control data link (SCDL) for transmission to mobile ground stations
- Joint Tactical Information Distribution System (JTIDS) for Tactical Air Navigation operation and Tactical Data Information Link-J (TADIL-J) generation and processing

- Satellite communications link

Voice Communication:

- Twelve encrypted UHF radios
- Two encrypted HF radios
- Three encrypted VHF radios with provision for Single Channel Ground and Airborne Radio System
- Multiple intercom nets

2.6 Link-16 Data Link

Link-16 is the designation of a particular tactical data link used to exchange real-time tactical data among units of the force. Link-16 uses the Joint Tactical Information Distribution System (JTIDS) data terminal. JTIDS is a communications component of the Link-16. The JTIDS component includes the Class 2 terminal software, hardware, RF equipments, and the high-capacity, secure, anti-jam waveform that they generate [Nor94]. This section discusses some of the features of the Link-16 and its hardware architecture. Finally, it provides a description of the Link-16 protocol.

2.6.1 Link-16 Features

Link-16 has four features, nodelessness, security, network participation groups, and stacked nets [Nor94]. Each of these features is discussed below.

2.6.1.1 Nodelessness

A node is defined as a unit required to maintain communications. Unlike many networks, there are no “nodes” in Link-16. One example of a node is a hub in a local area network. Given the a hub is required to maintain communications, when it goes

down, the communication link goes down. Since time slots in a Link-16 network are preassigned to each network participant, the link functions regardless of the status of any particular unit, which makes them independent from the other participants. The closest thing to a node in Link-16 is the Net Time Reference (NTR). An NTR is needed to start the network, for new units to synchronize with, and to enter the network. After a network has been established, Link-16 can continue to operate for hours without an NTR [Nor94].

2.6.1.2 Security

Both messages (bits) and transmissions (waveforms) are encrypted in Link-16. Messages are encrypted by a KGV-8B encryption device in accordance with a specified cryptovariable, i.e. key. Transmission security (TSEC) is provided by another cryptovariable that determines JTIDS waveform specifics. The waveform uses frequency hopping with a hop pattern determined by the net number and the TSEC cryptovariable. Due to the constant relocation of the carrier frequency across the frequency spectrum, it is difficult to detect and difficult to jam.

The TSEC cryptovariable also determines the amount of jitter in a signal. Jitter is the delay, or dead time, that occurs at the beginning of each time slot where no pulse energy is transmitted. Varying the amount of jitter from time slot to time slot makes it difficult for a jammer to know when to turn on the jamming signal [Nor94].

The pseudorandom noise (PN) determined by the TSEC cryptovariable increases the TSEC of the JTIDS signal. This is accomplished by performing an exclusive-or operation (XOR) on 32 message bits with the 32-chip PN sequence of ones and zeroes.

As a result, the transmitted data appears like incoherent noise to an unintended receiver [Nor94].

2.6.1.3 Network Participation Groups

JTIDS time slots can be allocated to one or more Network Participation Group (NPG). An NPG is a functional grouping of Link-16 messages that support a particular type of mission. The division of a net into functional groups allows JTIDS units to only participate in NPGs needed for functions which they perform [Nor94].

2.6.1.4 Stacked Nets

Time slots may be used for more than one net by assigning a different frequency-hopping pattern to each. Stacked nets (Figure 3) are nets which have the same TSEC and MSEC cryptovariables but different net numbers. For each time slot of a Link-16, a JTIDS Unit (JU) is either transmitting or receiving on one net. To use the stacked net structure, each net participant must be mutually exclusive. Stacked nets are very useful for air control purposes with mutually exclusive sets of controlling units and controlled aircraft. Stacked nets are also useful for voice communications, providing a potential for 127 different voice circuits for each of the two voice NPGs [Nor94].

2.6.2 Hardware Architecture

This section discusses the basic equipment required in the Link-16 architecture. Link-16 equipment is composed of the JTIDS terminal hardware and Tactical Digital Information Link-J (TADIL-J) database. The following paragraphs provide a brief description of each.

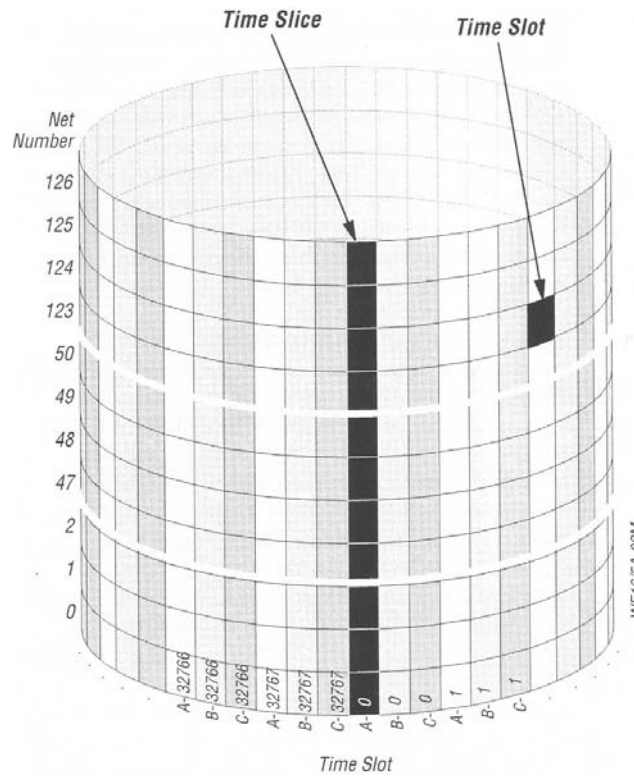


Figure 3. Stacked Nets [Nor94]

2.6.2.1 JTIDS Class II Terminal

This hardware component provides interoperability between units for both hardware and software compatibility. Terminal configurations vary in the number and type of Weapon Replaceable Assemblies (WRA) for specific platforms [Nor94]. Listed below are the principal WRAs and their function:

1. Digital Data Processor (DDP) – This unit performs most message formatting and Time Division Multiple Access management functions. In addition, Error Detection and Correction coding is performed here.
2. Interface Unit (IU) – Provides input and output functions necessary to adapt the DDP to a specific platform.

3. Secure Data Unit – A removable assembly mounted on the IU that contains the cryptovariables required to provide both message and transmission security for all terminal functions.
4. Receiver/Transmitter – This unit, under control of the DDP, creates the outgoing RF stream of pulses. It has a 200-watt transmitter that transmits on 51 different frequencies on a pseudo random hopping basis.
5. High Power Amplifier – Used to boost the power of transmissions on all shipboard terminals and E-2Cs.
6. Antennas – Each JTIDS platform has at least two antennas. The JTIDS terminal chooses the antenna providing the best Signal-to-Noise Ratio (SNR) for reception.
7. Notch Filter Assembly – An RF filter consisting of a dual-notch band-pass filter and a circulator. Not installed on all platforms.
8. MIDS – The reduced volume version of the JTIDS terminal. MIDS terminals are waveform compatible and interoperable with the JTIDS terminals.

2.6.2.2 TADIL-J

The Tactical Digital Information Link-J (TADIL-J) database provides a common standard for various platform host computers to communicate. The database is composed of a set of J series messages that support all battle group information exchange requirements. Each of the J series messages is composed of TADIL-J words and are mapped to a functional virtual circuit it supports. These virtual circuits are the Network Participation Groups -- the building blocks of the network [Nor94].

2.6.3 Time Division Multiple Access Protocol

Link-16 uses a Time Division Multiple Access (TDMA) protocol that divides time in discrete time slots to provide multiple and apparently simultaneous communications circuits. Each of the users or terminals take turns transmitting. Each user gets multiple transmit opportunities (time slots) per frame. Below is a brief discussion of frame and time slots.

2.6.3.1 Frame

A frame is the basic unit of time in Link-16. In Link-16, each 24-hour day is divided into 12-minute and 48-second intervals called epochs; there are 112.5 epochs per day. A frame is 12 seconds in duration and is composed of 1536 individual access/transmit units called time slots which are 7.8125 milliseconds in duration [Nor94].

2.6.3.2 Time Slot

A time slot is the basic unit of access in a JTIDS network. Each platform operating in the Link-16 network is assigned to either transmit or receive in one of 1536 available time slots. Epoch time slots are grouped into sets, named A, B, and C. As shown in Figure 3, each set contains 32,768 time slots numbered from 0 to 32,767 which is called the Slot Index. The time slots of each set are interlaced, or interleaved, with those of other sets in the following repetitive sequence [Nor94]:

A-0, B-0, C-0,
A-1, B-1, C-1,
A-2, B-2, C-2
•
•
•
A-32767, B-32767, C-32767

The above sequence repeats for each epoch.

2.6.4 Transmission Access Modes

There are currently three types of access modes for Link-16: dedicated, contention, and time slot reallocation access. Dedicated and contention access modes are currently in use, while time slot reallocation access is in development.

Dedicated access is the assignment of time slots to a uniquely identified unit for transmission purposes. Only the assigned JTIDS Unit (JU) can transmit during that time slot. Therefore, a slot is unused if the JU does not have any data to transmit. The advantage of dedicated access is that it provides each JU on an NPG with a predetermined portion of the network's capacity and guarantee that there is no transmission conflicts in a single-net environment. However, assets using this access mode are not interchangeable. For example, one aircraft cannot simply replace another aircraft. If it is necessary for this replacement to take place during an operation, the terminal must be reinitialized to transmit and receive during time slots matching those of the unit it would be replacing [Nor94].

Contention access is the assignment of time slots to a group of units as a pool for transmission purposes. In this mode, each unit randomly selects a transmission time slot from the pool. The frequency of a terminal's transmission depends on the access rate assigned to that terminal. The advantage of contention access is that each terminal is given the same initialization parameters for the time slot block. This simplifies network design and reduces the network management burden. Since JUs are not assigned a specific time slot, JUs are interchangeable. This allows the inclusion of new participants and allows units to be easily replaced. This feature is particularly important for aircraft,

and the U.S. Air Force uses contention access routinely. One disadvantage of contention access is that there is no guarantee that a transmission is received [Nor94].

Time slot reallocation (TSR) is an access mode which allows the network capacity of NPG to be assigned dynamically based on the projected needs of its participants. TSR allows network capacity to be distributed where it is needed, as it is needed, by periodically allocating time slots from a pool to each participant. Each unit reports its transmission requirements over the network and algorithms within the terminal redistribute the pool of time slots to meet them. If the requirement exceeds the available capacity, time slots are redistributed to participating units in proportion to their requirements so that there is a graceful degradation of the link. TSR can eliminate the need for the design option files currently used to reallocate NPG capacity at initialization time [Nor94].

2.7 Information Exchange Requirements

Information exchange requirements (IER) describe the information passed between and among forces, organizations, or administrative structures. IERs identify who exchanges what information with whom, as well as, why the information is needed and how it is used. The quality (i.e., frequency, timeliness, security) and quantity (i.e., volume, speed, and type of information such as data, voice, and video) are attributes of the information exchange included in the information exchange requirement [CJC01a].

Essentially, an IER is a detailed description of the operational architecture (or business process) for a mission or function. An operational architecture is the structure of components, their relationships, and the principles and guidelines governing their

design and evolution over time. The fields of an IER are shown in Table 1 and briefly described below.

1. Rationale/Universal Joint Task List (UJTL) – Select the most appropriate task from the UJTL or Service/Joint Mission Essential Task List.
2. Event/Action – List all events in the Mission Assessment Process that requires information to be exchanged from a sender and receiver. Events are specific trigger for a specific IER. For example, if the activity is “Launch missile,” launching a missile would trigger a number of IERs. Therefore, activities must be broken down into individual, sequenced events to correctly identify the IERs that those events triggered.
3. Information Characterization – Define, in enough detail for system engineering developers and testers, the general description of the information, how and what it is used for, and the detailed information elements supporting the exchange of information.
4. Sending Node – List all senders associated with the events mapped in the Mission Assessment Process. Use general descriptions of the sender, such as fighter aircraft instead of F-16.
5. Receiving Node – List all receivers associated with the events mapped in the Mission Assessment Process. Use general descriptions of the receiver, such as fighter aircraft instead of F-16.

6. Critical – Criticality is derived from the Cost of Failure analysis in the Concept of Operations.
- 7-9. Attribute Fields – There are 3 required attribute fields – Format, Timeliness, and Classification.
- 10-12. Optional Fields – There are many potential uses for the optional fields such as studies, lessons learned, real world observations, etc., which assist the review and approval process. Linking the IER to other IERs or identifying supporting tasks can also be shown in the optional field. Another very important use of the optional field is to provide any additional information to help developers, testers, and reviewers better understand data contained in the IER.

2.8 Doctrine

There are numerous Joint Doctrines to guide the employment of joint forces [JP01a] [JP02] [JP97]. This section covers the Joint Doctrine for Targeting [JP02]. First, the Doctrine is defined. Then, the purpose of targeting and JFC Staff responsibilities are described.

As defined by Joint Publication 1-02 [JP01b], fundamental principles that guide the employment of forces of two or more Services is a coordinated action toward a common objective.

Table 1. IER Matrix Format [USJ03]

GRD/ORD Required Fields					
1 Rationale/ UJTL #	2 Event/Action	3 Information Character- ization	4 Sending Node	5 Receiving Node	6 Critical
Set of joint mission tasks from the UJTL for each mission area in the CRD /ORD	Free text: Event or action that requires the information to be exchanged	Pick list and free text: The critical information characteristics that describe what information is being exchanged and how it will be used	Free text: Sending node	Free text: Receiving node	Logical field: Yes or No The criticality assessment of the information being exchanged in relationship to the mission being performed
ORD Required Fields (Fields 10 or more are optional)					
7 Format	8 Timeli ness	9 Classification	10 Optional	11 Optional	12 Optional
Pick list or free text : Description of data type	Numerical Field: Required maximum time from node to node expressed in seconds	Pick list field: Classification of the information	Free text or pick list field: As desired by the originator	Free text or pick list field: As desired by the originator	Free text or pick list field : As desired by the originator

The purpose of targeting is to provide a framework to develop warfighting solutions to meet a joint force commander's (JFC) objectives. Within military operations, targeting is focused on achieving specific effects in support of the JFC's objectives or subordinate component commander's objectives. Targets fall into two broad categories: planned and immediate. Planned targets are those known to exist in an operational area with actions scheduled against them to generate the effects desired to achieve JFC objectives. Immediate targets are those that have been identified too late to be included in the normal targeting process, and therefore have not been scheduled. Immediate targets have two subcategories: unplanned and unanticipated [JP02].

With the advice of subordinate component commanders, JFCs set priorities, provide clear targeting guidance, and determine the weight of effort to be provided to various operations. Subordinate component commanders identify high-value and high-payoff targets for acquisition and attack, employing their forces in accordance with the JFC's guidance to achieve missions and objectives assigned by the JFC. The JFC establishes the joint targeting process within an organizational framework optimized for targeting operations. A primary consideration in this framework is the joint force's ability to coordinate, deconflict, prioritize, synchronize, integrate, and assess joint targeting operations. The JFC is responsible for all aspects of the targeting process, from establishing objectives, coordination and deconfliction between component commanders, through combat assessment [JP02].

The following describes the responsibilities of the JFC Staff [JP02]:

1. Operations Directorate, J-3, assists the JFC in the discharge of assigned responsibility for the direction and control of operations, beginning with initial planning, follow-through, and completion of specific operations. In this capacity, the directorate plans, coordinates, and integrates operations.
2. Intelligence Directorate, J-2, intelligence collection efforts, analysis, validation, and battle damage assessment for all joint operations. In addition, J-2 has critical input to the J-3 and J-5 in the form of an adversaries course of action assessments essential to the joint target prioritization process and identification of high-value/high-payoff targets.

3. Logistics Directorate, J-4, identifies logistic issues unique or specific to targeting. J-4 compares the operational logistic plans to developing target lists to ensure protection of infrastructure and/or supplies required to support current and future operations.
4. Plans Directorate, J-5, when included performs the long-range or future joint targeting planning. Planning is conducted by various organizations in conjunction with J-3.

2.9 Summary

This chapter provides foundational information for a NETWARS-based study of the Joint STARS Link-16 communications element. The Global Information Grid is defined in which one of the components is the Link-16 communications element that plays a role in achieving information superiority. The Global Grid with its Global Grid Reference Model is introduced and how it relates to the OSI and TCP/IP Reference Models. Force template concepts are discussed to explain why force templates are needed, how they model coalition units, and what information they provide to the JBI. The description, capabilities, and communications channel of Joint STARS are also discussed. The features, hardware architecture, and the protocol of the Link-16 communications element are discussed in order to understand its architecture. Information Exchange Requirements is also discussed since this element is the one that generates network traffic in NETWARS. Finally, the discussion of how doctrines are used to guide the employment of joint forces during any contingencies.

III. Methodology

3.1 Problem Definition

A Link-16 network [Nor94] is a Time Division Multiple Access (TDMA) protocol. This protocol divides time into discrete time slots to provide multiple and apparently simultaneous communications circuits. The Link-16 network provides a communication channel for the exchange of, among other things, real-time tactical data among various ground, air, and sea platforms of the U.S. and NATO forces. For example, Joint STARS is a long-range, air-to-ground surveillance system designed to locate, classify, and track ground targets. This aircraft transmits surveillance data to the strike aircraft (fighter or bomber) using the Link-16 network. Due to the importance of the tactical data exchanged in the network, it is imperative that all participating terminals receive and send tactical data in a timely and reliable manner to accomplish the mission. To participate in a Link-16 network, each terminal is assigned one or more time slots to transmit or receive data. Therefore, it is crucial for the Link-16 network managers to assign sufficient capacity to all participating terminals before mission execution. The capacity assigned is dependent upon the product size and update rate that each terminal produces as specified in the IER database [CJC01a]. Although other communication networks exist, the focus of this research is the Link-16 element. While the Link-16 network is capable of data and voice communication, the focus of this study is on data communication.

3.1.1 Goals and Hypothesis

The goal of this research is to study the effects of increasing the data transfer requirements to the Link-16 network. One useful application for an increase in data transfer requirement is for the Joint STARS to transfer captured images securely and reliably to fighters, Air Operations Centers, or other units. It is hypothesized that the Link-16 network is able to handle the additional network load when given a multiple stacked net configuration; however, the capability to communicate with the other participants due to the limited amount of time slots available is decreased.

3.1.2 Approach

To accomplish this goal, an Interdiction Mission [ESC01] is used as the basis for a NETWARS scenario. An interdiction operation is conducted to divert, disrupt, delay, or destroy the enemy's surface military potential before it can be used effectively against friendly forces [JP97]. It is assumed that the Link-16 network is already in operation. For example, a Joint STARS aircraft is in the area of operation broadcasting collected surveillance data to the Link-16 network. Before strike aircraft take-off, mission essential data is pre-loaded according to an Air Tasking Order. Assuming there is no Link-16 network available to the strike aircraft while en route to the area of operations, updates are required when they reach the line of sight range (300 nm) of the operating Link-16 network. Although Link-16 can be received at ranges up to 500 nm with the use of a relay terminal, a normal range of 300 nm is used. As soon as the strike aircraft enter the Link-16 network operating in theater, they receive updated data via the Link-16

network. The strike aircraft also send status updates using the Link-16 network. The real-time tactical data exchanges are measured at this point.

3.2 System Boundaries

As depicted in Figure 4, the System Under Test (SUT) for this study consists of all USAF aircraft involved in an Interdiction Mission exchanging data with the strike aircraft using Link-16. Although other ground elements such as Air Operations Centers or Control and Reporting Centers are involved, only USAF aircraft are used for the simulation scenario. The Component Under Test (CUT) for this study is the Link-16 network element.

The E-3 Sentry is an airborne warning and control system (AWACS) aircraft that provides all-weather surveillance, command, control and communications needed by commanders of U.S., NATO and other allied air defense forces [Air00].

The EC-130E ABCCC is a modified C-130 “Hercules” aircraft that is used as an Airborne Battlefield Command and Control Center (ABCCC). The ABCCC functions as a direct extension of ground-based command and control authorities, with a primary mission of providing flexibility in the overall control of tactical air resources [Fed99].

The RC-135V/W Rivet Joint reconnaissance aircraft supports theater and national level consumers with real-time on-scene intelligence collection, analysis and dissemination capabilities [Air01].

3.3 System Services

The system provides transmission of situational awareness data provided by the Intelligence, Surveillance, and Reconnaissance (ISR) aircraft. Strike aircraft also broadcast their current status using the system. Possible system outcomes include: messages received successfully, messages received in error, and messages not received at all.

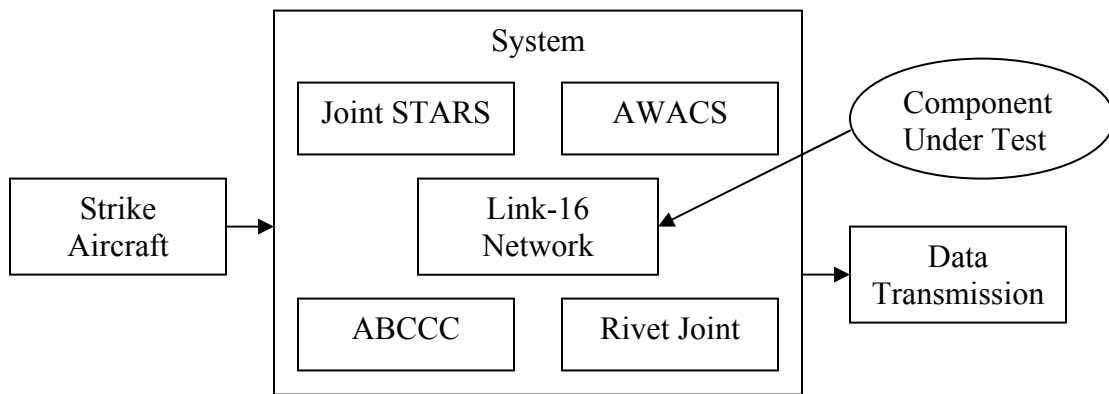


Figure 4. Joint Interdiction Mission

3.4 Performance Metrics

The following metrics are used:

1. Mean Delay – This metric is measured in seconds. This is the elapsed time of message delivery as measured from when a transmitting terminal receives the data to be transmitted and the receiving terminal receives the last bit of the message.
2. Throughput – Throughput is defined as the mean throughput of the Link-16 network and is measured in bits per second.

3.5 Parameters

3.5.1 System

1. Data Packing Option – The data packing option affects how much data is transmitted over the network. Four packing options for JTIDS data are described below [Nor94]:
 - Standard Double Pulse – This data packing option is the most anti-jam resistant and has the lowest throughput. It transmits three words per slot consisting of 70 bits of data per word for a total of 210 bits per slot. Data is sent twice for redundancy. This research only uses this data packing option.
 - Packed-2 Single Pulse – This data packing option transmits six words per slot that also consists of 70 bits of data per word for a total of 420 bits per slot. Data is sent once with this packing option.
 - Packed-2 Double Pulse – This data packing option transmits the same amount of data as the Packed-2 Single Pulse which is 420 bits per slot. The difference between the Packed-2 Single Pulse and the Packed-2 Double Pulse is that data is sent twice for redundancy with this data packing option.
 - Packed-4 Single Pulse – This data packing option has the highest throughput and also the least anti-jam resistance. It transmits twelve words per slot that consists of 70 bits of data per word for a total of 840 bits per slot. Data is sent once with this packing option.

2. Message Type – The message type affects how much data is transmitted over the network. For example, in a fixed-format message, a word consists of 75 bits of which only 70 bits are data. In a free-text message, all 75 bits are data. Only fixed-format message, which is equivalent to 70 bits of data, are used herein [Nor94].
3. Range – This is the line of sight range between aircraft. A normal range is defined as 300 nautical miles. An extended range is defined as 500 nautical miles with the use of relay with other terminals. The normal range was used for this study [Nor94].
4. Network Participation Groups (NPG) – This is a functional grouping according to the type of messages a terminal transmits. For example, NPG-7 is surveillance, messages exchanged on this NPG are: air, surface, and subsurface tracks, land point surface to air missile sites, and reference points [Nor94].
5. Transmission Access Mode – There are three types of access modes for Link-16: dedicated, contention, and time slot reallocation access. The dedicated access mode was used because this is the most common mode used by United States of America and North Atlantic Treaty Organization forces.
6. Stacked Nets – There are 127 possible stacked nets available in a Link-16 network, they are particularly useful for air control purposes and voice communications [Nor94]. The number of stacked nets in operation is used as a factor.

3.5.2 Workload

1. Terminals and Stacked Nets – This is the number of terminals and stacked nets used. This parameter is chosen as a factor to vary the number of terminals participating in the network and the number of stacked nets used in the network, thus affecting end-to-end delay and system throughput.
2. Capacity – The assigned capacity of a terminal participating in the Link-16 network affects how much data a terminal can transmit at a given time. This parameter is chosen as a factor.

3.6 Factors

The following factors and their corresponding levels are deemed the most significant for this research based on pilot studies.

3.6.1 Network Topology

1. Network 1:
 - Number of participants: 6
 - Stacked nets used: 1
 - Time slots in use per frame: 768
 - Maximum data rate: $768 \times 210 \text{ bits} = 161,280 \text{ bits per frame (13,440 bps)}$
2. Network 2:
 - Number of participants: 12
 - Stacked nets used: 3
 - Time slots in use per frame: 2,880

- Maximum data rate: $2,880 \times 210 \text{ bits} = 604,800 \text{ bits per frame}$
(50,400 bps)
3. Network 3:
- Number of participants: 18
 - Stacked nets used: 3
 - Time slots in use per frame: 3,456
 - Maximum data rate: $3,456 \times 210 \text{ bits} = 725,760 \text{ bits per frame}$
(60,480 bps)
4. Network 4:
- Number of participants: 24
 - Stacked nets used: 4
 - Time slots in use per frame: 4,608
 - Maximum data rate: $4,608 \times 210 \text{ bits} = 967,680 \text{ bits per frame}$
(80,640 bps)
5. Network 5:
- Number of participants: 24
 - Stacked nets used: 5
 - Time slots in use per frame: 4,608
 - Maximum data rate: $4,608 \times 210 \text{ bits} = 967,680 \text{ bits per frame}$
(80,640 bps)

3.6.2 Mission

1. Mission 1: Offered load of 6,720 bps is the approximate amount of data exchanged during an exercise or training mission.

2. Mission 2: Offered load of 30,000 bps is the approximate amount of data exchanged during a counterair mission that emphasizes air situational awareness and ground-to-air threat updates to the pilot [ESC01].
3. Mission 3: Offered load of 50,103 bps is the amount of data exchanged from mission 2 (30,000 bps) plus an additional 20,103 bps to transmit images.

3.7 Evaluation Technique

Simulation using NETWARS 2003-1 [Net03] is used as the evaluation technique for this study. This evaluation technique provides repeatable results in a controlled environment. The NETWARS JTIDS model used for this study was developed by the Space and Naval Warfare Systems Center San Diego (SSCSD), Modeling and Simulation Branch [Nav03]. At the time of writing this document, the required Verification and Validation document that SSCSD is required to submit to the Defense Information Systems Agency is currently in draft status. Therefore, a similar validation was completed to ensure a valid model was used for the NETWARS simulations.

The validation model configuration included two Operational Facilities (OPFAC) each consisting of the JTIDS terminal model configured as shown in Table 2. Network traffic was sent at a constant rate of 70 bps. NETWARS reported an average mean delay of 2 seconds. With the JTIDS model configuration in Table 2, the JTIDS terminal has a recurrence rate of one slot every 3 seconds. Therefore, the calculated expected delay is the average time a message must wait for a slot, plus the message transmission time within the slot. Since the messages arrive every second, three messages were sent during

each slot. When the messages arrive at the terminal, they must wait 1, 2, and 3 seconds for an available slot to come around for an average of 2 seconds.

Table 2. JTIDS Model Configuration

TSB Attribute Name	JTIDS_0	JTIDS_1
slot_type	T	R
msg_cat	7	7
Set	A	A
Index	0	0
RRN	8	8
Net	0	0
relay_delay	0	0
TSEC	0	0
packing	P4SP	P4SP

3.8 Workload

Table 3 shows the workload parameters and settings used for this research. The network load placed on the five different network topologies considered under study affects the mean delay of the Link-16 network.

Table 3. Workload Parameter Settings

Workload Parameter	Network Traffic Settings (bps)
Mission	6,720/30,000/50,103

3.9 Experimental Design

The experimental design of this study consists of one factor at five levels and one factor of three levels. Therefore, the number of required experiments for this study is $5 \times 3 = 15$. The total number of replications for each experiment is five, discovered sufficient from running pilot studies. Therefore, the total number of simulations is $15 \text{ experiments} \times 5 \text{ replications} = 75 \text{ simulations}$.

3.10 Summary

This chapter discussed the methodology used. The problem associated with the use of the Link-16 element by various ground and air platforms was defined. The goal of the research is stated. An approach to achieve the goal was discussed. The system is defined and system boundaries were stated. This chapter also provided a list of services the system provides and their possible outcomes. End-to-end delay and throughput, the two metrics used for this study were described. System and workload parameters were identified along with a discussion of how each parameter affects system performance. NETWARS 2003-1 is used as the evaluation technique. Also presented are the workload parameters and corresponding settings used for the scenario. Finally, the experimental design was discussed.

IV. Data Analysis

4.1 Introduction

This chapter discusses the result of the NETWARS simulation of the Link-16 network conducted for this study. A total of five replications were run which are sufficient to achieve a 90% confidence interval. The first result discussed is the throughput of the Link-16 network, including an explanation of why throughput is equivalent to network load. Then, a discussion of how network topology changes decrease the mean delay of the Link-16 network. The next section shows the offered load of the system. Then, an ANOVA on mean delay is presented with further discussion on significant factors. Finally, the confidence intervals of effects and interactions are presented and discussed.

4.2 Throughput Results

As shown in Figure 5, system throughput is equivalent to network load on the network. This is a result of using dedicated access modes in the JTIDS terminals; contention of time slots is not an issue. In addition, the appropriate amount of time slots were assigned to each JTIDS terminal to handle the data transmission, except for network 1 running missions 2 and 3 where the network topology does not have enough time slots available to support those two missions. As a result, the number of stacked nets in-use (Figure 12) and number of participants (Figure 13) did not affect the system throughput as long as there are a sufficient number of times slots assigned to each terminal.

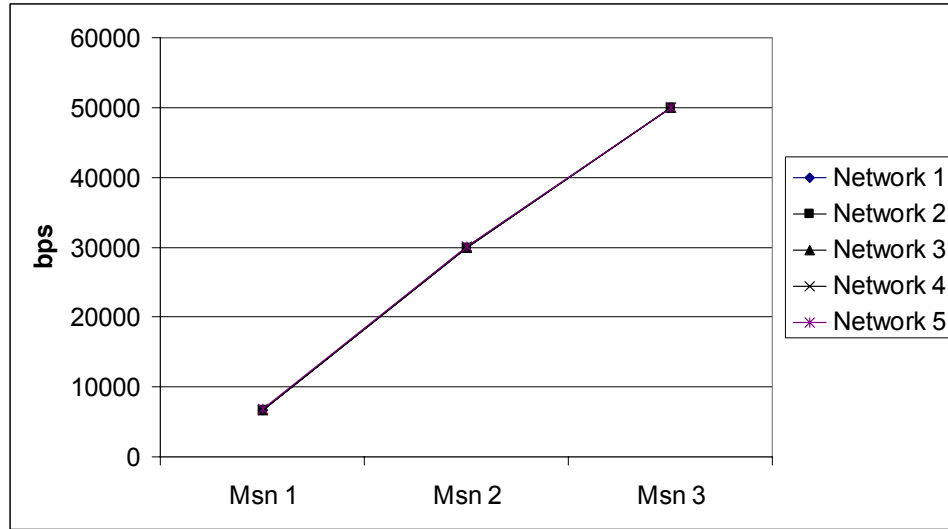


Figure 5. System Throughput

4.3 Mean Delay Results

Figure 6 shows the mean delay of the Link-16 network used for this study. Simulations were not conducted on network 1 under missions 2 and 3 because these conditions overloaded the terminals, resulting in mean delays greater than 0.5 seconds. The mean delay decreased for networks 2 through 5 in going from missions 2 to 3 due to the assignment of 96 time slots per second on one of the terminals exclusively for image transfer. Although this resulted in a decrease in system mean delay, all participants operating on this particular stacked net are left with only 32 time slots per second (6,720 bps) available to communicate with the other participants.

Figure 7 shows the mean delay of the Link-16 network decreases as the network topology is changed. For example, on mission 1, going from network 1 to network 2, there was a mean delay decrease as the number of time slots assigned increased. Table 4 summarizes the network topology parameters conducted for this study.

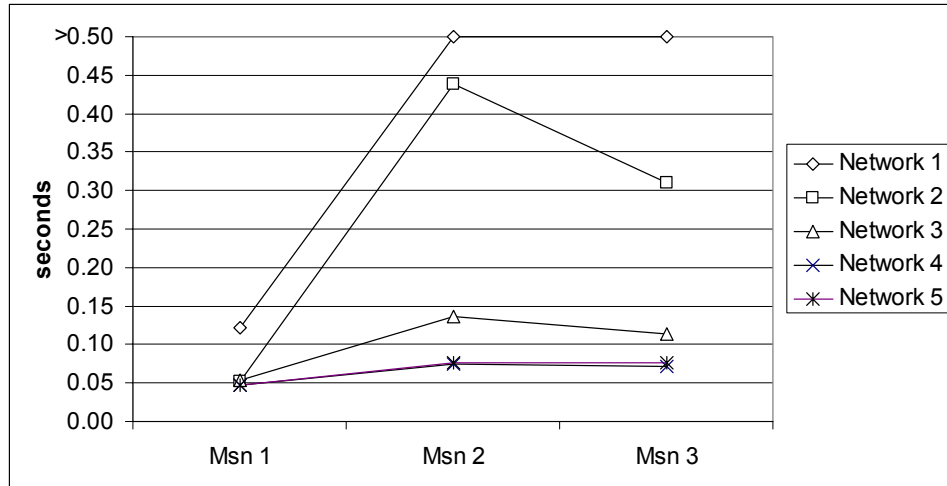


Figure 6. Mean Delay vs. Changing Mission

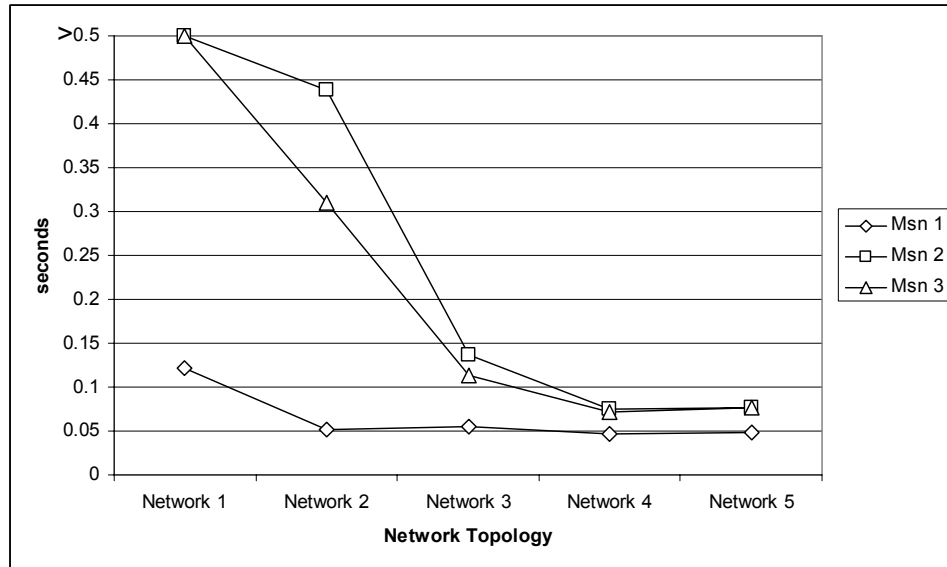


Figure 7. Mean Delay vs. Network Topology

Table 4. Link-16 Network Topology

Network Topology	Number of Stacked Nets	Number of Participants	Time Slots In Use Per Frame	Average Time Slots Per Second	Maximum Data Rate (bps)
Network 1	1	6	768	64	13,440
Network 2	3	12	2,880	80	50,400
Network 3	3	18	3,456	96	60,480
Network 4	4	24	4,608	96	80,640
Network 5	5	24	4,608	76.8	80,640

As shown in Figure 8, the mean delay decreases when there are more time slots assigned to a terminal.

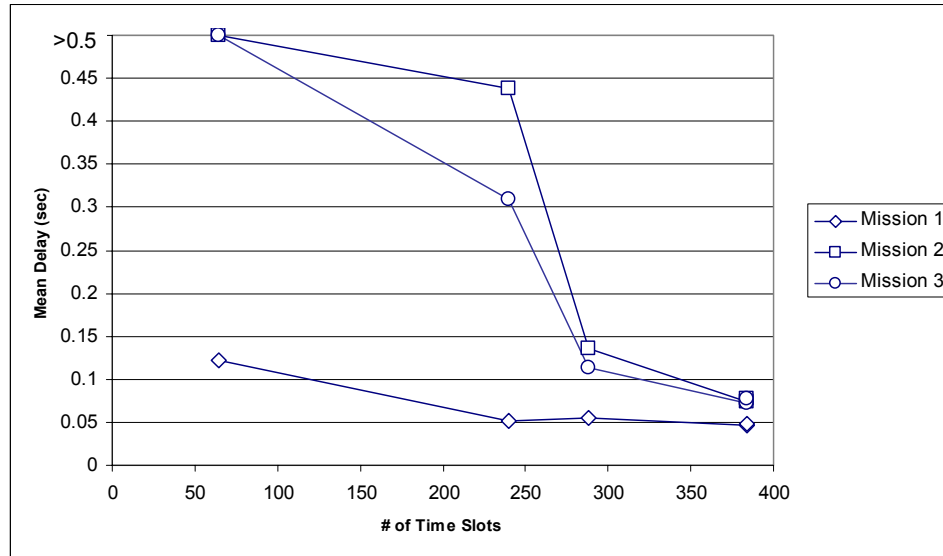


Figure 8. Mean Delay vs. Number of Time Slots

Figure 9 shows the mean delay of the Link-16 network decreases when the number of terminals is increased. This is due to the dedicated access mode used for this study; therefore, the number of terminals does not affect the mean delay as long as there is sufficient number of time slots assigned to a terminal. The number of terminals used does affect the number of time slots that can be assigned. For example, assuming that there is only one stacked net available for use and 16 terminals required for the mission. Since there are 128 time slots per second available, there are eight time slots per second available for each terminals.

Figure 10 shows that the mean delay increases for each mission as the offered load increases.

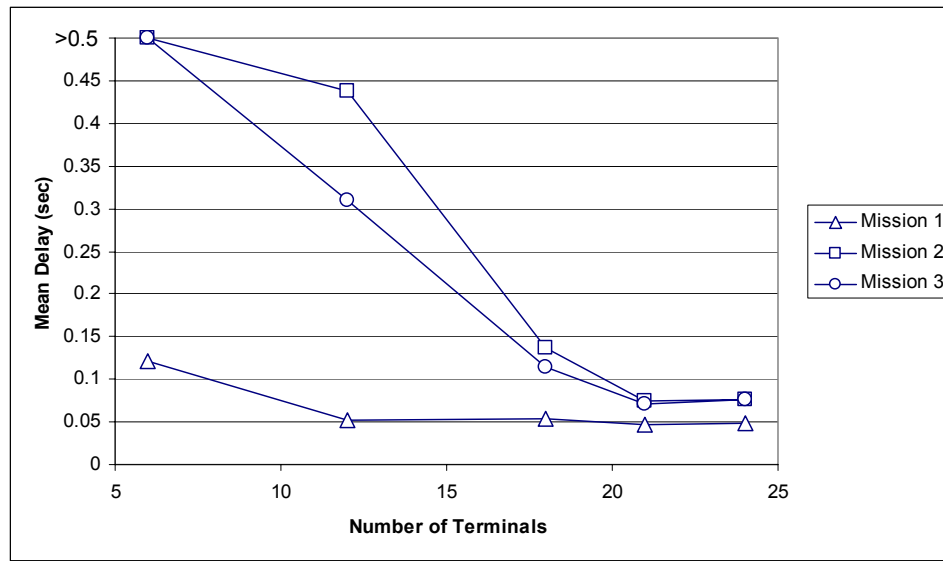


Figure 9. Mean Delay vs. Number of Terminals

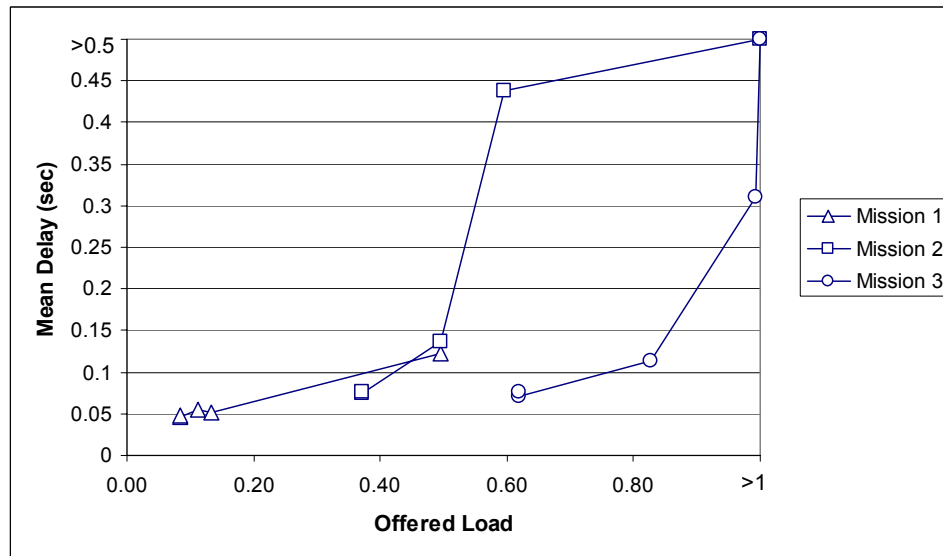


Figure 10. Mean Delay vs. Offered Load

In Figure 11, as the number of stacked nets increased, the mean delay decreased because on a multiple stacked net configuration, the Link-16 network can also have multiple subnetworks. For example, terminal 1 on stacked net 0 transmits on Time Slot Block (TSB) A-0-8; terminal 10 can also transmit on TSB A-0-8 on stacked net 1.

Although terminal 10 is not able to receive transmission from terminal 1 and vice versa, this poses a problem if terminal 1 and terminal 10 needs to communicate with each other.

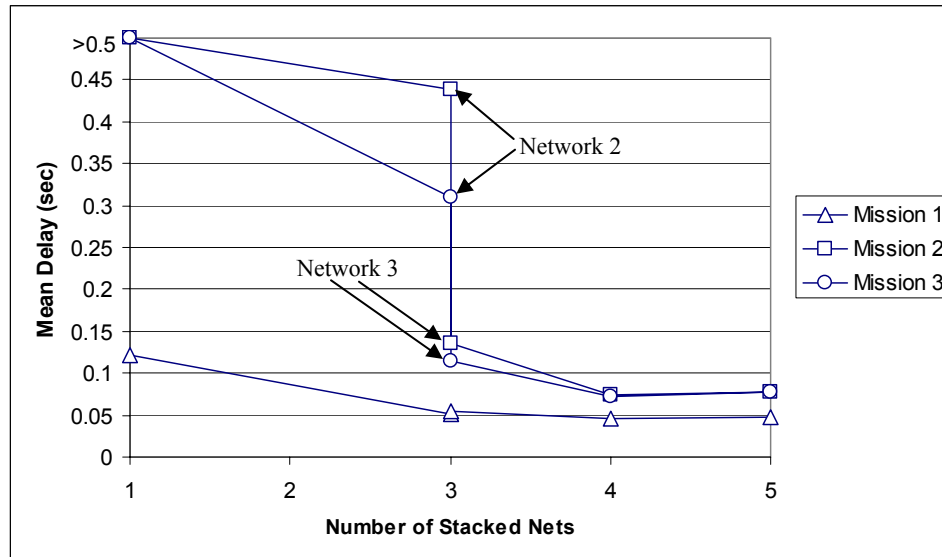


Figure 11. Mean Delay vs. Number of Stacked Nets

Figure 12 shows that the number of stacked nets does not affect the throughput of the Link-16 network due to the independence between stacked nets.

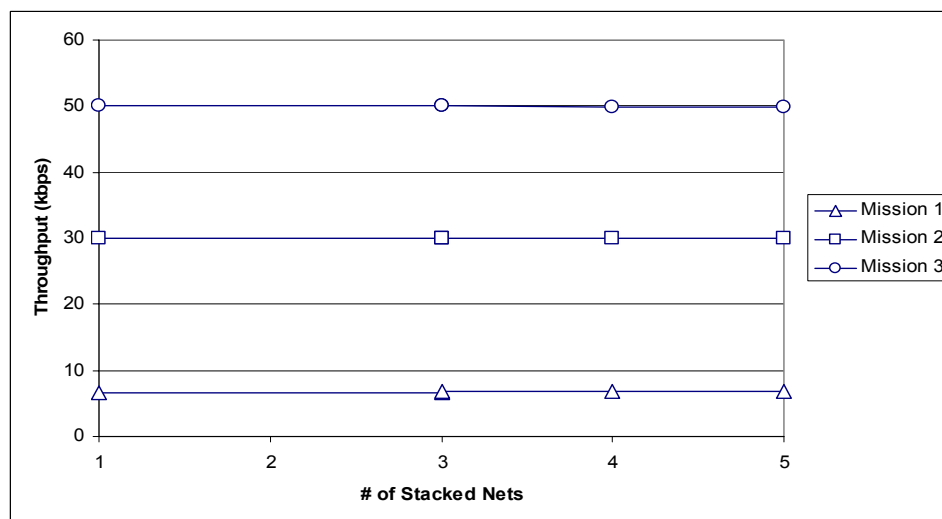


Figure 12. Throughput vs. Number of Stacked Nets

Also shown in Figure 13 is that the number of terminals does not affect the throughput of the Link-16 network.

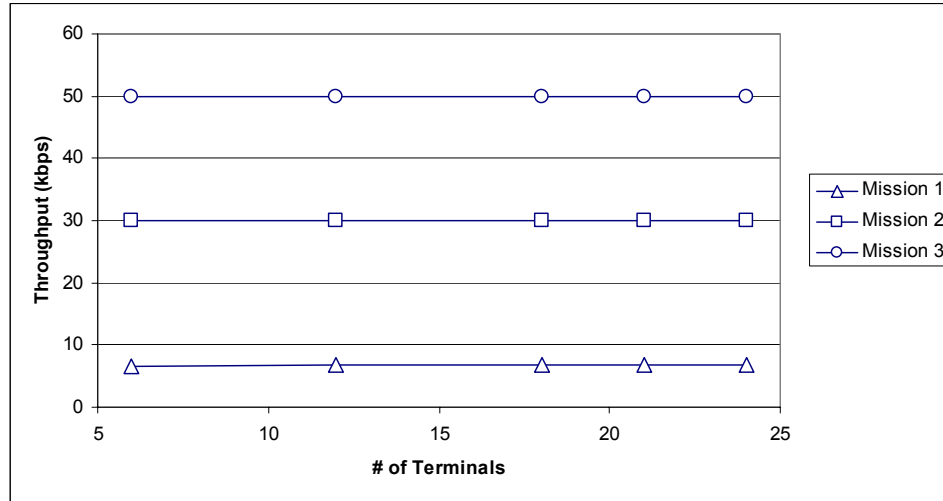


Figure 13. Throughput vs. Number of Terminals

4.4 Offered Load

As shown in Figure 14, the offered load for network 1 was above 100% when used with missions 2 and 3. Since missions 2 and 3 overloaded the system, simulations were not run under these conditions.

4.5 Analysis of Variance for Mean Delay

Table 5 summarizes ANOVA results for the mean delay of the Link-16 network and shows that the network topology, mission, and interactions were all statistically significant (F-computed value greater than F-table value) for a 90% confidence level. A total of 94.2% variations were accounted for in this model. The network topology (Table 4) which accounts for 22% variation was primarily caused by the amount and allocation of time slots. A 50% variation due to mission was caused by the increase in network

traffic on the network. The 22.2% variation due to interactions is shown in Table 7 and discussed further in paragraph 4.6.

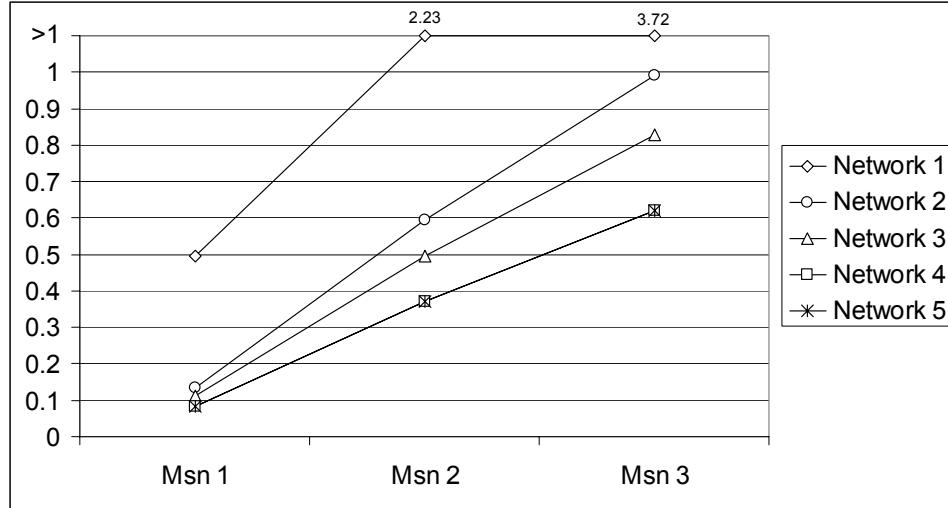


Figure 14. Offered Load

Table 5. ANOVA for Mean Delay

Component	Sum of Squares	Percentage of Variation	Degrees of Freedom	Mean Square	F-Computed	F-Table
y	1.76					
y..	0.93					
y-y..	0.83	100.00	59			
NW Topology	0.18	21.98	3	0.0607	61.01	2.20
Mission	0.41	50.03	2	0.2072	208.27	2.42
Interactions	0.18	22.22	6	0.0307	30.84	1.90
Errors	0.05	5.76	48	0.0010		

4.6 Confidence Interval for Effects and Interactions

Table 6 shows a 90% confidence interval for effects and indicates that the mission has a significant effect on the network topology. Networks 3, 4, and 5 performed better than network 2 because they were allocated more time slots. Network 3 had 576 (20% increase) more time slots than network 2. Networks 4 and 5 had 1,728 (60% increase) more time slots than network 2. Because of the low network traffic requirement and

allocation of more than the required number of time slots, mission 1 performed better than the other missions.

Table 6. 90% Confidence Interval for Effects

Parameter	Mean Effect	Standard Deviation	90% Confidence	Confidence Interval	
μ	0.1247	0.0041	0.0067	0.1180	0.1314
Network					
2	0.1417	0.0071	0.0116	0.1301	0.1533
3	-0.0235			-0.0351	-0.0119
4	-0.0605			-0.0721	-0.0489
5	-0.0577			-0.0693	-0.0461
Missions					
1	-0.0747	0.0058	0.0095	-0.0842	-0.0652
2	0.0565			0.0470	0.0660
3	0.0182			0.0087	0.0277
Interactions		0.0100	0.0164	See Table 7	

Table 7 shows a 90% confidence interval for interactions and shows that all interactions were significant except on networks 3, 4, and 5 when operating mission 3. This result was caused by the increased network traffic of image transfer being allocated to only one of the available stacked nets. Another cause is that networks 3, 4, and 5 were already allocated a large number of time slots, averaging 96, 96, and 76.8 time slots per second, respectively. Therefore, we can determine that for a large network traffic load with a high average number of time slots per second, other configuration changes, i.e. number of stacked nets in use or number of participants, does not affect the mean delay of the system.

Table 7. 90% Confidence Interval for Interactions

	Msn 1		Msn 2		Msn 3	
Network 2	-0.1563	-0.1235	0.0984	0.1312	0.0087	0.0415
Network 3	0.0112	0.0441	-0.0382	-0.0054	-0.0222	0.0106
Network 4	0.0405	0.0733	-0.0625	-0.0297	-0.0272	0.0057
Network 5	0.0390	0.0718	-0.0632	-0.0304	-0.0250	0.0078

Figure 15 shows that for mission 1 operating under network 2 performed statistically better than networks 3, 4, and 5. For the given configuration with low network traffic and high allocation of time slots, the mean delay is already low. Therefore, adding more than the required amount of time slots to an already low mean delay does not decrease the mean delay.

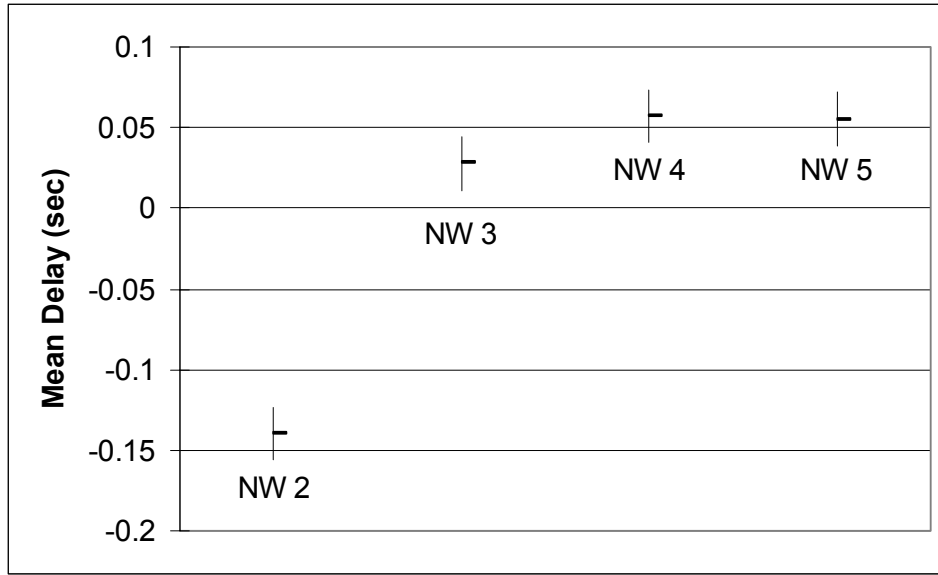


Figure 15. Mission 1 Confidence Interval for Interactions

In Figure 16, networks 3, 4, and 5 statistically outperformed network 2 when operating under mission 2. Because mission 2 requires a medium network traffic load, more time slots are required to realize an improvement in mean delay.

As shown in Figure 17, increasing the number of time slots for a high network traffic load does not improve the mean delay of the system.

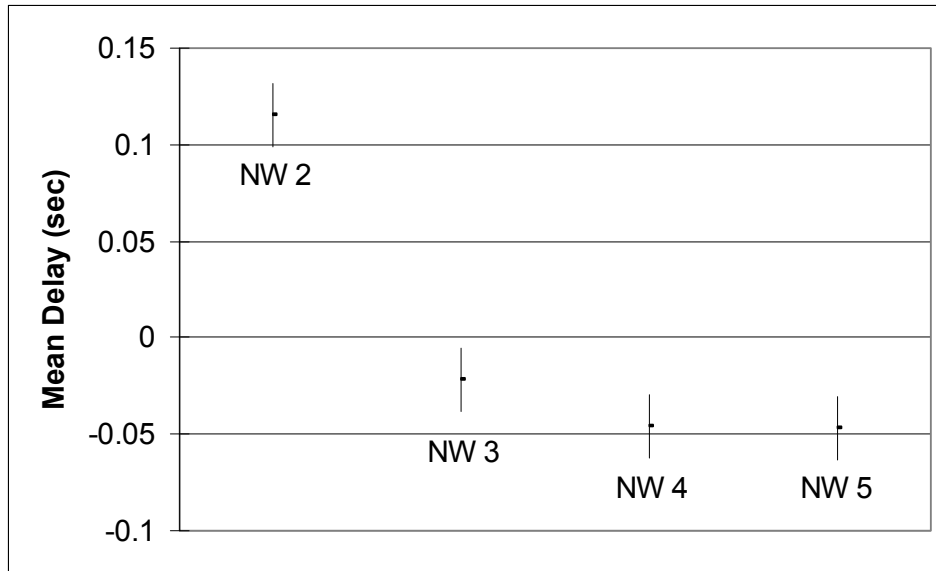


Figure 16. Mission 2 Confidence Interval for Interactions

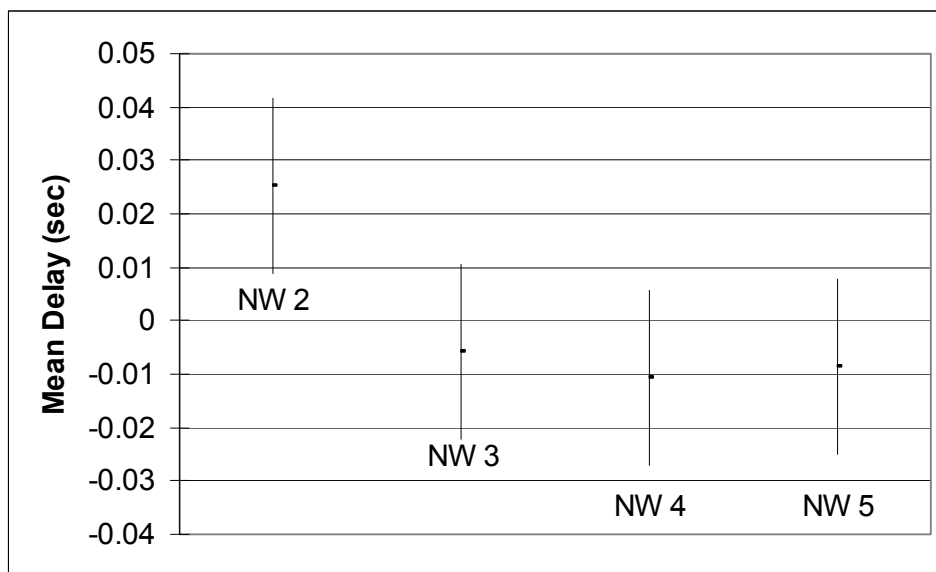


Figure 17. Mission 3 Confidence Interval for Interactions

4.7 Summary

This chapter discussed the result of the NETWARS simulation of the Link-16 network. First result discussed was the throughput of the system was equivalent to the network load placed on the network due to the static assignment of time slots; therefore

contention of time slots was not an issue. Then, the mean delay of the Link-16 network was discussed and the reason for the mean delay decrease. Then, the offered load of the Link-16 network was shown. Then, the result of the ANOVA on the mean delay of the system was shown with the network topology, mission, and interactions were all significant using a 90% confidence level. Finally, the confidence interval of effects and interactions were shown and discussed.

V. Conclusions and Future Work

5.1 Conclusions

As a result of the NETWARS simulations conducted for this study, the network traffic load (mission) had significant effect on the Link-16 network topology. Based on this result, it is determined that the selection of a network topology for a given mission is critical to achieve mission success. Because Link-16 is a static network, addition of new participants to the mission requires modification of the Link-16 design to include testing and distribution. For a low network traffic mission, operating on a network having more assigned time slots than required proves advantageous to the Link-16 network as shown in Figure 15. However, as network traffic increases, adding more time slots to the network does not decrease the mean delay of the Link-16 network.

The main parameter affecting the mean delay of the Link-16 network was the number of time slots assigned to a participant. As the number of assigned time slots increases, the mean delay of the system decreases. A fundamental constraint of the Link-16 network is that it is limited to 128 time slots per second. Data throughput can be increased by changing the data packing option to a higher data rate but doing so reduces the anti-jam resistance of the Link-16 network. The highest achievable data rate from one terminal when assigned all 128 time slots is 26,880 bps using the Packed-2 option. In this case, this terminal has no time slots available to receive data from any other terminals.

Overall, the Link-16 network is able to handle the increase in network traffic when using multiple stacked nets. However, this decreases the ability of a participant to

communicate with the other participants. Using additional stacked nets alone on a Link-16 network does not decrease the mean delay of the system. It does however allow the system to have additional subnetworks which gives the system more time slots and a corresponding decrease in mean delay. For example, consider the two stacked nets operating in Figure 18. Assuming both stacked nets are using 128 time slots per second each to minimize mean delay, they cannot communicate with each other because the maximum number of time slots are already in use for their own subnetwork. For the two stacked nets to communicate with each other, they need to decrease the number of time slots of each stacked nets. For example, terminal 1 is assigned TSB A-0-8 to transmit on stacked net 0, terminal 4 can be assigned TSB A-0-8 to receive on stacked net 0, but this TSB is no longer available for use in stacked net 1. This is a problem if there are many participants that need to communicate with each other.

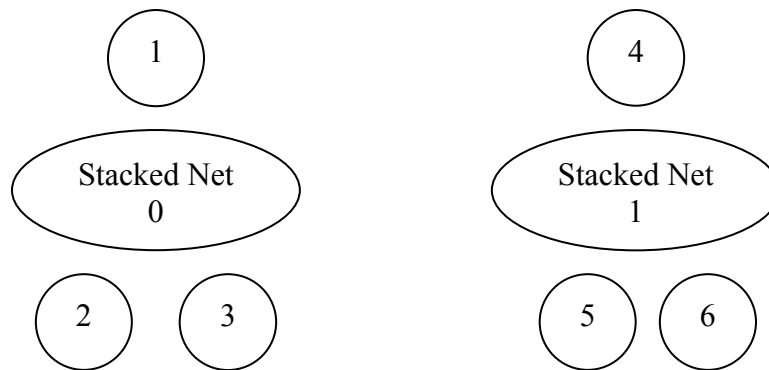


Figure 18. Stacked Net Example

The Link-16 network architecture is difficult to manage due to the static assignment of time slots designed by Link-16 network managers. There exists numerous documents describing Link-16 network architectures designed for use in particular

missions or areas of operations. These documents are very specific on the Link-16 network design, e.g., what TSB is assigned to each participant. Any deviation from the network design by unauthorized personnel is prohibited [CJC01b]. In addition, the static assignment of time slots can be inefficient in that valuable time slots may go unused.

5.2 Future Work

Future research that could be examined on the Link-16 network would be the use of other access modes, e.g., contention and time slot reallocation. Another candidate for future work would be the combined use of all access modes. Since the static assignment of time slots in a Link-16 network makes this architecture very difficult to manage, future research could be done on the dynamic time slot allocation capability of the Link-16 network for all participants. Adding this capability on the network could alleviate the network management difficulty faced today. Another area that could be researched would involve finding a technique to increase the number of time slots per second beyond the current limit.

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