ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INVESTIGATION AND OPTIMIZATION OF SOME TACTICAL DATA LINK TECHNOLOGIES

M.Sc. Thesis by

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April, 2017

ANKARA

INVESTIGATION AND OPTIMIZATION OF SOME TACTICAL DATA LINK TECHNOLOGIES

A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Ankara Yıldırım Beyazıt University
In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electronics and Communication Engineering, Department of Electronics and Communication Engineering

by

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April, 2017

ANKARA

M.Sc. THESIS EXAMINATION RESULT FORM

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ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my thesis supervisor Prof.Dr.Şerafettin EREL, for his supervision, generous support, encouragement, and guidance through the M.Sc. process.

I would like to thank my thesis committee members, Assoc.Prof.Dr.Mehmet Akif ERİŞMİŞ and Asst.Prof.Dr.Serdar ÖZYURT, for their helpful suggestion, insightful comments, and hard questions.

I would also like to thank Yavuz DURDAK for their encouragement and support.

I expand thanks to my colleagues for their encouragement and patience during the M.Sc. process.

Lastly, I would like to thank my wife and my little daughter for everything.

2017, 06 April **Ersin ÖZTÜRK**

INVESTIGATION AND OPTIMIZATION OF SOME TACTICAL DATA LINK TECHNOLOGIES

ABSTRACT

Tactical Data Link Systems (TDLSs) provide a tactical information exchange between air, ground and naval units near real time in the battlefield area. Combat platforms have many different TDL capabilities such as Link-11, Link-16, Link-22, VMF and JREAP. Every TDL has different characteristics. The main problem is to decide which TDL is more effective in terms of transmission of data to another platform. In this thesis, a detailed literature survey about TDL systems has been carried out. This knowledge is presented in Chapter 1. The optimization theory is briefly mentioned in Chapter 2. In Chapter 3, an optimization is made with regard to the transmission of data in the operational area. And finally, the conclusion is presented in Chapter 4.

Key Words: Tactical Data Links (TDLs), Link-11, Link-16, Link-22, Variable Message Format (VMF), Joint Range Extension Application Protocol (JREAP), Optimization of TDL.

BAZI TAKTİK VERİ LİNK (TVL) TEKNOLOJİLERİNİN İNCELENMESİ VE OPTİMİZASYONU

ÖZ

Taktik Veri Link Sistemleri (TVLS) savaş alanında hava, kara ve deniz birimleri arasında yakın gerçek zamanlı taktik bilgi değişimini sağlayan sistemlerdir. Savaşan platformlar Link-11, Link-16, Link-22, Değişken Mesaj Formatı (DMF) ve Menzil Uzatma Protokolü (MUP) gibi birçok farklı TVL kabiliyetlerine sahiptirler. Her TVL farklı özelliklere sahiptir. Asıl problem, diğer platforma gönderilecek veri açısından hangi TVL'nin daha etkin olduğuna karar vermektir. Bu tezde TVL'ler hakkında detaylı bir literatür taraması yapılmıştır. Bu bilgiler Bölüm 1'de sunulmuştur. Bölüm 2'de optimizasyon teorisinden kısaca bahsedilmiştir. Bölüm 3'te operasyonel sahada veri gönderimine ilişkin optimizasyon yapılmıştır. Son olarak Bölüm 4'te sonuç bölümü sunulmuştur.

Anahtar Kelimeler: Taktik Veri Linkleri (TVL), Link-11, Link-16, Link-22, Değişken Mesaj Formatı (DMF), Menzil Uzatma Protokolü (MUP), TVL'lerin optimizasyonu.

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NOMENCLATURE

Acronyms

AAR	Anti Air Warfare
AHP	Analytical Hierarchical Processing
AJ	Anti Jamming
AM	Amplitude Modulation
AN	Airborne Network
BER	Bit Error Rate
BLOS	Beyond Line of Sight
C2	Command Control
C2I	Command Control Information
CCSK	Cyclic Code Shift Keying
CNR	Combat Network Radio
CSMA	Carrier Sense Multiple Access
DAMA	Demand Assigned Multiple Access
DLP	Data Link Processor
DLRP	Data Link Reference Point
DP/A MUX	Data Processor Avionic Multiplexer
DTS	Data Terminal Set
ECM	Electronic Counter Measure
EHF	Extremely High Frequency
EPM	Electronic Protective Measure
FA	Functional Area
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FOC	Fiber Optic Cable
FPU	Forwarder Participating Unit
FRU	Forwarder Reporting Unit
FTD	Full Transmission of Data
FUV	VMF Unit Forwarder
GPS	Global Position System
HMI	Human Machine Interface
IEM	Initial Entry Message

IFF	Identification Friendly and Foe
IP	Internet Protocol
IPF	Interference Protection Feature
ISR	Intelligence Surveillance Reconnaissance
JRE	Joint Range Extension
JREAP	Joint Range Extension Application Protocol
JTIDS	Joint Tactical Digital Information System
JU	JTIDS Unit
KG-40	Key Generator 40
LAN	Local Area Network
LDR	Low Data Rate
LET	Link-16 Enhanced Throughput
LLC	Link Level Communication Security
LOS	Line of Sight
LPD	Low Probability of Detect
LPI	Low Probability of Intercept
LTD	Limited Transmission of Data
MODEM	Modulator Demodulator
MS	Mini Slot
MSEC	Message Security
MSK	Minimum Shift Keying
MTDL	Multi Tactical Data Link
NATO	North Atlantic Treaty Organization
NCE	NILE Communication Equipment
NCS	Network Control Station
NCS	Network Cycle Structure
NCT	Network Cycle Time
NILE	NATO Improve Link Eleven
NMU	Network Management Unit
NN	Nile Network
Non-C2	Non-Command Control
NPG	Network Participating Group
NTDS	Naval Tactical Data System
NTR	Network Time Reference

NU	Nile Unit
OLM	OPTASK Link Message
OPTASK	Operational Task
PA	Power Amplifier
PDU	Protocol Data Unit
PPLI	Precise Participant Location Identification
PU	Participating Unit
QPSK	Quadrature Phase Shift Keying
R/S	Receiver Synthesizer
RELNAV	Relative Navigation
RF	Radio Frequency
RPS	Remote Power Supply
RS	Reed Solomon
RTI	Receiver Transmitter Interface
RTT-I	Round Trip Timing Interrogation
RTT-R	Round Trip Timing Response
RU	Reporting Unit
SATCOM	Satellite Communication
SIPRNET	Secret Internet Protocol Network
SMP	Signal Message Processor
SN	Super Network
SNC	System Network Center
SNMU	Super Network Management Unit
SPC	Signal Process Controller
SRU	Shop Replaceable Unit
STANAG	Standard of Agreement
TACAN	Tactical Air Navigation
TADIL	Tactical Digital Information Link
TCP	Transmission Control Protocol
TDL	Tactical Data Link
TDLS	Tactical Data Link System
TDMA	Time Division Multiple Access
TDS	Tactical Data System
TOD	Time of Day

TP/G MUX	Tailored Processor Ground Multiplexer
TRR	Track Reporting Responsibility
TSEC	Transmit Security
U/VHF	Ultra/Very High Frequency
UDP	User Datagram Protocol
UHF	Ultra High Frequency
USA	United States of America
UTC	Coordinated Universal Time
VMF	Variable Message Format
VUC	VMF Unit Controller
VUP	VMF Unit Participant
VURO	VMF Unit Receive Only
VURP	VMF Unit Routing Participant
WAN	Wide Area Network
WGS-84	World Wide Geodetic System
XML	Extensible Markup Language

CHAPTER 1

THE INTRODUCTION OF TACTICAL DATA LINKS

A Tactical Data Link (TDL) may be said to ensure the mechanism for the automated real-time and near real-time information exchange between the system of air, maritime and land platforms.

TDLs are the solutions to provide data networks and applications, maintaining Situational Awareness and supplying the information of battle space. NATO Standard of Agreements describes a data link as, "A data link is characterized by its standardized message formats and transmission characteristics."

Comprehensive and timely intelligence on enemy/friendly force disposition and activities is needed by the warrior to establish battlefield situational awareness, threat warning and avoidance indications, and threat acquisition and targeting information. Because this intelligence information is critical to the successful outcome of each conflict, it is demanded by warfighters at all battlefield area.

There is an insatiable demand for more data, from all sources, with lower latency and most importantly, automatically filtered, correlated and fused to present the warrior with a clear, comprehensive and accurate view of the battlefield.

The Tactical Data Link (TDL) systems that provide information must perform multiple functions interoperate with lots of existing systems and have an open architecture based on widely-accepted commercial standards [1].

TDLs can be fast, clear, secure, resistant to Electronic Counter Measure (ECM), and provide information in a consistent format that is unambiguous and easy to assimilate.

All TDLs have a similar main structure. These are *a data source* which can normally be a sensor system such as radar or can be a manual input, *a HMI (Human Machine Interface) system* which can be controlled parameters of TDL operations, *a* *cryptographic system* which can provide to encrypt data transformation and to improve resistance to hostile ECM, *a communication system* which typically consist of modem, radio transceiver and antenna and the last one *a message set* which can allow to exchange recognized (air, surface and land) picture, weapons coordination control, network management and many other functions information.

TDLs might have different types of communications such as point-to-point, Broadcast and Netted. A point-to-point link is a connection between two units. Multiple communication is not possible in a point-to-point system.

Broadcast Link can be identified as one-to-many where the transmission mode is unidirectional (one directional). Netted TDLs permit all participants in the network to transmit and receive to/from other participants. Netted links are the most effective TDLS among the communication types.

Figure 1.1 Tactical Data Link Communication System Composition Block Diagram shows a typical TDL system that can be used on battlefield area.

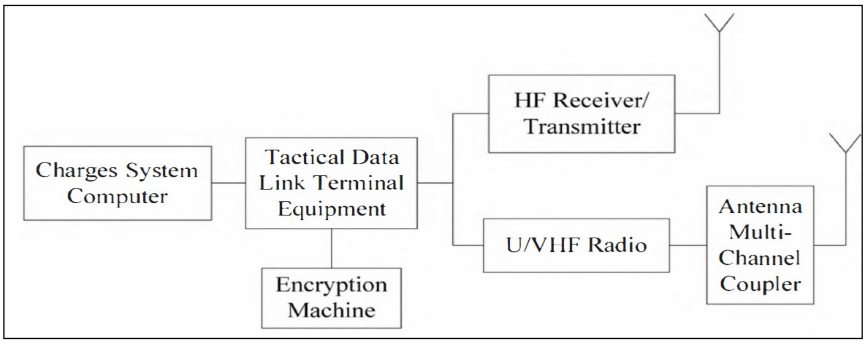


Figure 1.1 TDL communication system composition block diagram [2]

In order to get the high-density rapidly changing air picture and effectively manage the air battle, tactical data links are often required to transfer a large amount of information among command and control units. TDLs have played more and more important roles in the modern battlefield and attracted much attention in recent years. Because they are used in hostile environments and rapidly changing battlefield scenarios, TDLs must have sufficient timeliness, high capacity, strict security and sufficient survivability [3].

TDLs have different message structures. There is no such thing as a typical TDL message structure. Actually, every TDL has different requirements in terms of signal processing, cryptographic operations and message contents.

In battle space area, combat platforms have many different TDL capabilities. They are Link-11, Link-16, Link-22, VMF and JREAP. TDLs have different characteristics and all platforms have no entire TDLs. The main problem is to determine which TDL is more effective in terms of transmission of data to another platform.

1.1 Link-11 Tactical Data Links

Link 11 uses standard message formats for the exchange of digital information among airborne, land-based, shipboard tactical data systems and employs netted communication techniques. Link 11 ensures mutual exchange of information among net participants by using high-frequency (HF) or ultrahigh-frequency (UHF) radios. Link 11 is half-duplex, netted, secure data link and requires a Net Control Station (NCS) and Participating Units (PUs) to operate [4].

Link-11 has two main types of communications. First is Link-11A used for air-to-air operation or ground/surface-to-air operation in battle space area. Second is Link-11B used for ground-to-ground communication between pair participants. Link-11A and Link-11B make use of the same message structure for communication.

A PU (Participating Unit) is Tactical Data System (TDS) unit that is operating in a Link-11 net in any mode of operation [5].

1.1.1 Link-11A Tactical Data Link

A typical shipboard Link-11A communications system (Figure 1.2) consists of the following components: TDS (Tactical Data System) digital computer, cryptographic device, Link-11 data terminal set, communications switchboard, HF/UHF radio set transceivers (transmitter-receiver), antenna coupler and antenna [6].

The data terminal set is the center of the Link-11 system. The communications switchboard is used to select the desired HF or UHF transceiver. An external frequency standard is also part of many Link-11 systems [6].

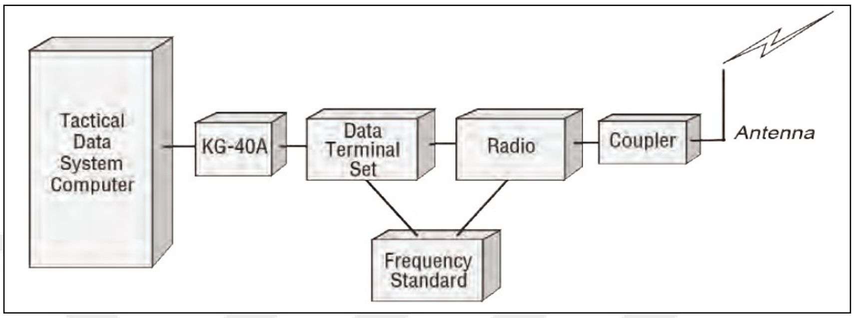


Figure 1.2 Link-11A communication system [4]

LINK-11A is an automated, one- or two-way, HF data link to distribute information within the Tactical Data System (TDS) [7].

The computer system is called a Tactical Data System (TDS). Airborne units are referred to as Airborne TDSs (ATDSs). Shipboard units are referred to as Naval Tactical Data System (NTDSs). The encryption device (crypto) is a Key Generator-40 Alpha (KG-40A).

1.1.1.1 Link-11A Data Transmission

Radar, navigation system and operator data are received by the tactical computer. In order to share this database with other TDS computers, the information must be formatted into messages that have a specific and well-defined structure. Commands and other administrative information are also formatted into messages for distribution to other units. These digital messages are placed into a buffer. The buffer is an area within the computer memory reserved for input or output. When an output buffer is built, its contents are sent, one word at a time, to the KG-40A device to be encrypted [4].

The encrypted data is then sent on to the DTS (Data Terminal Set). The DTS converts this encrypted data from digital format to an analog audio signal. This signal is then directed to the Link 11 transmitter. The transmitter modulates a radio frequency carrier with the audio signal and passes it through the antenna coupler. This signal is transmitted to the other participant units in the link by antenna [4] (Figure 1.3).

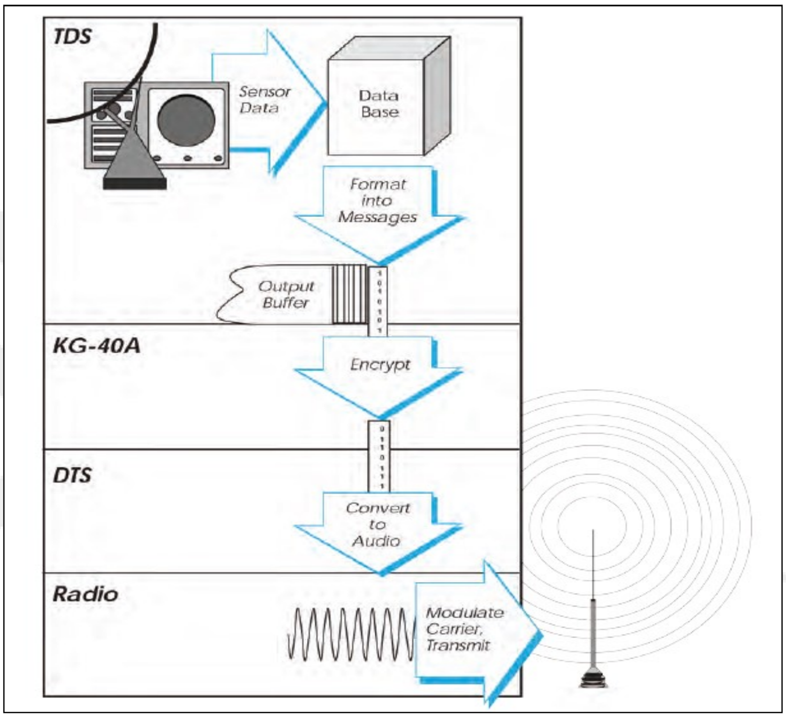


Figure 1.3 Data transmission of Link-11A [5]

The Link-11 is a variation of Tactical Digital Information Links (TADIL) series. It transmits binary data over RF network based on a digital modulation technique such as Quadrature Phase Shift Keying (QPSK) [8].

Interoperability of Link-11 is still an interesting problem in many communication systems. The important thing is to provide cost effective implementation of TDL [9].

1.1.1.2 Link-11A Data Reception

When a transmitted signal is received, the audio portion is demodulated from the radio frequency (RF) signal by the receiver. The resultant audio signal is sent to the

DTS, where it is converted back into digital data. The digital data is then passed to the KG-40A one frame (a parallel group of bits) at a time, where its information is decrypted. Finally, this decrypted data is sent to the TDS computer, where it is collected in an input buffer for processing [4] (Figure 1.4).

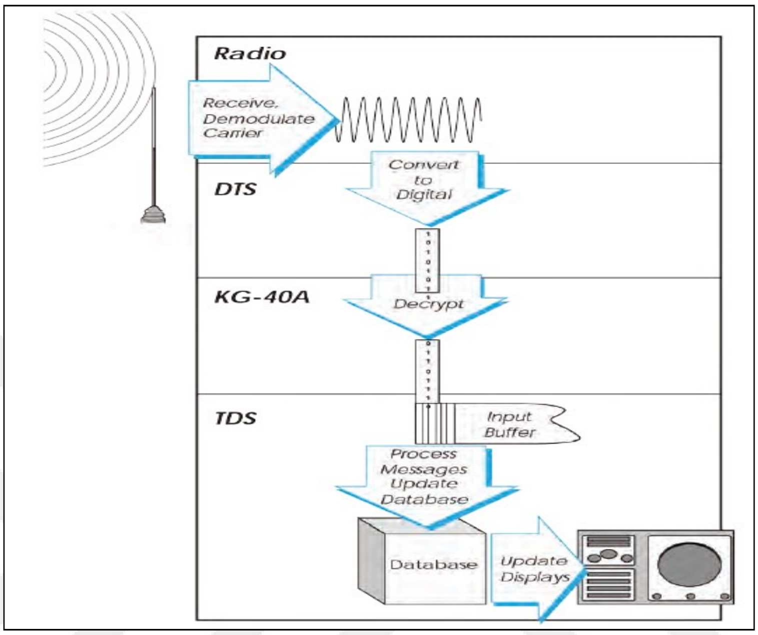


Figure 1.4 Data reception of Link-11A [5]

Link 11A allows aircraft to receive track data from off-board sources such as other aircraft, ships with Link 11A capability. The link 11A data provides a major input if other ships or aircraft operate with the aircraft [10].

The off-board track data can notify the aircraft of target locations beyond the detection range of the onboard sensors. This knowledge allows the earliest possible target detection and tracking by onboard sensors [10].

1.1.1.3 Link-11 Net Operating Modes

The Net Sync mode of operation is used to establish a uniform time base from which all net data communications normally initiate. Net Test provides an overall evaluation of the net and equipment performance. Roll call is the normal mode of operation. In this mode, the operator on the NCS platform enters own ship's address and an assigned address (PU number) for each PU in the proper switch position.

When the link is initiated, each PU is polled for data. Polling consists of sending a call-up message. When the broadcast mode is used, one PU will continuously send a series of data transmissions to all the members of the net. In the Short Broadcast mode, a picked station or the NCS sends a data transmission to the other members of the net. In the Radio Silence mode, the radio set key line and the data terminal set audio output are disabled. The receive capability of the DTS is not affected. The Radio Silence mode is manually initiated and terminated [6].

1.1.1.4 The Data Terminal Set

The DTS is designed as a Modulator/Demodulator (MODEM). Normally, it operates in half-duplex mode and can achieve data sending or receiving, but cannot do both simultaneously. The single exception is during system test. When DTS operates in system test mode, it can send and receive data at the same time (full-duplex mode) [4].

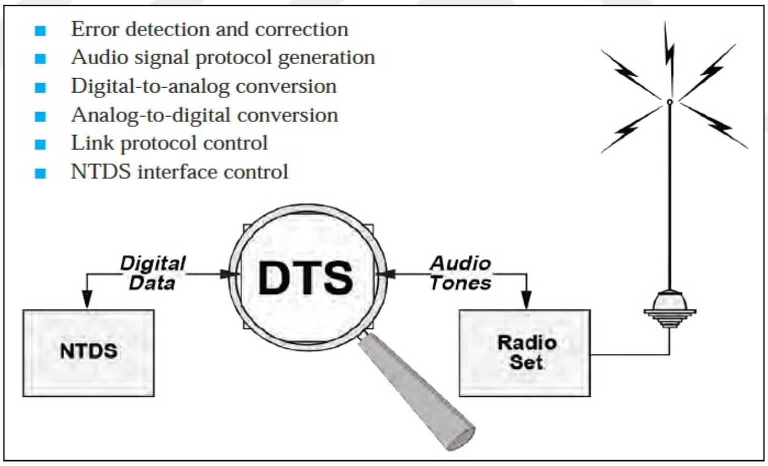


Figure 1.5 The data terminal set functions [4]

1.1.1.5 Link-11A Radios

HF radios use a modulation technique called Amplitude Modulation (AM) in which the Link 11 audio signal is used to modulate [4].

UHF radios use a modulation technique called Frequency Modulation (FM). The Link 11 audio signal is used to modulate or shift the radio frequency about a center frequency [4].

This technique of modulation is more resistant to interference than the technique of AM. During the demodulation process, FM receivers limit the number of amplitude deviations. Only frequency deviation is used to extract the information from the signal. However, UHF is limited in range to line-of-sight [4].

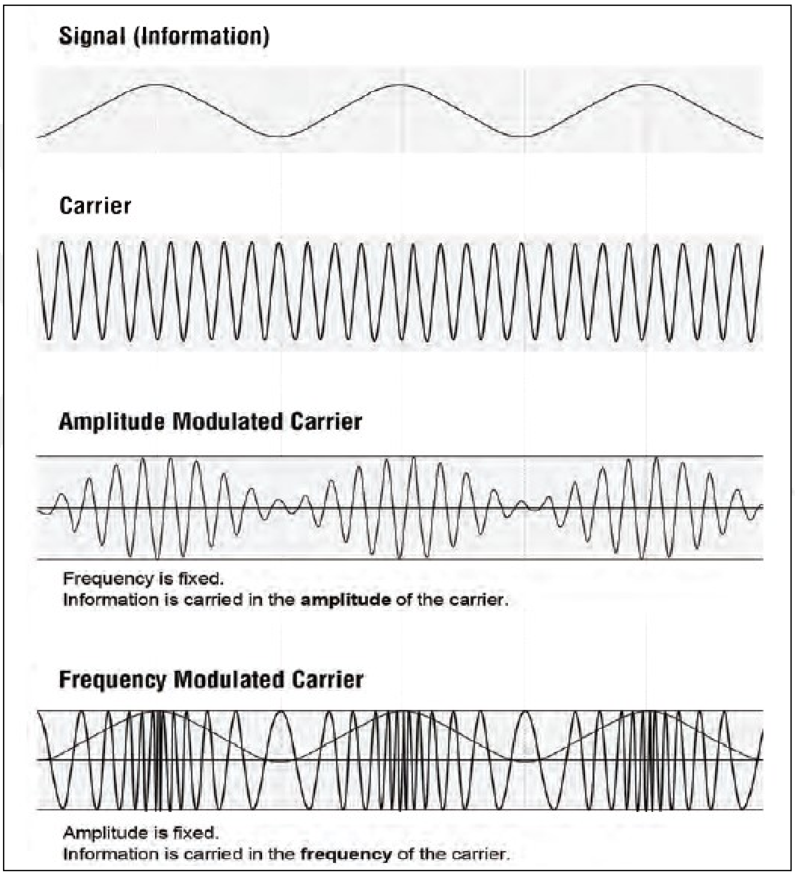


Figure 1.6 Link-11A HF and UHF radios [4]

1.1.2 Link-11B Tactical Data Link

In the late 1980s and early 1990s, the USA and NATO were looking for a TDL to replace legacy serial point-to-point TDL. For this purpose, ground Link-11 was developed. This is known as Link-11B. Link-11B uses almost the same message catalog as Link-11A, but the transmission characteristics of the system are different. Link-11B transmission medium is landline such as wire, Fiber Optic Cable (FOC).

Link-11B operates in a full duplex point-to-point mode between single units. Like Link-11A, data can be transmitted either plain or encrypted. Link-11B units are known as Reporting Unit (RU) to differentiate them from Link-11A Participant Units (PUs). As it is a point-to-point TDL, Link-11B can only connect one RU directly to another.

1.1.2.1 Link-11B Architecture

In Link-11B architecture, individual RUs may only be directly connected in pairs. In order to set up a more complex Link-11B structure, some of the RUs must act as Forwarding RUs (FRUs). An FRU is able to receive Link-11B data from one RU and forward this data to other RUs.

1.1.2.2 Link-11B Modes of Operations

An RU can be in one of the several different states and will go through each of these states during the initialization process.

Inactive: The Link has not been selected for use.

Ready: During the Ready state, a Link idle pattern is transmitted,

Active: When a unit is active, it exchanges test messages with the connected RU or FRU.

Operational: Data Link Messages and Track reports are exchanged. A Link-11B RU is able to operate in one of three modes of operation. These are Full Transmission of Data (FTD), Limited Transmission of Data (LTD) and Receive Only.

1.2 Link-16 Tactical Data Link

1.2.1 Link-16 Overview

Link-16 is synonymous with Tactical Digital Information Link (TADIL) J [11]. It provides a network to the participants on the surface (land and sea) and in air to exchange tactical information in the presence of an adversary. It uses RF frequencies in UHF band and needs a line of sight (LOS) connection between the network participants. Link-16 operates in the L-band and is a good example of a waveform designed to resist interference [12].

Link-16 uses standard formatted message structure, called J-type messages. Both the message security (crypto) and anti-jamming measures are provided by Link-16. It uses a Time-Division Multiplexing Access (TDMA) process for the participants to transmit and receive data. Frequency hopping technique is used to spread the spectrum (anti-jamming) and to establish multi nets in the same area between participants. This property of allocating frequency sequences to form nets can be considered as Frequency Division Multiplexing Access (FDMA). It uses a network participation group (NPG) structure to group the participants accomplishing certain tasks. JU (JTIDS/MIDS Units) is the Link-16 participant names [13].

In October 1994 Link 16 was designated as the primary tactical data link for all military service and defense agency command, control and intelligence (C2I) systems [14].

Link-16 is regarded as a Legacy technology, but it is not true. Since the Link-16/JTIDS system will be around for many years, the study of potential system improvements against hostile interference is non-trivial [15].

In order to facilitate avionics mission replanning, personnel on multiple aircraft need to collaborate by exchanging target imagery and display annotations over Link-16 wireless networks [16].

To complete the exchange of information between the weapon and C2 (Command and Control) platforms, verify the interoperability within the data link. Additionally, it must be ensured that the data link system and building a steady coordinated. In order to do this, the simulation of the data link is needed [17].

Important capabilities;

- Nodelessness
- Jam resistance
- Improved security
- Increased data rate (throughput)
- Increased volume and granularity of information exchange
- Reduced data terminal size, allowing installation in fighter and attack aircraft
- Digitized, jam-resistant, secure voice capability
- Relative navigation
- Precise Participant Location and Identification (PPLI)

Figure 1.7 Additional capabilities to Link-11 [4]

Link-16 participants have three main components which provide communication with other subscribers. These are Data Link Processor (DLP), Link-16 Terminal and antenna. DLP processes Link-16 J-series messages according to Standard of Agreement (STANAG) 5516.

Link-16 Terminal refers to RF component of TDL that are responsible for transmitting and receiving messages to the atmosphere. The antenna is in charge of only radiate RF wave as Omni-directional.

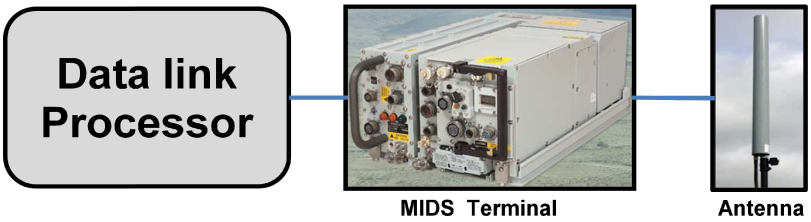


Figure 1.8 Three Link-16 main components

Figure 1.9 Fighter MIDS low volume terminal [18]

MIDS Low Volume Terminal consists of two Line Replacement Units (LRUs): the Main Terminal and the Remote Power Supply (RPS). The Main Terminal consists of 10 Shop Replaceable Units (SRUs). These are; Chassis, Power Amplifier (PA), Exciter/IPF (Interference Protection Feature), Receiver Synthesizer (R/S, 2 per terminal), Signal Processor/Message Processor (SMP), TACAN (optional), Voice (optional), Data Processor/Avionics Multiplexer (DP/A-MUX), Tailored Proc./Ground Multiplexer (TP/G-MUX), Receiver-Transmitter Interface (RTI)/Discrete [19].

1.2.2 Link-16 J-Series Messages

Link-16 has a specific message format called J-Series messages. These messages are generally produced by DLP software. Some J-Series messages can be produced by Link-16 terminal such as PPLI messages which belong to the remote terminal.

All messages have specific label and sub-label. Whereas labels are three bits, sub-labels are two bits. So labels are up to 0-31 and sub-labels are up to 0-7.

Example: J3.2 Air PPLI message's label is 3, and sub label is 2.

J12.0 Command and Control message's label is 12, and sub-label is 0.

All messages have a specific role for Link-16 networks. Messages are totally 32x8=256. Table 1.1 shows Link-16 messages and their operational purposes.

Table 1.1 Tactical information of Link-16 messages [20].

Network Management	J8.0 Unit Designator
J0.0 Initial Entry	J8.1 Mission Correlator Change
J0.1 Test	**Weapons Coordination and Management**
J0.2 Network Time Update	J9.0 Command
J0.3 Time Slot Assignment	J10.2 Engagement Status
J0.4 Radio Relay Control	J10.3 Hand Over
J0.5 Repromulgation Relay	J10.5 Controlling Unit Report
J0.6 Communication Control	J10.6 Pairing
J0.7 Time Slot Reallocation	**Control**
J1.0 Connectivity Interrogation	J12.0 Mission Assignment
J1.1 Connectivity Status	J12.1 Vector
J1.2 Route Establishment	J12.2 Precision Aircraft Direction
J1.3 Acknowledgment	J12.3 Flight Path
J1.4 Communication Status	J12.4 Controlling Unit Change
J1.5 Net Control Initialization	J12.5 Target/Track Correlation
J1.6 Needline Participation Group Assignment	J12.6 Target Sorting
Precise Participant Location and Identification	J12.7 Target Bearing
J2.0 Indirect Interface Unit PPLI	**Platform and System Status**
J2.2 Air PPLI	J13.0 Airfield Status Message
J2.3 Surface PPLI	J13.2 Air Platform and System Status
J2.4 Subsurface PPLI	J13.3 Surface Platform and System Status
J2.5 Land Point PPLI	J13.4 Subsurface Platform and System Status
J2.6 Land Track PPLI	J13.5 Land Platform and System Status
Surveillance	**Electronic**
J3.0 Reference Point	J14.0 Parametric Information
J3.1 Emergency Point	J14.2 Electronic Warfare Control/Coordination
J3.2 Air Track	**Threat Warning**
J3.3 Surface Track	J15.0 Threat Warning
J3.4 Subsurface Track	**National Use**
J3.5 Land Point or Track	J28.0 U.S. National 1 (Army)
J3.6 Space Track	J28.1 U.S. National 2 (Navy)
J3.7 Electronic Warfare Product Information	J28.2 U.S. National 3 (Air Force)
Antisubmarine Warfare	J28.2 (0) Text Message
J5.4 Acoustic Bearing and Range	J28.3 U.S. National 4 (Marine Corps)
Intelligence	J28.4 French National 1
J6.0 Intelligence Information	J28.5 French National 2
Information Management	J28.6 U.S. National 5 (NSA)
J7.0 Track Management	J28.7 UK National
J7.1 Data Update Request	J29 National Use (reserved)
J7.2 Correlation	J30 National Use (reserved)
J7.3 Pointer	**Miscellaneous**
J7.4 Track Identifier	J31.0 Over-the-Air Rekeying Management
J7.5 IFF/SIF Management	J31.1 Over-the-Air Rekeying
J7.6 Filter Management	J31.7 No Statement
J7.7 Association	

Link-16, MSEC (Message Security) is applied to the J-Series messages only. At the physical layer, TRANSEC (Transmit Security) is applied to the entire transmission. The TRANSEC techniques include random-start interleaving, chip scrambling, frequency hopping and timing jittering [21].

1.2.3 Link-16 Architecture

Link-16 uses two main principals. These are TDMA and FDMA. By using TDMA architecture, platforms share times for communication. Platforms communicate with other platforms in their specific times. By using FDMA architecture, platform groups are separated from other groups. There is no need for these groups to communicate each other.

1.2.3.1 Link-16 TDMA Architecture

Link-16 System uses an architecture which is known as TDMA. TDMA is not a system unique to Link-16, additionally being used some communication systems, such as phones, mobile phones etc.

TDMA is designed to ensure multiple users with a near real-time communication and all users exchange data as full duplex communication effectively. All JU participants have unique time in order to send data in a fixed period.

The basis of TDMA is a cycle known as the Epoch. The 24 hour day is divided into 112.5 epochs. Each epoch is 12.8 minutes long. The Epoch is further broken down into 98.304 time slots, each of which is 7.8125 millisecond in duration (Figure 1.10/1.11). All participants share these time slots for transmission and receptions.

To simplify the architecture, Epochs are further divided into 64 frames which are twelve seconds. Each frame contains 1536 time slots and these time slots are grouped into three sets. They are SET A, SET B and SET C.

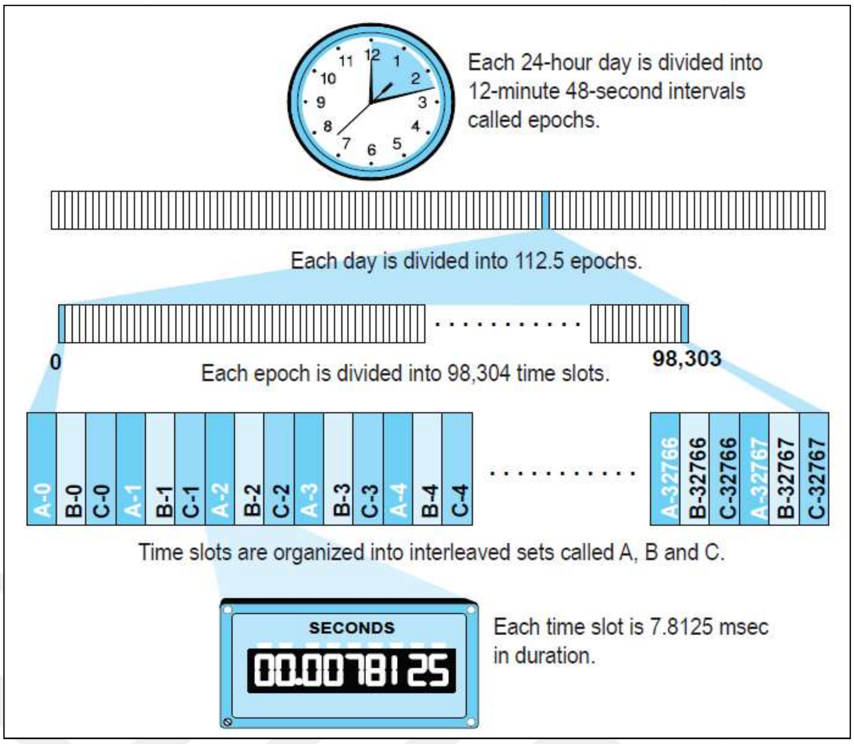


Figure 1.10 Link-16 TDMA architecture [4]

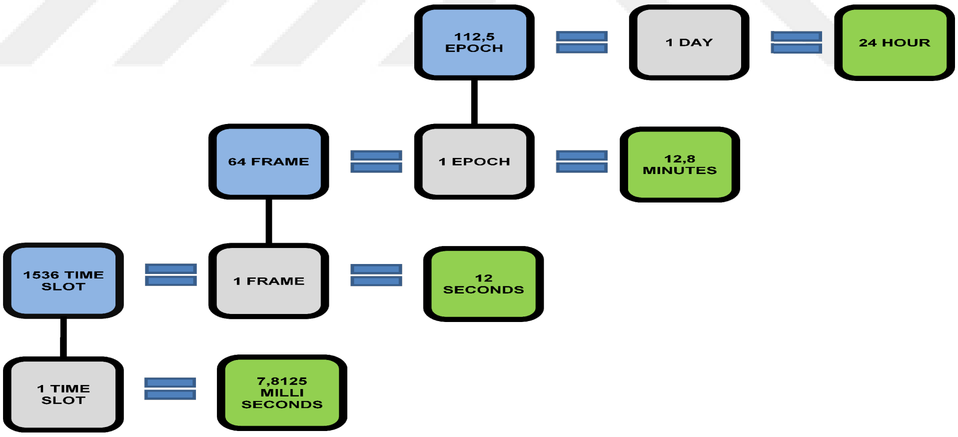


Figure 1.11 Summary of Link-16 TDMA architecture

Link-16 occupies 969-1206 MHz and achieves jam resistance with a waveform that incorporates direct sequence spreading, time jitter, and frequency hopping. As a Time-Division Multiple Access (TDMA) system, all users are synchronized, and transmissions occur only during precisely defined time slots [22].

Link-16 uses Time Division Multiple Access; therefore, nets and time slots should be allocated to protect from collisions. The nets and time slots are manually and statistically allocated to participants by operational or technical experts [23].

Then the allocated information is installed to all nodes before the system starts. The nodes can exchange data without collisions. This work is called Link-16 network design [23].

1.2.3.2 Link-16 FDMA Architecture

Link-16 uses 51 discrete frequencies and uses frequency hopping period own special depending on crypto. Within each time slot, the MIDS transmitter and receiver changes frequency up to 77000 times per second, hopping between the 51 frequencies according to a pattern determined by MIDS crypto. Link-16 signal consists of 6.4-microsecond pulse and 6.6-microsecond duration (Figure 1.12).

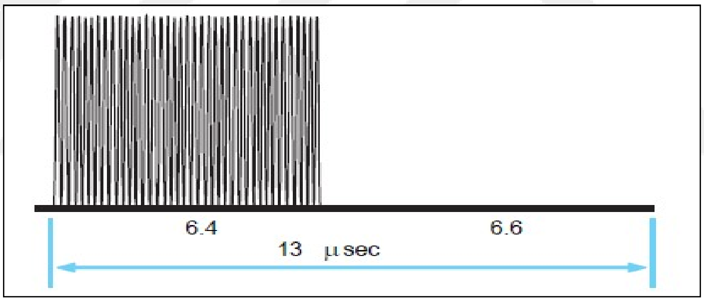


Figure 1.12 Simple Link-16 pulse

The system uses a wide frequency band from 960 to 1215 MHz. The identification friend or foe (IFF) transponders used by civilian and military aircraft operate at 1030 MHz and 1090 MHz. These two frequencies have been reduced from the Link-16 frequency band by filtering [25].

Link-16 Terminal, by using frequency hopping transmission, divides the frequency band of 960MHz~1215MHz into three frequency hopping sections. These are 969~1008MHz, 1053~1065MHz and 1113~1206. Thus, it keeps out from the tactical navigation system and IFF (identification friend-or-foe) frequencies in the same frequency section [24].

The frequency hopping space of Link-16 terminal is 3MHz with 51 frequencies in total [24]. One of those hopping frequencies is random. And time difference between them is 13 μsec [26]. Link-16 data may be transmitted as either single or double pulse. Pulse quantity is related to the amount of data to be transmitted [27].

Link-16 uses different nets by means of FDMA. A single net means that each network member has the same crypto and the same net number. The structure of single net is shown in Figure 1.13. For each time slot in a Link-16 net, network members can be used to send or receive messages. They avoid data conflicts. And each time slot can have only one network member to send messages [28].

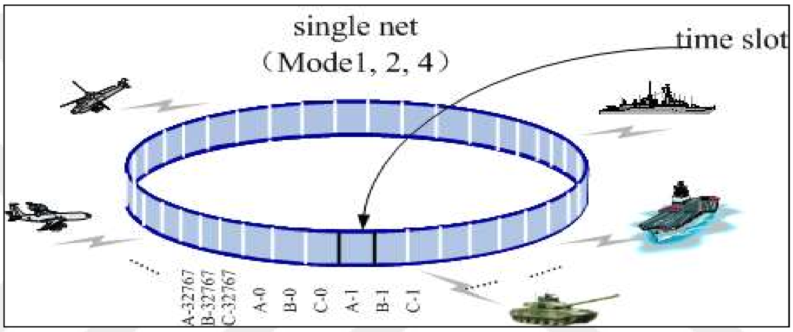


Figure 1.13 Link-16 with a single net [28]

The structure of Link-16 with multiple nets is formed by a number of overlapping nets. As shown in Figure 1.14, by allocating network members in multiple nets, the capacity of Link-16 can be extended to work simultaneously. By assigning different frequency hopping patterns to different nets, the multiple nets can be achieved. The frequency hopping pattern show differences according to crypto, net ID and time slot ID. Each net is able to work independently so that multiple nets can work in parallel [28].

With high precise timing, slots assignment and net manage mechanism, Link-16 composes a non-central management unit network. This network structure greatly developed the determination and continuity of the entire net. More than one Link-16 net can exist in the same place and time. Different net can be distinguished with a 7-bits net number, so up to 127 maximum potential net could exist in the same place and time. However, only up to 20 and 30 can exist at the same time without interfering with one another during actual operations [29].

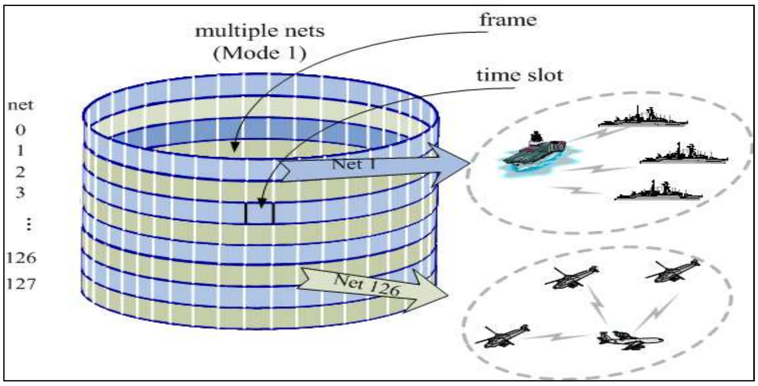


Figure 1.14 Link-16 with multiple nets [28]

1.2.3.3 Link-16 Transmit and Receive Models

Waveform used in Link 16 transmits data by using 32 chips and 32-ary cyclic code shift keying (CCSK) symbols. Random sequences are used to generate the CCSK waveforms (Table 1.2). The system employs a (31, 15) Reed-Solomon (RS) code [30]. Although Link-16 has very limited effective bandwidth for image transfer (e.g., roughly 30 to 340 Kbps divided among all aircraft communicating with a common JTIDS terminal), it is widely used for tactical communication between military aircraft [31].

Table 1.2 32-Chip CCSK sequence chosen for Link-16 [32].

5-bit symbol	32-chip CCSK sequence chosen for JTIDS
00000	S_0 = 01111100111010010000101011101100
00001	S_1 = 11111001110100100001010111011000
00010	S_2 = 11110011101001000010101110110001
⋮	⋮
11111	S_{31} = 00111110011101001000010101110110

The system model of a JTIDS-type transmitter is shown in Figure 1.15. According to this figure, the transmitter consists of a (31, 15) RS encoder, a symbol interleaver, a CCSK 32-ary baseband symbol modulator, a data chip scrambler, a frequency-hopping circuit, an MSK chip modulator and a transmitting antenna.

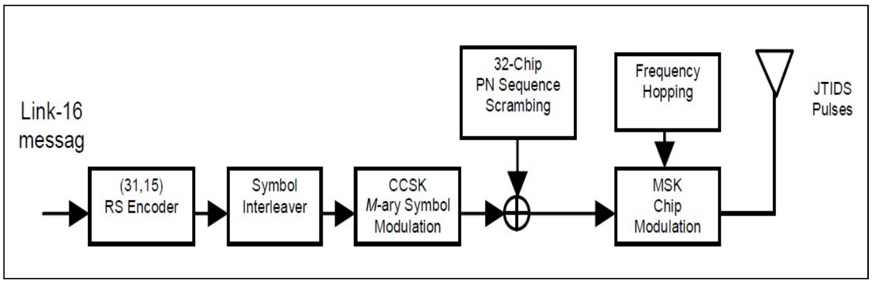


Figure 1.15 Model of Link-16 transmitter [33]

At the receiver (Figure 1.16), the receiving process is the reverse of the transmission process. All parts of the receiver are the same as a transmitter.

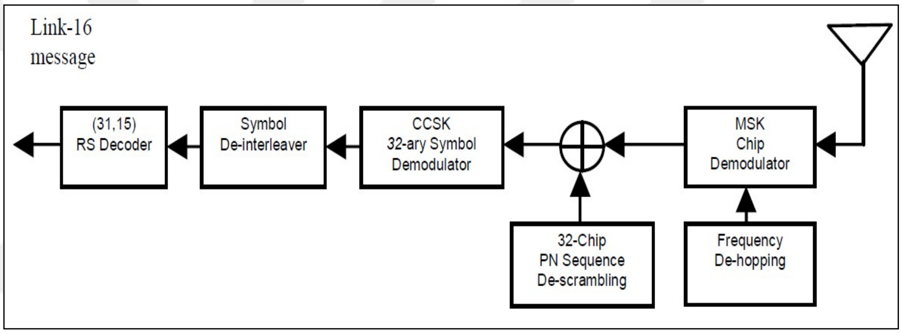


Figure 1.16 Model of Link-16 receiver [33]

As a result, Link-16 waveform is a hybrid of direct sequence/frequency-hopping spread spectrum system and Reed-Solomon (RS) codes with channel coding [34].

Tactical Data Link Communication System is mainly planned for rapid and secure information exchange. For digital sound transmission, a BER (bit error ratio) of 10^{-4} and even 10^{-3} is suitable. But for data transmission in TDL, a BER of 10^{-4} cannot be acceptable [35].

One shortcoming of Link-16 terminal is the limited data throughput, which decreases its effectiveness for the transmission of mass data such as Intelligence, Surveillance, and Reconnaissance (ISR) imagery or live video feeds. This shortcoming limits its usage to situational awareness functions, command and control and derivative functions such as weapons guidance [36].

However, Link-16 Enhance Throughput (LET) feature which is added to Link-16 will upgrade TDL data rate up to 1.1 Mbps. Implementation of LET includes modification of the Link-16 baseband coding, in terms of error detection and correction capabilities [37].

The introduction of LET would allow significant improvements of the current Link-16 networks. These improvements are providing more participants and more available information in a network, obtaining more reliable air picture thanks to reduced latency and higher data-flow, and getting operational networks with full Electromagnetic Compatibility (EMC) [37].

1.2.3.4 Link-16 Time Synchronization

Link-16 has defined roughly two type synchronization mechanism. These are GPS synchronization and Network Time Reference (NTR) synchronization. In GPS synchronization method, all participants must have an external time reference. When all platforms synchronize with GPS, they will become synchronized with each other.

NTR time synchronization method operates in two modes during synchronization process: passive mode and active mode. Passive mode is applied when a node is in silence mode due to the need of “low probability of intercept”, especially in stealth-capable fighter [38].

Passive mode is intrinsic to RELNAV (Relative Navigation) function [38]. In passive mode, the participant uses other participants PPLI messages to join Link-16 Network.

Active mode occurs when a node that wants to receive time synchronization exchanges messages with NTR in order to synchronize with it. There are two phases in active mode: course synchronization and fine synchronization. After two phases platform can join Link-16 Network [39].

Course Synchronization

Coarse synchronization is the first phase of active mode. To support the entry nodes that attempt to join the network, NTR transmits an Initial Entry Message (IEM) in an IEM slot [40].

The IEM slot is the first time slot in every frame. Coarse synchronization begins by listening to an IEM. When the terminal listens to an IEM message, network time synchronization can be achieved. However, it can be an error due to propagation delay [40].

Fine Synchronization

After coarse synchronization, the joining terminal transmits a round-trip timing interrogation (RTT-I) message to the NTR to obtain fine synchronization. In coarse synchronization, the terminal has time synchronization, but this synchronization has an error of propagation delay. In fine synchronization, error propagation delay is absent. In Link-16, the node exchanges an RTT messages with NTR to calculate the propagation delay error [40] (Figure 1.17).

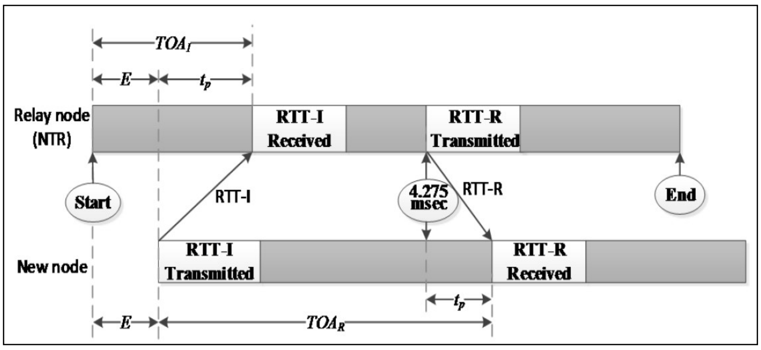


Figure 1.17 Process of exchanging RTT messages [40]

$$t_p = TOA_I - E \quad (1)$$

$$t_p = TOA_R + E - (4.275 \times 10^{-3}) \quad (2)$$

$$E = \frac{TOA_I - TOA_R + (4.275 \times 10^{-3})}{2} \quad (3)$$

Figure 1.18 Equations for calculating delay time [40]

Equations (1) and (2) calculate the transmission time (propagation delay) of the network. Equation (3) is easily derived from (1) and (2) (Figure 1.18).

1.3 Link-22 Tactical Data Link

As part of the Improved Link-11 program, NATO is currently developing the Link-22 system [41].

For approximately fifty years, NATO Link-11 has been used by many nations. Link-11 has been replaced by Link-16 in many tactical functions, even though it is still widely used. But, either Link-11 or Link-16 is not able to fully ensure the tactical communications requirements in Electronic Protective Measures (EPM) capabilities and in comprehensive message catalog required for modern naval operations. So as to solve these problems, NILE (NATO Improved Link Eleven) program was started in March 1990.

The original requirements were adjusted in 1994. These aims were to replace Link-11 with a system working at the same frequency, to complement Link-16 operations, to improve allied interoperability and to make uninterrupted multimedia operations.

Link-22 provides improvements in the following ways;

- The parallel tone modem used in Link- 11. It is replaced by a single tone modem of the sort used in most current HF data communication applications. Both of them occupy 3 kHz bandwidth.

- Link-22 uses a TDMA network protocol. But Link-11 uses the interrogation-response protocol. Each member of the network is assigned a number of 112.5 ms slots in the TDMA format.

- Link-22 uses 72 bit F-series messages. (It is quite similar to the 70 bit J-series messages of Link 16. Link-11 uses 48 bit M-series messages.) [41]

1.3.1 Link-22 System Architecture

It is used a layered communications to produce open system architecture, with well-defined interfaces between the subcomponents by the design of Link 22.

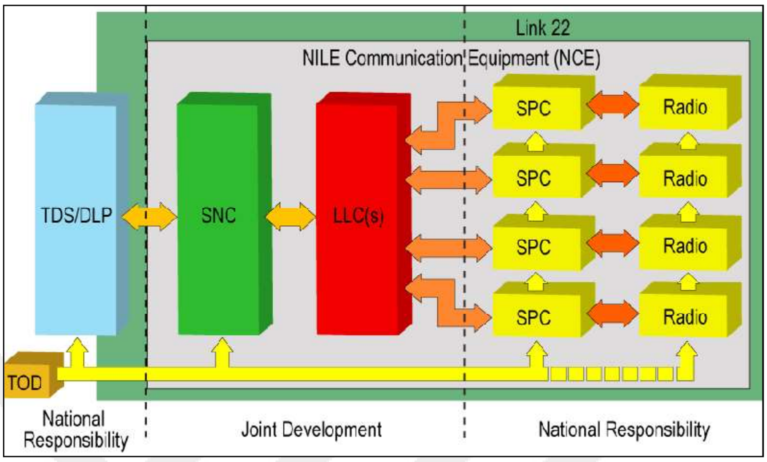


Figure 1.19 Link-22 architecture [42]

The approach maximizes extensions and enables contributions from multiple providers. NILE Communications Equipment (NCE) components have been shown by the gray box in the figure. These components are System Network Controller (SNC), Link-Level COMSEC (LLC), Signal Processing Controllers (SPCs) and Radios (Figure 1.19).

The Link 22 system which is shown by the outer green box in the figure consists of the NCE and the Link 22 portion of the Data Link Processor (DLP). Within the DLP, this consists of the interface to the SNC. The DLP handles the tactical messages that it transmits and receives on the data link [42].

The tactical messages are defined in the NATO Standardization Agreement [STANAG 5522]. The DLP is connected to the Tactical Data System (TDS) and it is also known as Host System of the NILE unit. Indeed, DLP processes the received tactical messages and generates tactical messages for transmission in accordance with the unit's national requirements [42].

All NILE system components have been jointly defined and designed. The SNC and LLC subsystems have been commonly developed. The development of all other Link

22 subsystems is a national or manufacturer's responsibility. Time of Day (TOD) is the time source of Link-22 equipment [42].

1.3.2 Link-22 Media

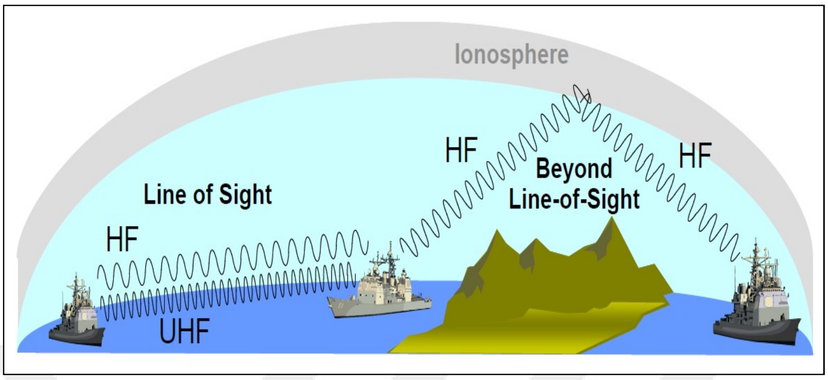


Figure 1.20 Media of Link-22 TDL [42]

Link-22 media which uses high frequency (HF) band provides Beyond Line-of-Sight (BLOS) communications and it is optimized for transmissions up to more than 300 nautical miles. Media using Ultra High Frequency (UHF) band provides Line-of-Sight communications only. Within both bands, either fixed frequency or frequency hopping radios may be employed, for a total of four different media types. These are HF Fixed Frequency, UHF Fixed Frequency, HF Frequency Hopping, and UHF Frequency Hopping [42].

Each media has one or more different settings, which use different modulation and encoding schemes. Along with the fragmentation rate, these factors determine the number of bits per network packet that are available for transmission [42].

1.3.3 Link-22 Super Network

Link 22 Super Network is an operational Link 22 system. A Link 22 Super Network consists of minimum two units communicating with each other. The most complex Link 22 Super Network may contain maximum 125 units with eight NILE Networks.

A unit participating within the Link 22 Super Network can be a member of up to four of the NILE Networks. A complex Link-22 Super Network is shown below [42] (Figure 1.21/1.22).

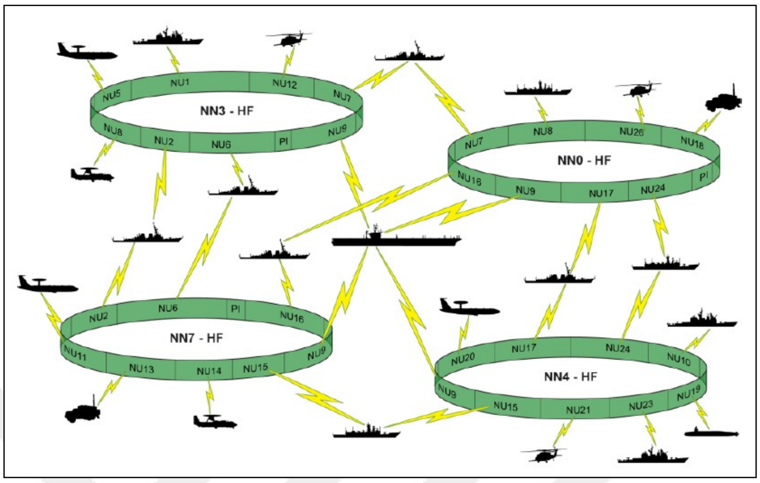


Figure 1.21 Example 1 of Link-22 Network [42]

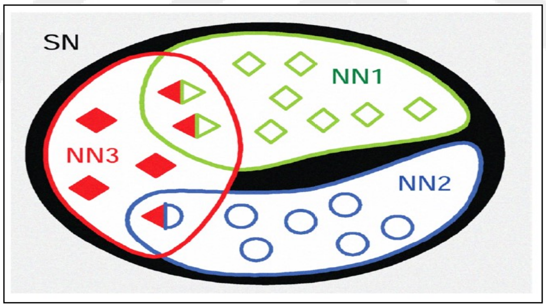


Figure 1.22 Example 2 of Link-22 Network [43]

A Link 22 net consists of a Super Network (SN). In an SN, there are up to 125 NILE Units (NUs). One designated NU will behave as SN management unit (SNMU). The SN consists of maximum eight NILE Networks (NNs). Each is composed of a subset of all NUs [43].

NUs are able to simultaneously participate in maximum four NNs. It is provided that the corresponding RF radios are available. In sometimes, NUs can forward messages between NNs [43].

1.3.4 Link-22 TDMA Architecture

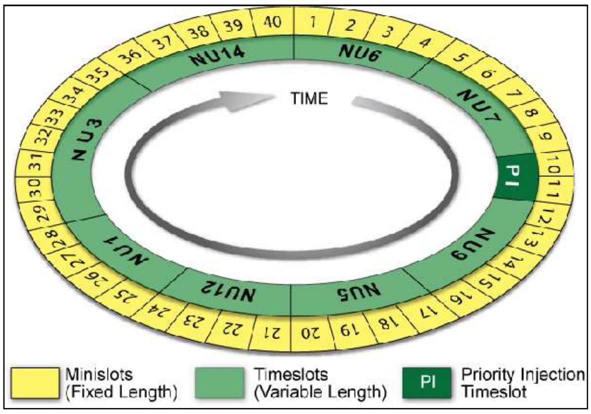


Figure 1.23 Link-22 Network cycle structure [42]

For each NILE Network (NN), TDMA protocol is defined by The Network Cycle Structure (NCS). An NN is operating with a common RF and communication medium, administrated by a network management unit (NMU), organized as a dynamic TDMA structure [43].

TDMA structure is composed of transmission slots which have constant length mini-slots (MS) and variable length transmission slots. These transmission slots are assigned to each NU which is a member of the NN. Synchronization is guaranteed by Coordinated Universal Time (UTC) access. A timeslot is either allocated to a specific NILE unit or is a Priority Injection timeslot. A unit may only transmit in its allocated timeslot(s) or for certain high-priority messages. It may also transmit them in a Priority Injection timeslot. This provides that each unit has an opportunity to transmit at least once within a given period of time, called the Network Cycle Time (NCT) [43].

The NCT is the number of mini-slots that form the network cycle (sum of the length of all timeslots). The NCT in Figure 1.23 is 40 mini-slots; however, this can vary up to a maximum of 1024 mini-slots. An NCS can be defined by the planners in the OPTASK Link Message (OLM) which is planned link communication. The planners take into account how many tactical messages per second a unit will need. When the NCS is defined in the OLM, the DLP will initialize the network with the supplied NCS [42].

1.3.5 Link-22 Messages

Link-22 Messages fall into two categories. These are F-Series Messages which are unique to Link-22 and FJ-Series Messages which have been directly extracted from the J-Series message catalog. The first bit of Link-22 messages indicates that this message is F Series Message (Link-22 unique) or FJ Series Message (Link-22 non-unique). This bit is known as Series Indicator (SI). Link-22 messages are used for the exchange of information among Link-22 users. These messages consist of up to 8 words and each word consists of 72 bits.

1.4 Variable Message Format (VMF)

U.S. Department of Defense developed the VMF standard to allow messages of variable lengths to be sent over TDLs. A VMF message is bit-oriented and attempts to minimize the use of TDLs by sending only the required data. The objective is to be flexible enough to be able to communicate with any legacy. And new host requiring additional header fields can be added without modifying the underlying specification. VMF is independent of communication media, in this way hardware can be very small volume and portable by humans [44].

1.4.1 VMF Structure

The core of the VMF protocol is the Protocol Data Unit (PDU) which contains the header and the user data, much like a typical TCP/IP packet. The PDU is processed at the application layer and is composed of the application header and the user data, which can be multiple formats [44].

1.4.2 VMF Functional Areas

Functional Areas (FA) are the major Operational areas into which the K-Series messages used by VMF TDL. VMF Functional Areas resemble Link-16 Network Participation Groups (NPGs). These Functional Areas identify the K-Series Messages group. Each message is sent and received in its own group.

Table 1.3 VMF functional areas [4].

Message Designator	Warfare Functional Area
K00.Y	Network Control Messages
K01.Y	General Information Exchange Messages
K02.Y	Fire Support Operation Messages
K03.Y	Air Operations Messages
K04.Y	Intelligence Operations Messages
K05.Y	Land Combat Operations Messages

1.4.3 VMF Messages

VMF messages are designated with an initial "K" and as such are known as the K-series messages. The numbering convention used for VMF messages is "Kx.y", where "x" is the FAD and "y" is the message number assigned sequentially. As such, Kx.1 is the assigned to the first message of all currently defined messages within a functional area. For example, K05.1 is the numbering convention for the Land Combat Operations functional area Position Report message [4]. VMF data is able to send to Link-16 Network successfully by special methods [45].

Table 1.4 Example of VMF messages [4].

Message Number	Message Title	Message Purpose
K02.27	Close Air Support Request	To request immediate or preplanned close air support.
K02.28	Close Air Support Mission Battle Damage Assessment (CASBDA) Report	To report battle damage assessment after the completion of a CAS mission.
K02.31	Mission Request Rejection	To inform a requestor that a planned or immediate CAS mission(s) request is rejected.
K02.32	Close Air Support Request Acceptance	To inform command and control agencies that a close air support mission request has been accepted for a planned or immediate mission.
K02.33	Close Air Support Aircrew Briefing	To provide aircrews all essential information for a close air support mission.
K02.34	Aircraft On-Station	For the pilot or flight leader to notify the control agency that he and his flight have arrived at the prescribed control station.

1.5 Joint Range Extension Application Protocol (JREAP)

The JREAP protocols provide TDL information to transmit and receive by using digital media. Additionally, TDL messages are embedded to JREAP messages and these composite messages are sent by satellites or terrestrial devices. At the same time, JREAP has specific functions in order to ensure data communication effectively. JREAP specific functions are to extend the range-limited TDL messages to Beyond Line Of Sight (BLOS), to reduce dependence on relay platform, to minimize data loading in network used frequently, to generate an alternative connection to TDLs in case of loss communication, to provide communication for platforms which have not capability of any TDLs.

1.5.1 JREAP Message Structure

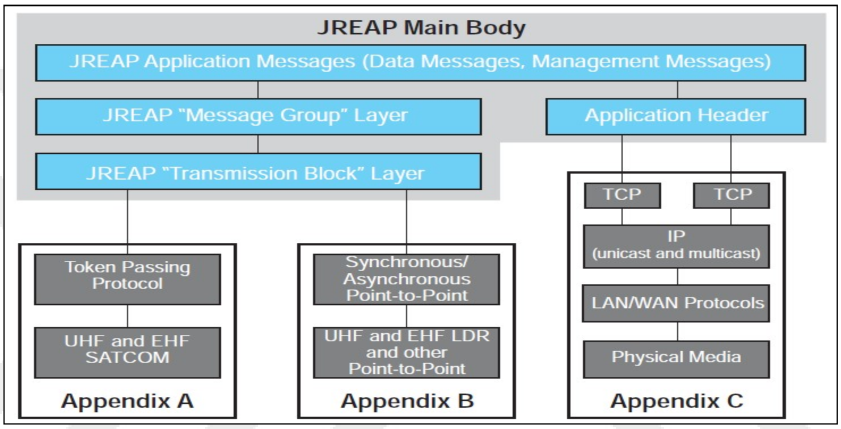


Figure 1.24 Structure for JREAP messages [4]

JREAP has three main message structures to send or receive a message to other JREAP participants. These are JREAP-A, JREAP-B and JREAP-C. All protocols have specific Appendix in NATO STANAG.

1.5.2 JREAP -A

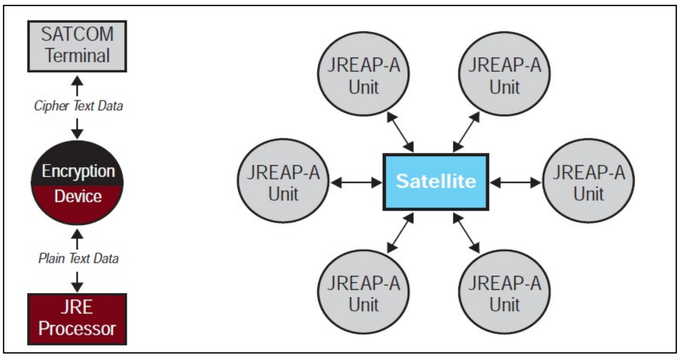


Figure 1.25 Example of JREAP- A network [4]

JREAP-A uses a token passing protocol over half-duplex communication channels to send and receive Tactical Data Link messages. JREAP-A implements the full-stack header and uses a token passing protocol, where one unit is allocated a particular period of time to transmit data while all other units listen and receive the data. JREAP-A is commonly used over 25kHz Ultra High Frequency (UHF) Demand Assigned Multiple Access (DAMA)/Time Division Multiple Access (TDMA), Extremely High Frequency (EHF) Low-Data-Rate (LDR), and 5/25kHz UHF Non-DAMA SATCOM systems. These communication links are multi-participant satellite communication networks [4].

1.5.3 JREAP -B

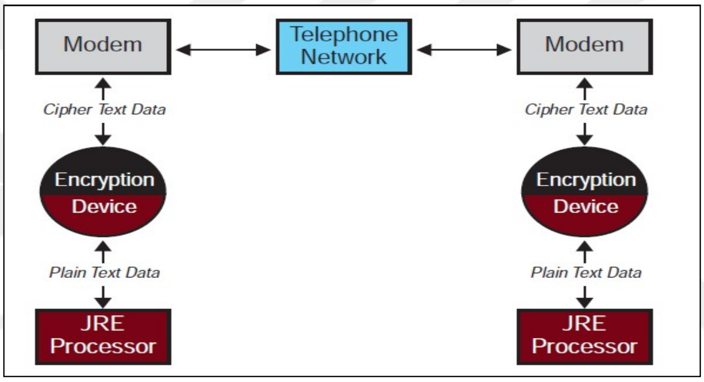


Figure 1.26 Example of JREAP- B network [4]

JREAP-B is used in synchronous or asynchronous point-to-point communications. JREAP-B is commonly used with full-duplex serial data communications carried by protocols such as TIA/EIA RS-232 and RS-422 and implements the full-stack header of the JREAP protocol. These communication networks can be local, or they can use long haul transmission media such as secure telephone circuits [4].

1.5.4 JREAP -C

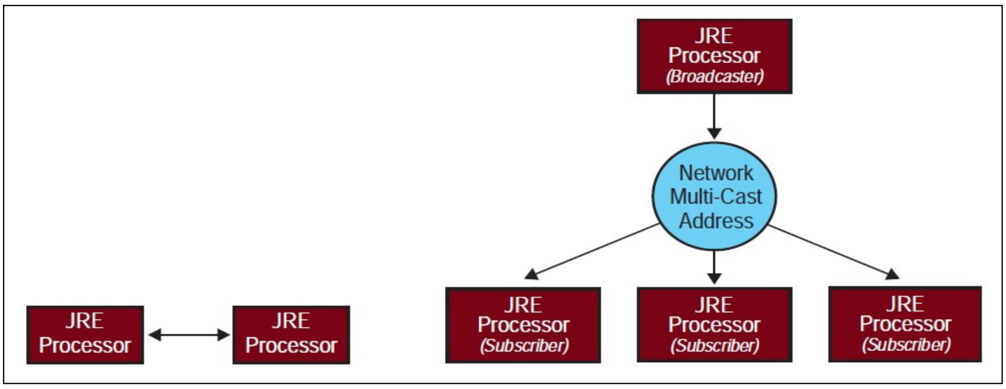


Figure 1.27 Example of JREAP- C network [4]

JREAP-C is an implementation of the JREAP protocol that transmits Tactical Data Link messages over Internet Protocol networks such as Secret Internet Protocol Router Network (SIPRNET). JREAP-C differs from JREAP-A and JREAP-B by implementing the application header instead of the full stack header. This is done because of the error detection and correction. And addressing is not necessary as they are handled by the lower layers of the stack. This permits fast and reliable transmission of messages over a network [4].

JREAP-C defines two modes of operation which are unicast and multicast. Unicast operations are used to send data link messages to a particular unit and operate as a one-to-one or peer-to-peer data link. Multicast operations are used to broadcast data link messages to a collection of users [4].

CHAPTER 2

OPTIMIZATION THEORY

2.1 Definition of Optimization

Optimum is a Latin word meaning final ideal. Optimization can be defined as the process of finding the best solution or design of a problem. Engineers are required to take decisions in the design, manufacturing or maintenance phases. The ultimate aim of these decisions is to keep capital, material or technology in the minimum effort and to keep profit maximum level. Optimization is therefore defined as the process of finding the conditions that will achieve the intended maximum or minimum [46].

2.2 Basic Concepts of Optimization

The mathematical definition of a general optimization problem consists of three parts. These are Decision Variable, Objective function and Constrains [47].

2.2.1 Decision Variable

Decision variables are used to find the optimum value. These variables can be harvesting rate or effort, the level of investment, distribution of tasks, parameters etc. Our objective is to find the *best* value for the decision variable. The decision variable is denoted by x, y, z, d, k, etc. Variables can be a number, a vector, a sequence, a function, a matrix, etc [47].

2.2.2 Objective Function

The size to be optimized as maximum or minimum is called the objective function. A system may have more than one possible solution. Some of these may be better than others. For this reason, it must be a criterion to compare these alternative designs. Such criteria are called objective function and as depending on the requests, they are either minimum or maximum value searched. For example, minimize the cost, minimize the weight, maximize the profits and minimize the use of energy [46].

2.2.3 Constraints

The limits on value of parameters are called as constraints. These are the functions which affect our decision and limit the values that the decision variables can take. For example;

- The structure must be able to carry the loads that have come on without any damage.
- The life of a machine element subjected to a cycling loading must be 1 million cycles (minimum).
- Dimensions of a machine element must not exceed available amounts of space [46].

2.3 Graphical Optimization

Graphical optimization is the optimization without the use of mathematical methods in the solution of the optimum solution to find the optimal solution with the help of graphs drawn. Since graphical optimization involves finding the optimal resulting goal and constraint functions by obtaining equilibrium curves, the MATLAB program can be used to obtain these graphs [48].

2.4 Classical Optimization Techniques

Classical optimization techniques use differential analysis techniques to find minimum values of continuous and derivable functions. This technique also forms an infrastructure for more advanced techniques [49].

2.4.1 Necessary and Sufficiency Conditions

To determine whether the optimization results are the actual optimum value in the applications or not, necessary and sufficient conditions are taken into consideration [49].

Necessary Condition is called the conditions that must satisfy the conditions at the optimum point. That is, if no point provides the necessary conditions, there is no optimum point in this problem. However, the point that satisfies the requirements may not be optimum or may not be a single point. Points that meet the requirements are called candidate points. Therefore, other conditions are needed to separate the optimum and non-optimal points. These conditions are called as sufficiency conditions [49].

A point is Sufficienc*y* Condition Optimum Point if it satisfies the conditions and there is no need to perform further tests. However, in situations where these conditions are not met or are not being used, it cannot be said that any of the candidate points is not optimal [49].

Summary,

- Optimum points should provide the necessary conditions. Points that do not fulfill these conditions can not be the optimum point.
- A point that meets the necessary conditions may not be optimal; That is, it can provide the necessary conditions at non-optimal points.
- A candidate point that provides sufficiency conditions is really optimal.
- If sufficient conditions are not used or calculated, we cannot conclude that candidate points are optimal [49].

2.4.2 Single-Variable Optimization

A function of one variable f (x) is said to have a local minimum or relative minimum at $x = x*$, if $f(x*) \leq f(x* + h)$ for all sufficiently small positive and negative values of h. Similarly, a point $x*$ is called a local maximum or relative maximum, if $f(x*) \geq f(x* + h)$ for all values of h sufficiently close to zero [50].

A function f (x) is said to have a global minimum or absolute minimum at $x*$, if $f(x*) \leq f(x)$ for all x, and not just for all x close to $x*$, in the domain over which f (x) is defined. Similarly, a point $x*$ will be a global maximum of f (x), if $f(x*) \geq f(x)$ for all x in the domain [50].

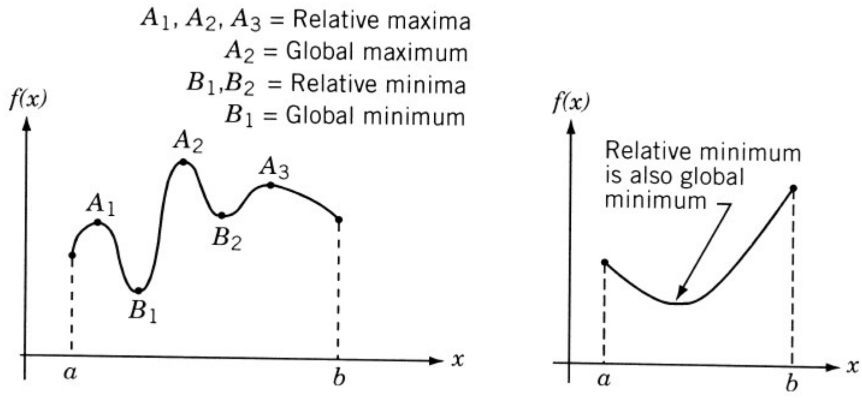


Figure 2.1 Local and Global Maxima/Minima [50]

In Figure 2.1; while A_1, A_2 and A_3 are local maxima, A_2 is a global maximum. Additionally, while B_1 and B_2 are local minima, B_1 is the global minimum.

2.4.3 Multi-Variable Optimization

In order to have a maximum or minimum value at $x = x*$ for multi-variable f (x), the requirement is expressed as follows:

$$\frac{\partial f}{\partial x_1}(x^*) = \frac{\partial f}{\partial x_2}(x^*) = \cdots = \frac{\partial f}{\partial x_n}(x^*) = 0 \qquad (2.1)$$

Figure 2.2 Multi-variable equation [49]

A sufficient condition for the candidate point to have a maximum and minimum value depends on the definition of the matrix of second-order partial derivatives of the function [49].

2.4.4 Constrained Optimization

As mentioned in the previous sections, the majority of optimization problems involve constrained functions. In unconstrained optimization problems, the optimum value determines the structure of the objective function. However, constrained functions in constrained optimization play an important role in finding an optimum solution [51].

Constrained optimization problems are divided into two parts as depending on the type of constraint. These are Equality Constraint and Inequality Constraint. Each different approach is used to obtain the optimal solution [51].

2.4.4.1 Equality Constraint

The equality constraints include optimization problems as follows;

$$\min f(x)$$

s.t.

$$g_j(x) = 0, \quad j = 1,2,\ldots m$$

$$x = [x_1, x_2, \ldots, x_n]^T$$

Figure 2.3 Example of equality constraint [51]

In Figure 2.3, m and n denote the number of restrictive functions and design variable, respectively. It has to be $m \leq n$ to reach the optimum solution. If $m>n$, the problem is over defined; in other words, there are too many constraints involved in the problem and there is no solution [51].

2.4.4.2 Inequality Constraint

The inequality constraints include optimization problems as follows;

$$\min f(x)$$

s.t.

$$g_j(x) \leq 0, \quad j = 1,2,\ldots m$$

$$x = [x_1, x_2, \ldots, x_n]^T$$

Figure 2.4 Example of inequality constraint [51]

The requirements for both equality and inequality optimization problems can be compiled as requirements of Kuhn-Tucker. The Kuhn-Tucker requirements are used to check whether a given point is likely to be optimal or to determine the candidate minimum points. The important point is presented in below:

- K-T conditions are only applied at regular (regular) points.
- The points that do not satisfy the K-T conditions can not be the local minimum if they are not irregular points. The points that satisfy K-T requirements are called Kuhn-Tucker points.
- Points that satisfy K-T requirements may be constrained or unconstrained.
- If there is equality constrained and none of the unequal constraints are active, these are the stationary points that provide K-T conditions. So these points can be a minimum, maximum or turning points [51].

CHAPTER 3

OPTIMIZATION OF SOME TACTICAL DATA LINKS

Current fielded multi-tactical data link (MTDL) networks consist of complex legacy equipment which requires specialized and extensive training. This problem persists across both Army and Naval MTDL networks. So, tactical networks admittedly face a much more challenging environment such as including lack of fixed infrastructure, unparalleled security requirements and a reverse economy of scale [52].

In the modern operational area, operations are more complex because of advancing technology. During complex operations, communication is the most important factor in terms of attaining of the objective.

Wide variety platforms operate in battle space area such as Fighters (F-16s), Airborne Early Warning Command and Control Aircraft, Ships, Ground Command and Control Centers, Surface to Air Missiles etc.

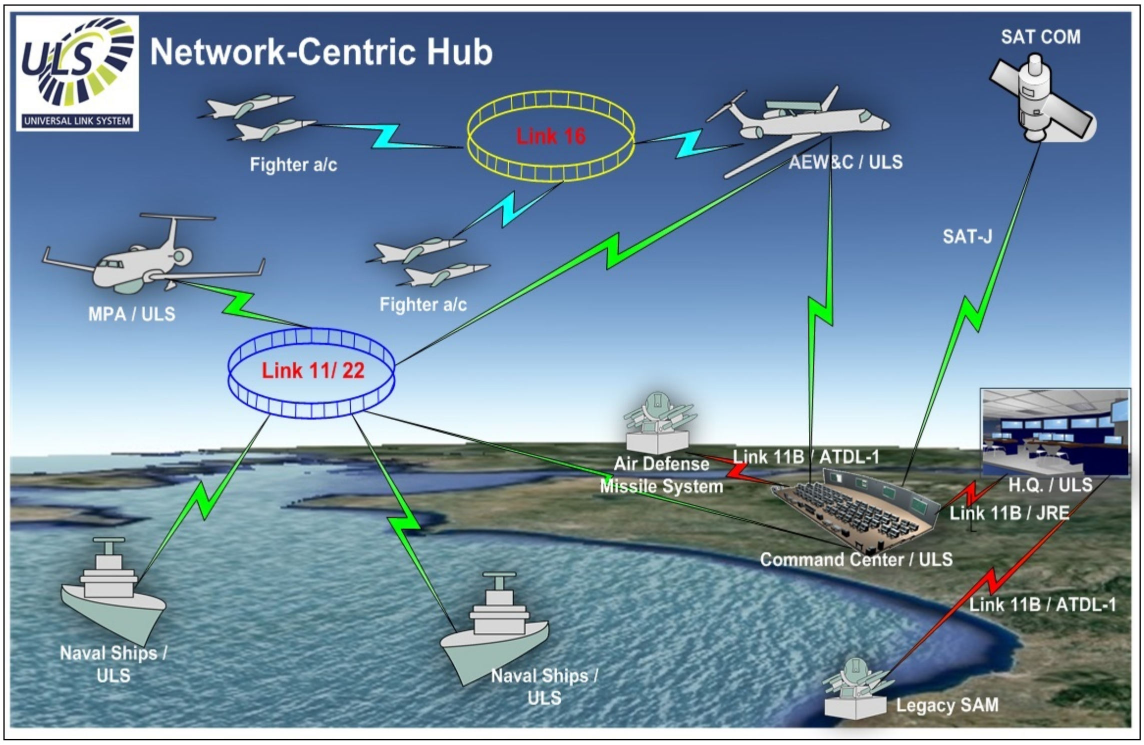


Figure 3.1 Example of Operational Area [53]

These platforms have a variety of missions. While some F-16s intercept hostile aircraft, other F-16s can make bombardment critical place of the enemy. And these platforms can have different capability used in the operational area.

According to platform aerodynamic structure, capabilities show diversity. For example; Fighters must be very fast, must have excellent aerodynamic and its volumes are small size. That's why, communication devices of fighters need to be pluggable size. However, the naval platform is a perfect condition regarding it has plenty of places to plug communication devices. Only TDL having low volume terminal can be implemented in too fast platforms.

Additionally, operational platforms have much varieties of TDL. In the theater of war, it is very important to send the right data in the right TDL. If we don't send the data by the right way, the data can't be reaching to the destination platform. Furthermore, if the data is sent by unsuitable TDL, data delivery may take a long time. Within the battlefield, the data rate is a critical factor.

As mentioned in many parts of the thesis, TDLs have many different characteristics. Each TDL has its own outstanding feature. So, each platform must use correct TDL, It is the dramatical agent. At this point, optimization gains an importance. In this thesis, IBM ILOC CPLEX optimization tool is used.

3.1 Optimization of Operational Scenario Parameters

In the operational scenario, we have many parameters to solve the optimization problem. These parameters will use to define the problem and solve the problem. It was assumed that all platforms were within the same Line of Sight (LOS) in this scenario.

3.1.1 Entity Parameters

Entity Sets are participants which join the operation. These participants send their data to other platforms. In order to solve the optimization problem, participant symbols that will use are in below.

- F1, F2, F3 and F4 stand for Fighter Aircraft.
- A1 and A2 stand for Airborne Early Warning Command and Control Aircraft.
- N1 and N2 stand for Naval Command and Control.
- G1 and G2 stand for Ground Command and Control Centers.
- S1 stands for Surface to Air Missile.
- H1 stands for Human (Forward Air Controller)

3.1.2 Data Parameters

Data Sets are data type shared between participants. Data is categorized in terms of the topic to be associated. These are in below.

- NM: Network Management Data
- PLIS: Participant Location Identification and Status Data
- SUR: Surveillance Data
- INT: Intelligence Data
- WC: Weapon Coordination Data
- FCNT: Fighter Control Data
- EW: Electronic Warfare Data
- FT: Free Text

3.1.3 Capability Parameters

Capability Sets are Tactical Data Links (TDLs). These capabilities are optimized by our new model. These abbreviations are given below. These shortenings will be used in optimization model.

- L11A: Link-11A Tactical Data Link (shipping by air)
- L11B: Link-11B Tactical Data Link (shipping by ground) (Serial Communication)
- L16: Link-16 Tactical Data Link (shipping by air)
- L22: Link-22 Tactical Data Link
- VMF: Variable Message Format Tactical Data Link
- JRP-A: Joint Range Extension Application Protocol A (shipping by Satellite)
- JRP-B: Joint Range Extension Application Protocol B (shipping by ground) (Serial Communication)
- JRP-C: Joint Range Extension Application Protocol C (shipping by ground) (Ethernet Communication)

3.1.4 Data Size Parameters

Data Size Sets are meaning the data volume which will send from participants to other participants.

- Sm stands for Small Data.
- Md stands for Medium Data.
- Lr stands for Large Data.

3.1.5 Data Rate Parameters

Data Rate Sets mean the data speed which will be sent from participants to other participants by using Capability Sets.

- N: Normal Rate
- G: Good Rate
- VG: Very Good Rate
- UG: Ultra Good Rate

3.1.6 Security Level Parameters

Security Level Sets are classification level of data in the operational area. These are given below.

- UC: Unclassified
- C: Confidential
- ST: Secret
- TS: Top Secret

3.1.7 Significance Level Parameters

All data has importance level in battle space area. In optimization model, this issue is considered.

- NS: Normal Significance
- S: Significance
- VS: Very Significance

3.2 Summary of Optimization Sets

All parameters are a member of a Set. These sets are used due to nature of optimization. These sets are submitted in this section.

1) Entity Set (k) ={ F1, F2, F3, F4, A1, A2, N1, N2, G1, G2, S1, H1}

2) Data Set (i) ={NM, PLIS, SUR, INT, WC, CNT, EW}

3) Capability Set (j) ={L11A, L11B, L16, L22, VMF, JRP-A, JRP-B, JRP-C}

4) Data Size Set (l) ={Sm, Md, Lr}

5) Data Rate Set (l) ={N, G, VG, UG}

6) Security Level Set (s) ={UC, C, ST, TS}

7) Significance Level Set (c) ={NS,S,VS}

3.3 Optimization Tables

In order to solve optimization problem by using IBM ILOG CPLEX optimization tool, we have to use some tables which are associated with parameters and our optimization sets.

Table 3.1 Optimization sets.

DataType	CapSet	DataR	SecL	SignL	DataSize	NodeSet
NM	L11A	N: Normal Rate	UC: Unclassified	NS: Normal Significance	Sm: Small Data	F1
PLIS	L11B	G: Good Rate	C: Confidential	S: Significance	Md: Medium Data	F2
SUR	L16	VG: Very Good Rate	ST: Secret	VS: Very Significance	Lr: Large Data	F3
INT	L22	UG: Ultra Good Rate	TS: Top Secret			F4
WC	VMF					A1
FCNT	JRPA					A2
EW	JRPB					N1
FT	JRPC					N2
						G1
						G2
						S1
						H1

Table 3.2 Numerical values of optimization sets.

DataType	CapSet	DataR	SecL	SignL	DataSize	NodeSet
NM	L11A	1	1	1	1	F1
PLIS	L11B	2	2	2	2	F2
SUR	L16	3	3	3	3	F3
INT	L22	4	4			F4
WC	VMF					A1
FCNT	JRPA					A2
EW	JRPB					N1
FT	JRPC					N2
						G1
						G2
						S1
						H1

Table 3.1 and Table 3.2 have the same optimization parameters and sets given in the previous sections. However, there are some differences in this section. Data Rate, Security, Significance Level and Data Size sets are numerical to optimize the model.

Table 3.3 Maximum numerical values of capability sets.

CapSet	DataS	DataR	SecL	SignL
L11A	3	1	3	3
L11B	3	1	3	3
L16	3	3	4	3
L22	3	3	4	3
VMF	2	3	3	3
JRP-A	3	3	4	3
JRP-B	3	4	4	3
JRP-C	3	4	4	3

In Table 3.2, characteristics of capability sets are added to optimization tool. This is very important to optimize the model by a software tool.

Table 3.4 Capabilities of participants.

Node Set	Capability Set							
	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
F1	0	0	1	0	1	0	0	0
F2	0	0	1	0	1	0	0	0
F3	0	0	1	0	1	0	0	0
F4	0	0	1	0	1	0	0	0
A1	1	0	1	1	1	1	0	0
A2	1	0	1	1	1	1	0	0
N1	1	0	1	1	0	1	0	0
N2	1	0	1	1	0	1	0	0
G1	1	1	1	1	0	1	1	1
G2	1	1	1	1	0	1	1	1
S1	1	1	0	0	0	0	1	0
H1	0	0	0	0	1	0	0	0

In Table 3.3, Participant capabilities are presented. In this table, we understood which participant can communicate with each other. “1” is meaning two participants communicate with each other by using specific capability. “0” is meaning vice versa.

In Annex A, pseudo example demand table is presented in the operational area. We must optimize these demands by using optimization tool (IBM ILOG CPLEX). In Annex A; Data Type, Originator, Destination, Data Size, Security Level, Significance Level and Data Rate columns are characteristics of demands. L11A, L11B, L16, L22, VMF, JRP-A, JRP-B and JRP-C columns are utilities of demands.

An example of some demands is presented in below. These demands were selected randomly. According to optimization equations, results will be selected optimum level. Bolds show results after optimization performs.

Table 3.5 Demand examples from ANNEX A

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
1	NM	G1	F1	1	2	1	1
2	NM	G1	F2	1	2	1	1
.	.	.	.	.	.	.	.
5	NM	G1	A1	1	2	1	1
6	NM	G1	A2	1	2	1	1
.	.	.	.	.	.	.	.
9	NM	G1	G2	1	2	1	1
10	NM	G1	S1	1	2	1	1
.	.	.	.	.	.	.	.
20	PLIS	F1	H1	2	3	3	2
21	PLIS	F2	F1	3	3	3	2
22	PLIS	F2	F3	3	3	3	2
23	PLIS	F2	F4	3	3	3	2
24	PLIS	F2	A1	3	3	3	2
.	.	.	.	.	.	.	.
55	PLIS	A1	A2	3	3	3	2
56	PLIS	A1	N1	3	3	3	2
57	PLIS	A1	N2	3	3	3	2
.	.	.	.	.	.	.	.
121	SUR	A1	F4	3	3	3	2
122	SUR	A1	A2	3	3	3	2
123	SUR	A1	N1	3	3	3	2
124	SUR	A1	N2	3	3	3	2
125	SUR	A1	G1	3	3	3	2
126	SUR	A1	G2	3	3	3	2
127	SUR	A1	H1	2	3	3	2
.	.	.	.	.	.	.	.
144	SUR	N1	N2	3	3	3	2
145	SUR	N1	G1	3	3	3	2
.	.	.	.	.	.	.	.
200	INT	G2	F4	1	2	2	3
201	INT	A1	A2	3	4	2	2
.	.	.	.	.	.	.	.
203	INT	N1	N2	1	3	1	1
.	.	.	.	.	.	.	.
211	WC	G1	S1	2	3	1	1
.	.	.	.	.	.	.	.
232	FCNT	A2	F3	2	4	3	3
233	FCNT	N1	F3	2	4	3	3
.	.	.	.	.	.	.	.
293	EW	G1	A1	2	2	1	3
.	.	.	.	.	.	.	.
312	FT	A1	S1	2	1	1	1

3.4 Optimization Settings

3.4.1 Decision Variable

Decision variables are the variables within a model that one can control. They are not random variables. This is essential for optimization.

Our objective is to find the *best* value for the decision variable. The decision variable is denoted by x, y, z, d, k, etc. Variables can be a number, a vector, a sequence, a function, a matrix, etc [47].

We defined the decision variable as two-dimensional matrix. Matrix Link is depended on "demand" and "CapabilitySet".

IBM ILOC CPLEX codes of decision variable are in Figure 3.2.

```


/*********************
*DECISION VARIABLES
*********************/

dvar boolean    link[D][CapSet];


```

Figure 3.2 Decision Variable Codes

Decision Variable is defined as Boolean. In Figure 3.2 "D" is stood for demand and "CapSet" is stand for CapabilitySet. If demand is sent by using capability, the result is "1". If demand is not sent by using capability, the result is "0".

The summary is presented in below.

Link [demand] [CapabilitySet] = {1 If demand is sent by using capability,

{0 Otherwise;

3.4.2 Objective Function

The size to be optimized as maximum or minimum is called the objective function. In order to find an optimum solution in terms of sending data, we must maximize multiplication of Utility and Link Matrix. As described in Part 3.4.1, Link is a Boolean matrix. In the same way, Utility is defined as a matrix. It is depended on “d” and “k”. Symbol “d” is a demand which is come from demand table in Annex A. Symbol “k” is capability which is come from Capability Set Table. The objective function [50] is presented in below.

$$\boldsymbol{Max} \sum_{k} \sum_{d} \mathbf{C1}[\mathbf{d},\mathbf{k}] * \mathbf{C2}[\mathbf{d},\mathbf{k}] \tag{3.1}$$

$C1_{[d,k]}$ is $Link_{[d,k]}$, $C2_{[d,k]}$ is $Utility_{[d,k]}$.

IBM ILOC CPLEX codes of the objective function are in Figure 3.3.

```
//Objective Function

maximize    sum(d in D,k in CapSet)  Utility[d,k]*link[d,k];

```

Figure 3.3 Objective Function Codes

Utility Matrix is an essential part of this thesis. That’s why, it will be described as detailed in Section 3.5.

A system may have more than one possible solution. Some of these may be better than others. IBM ILOC CPLEX tool optimizes for the best option of multiplication of Utility and Link Matrix for all demands.

Finally, it produces a new Link Matrix. In this new Link Matrix, there is only “1” value per line. Others are “0”. This means that, Column with value “1” is the optimum solution. The Link corresponding to the mentioned column has been selected. Additionally, there is also another factor for optimization. Constraints prevent selection of each link.

3.4.3 Constraints

The limitation of optimization on the value acquisition of parameters is called as constraints. The constraint is the most indispensable part of optimization. IBM ILOC CPLEX tool requires the entry of constraints. There are some constraints in this optimization.

3.4.3.1 Possession of Capability Constraint

In an environment where all platforms are available, only platforms which have the same link capability are able to communicate with each other. This means that, two platforms cannot communicate if they have not the same link. This constraint is defined in Table 3.4. According to this table, platforms with a value of "1" can communicate each other.

Codes of this constraint are in Figure 3.4.

```
subject to {


    forall(d in D,i in NodeSet:d.Orig==i,j in NodeSet:d.Dest==j,k in CapSet)
      CapabilityFeasible:
         link[d][k]<=CapTest[i][k]*CapTest[j][k];

    forall(d in D)
      SatisfyAllDemands:
         sum(k in CapSet)link[d][k]==1;

```

Figure 3.4 Possession of Capability Constraint

3.4.3.2 Data Size Constraint

All capability has a data size capacity in terms of sending data. Furthermore, demand data needs a transmit capacity for information. If a demand data size is bigger than the capacity of capability, this data cannot be sent by the capability. This is optimization data size constraint.

Data size constraint is defined in Table 3.1. The demand data size is presented in Annex A.

Codes of this constraint are in Figure 3.5.

```
subject to  {

    forall(d in D)
      DataSizeConstraint:
        d.DataS <=sum(k in CapSet) DataS_max[k]*link[d][k];
```

Figure 3.5 Data Size Constraint

3.4.3.3 Security Level Constraint

All capability has a security level. Similarly, demand data needs a security level for sending data. If a demand security level is bigger than the security level of capability, this data cannot be sent by the capability. This is optimization security level constraint.

Security level constraint is defined in Table 3.1. The demand security level is presented in Annex A.

Codes of this constraint are in Figure 3.6.

```
subject to  {



    forall(d in D)
      SecLConstraint:
        d.SecL <=sum(k in CapSet) SecL_max[k]*link[d][k];
```

Figure 3.6 Security Level Constraint

3.4.3.4 Data Rate Constraint

All capability has a maximum data rate. Similarly, demand data needs a data rate for transmitting data. If a demand data rate is bigger than the data rate of capability, this data cannot be sent by the capability. This is optimization data rate constraint.

Data rate constraint is defined in Table 3.1. The demand data rate is presented in Annex A.

Codes of this constraint are in Figure 3.6.

```
subject to  {


    forall(d in D)
      DataRConstraint:
        d.DataR <=sum(k in CapSet) DataR_max[k]*link[d][k];


```

Figure 3.7 Data Rate Constraint

3.4.3.5 Significance Level Constraint

All capability has a maximum significance level in terms of transmitting data. Similarly, demand data needs a significance level for sending data. If a demand significance level is bigger than the significance level of capability, this data cannot be sent by the capability. This is optimization significance level constraint.

Significance level constraint is defined in Table 3.1. The demand significance level is presented in Annex A.

Codes of this constraint are in Figure 3.6.

```
subject to  {


    forall(d in D)
      SignLConstraint:
        d.SignL <=sum(k in CapSet) SignL_max[k]*link[d][k];


```

Figure 3.8 Data Significance Constraint

3.4.4 IBM ILOC CPLEX Model Codes

IBM ILOC CPLEX codes of this model are presented in shortly below and in detailed ANNEX B.

```
/****************************
*SETS, TUPLES AND PARAMETERS
****************************/
{string}        DataType=...;
{string}        CapSet=...;
{string}        NodeSet=...;
{int}     DataR=...;
{int}     SecL=...;
{int}     SignL=...;
{int}     DataS=...;

tuple     Demand {
                int       Index;
                string          DataType;
                string    Orig;
                string    Dest;
                int       DataS;
                int       SecL;
                int       SignL;
                int       DataR;
                };
{Demand}  D=...;
int   DataS_max[CapSet]=...;
int   DataR_max[CapSet]=...;
int   SecL_max[CapSet]=...;
int   SignL_max[CapSet]=...;
int   Utility[D][CapSet]=...;
int   CapTest[NodeSet][CapSet]=...;
```

```
/********************
*DECISION VARIABLES
*********************/
dvar boolean       link[D][CapSet];


/*******************
*MATHEMATICAL MODEL
*******************/
//Objective Function
maximize   sum(d in D,k in CapSet)  Utility[d,k]*link[d,k];
subject to   {
        forall(d in D,i in NodeSet:d.Orig==i,j in NodeSet:d.Dest==j,k in CapSet)
          CapabilityFeasible:
                 link[d][k]<=CapTest[i][k]*CapTest[j][k];

        forall(d in D)
          SatisfyAllDemands:
                 sum(k in CapSet)link[d][k]==1;

        forall(d in D)
          DataSizeConstraint:
                d.DataS <=sum(k in CapSet) DataS_max[k]*link[d][k];

        forall(d in D)
          SecLConstraint:
                d.SecL <=sum(k in CapSet) SecL_max[k]*link[d][k];

        forall(d in D)
          DataRConstraint:
                d.DataR <=sum(k in CapSet) DataR_max[k]*link[d][k];

        forall(d in D)
          SignLConstraint:
                d.SignL <=sum(k in CapSet) SignL_max[k]*link[d][k];

};
```

3.4.5 IBM ILOC CPLEX Data Codes

IBM ILOC CPLEX codes of data are presented in shortly below and in detailed ANNEX C.

```
SheetConnection sheet("Ersin0710.xlsx");

DataType          from SheetRead(sheet,"DataType");

NodeSet           from SheetRead(sheet,"NodeSet");
```

CapSet	from SheetRead(sheet,"CapSet");
DataR	from SheetRead(sheet,"DataR");
SecL	from SheetRead(sheet,"SecL");
SignL	from SheetRead(sheet,"SignL");
DataS	from SheetRead(sheet,"DataS");
D	from SheetRead(sheet,"D");
DataS_max	from SheetRead(sheet,"DataS_max");
DataR_max	from SheetRead(sheet,"DataR_max");
SecL_max	from SheetRead(sheet,"SecL_max");
SignL_max	from SheetRead(sheet,"SignL_max");
Utility	from SheetRead(sheet,"Utility");
CapTest	from SheetRead(sheet,"CapTest");

3.5 Produce of Utility Matrix

As mentioned in previous parts, Utility Matrix is a substantial parameter for optimization model. Link Matrix values are used as Boolean due to the influence of constraints. Utility matrix contributes the optimization in the final part. In this part, we will produce utility table with three different ways. They are Method of Spider Web Diagram Area Calculation, Method of Expected Value and Method of Analytical Hierarchical Processing (AHP). According to [54], for each of the TDL technology, a spider web diagram has been produced. The axis of the spider web charts are:

• Data Throughput - defined in Table 3.6.

• Latency - (1hop) defined in Table 3.6.

• LPI/LDP/AJ - Low Probability Intercept / Low Probability of Detection / Anti-Jam defined in Table 3.6.

• Security - defined in Table 3.6.

• Range - defined in Table 3.6.

• IP Connectivity - defined in Table 3.6.

Table 3.6 Characteristic Scaling Table [54]

Throughput		Latency		Range		LPI / LPD / AJ		IP Connectivity		Security	
1	< 1Mbit	1	> 1s	1	<1km	1	low capability	1	No	1	No COMSEC
2	< 2Mbit	2	< 1s	2	<10km	2	medium capability	2	Applicable	2	Yes COMSEC
3	< 10Mbit	3	< 250 ms	3	<50km	3	high capability	3	Yes		
4	< 50Mbit	4	< 100 ms	4	<150km						
5	< 200Mbit	5	< 20 ms	5	<400km						
6	< 1Gbits	6	< 5 ms	6	<800km						
7	> 1Gbits			7	>800km						

In Table 3.6, Characteristic values are divided into levels. Different levels are considered for each characteristic. For example, throughput is divided into seven levels while latency is divided into six levels. All characteristic and characteristic's levels are used in spider web diagram.

The selection of the parameters modeled in the spider web diagrams can be used to focus the analysis on any particular characteristic of the data link. On the spider web diagram presented, some of the values used are a mean of the minimum and maximum values for a given characteristic [54].

3.5.1 Method of Spider Web Diagram Area Calculation

In this part, Utility Matrix will be produced according to spider web diagram area mentioned above. If the area of ability is greater in spider web diagram, that ability will have more effect on the utility.

In this method, an assessment of characteristics of each of the Tactical Data Link technologies is represented as a model containing a number of abstract quantitative values. These values are compared with each other. A result was reached.

3.5.1.1 Calculation of Area for Each Tactical Data Link

In this part, area of each spider web diagram will be calculated by using sinusoidal area formula for each Tactical Data Link.

Calculation of Area for Link-11A

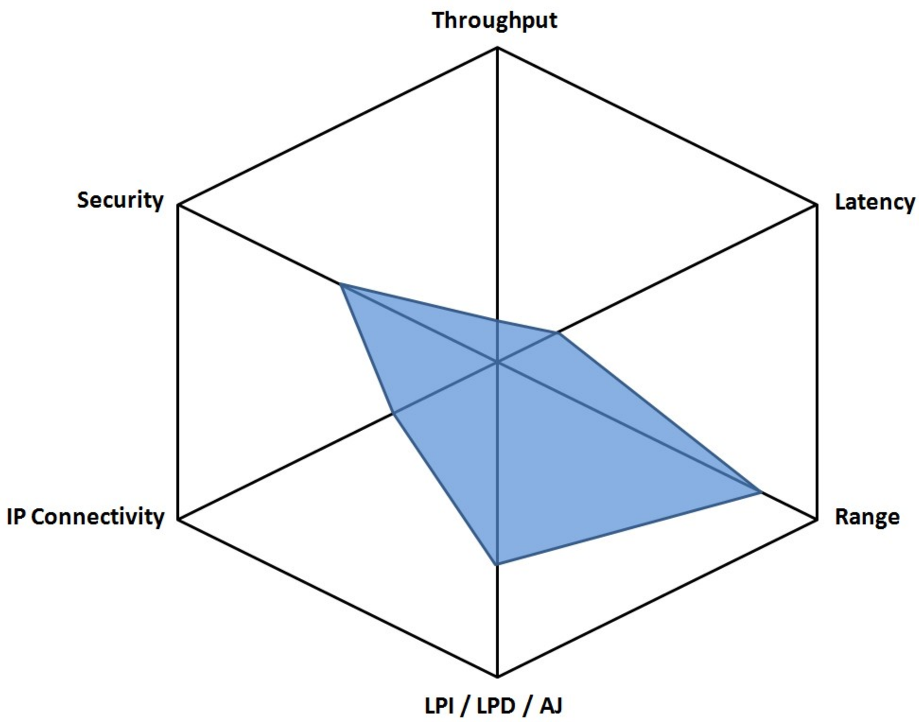


Figure 3.9 Link-11A Spider Web Diagram [54]

Throughput (Thput): 1/7= 0.1428

Latency (Latcy): 1/6= 0.1666

Range (Rng): 6/7= 0.8571

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 1/3= 0.3333

Security (Scrty): 1/2= 0.5

Link-11A Spider Web Diagram Area=1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

Link-11A Spider Web Diagram Area=1/2*(√3/2)*(0.1428* 0.1666+0.1666* 0.8571+0.8571* 0.6666+0.6666* 0.3333+0.3333* 0.5+0.5*0.1428)

Link-11A Spider Web Diagram Area=0.433*1.1981

Link-11A Spider Web Diagram Area=0.5187

Calculation of Area for Link-11B

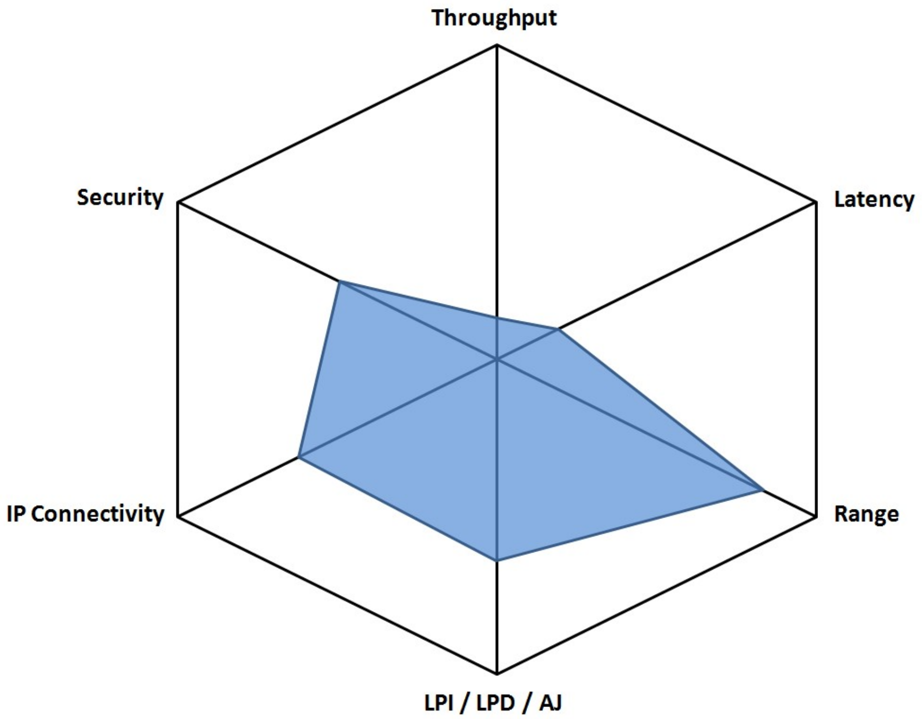


Figure 3.10 Link-11B Spider Web Diagram [54]

Throughput (Thput): 1/7= 0.1428

Latency (Latcy): 1/6= 0.1666

Range (Rng): 6/7= 0.8571

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 2/3= 0.6666

Security (Scrty): 1/2= 0.5

Link-11B Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

Link-11B Spider Web Diagram Area =1/2*(√3/2)*(0.1428* 0.1666+0.1666* 0.8571+0.8571* 0.6666+0.6666* 0.6666+0.6666* 0.5+0.5*0.1428)

Link-11B Spider Web Diagram Area =0.433*1.5869

Link-11B Spider Web Diagram Area =0.6871

Calculation of Area for Link-16

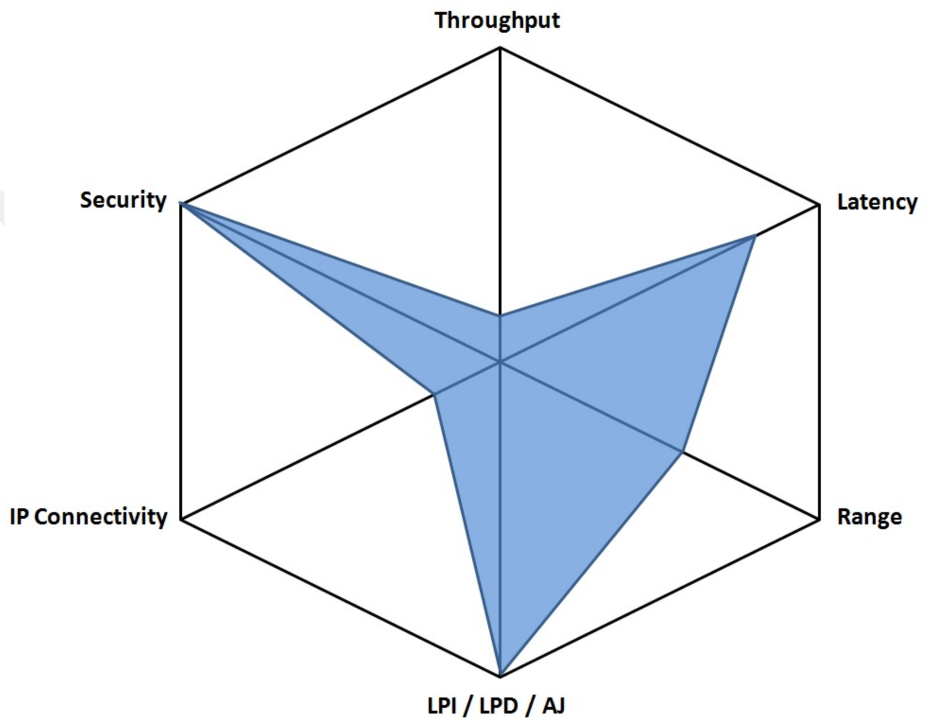


Figure 3.11 Link-16 Spider Web Diagram [54]

Throughput (Thput): 1/7= 0.1428

Latency (Latcy): 4/6= 0.6666

Range (Rng): 5/7= 0.7142

LPI/LPD/AJ (LPI): 3/3= 1

IP Connectivity (IPCon): 1/3= 0.3333

Security (Scrty): 2/2= 1

Link-16 Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

Link-16 Spider Web Diagram Area =1/2*(√3/2)*(0.1428* 0.6666+0.6666* 0.7142+0.7142* 1+1* 0.3333+0.3333* 1+1*0.1428)

Link-16 Spider Web Diagram Area =0.433*2.0948

Link-16 Spider Web Diagram Area =0.907

Calculation of Area for Link-22

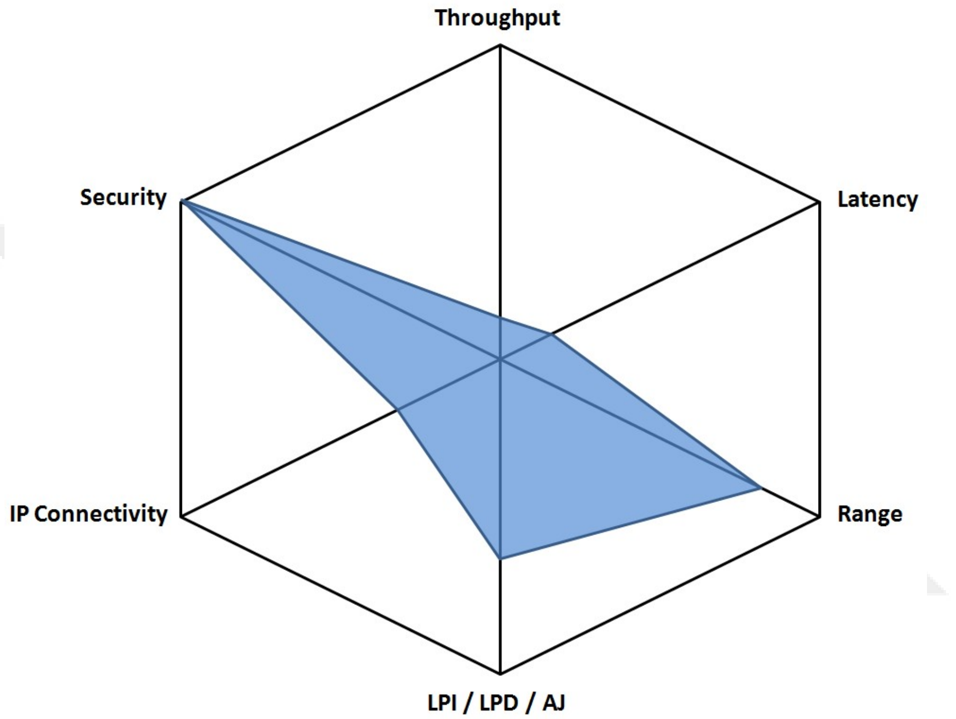


Figure 3.12 Link-22 Spider Web Diagram [54]

Throughput (Thput): 1/7= 0.1428

Latency (Latcy): 1/6= 0.1666

Range (Rng): 6/7= 0.8571

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 1/3= 0.3333

Security (Scrty): 2/2= 1

Link-22 Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

Link-22 Spider Web Diagram Area =1/2*(√3/2)*(0.1428* 0.1666+0.1666* 0.8571+0.8571* 0.6666+0.6666* 0.3333+0.3333* 1+1*0.1428)

Link-22 Spider Web Diagram Area =0.433*1.4362

Link-22 Spider Web Diagram Area =0.6218 (for Link-22)

Calculation of Area for VMF

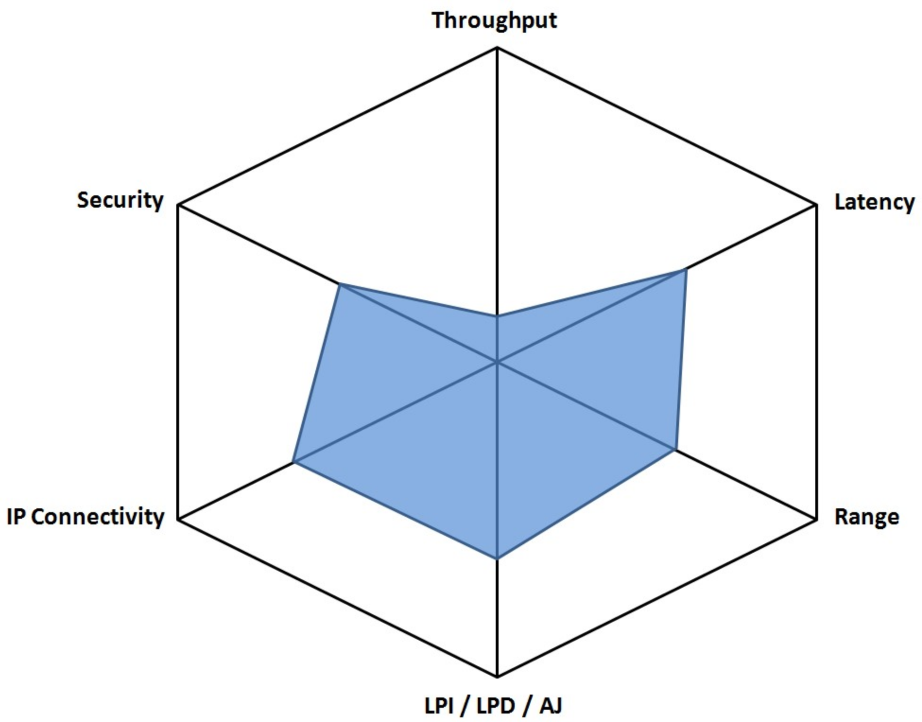


Figure 3.13 VMF Spider Web Diagram [54]

Throughput (Thput): 1/7= 0.1428

Latency (Latcy): 4/6= 0.6666

Range (Rng): 4/7= 0.5714

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 2/3= 0.6666

Security (Scrty): 1/2= 0.5

VMF Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

VMF Spider Web Diagram Area =1/2*(√3/2)*(0.1428* 0.6666+0.6666* 0.5714+0.5714* 0.6666+0.6666* 0.6666+0.6666* 0.5+0.5*0.1428)

VMF Spider Web Diagram Area =0.433*1.706

VMF Spider Web Diagram Area =0.738

Calculation of Area for JREAP-A

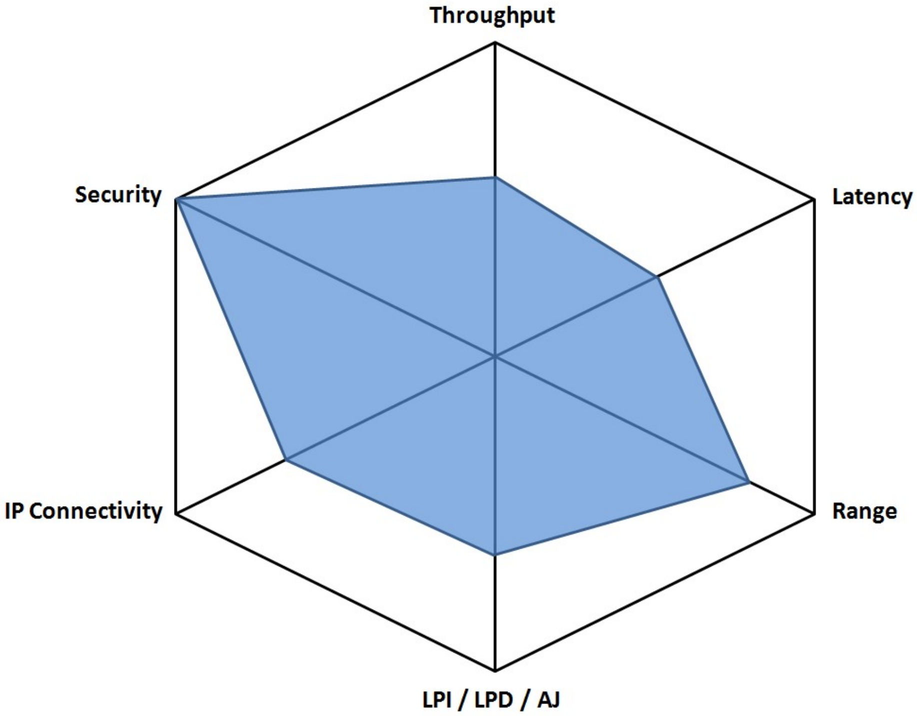


Figure 3.14 JREAP-A Spider Web Diagram [54]

Throughput (Thput): 4/7= 0.5714

Latency (Latcy): 3/6= 0.50

Range (Rng): 6/7= 0.8571

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 2/3= 0.6666

Security (Scrty): 2/2= 1

JREAP-A Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

JREAP-A Spider Web Diagram Area =1/2*(√3/2)*(0.5714* 0.50+0.50* 0.8571+0.8571* 0.6666+0.6666* 0.6666+0.6666*1+1*0.5714)

JREAP-A Spider Web Diagram Area =0.433*2.9679

JREAP-A Spider Web Diagram Area =1.2851

Calculation of Area for JREAP-B

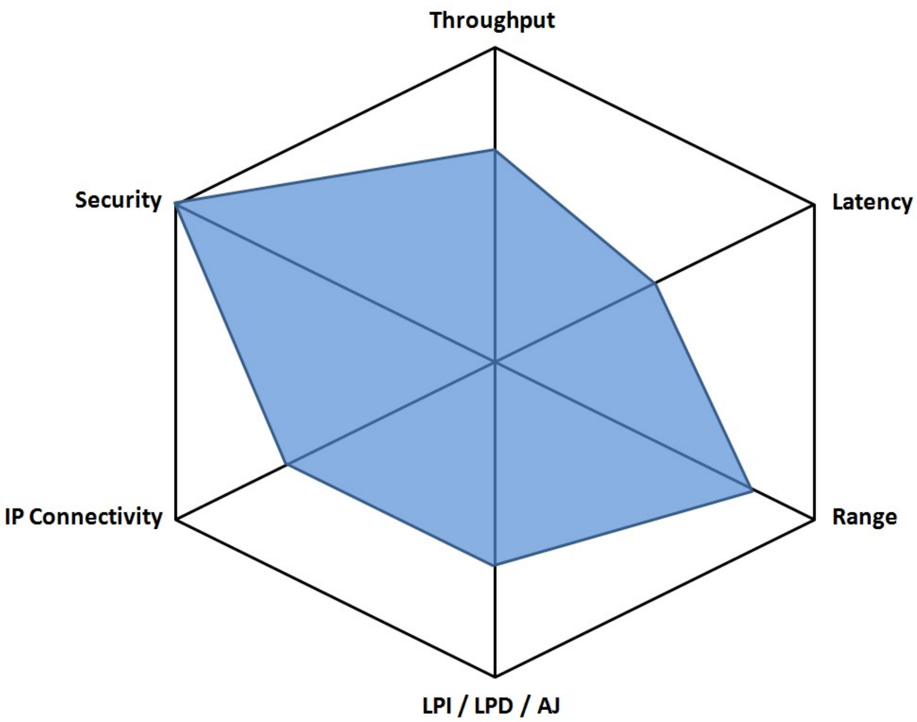


Figure 3.15 JREAP-B Spider Web Diagram [54]

Throughput (Thput): 5/7= 0.7142

Latency (Latcy): 3/6= 0.50

Range (Rng): 6/7= 0.8571

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 2/3= 0.6666

Security (Scrty): 2/2= 1

JREAP-B Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

JREAP-B Spider Web Diagram Area =1/2*(√3/2)*(0.7142* 0.50+0.50* 0.8571+0.8571* 0.6666+0.6666* 0.6666+0.6666* 1+1*0.7142)

JREAP-B Spider Web Diagram Area =0.433*3.1821

JREAP-B Spider Web Diagram Area =1.3778

Calculation of Area for JREAP-C

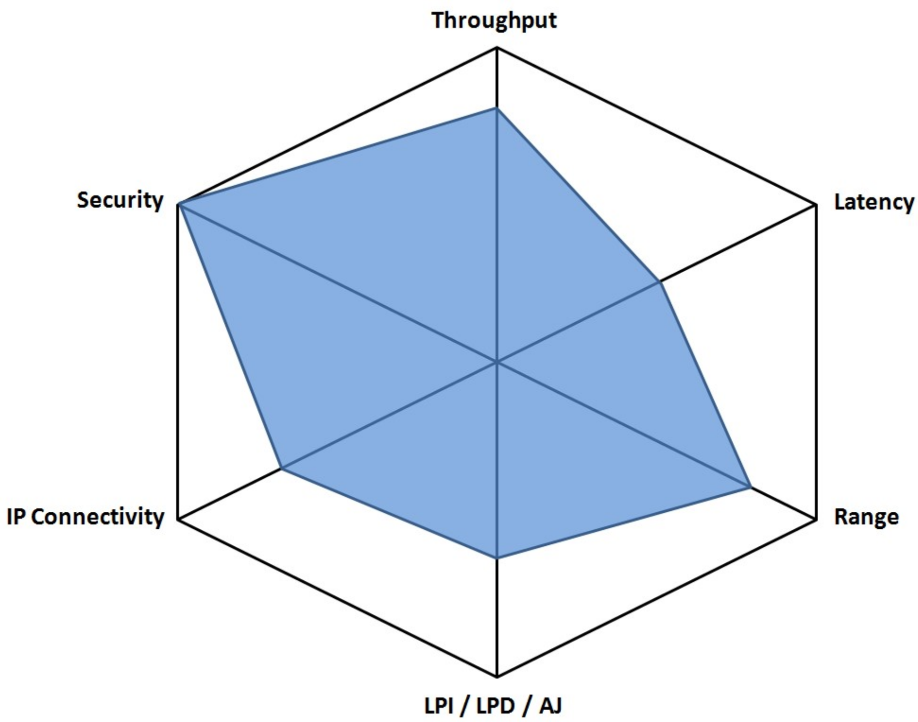


Figure 3.16 JREAP-C Spider Web Diagram [54]

Throughput (Thput): 6/7= 0.8571

Latency (Latcy): 3/6= 0.50

Range (Rng): 6/7= 0.8571

LPI/LPD/AJ (LPI): 2/3= 0.6666

IP Connectivity (IPCon): 2/3= 0.6666

Security (Scrty): 2/2= 1

JREAP-C Spider Web Diagram Area =1/2*sin (60)*(Thput* Latcy+ Latcy* Rng+ Rng* LPI+LPI*IPCon+ IPCon* Scrty+ Scrty* Thput)

JREAP-C Spider Web Diagram Area =1/2*(√3/2)*(0.8571* 0.50+0.50* 0.8571+0.8571* 0.6666+0.6666* 0.6666+0.6666*1+1*0.8571)

JREAP-C Spider Web Diagram Area =0.433*3.3964

JREAP-C Spider Web Diagram Area =1.4706

3.5.1.2 Produce Utility Matrix with Spider Web Diagram Area

All area values are calculated in Section 3.5.1.1. These values are presented in Table 3.7. According to Table 3.7, sorting Tactical Data Links high to low is JREAP-C, JREAP-B, JREAP-A, Link-16, VMF, Link-11B, Link-22 and Link-11A.

Table 3.7 Utility Matrix from Spider Web Diagram Area

L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
0.5187	0.6871	0.9070	0.6218	0.7380	1.2800	1.3700	1.4700

Table 3.7 values are used in the first method for all demands. These values are presented in ANNEX D. Results will be evaluated in conclusion section.

3.5.2 Method of Expected Value

In this part, Utility Matrix will be produced according to spider web diagram's axis mean values. Spider web diagram's axis expresses characteristics of TDLs. All characteristics are used to produce a function for each TDL; it could be able to give an idea regarding the result. This is the expected value of the function.

For example; suppose that a student's score is expressed by a function. The score that the student received from the next exam can be found with the expected value. Similarly, when we produce a function by using spider web diagram's axis mean values, function's expected value can be use for Utility Matrix. It is like using the average value of the function.

If the expected value of capability is greater in function, that capability will have more effect on the utility.

3.5.2.1 Calculation of Expected Value for Each Tactical Data Link

In this part, each function will be produced by using MATLAB codes for each Tactical Data Link. After that, all expected value will be calculated by using MATLAB functions.

Calculation of Expected Value for Link-11A

Throughput: 1/7= 0.1428	for parameter 1,	F(p): 0.1428
Latency: 1/6= 0.1666	for parameter 2,	F(p): 0.1666
Range: 6/7= 0.8571	for parameter 3,	F(p): 0.8571
LPI/LPD/AJ: 2/3= 0.6666	for parameter 4,	F(p): 0.6666
IP Connectivity: 1/3= 0.3333	for parameter 5,	F(p): 0.3333
Security: 1/2= 0.5	for parameter 6,	F(p): 0.5

Using the above values, a "p-Fp graph" was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.1428 0.1666 0.8571 0.6666 0.3333 0.5];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);

a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for Link-11A');
xlabel('Parameters (p)');
```

ylabel('Size (Fp)');

expectedvalue=expfit(Fx);

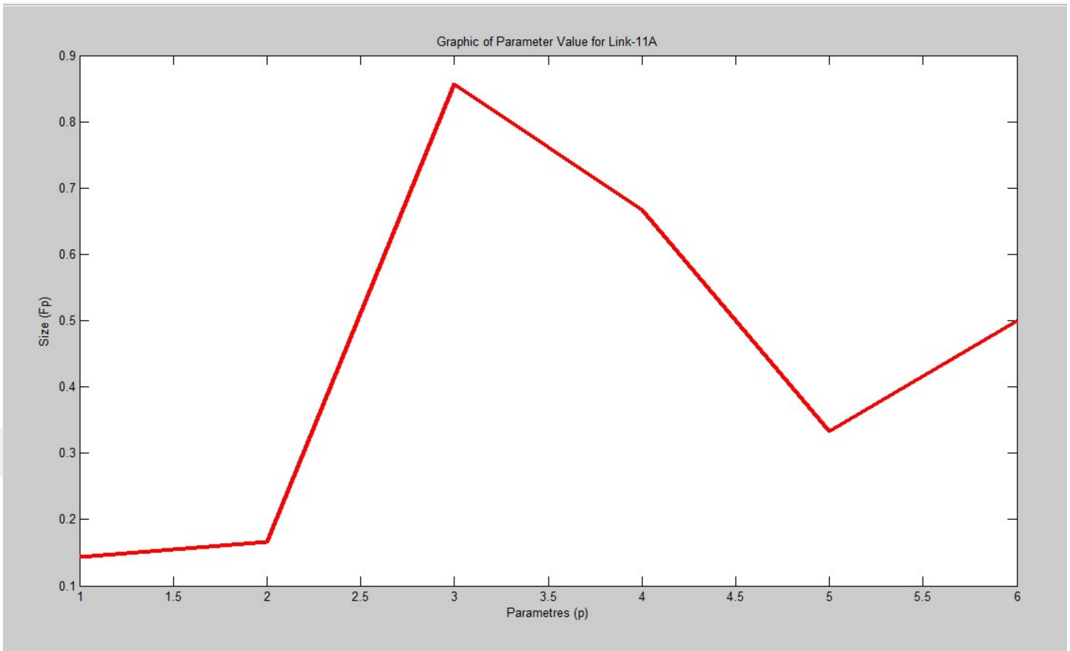


Figure 3.17 Link-11A Function

Link-11A Expected Value =0.4444

Calculation of Expected Value for Link-11B

Throughput: 1/7= 0.1428	for parameter 1,	F(p): 0.1428
Latency: 1/6= 0.1666	for parameter 2,	F(p): 0.1666
Range: 6/7= 0.8571	for parameter 3,	F(p): 0.8571
LPI/LPD/AJ: 2/3= 0.6666	for parameter 4,	F(p): 0.6666
IP Connectivity: 2/3= 0.6666	for parameter 5,	F(p): 0.6666
Security: 1/2= 0.5	for parameter 6,	F(p): 0.5

Using the above values, a “p-Fp graph” was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.1428 0.1666 0.8571 0.6666 0.6666 0.5];
```

```
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);

a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for Link-11B');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

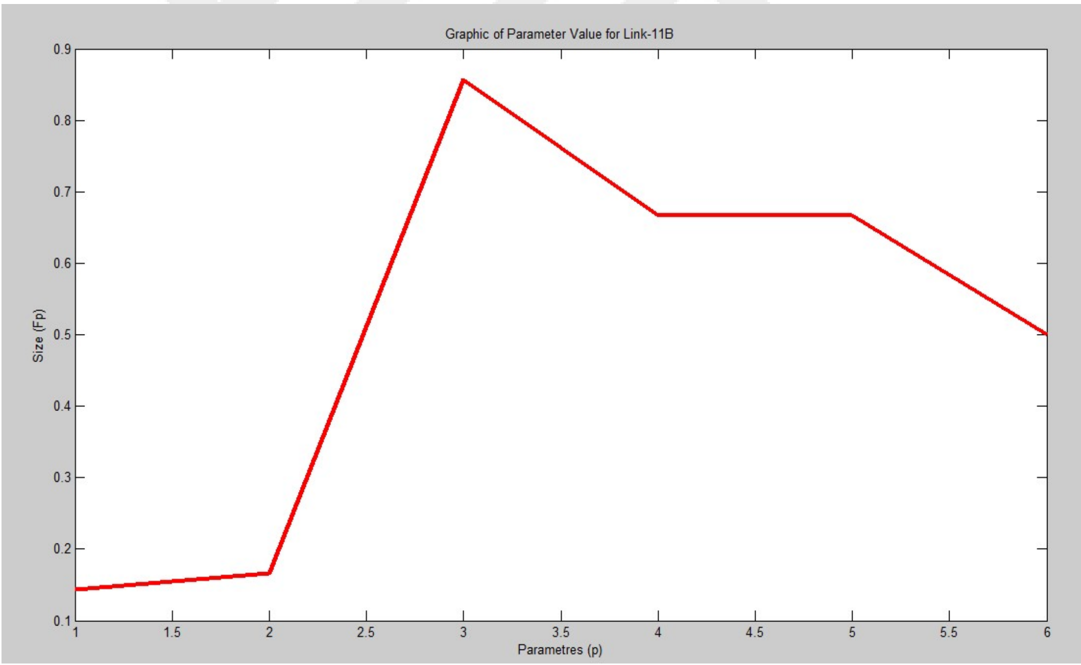


Figure 3.18 Link-11B Function

Link-11B Expected Value =0.5

Calculation of Expected Value for Link-16

Throughput: 1/7= 0.1428 for parameter 1, F(p): 0.1428

Latency: 4/6= 0.6666 for parameter 2, F(p): 0.6666

Range: 5/7= 0.7142 for parameter 3, F(p): 0.7142

LPI/LPD/AJ: 3/3= 1 for parameter 4, F(p): 1

IP Connectivity: 1/3= 0.3333 for parameter 5, F(p): 0.3333

Security: 2/2= 1 for parameter 6, F(p): 1

Using the above values, a "p-Fp graph" was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.1428 0.6666 0.7142 1 0.3333 1];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);

a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for Link-16');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

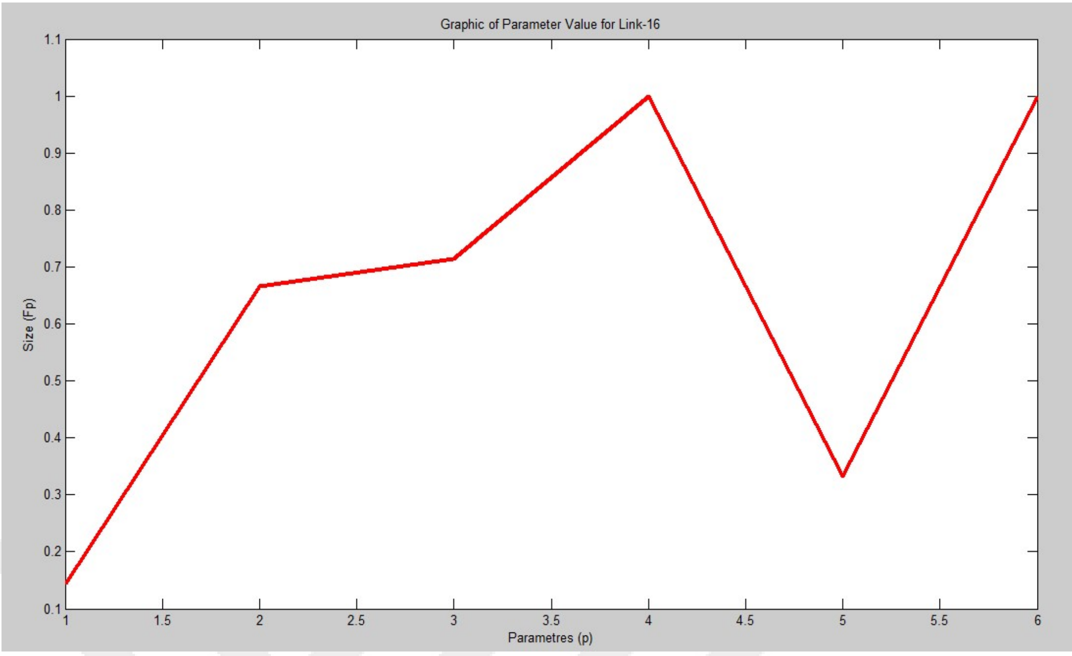


Figure 3.19 Link-16 Function

Link-16 Expected Value =0.6428

Calculation of Expected Value for Link-22

Throughput: 1/7= 0.1428	for parameter 1,	F(p): 0.1428
Latency: 1/6= 0.1666	for parameter 2,	F(p): 0.1666
Range: 6/7= 0.8571	for parameter 3,	F(p): 0.8571
LPI/LPD/AJ: 2/3= 0.6666	for parameter 4,	F(p): 0.6666
IP Connectivity: 1/3= 0.3333	for parameter 5,	F(p): 0.3333
Security: 2/2= 1	for parameter 6,	F(p): 1

Using the above values, a "p-Fp graph" was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.1428 0.1666 0.8571 0.6666 0.3333 1];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);
```

```
a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for Link-22');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

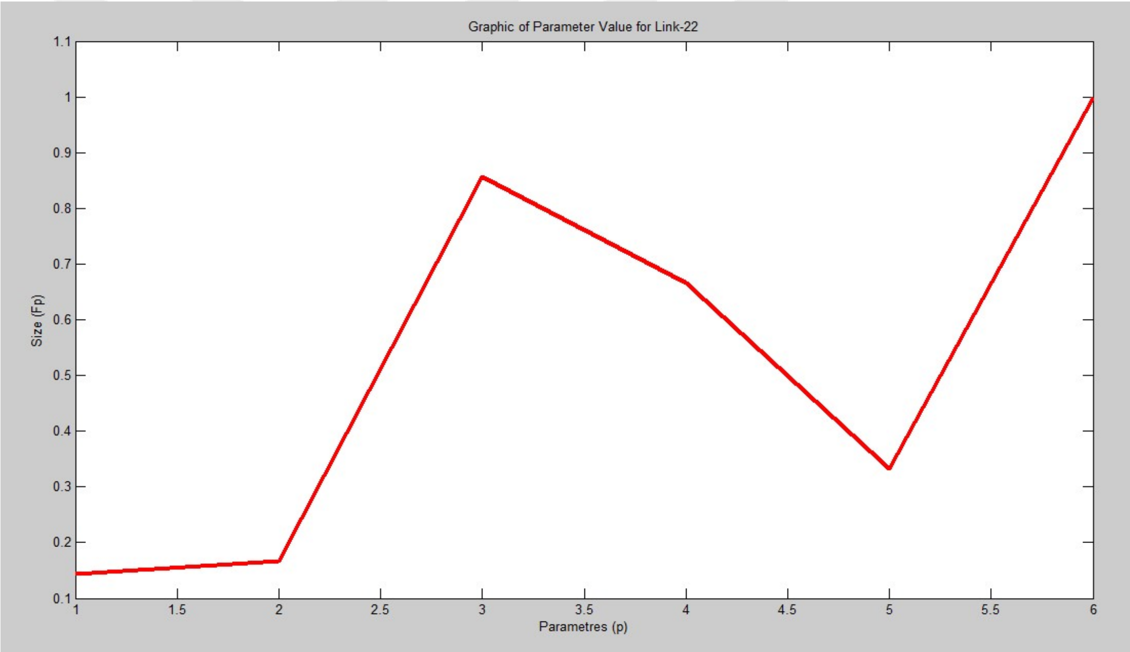


Figure 3.20 Link-22 Function

Link-22 Expected Value =0.5277

Calculation of Expected Value for VMF

Throughput: 1/7= 0.1428	for parameter 1, F(p): 0.1428
Latency: 4/6= 0.6666	for parameter 2, F(p): 0.6666
Range: 4/7= 0.5714	for parameter 3, F(p): 0.5714

LPI/LPD/AJ: 2/3= 0.6666 for parameter 4, F(p): 0.6666

IP Connectivity: 2/3= 0.6666 for parameter 5, F(p): 0.6666

Security: 1/2= 0.5 for parameter 6, F(p): 0.5

Using the above values, a "p-Fp graph" was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.1428 0.6666 0.5714 0.6666 0.6666 0.5];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);

a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for VMF');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

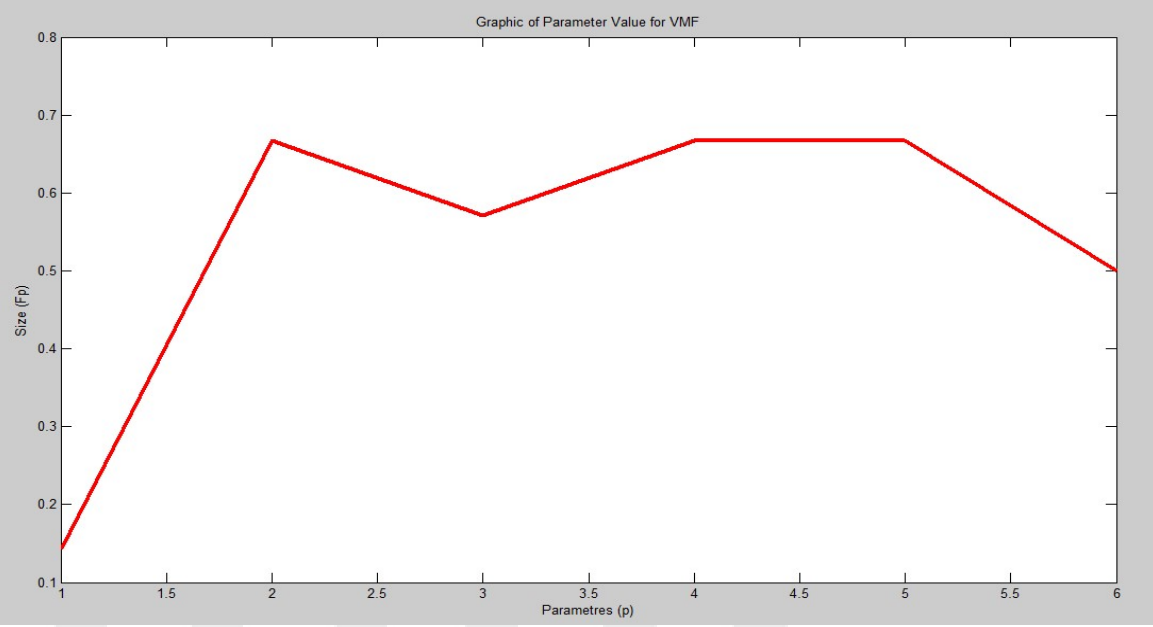


Figure 3.21 VMF Function

VMF Expected Value =0.5357

Calculation of Expected Value for JREAP-A

Throughput: 4/7= 0.5714	for parameter 1, F(p): 0.5714
Latency: 3/6= 0.5	for parameter 2, F(p): 0.5
Range: 6/7= 0.8571	for parameter 3, F(p): 0.8571
LPI/LPD/AJ: 2/3= 0.6666	for parameter 4, F(p): 0.6666
IP Connectivity: 2/3= 0.6666	for parameter 5, F(p): 0.6666
Security: 2/2= 1	for parameter 6, F(p): 1

Using the above values, a “p-Fp graph” was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.5714 0.5 0.8571 0.6666 0.6666 1];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);
```

```
a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for JREAP-A');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

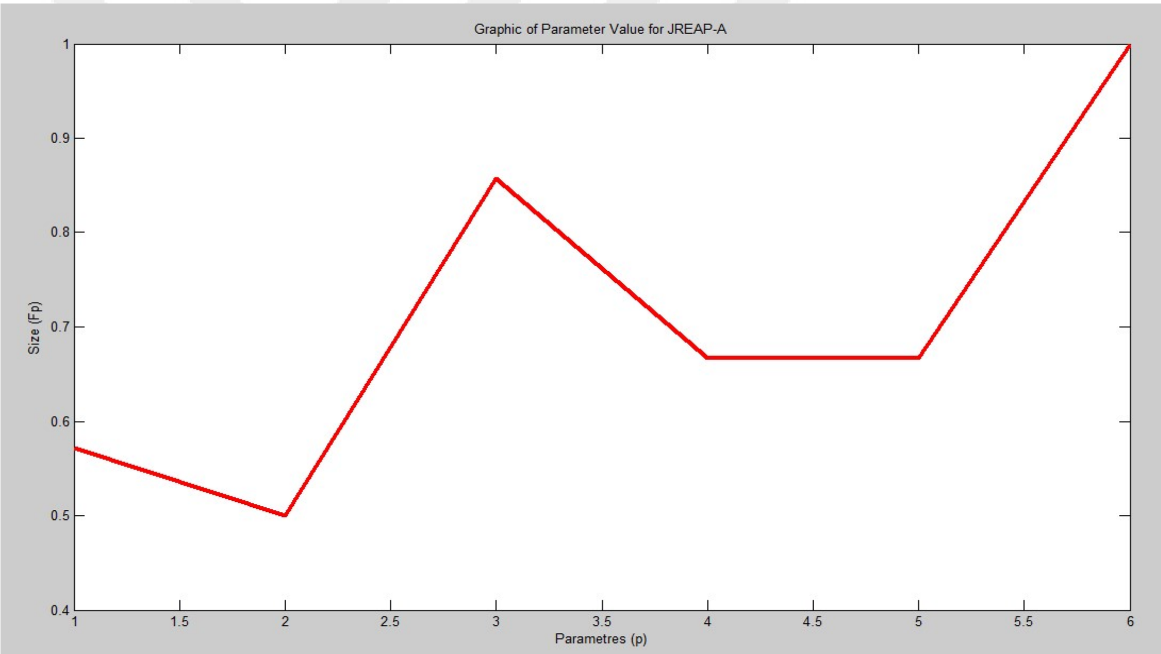


Figure 3.22 JREAP-A Function

JREAP-A Expected Value =0.7103

Calculation of Expected Value for JREAP-B

Throughput: 5/7= 0.7142 for parameter 1, F(p): 0.7142

Latency: 3/6= 0.5 for parameter 2, F(p): 0.5

Range: 6/7= 0.8571 for parameter 3, F(p): 0.8571

LPI/LPD/AJ: 2/3= 0.6666 for parameter 4, F(p): 0.6666

IP Connectivity: 2/3= 0.6666 for parameter 5, F(p): 0.6666

Security: 2/2= 1 for parameter 6, F(p): 1

Using the above values, a “p-Fp graph” was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.7142 0.5 0.8571 0.6666 0.6666 1];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);

a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for JREAP-B');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

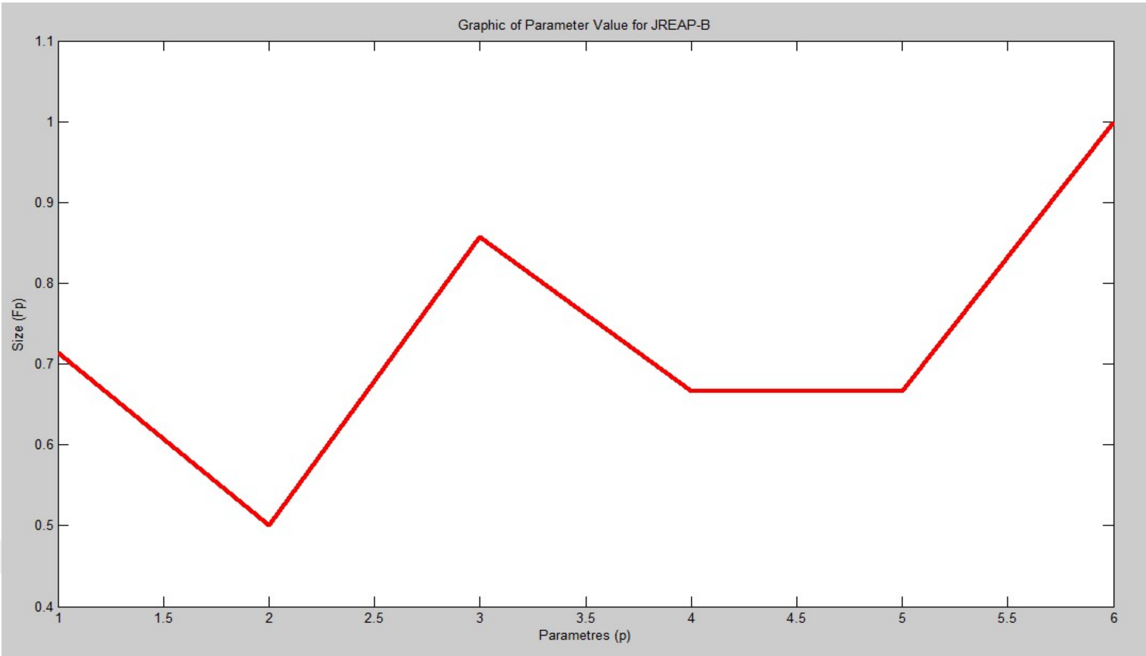


Figure 3.23 JREAP-B Function

JREAP-B Expected Value =0.7341

Calculation of Expected Value for JREAP-C

Throughput: 6/7= 0.8571	for parameter 1,	F(p): 0.8571
Latency: 3/6= 0.5	for parameter 2,	F(p): 0.5
Range: 6/7= 0.8571	for parameter 3,	F(p): 0.8571
LPI/LPD/AJ: 2/3= 0.6666	for parameter 4,	F(p): 0.6666
IP Connectivity: 2/3= 0.6666	for parameter 5,	F(p): 0.6666
Security: 2/2= 1	for parameter 6,	F(p): 1

Using the above values, a “p-Fp graph” was produced with the following MATLAB codes.

Codes of MATLAB

```
p=[1 2 3 4 5 6];
Fp=[0.8571 0.5 0.8571 0.6666 0.6666 1];
polyfit(p,Fp,6)
Function=polyfit(p,Fp,6);
```

```
a=Function(1,1);
b=Function(1,2);
c=Function(1,3);
d=Function(1,4);
e=Function(1,5);
f=Function(1,6);
g=Function(1,7);

x=(1:6);
Fx=a*x.^6+b*x.^5+c*x.^4+d*x.^3+e*x.^2+f*x+g;

plot(x,Fx,'LineWidth',3,'color','red')
title('Graphic of Parameter Value for JREAP-C');
xlabel('Parameters (p)');
ylabel('Size (Fp)');

expectedvalue=expfit(Fx);
```

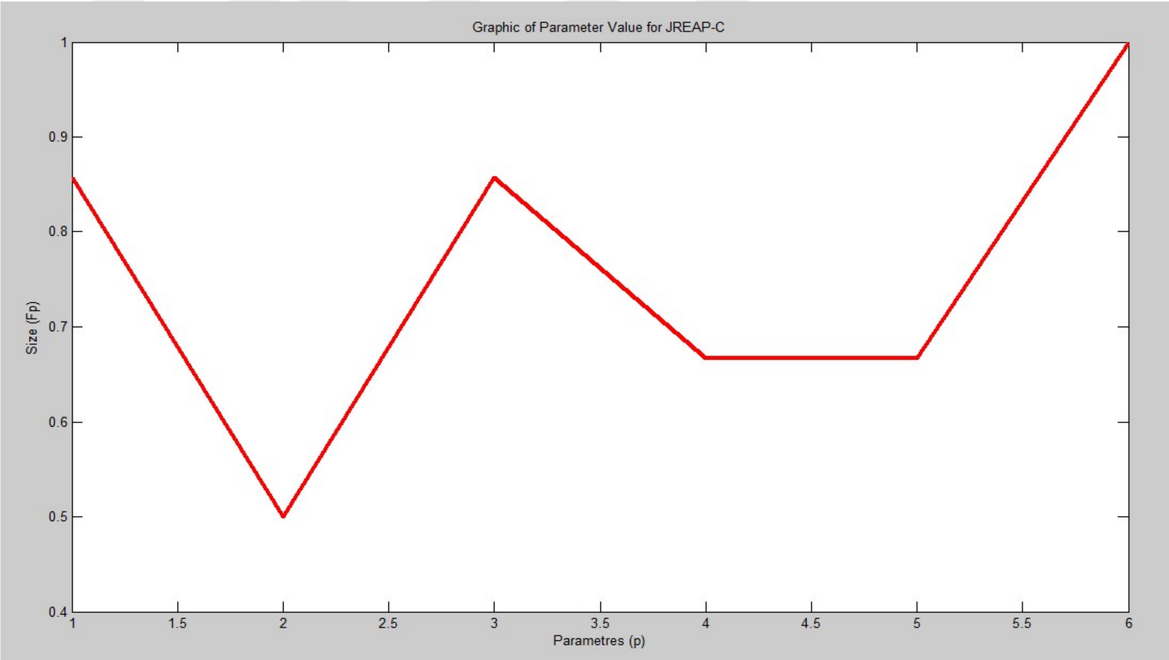


Figure 3.24 JREAP-C Function

JREAP-C Expected Value =0.7579

3.5.2.2 Produce Utility Matrix with Expected Value

All expected values are calculated in Section 3.5.2.1. These values are presented in Table 3.8. According to Table 3.8, sorting Tactical Data Links high to low is JREAP-C, JREAP-B, JREAP-A, Link-16, VMF, Link-22, Link-11B and Link-11A. There is a small difference in this method compared with the calculation of area method. In this method, the Link-22 value is bigger than Link-11B.

Table 3.8 Utility Matrix from expected value.

L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
0.4444	0.5000	0.6428	0.5277	0.5357	0.7100	0.7300	0.7500

Table 3.8 values are used in the second method for all demands. These values are presented in ANNEX D. Results will be evaluated in conclusion section.

3.5.3 Method of Analytical Hierarchical Processing (AHP)

Analytic Hierarchical Processing (AHP) is a mathematical theory developed by Thomas Saaty in the mid-1970s for measurement and decision making. AHP is used to determine the relative importance of a set of criteria. AHP is based on a comparison of two elements with the help of a matrix on a scale determined at each level of the hierarchy, and scaling the weights in this count. AHP stages are shown below [55].

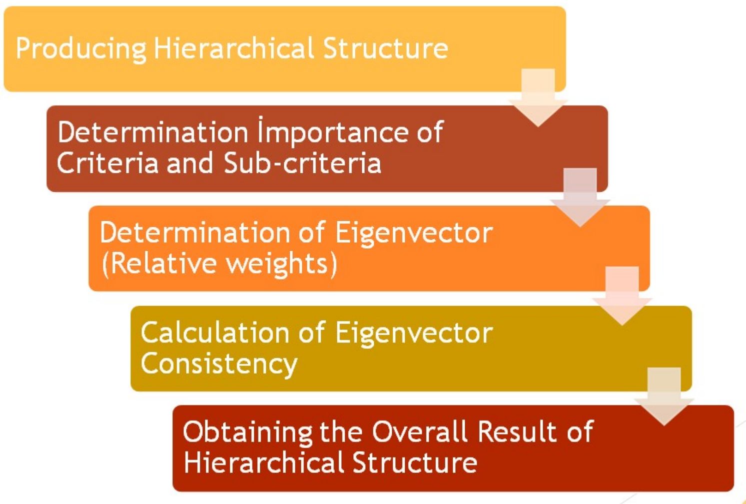


Figure 3.25 AHP Stages [55]

In Step 1 Producing Hierarchical Structure: The aim is to put forth and criteria/ sub-criteria determine.

In Step 2 Determination Importance of Criteria and Sub-criteria: Importance ratios are determined among themselves. For the decision criterion matrix, each criterion is compared in pairs.

Table 3.9 Comparison in pairs [56].

A=	1	a_{21}	a_{31}	...	a_{n1}
	$1/a_{21}$	1	a_{32}	...	a_{n2}
	$1/a_{31}$	$1/a_{32}$	1	...	a_{n3}
	...	...	...	...	...
	$1/a_{n1}$	$1/a_{n2}$	$1/a_{n3}$	...	1

In Table 3.9, "a_{ij}" is the importance of "criteria i" to "criteria j". In order to determine their superiority at this stage, the following importance scale is used by Saaty [57].

Table 3.10 Importance Scale [58].

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment moderately favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities of 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

In Step 3 Determination of Eigen Vector (Relative Weights): The method shown in the following Figure is used.

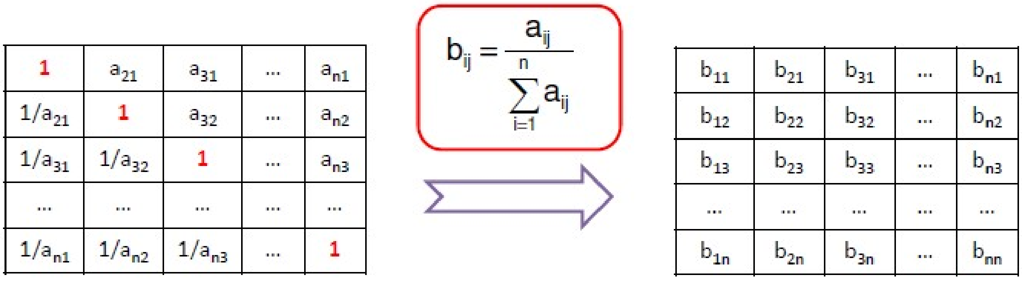


Figure 3.26 Interim Matrix [56]

All "b" values are produced by the formula in the Figure 3.26. The column vectors (W) need to be calculated in order to determine the percentage significance distributions of the criterions. The formula of Criteria Importance Degree Calculation is presented in Figure 3.27 [56].

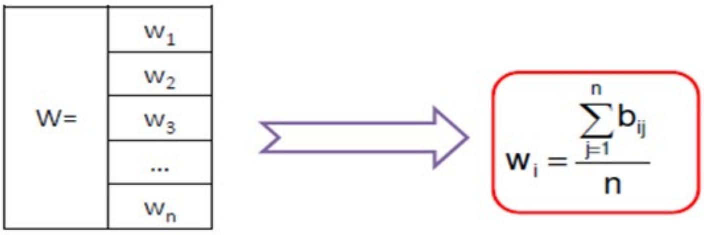


Figure 3.27 Criteria Importance Degree Calculation [56]

In Step 4 Calculation of Eigen Vector Consistency: The fact that the eigenvector has been calculated does not mean that the relative importance values are true. The decision maker may have inadvertently misjudged or may have been misleaded on some criteria, especially during large-scale problems.

The consistency ratio (CR) for each binary comparison matrix is calculated and it is desirable that the upper limit for this ratio is 0.10. Calculation of CR is presented in below.

$$D = [a_{ij}]_{nxn} \times [w_i]_{nx1} = [d_i]_{nx1} \Longrightarrow \lambda_{max} = \frac{\sum_{i=1}^{n} \frac{d_i}{w_i}}{n}$$

Figure 3.28 Calculation Consistency Ratio (CR) [56]

In Step 5 Obtaining the Overall Result of Hierarchical Structure: The previous four stages are calculated for the entire hierarchical structure. The decision vectors of size mxn are constructed by combining the superiority vectors of each of the measures in the hierarchical structure.

In this part, Utility Matrix will be produced according to AHP weight results. If the AHP weight of capability is greater, that capability will have more effect on the utility.

3.5.3.1 Calculation of Weights by Using AHP for Each Tactical Data Link

In this part, the Expert Choice software was used to solve the problem and calculations were made for the steps described above. Finally, weights and consistency were calculated for Utility Matrix.

Producing Hierarchical Structure

Firstly, a hierarchical structure was produced and capabilities were defined by using Expert Choice Software. Our criteria are IP Connectivity, Latency, LPI/LPD/AJ, Range, Security, and Throughput. Alternatives are our capabilities.

The aim was determined as “to select the optimum Tactical Data Link”. It is presented in Figure 3.29.

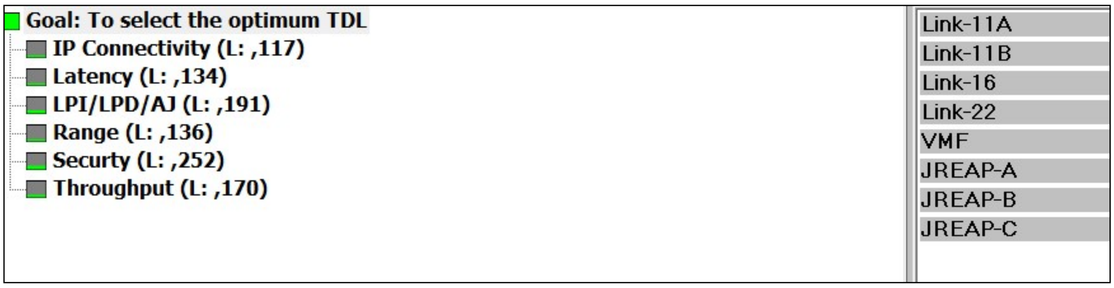
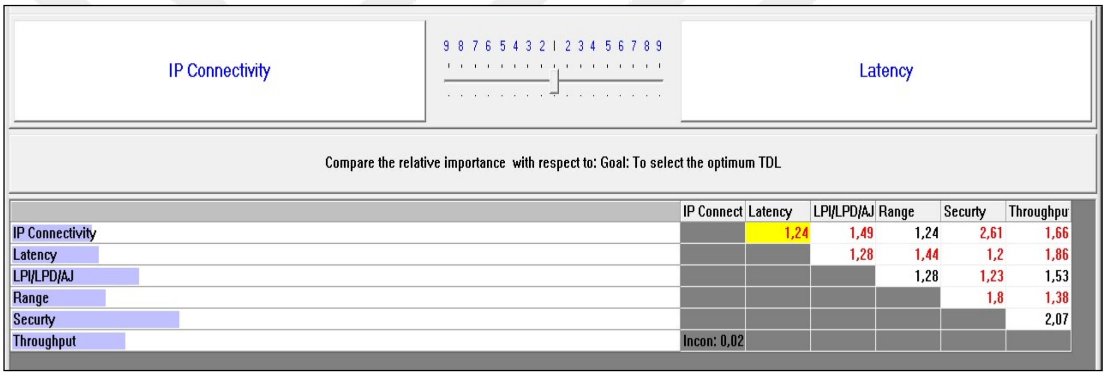


Figure 3.29 Hierarchical Structure

Determination Importance of Criteria and Sub-criteria

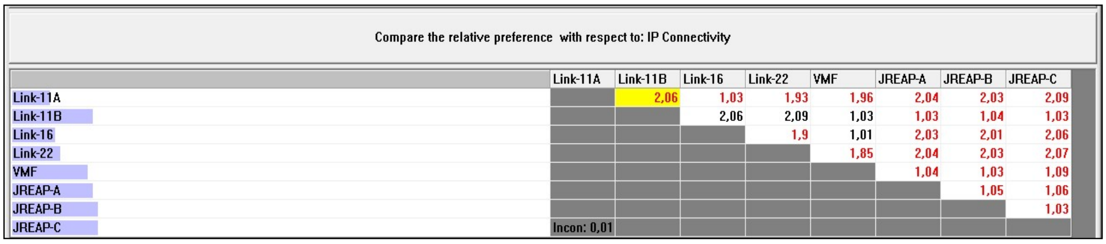
Each criterion was compared between each other with AHP scale table (Table 3.10) in mind.



	IP Connect	Latency	LPI/LPD/AJ	Range	Securty	Throughpu
IP Connectivity		1,24	1,49	1,24	2,61	1,66
Latency			1,28	1,44	1,2	1,86
LPI/LPD/AJ				1,28	1,23	1,53
Range					1,8	1,38
Securty						2,07
Throughput	Incon: 0,02					

Figure 3.30 Comparison of Criteria

After that, criteria were compared for each capability. They are presented in following figures. All comparisons were done by TDL experts.



	Link-11A	Link-11B	Link-16	Link-22	VMF	JREAP-A	JREAP-B	JREAP-C
Link-11A		2,06	1,03	1,93	1,96	2,04	2,03	2,09
Link-11B			2,06	2,09	1,03	1,03	1,04	1,03
Link-16				1,9	1,01	2,03	2,01	2,06
Link-22					1,85	2,04	2,03	2,07
VMF						1,04	1,03	1,09
JREAP-A							1,05	1,06
JREAP-B								1,03
JREAP-C	Incon: 0,01							

Figure 3.31 Comparison of IP Connectivity

Compare the relative preference with respect to: Latency

	Link-11A	Link-11B	Link-16	Link-22	VMF	JREAP-A	JREAP-B	JREAP-C
Link-11A		1,03	2,46	1,03	2,44	2,06	2,16	2,23
Link-11B			2,61	1,02	2,34	2,01	2,07	2,09
Link-16				2,3	1,04	1,16	1,14	1,09
Link-22					2,44	2,03	2,14	2,19
VMF						1,24	1,18	1,12
JREAP-A							1,04	1,08
JREAP-B								1,03
JREAP-C	Incon: 0,00							

Figure 3.32 Comparison of Latency

Compare the relative preference with respect to: LPI/LPD/AJ

	Link-11A	Link-11B	Link-16	Link-22	VMF	JREAP-A	JREAP-B	JREAP-C
Link-11A		1,02	2,5	1,04	1,04	1,03	1,07	1,1
Link-11B			2,38	1,02	1,03	1,02	1,06	1,07
Link-16				2,34	2,59	2,3	2,21	2,18
Link-22					1,04	1,02	1,06	1,07
VMF						1,02	1,04	1,07
JREAP-A							1,02	1,04
JREAP-B								1,03
JREAP-C	Incon: 0,00							

Figure 3.33 Comparison of LPI/LPD/AJ

Compare the relative preference with respect to: Range

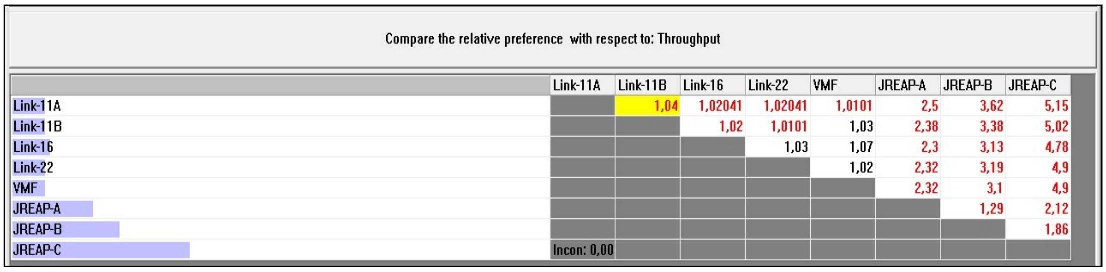
	Link-11A	Link-11B	Link-16	Link-22	VMF	JREAP-A	JREAP-B	JREAP-C
Link-11A		1,03	2,04	1,04	2,09	1,05	1,06	1,1
Link-11B			2,06	1,04	2,14	1,02	1,05	1,09
Link-16				2,09	1,01	2,06	2,12	2,14
Link-22					2,14	1,02	1,04	1,07
VMF						2,06	2,07	2,11
JREAP-A							1,02	1,04
JREAP-B								1,02
JREAP-C	Incon: 0,00							

Figure 3.34 Comparison of Range

Compare the relative preference with respect to: Securty

	Link-11A	Link-11B	Link-16	Link-22	VMF	JREAP-A	JREAP-B	JREAP-C
Link-11A		1,05	3,01	2,88	1,03	3,04	3,1	3,13
Link-11B			2,93	2,83	1,02	2,99	3,04	3,1
Link-16				1,01	2,8	1,03	1,04	1,06
Link-22					2,59	1,05	1,08	1,11
VMF						3,07	3,1	3,19
JREAP-A							1,02	1,04
JREAP-B								1,02
JREAP-C	Incon: 0,00							

Figure 3.35 Comparison of Security



Compare the relative preference with respect to: Throughput

	Link-11A	Link-11B	Link-16	Link-22	VMF	JREAP-A	JREAP-B	JREAP-C
Link-11A		1,04	1,02041	1,02041	1,0101	2,5	3,62	5,15
Link-11B			1,02	1,0101	1,03	2,38	3,38	5,02
Link-16				1,03	1,07	2,3	3,13	4,78
Link-22					1,02	2,32	3,19	4,9
VMF						2,32	3,1	4,9
JREAP-A							1,29	2,12
JREAP-B								1,86
JREAP-C	Incon: 0,00							

Figure 3.36 Comparison of Throughput

Determination of Eigen Vector (Relative Weights) and Eigen Vector Consistency

Eigen-vector was produced automatically by Expert Choice Software and weights were generated. These are presented in Figure 3.37. Additionally, inconsistency was produced automatically as 0.01. This value is not bigger than 0.1. Therefore, it is understood that the AHP model produced is consistent.

Obtaining the Overall Result of Hierarchical Structure

In this part, all weights of capabilities were produced by Expert Choice Software. These are presented in Figure 3.37

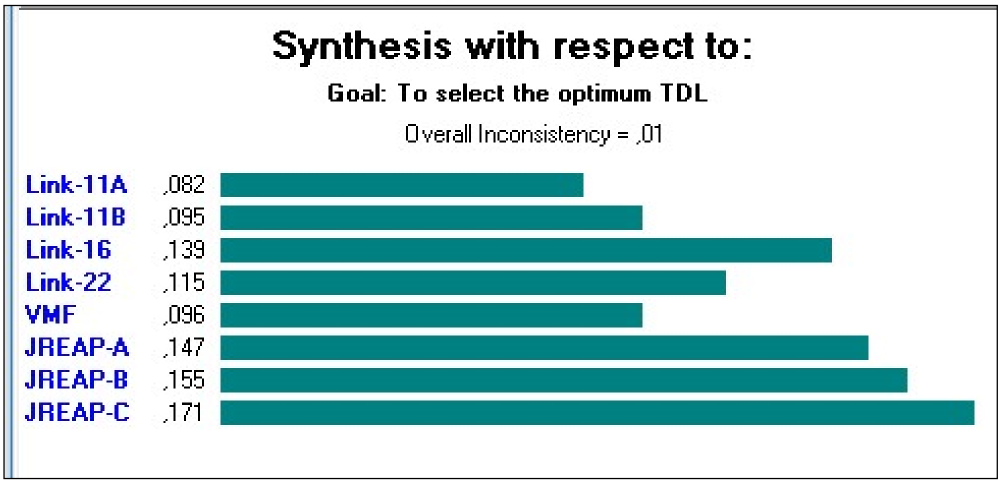


Figure 3.37 Capabilities Weights

3.5.3.2 Produce Utility Matrix with AHP Weights

All weights are calculated in Section 3.5.3.1. These values are presented in Table 3.11. According to Table 3.11, sorting Tactical Data Links high to low is JREAP-C, JREAP-B, JREAP-A, Link-16, Link-22, VMF, Link-11B and Link-11A. There is a small difference in this method compared with expected value method. In this method, the Link-22 value is bigger than VMF.

Table 3.11 Utility Matrix from AHP weights.

L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
0.082	0.095	0.139	0.115	0.096	0.147	0.155	0.171

Table 3.11 values are used in the third method for all demands. These values are presented in ANNEX D. Results will be evaluated in conclusion section.

CHAPTER 4

CONCLUSION

4.1 Optimization Results

Utility Matrix was formed by three methods. The first method was Calculation of Area of Spider Web Diagram; the second method was expected value theory and the third method was Analytical Hierarchical Processing (AHP) Method. They have little changes between each other in terms of sorting Tactical Data Links high to low. Codes and matrixes have been added to IBM ILOC CPLEX tool three times. And all codes were executed three times. Solutions with utility matrix resulted from Calculation Area Method were presented in Figure 4.1. Solutions with utility matrix resulted from Expected Value Method were presented in Figure 4.2. Solutions with utility matrix resulted from AHP Method were presented in Figure 4.3.

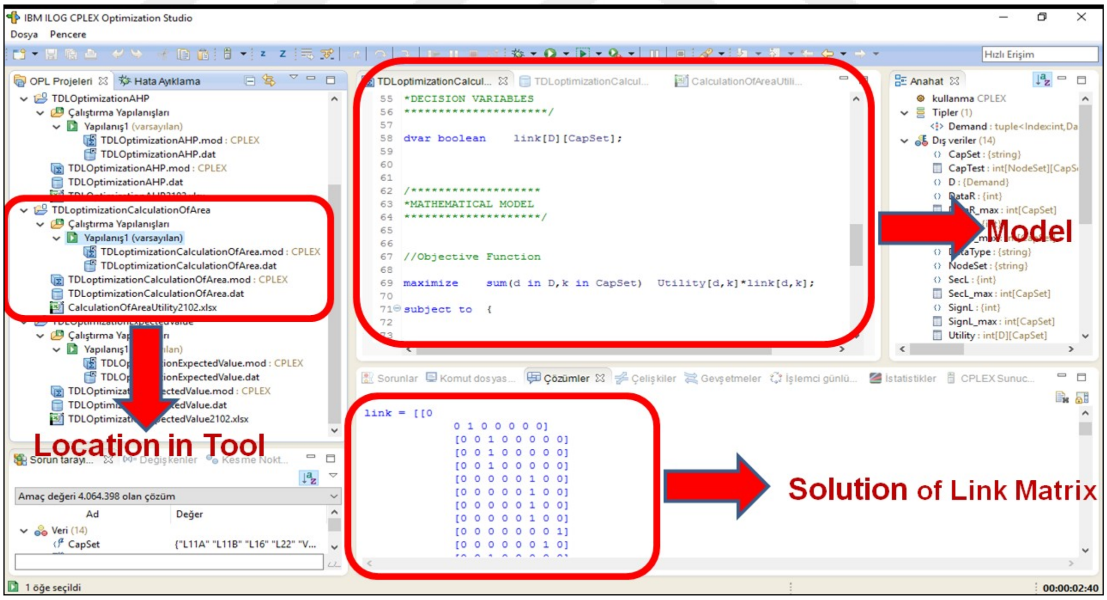


Figure 4.1 Solutions with Utility Matrix Resulted from Calculation Area Method

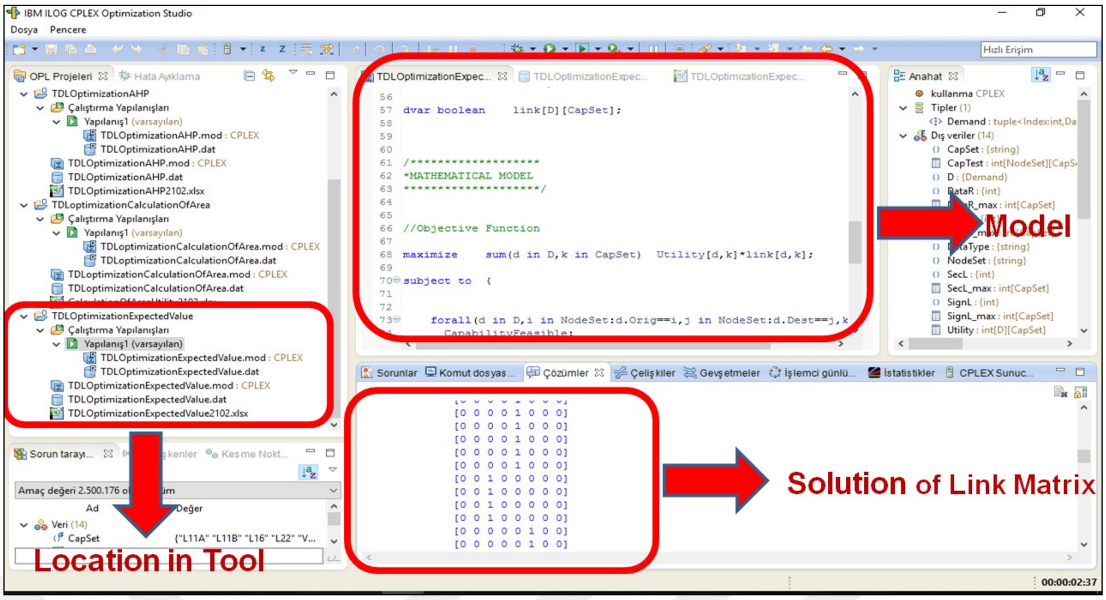


Figure 4.2 Solutions with Utility Matrix Resulted from Expected Value Method

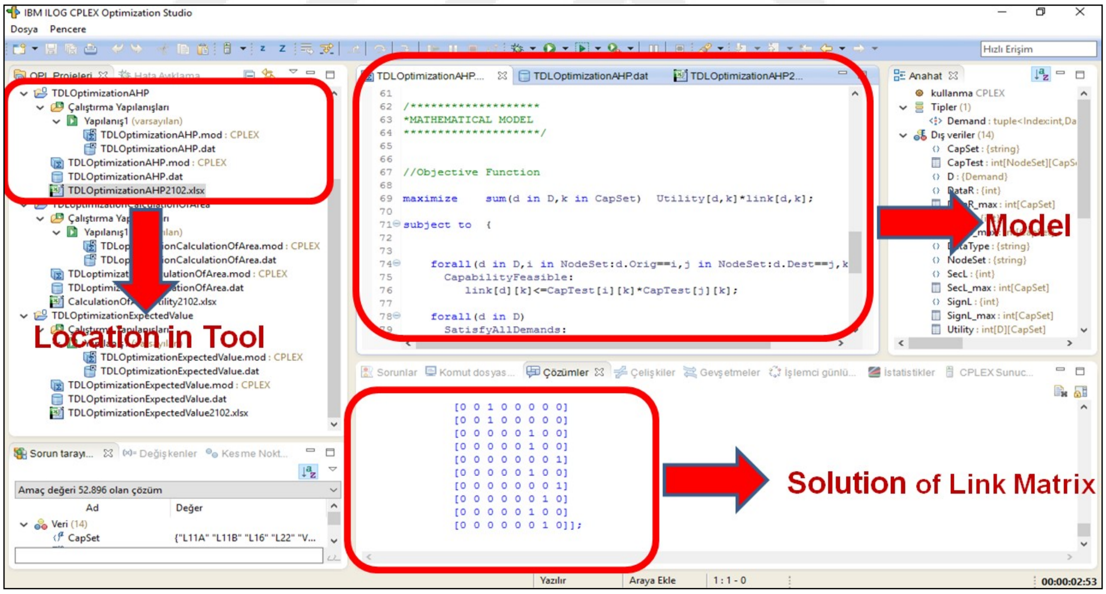


Figure 4.3 Solutions with Utility Matrix Resulted from AHP Method

We see the optimization results in Figure 4.1, Figure 4.2 and Figure 4.3. Although Utility Matrices have little changes between each other in terms of sorting Tactical Data Links high to low, results of three methods were the same in terms of selected demands.

We understood that minor changes in Utility Matrices have not been a factor for selected demands.

Detailed output of IBM ILOC CPLEX was presented in ANNEX D for three methods. However, three methods' results are the same because giving the same results in the IBM ILOC CPLEX tool. Example optimization results of first 50 demands are put forward in this part (Table 4.1)

In Table 4.1, "1" indicates that the capability to be used for a specific demand. For example, demand 1 must be sent by Link-16, demand 5 must be sent by JRP-A, demand 9 must be sent by JRP-C, etc. These are solutions of our problems that we mentioned above.

Table 4.1 Example optimization results of first 50 demands

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
1	0	0	1	0	0	0	0	0
2	0	0	1	0	0	0	0	0
3	0	0	1	0	0	0	0	0
4	0	0	1	0	0	0	0	0
5	0	0	0	0	0	1	0	0
6	0	0	0	0	0	1	0	0
7	0	0	0	0	0	1	0	0
8	0	0	0	0	0	1	0	0
9	0	0	0	0	0	0	0	1
10	0	0	0	0	0	0	1	0
11	0	0	1	0	0	0	0	0
12	0	0	1	0	0	0	0	0
13	0	0	1	0	0	0	0	0
14	0	0	1	0	0	0	0	0
15	0	0	1	0	0	0	0	0
16	0	0	1	0	0	0	0	0
17	0	0	1	0	0	0	0	0
18	0	0	1	0	0	0	0	0
19	0	0	1	0	0	0	0	0
20	0	0	0	0	1	0	0	0
21	0	0	1	0	0	0	0	0
22	0	0	1	0	0	0	0	0
23	0	0	1	0	0	0	0	0
24	0	0	1	0	0	0	0	0
25	0	0	1	0	0	0	0	0
26	0	0	1	0	0	0	0	0
27	0	0	1	0	0	0	0	0
28	0	0	1	0	0	0	0	0
29	0	0	1	0	0	0	0	0
30	0	0	0	0	1	0	0	0
31	0	0	1	0	0	0	0	0
32	0	0	1	0	0	0	0	0
33	0	0	1	0	0	0	0	0
34	0	0	1	0	0	0	0	0
35	0	0	1	0	0	0	0	0
36	0	0	1	0	0	0	0	0
37	0	0	1	0	0	0	0	0
38	0	0	1	0	0	0	0	0
39	0	0	1	0	0	0	0	0
40	0	0	0	0	1	0	0	0
41	0	0	1	0	0	0	0	0
42	0	0	1	0	0	0	0	0
43	0	0	1	0	0	0	0	0
44	0	0	1	0	0	0	0	0
45	0	0	1	0	0	0	0	0
46	0	0	1	0	0	0	0	0
47	0	0	1	0	0	0	0	0
48	0	0	1	0	0	0	0	0
49	0	0	1	0	0	0	0	0
50	0	0	0	0	1	0	0	0

According to Annex-D, Link-11A is selected 4 times, Link-11B is selected 0 times, Link-16 is selected 171 times, Link-22 is selected 0 times, VMF is selected 16 times, JREAP-A is selected 139 times, JREAP-B is selected 22 times, JREAP-C is selected 20 times. These are presented in Figure 4.5. We can understand in this chart, Link-16 is the best Link when platforms are within the same Line of Sight (LOS). (For; according to Section 3.2, it was assumed that all platforms were within the same Line of Sight (LOS) in this scenario.)

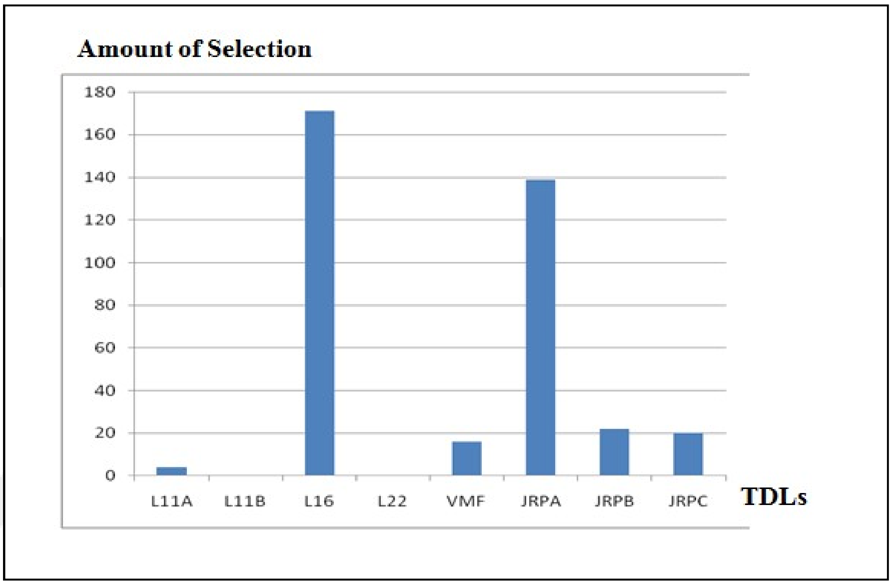


Figure 4.4 Capability Amount of Selection

Table 4.2 shows the amount of result which data type is mostly carried with which capability. For example, a total of 59 surveillance messages must be sent by Link-16 (24 of 59), VMF (2 of 59), JREAP-A (26 of 59), JREAP-B (2 of 59) and JREAP-C (5 of 59).

Table 4.2 The amount of result with capability and data type

DataType	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C	Total Demand
NM	0	0	4	0	0	4	1	1	10
PLIS	0	0	60	0	12	27	4	4	107
SUR	0	0	24	0	2	26	2	5	59
INT	0	0	24	0	2	4	2	2	34
WC	0	0	0	0	0	0	8	0	8
FCNT	0	0	24	0	0	0	0	0	24
EW	0	0	0	0	0	56	0	4	60
FT	4	0	35	0	0	22	5	4	70

Line chart and bar chart of Table 4.2 is presented in below.

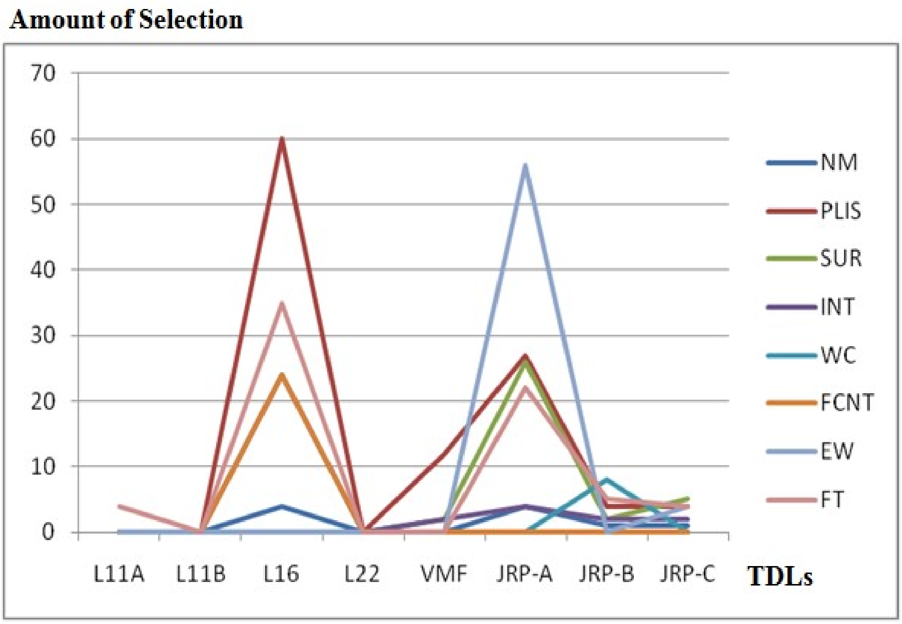


Figure 4.5 Line Chart of Capability and Data Type

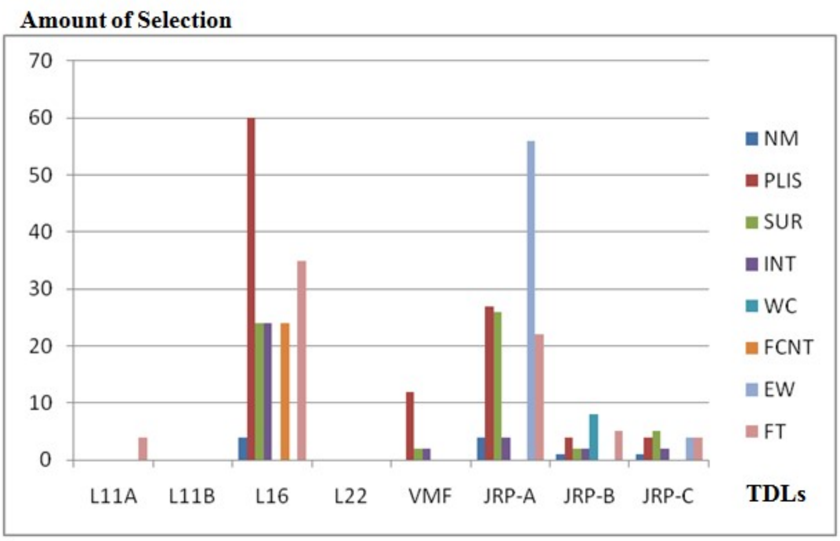


Figure 4.6 Bar Chart of Capability and Data Type

We can understand from the above charts, Link-16 is the best Link when platforms are within the same Line of Sight (LOS). The second best link is JREAP-A because it has similar properties in Radio Frequency layer. Link-11B was never preferred owing to be a legacy wire link. JREAP-B and JREAP-C cover all capabilities of Link-11B. Link-22 is a surprising result because it is a modern link. The reason of this, all platforms are within the same Line of Sight (LOS). Link-22 is strong in the absence of Line of Sight.

4.2 Check the Results as Sampling

In this part, the results will be checked by sampling method.

4.2.1 First Example

According to demand table (Annex A); for demand 1, the originator is G1 (Command and Control Center 1) and the destination is F1 (Fighter 1). Data size is small (1), the security level is confidential (2), the significance level is normal significance (1) and minimum speed requested is the normal rate (1).

According to Table 3.4 (participant capabilities table), platform G1 has Link-11A, Link-11B, Link-16, Link-22, JREAP-A, JREAP-B and JREAP-C. Platform F1 has Link-16 and VMF. There is only one matching capability. It is Link-16.

According to Table 3.3 (maximum characteristic of capabilities), Link-16 is able to send very good rate (3), top secret (4), very significance (3) and large data (3). All characteristics are bigger than demand. The data must send Link-16. When we control optimization result in Annex D, we can see that Link-16 is selected. The result is true.

4.2.2 Second Example

According to demand table (Annex A); for demand 56, the originator is A1 (Airborne Early Warning Command and Control Aircraft 1) and the destination is N1 (Naval Platform 1). Data size is large (3), the security level is secret (3), the significance level is very significance (3) and minimum speed requested is the good rate (2).

According to Table 3.4 (participant capabilities table), platform A1 has Link-11A, Link-16, Link-22, VMF and JREAP-A. Platform N1 has Link-11A, Link-16, Link-22 and JREAP-A. Link-11A, Link-16, Link-22 and JREAP-A are matching capabilities.

According to Table 3.3 (maximum characteristic of capabilities), Link-11's maximum data rate is Normal Rate (1). However, the demand data's requested speed is the good rate (2). That's why; Link-11 doesn't pass the constraints. Link-16, Link-22 and JREAP-A are able to send demand 56. All characteristics are bigger than demand for Link-16, Link-22 and JREAP-A. When we control optimization result in Annex D, we can see that JREAP-A is selected because of the Utility Matrix. According to Table 3.7, Table 3.8 and Table 3.11; JREAP-A is bigger than Link-16 and Link-22. The result is true.

4.2.3 Third Example

According to demand table (Annex A); for demand 211, the originator is G1 (Command and Control Center 1) and the destination is S1 (Surface to Air Missile 1). Data size is medium (2), the security level is secret (3), the significance level is normal significance (1) and minimum speed requested is the normal rate (1).

According to Table 3.4 (participant capabilities table), platform G1 has Link-11A, Link-11B, Link-16, Link-22, JREAP-A, JREAP-B and JREAP-C. Platform S1 has Link-11A, Link-11B and JREAP-B. Link-11A, Link-11B and JREAP-B are matching capabilities.

According to Table 3.3 (maximum characteristic of capabilities), Link-11A, Link-11B and JREAP-B characteristics are bigger than demand. When we control optimization result in Annex D, we can see that JREAP-B is selected because of the Utility Matrix. According to Table 3.7, Table 3.8 and Table 3.11; JREAP-B is bigger than Link-11A and Link-11B. The result is true.

4.3 A Different Perspective on Optimization

In this section, by varying the parameters results will be evaluated with different perspectives.

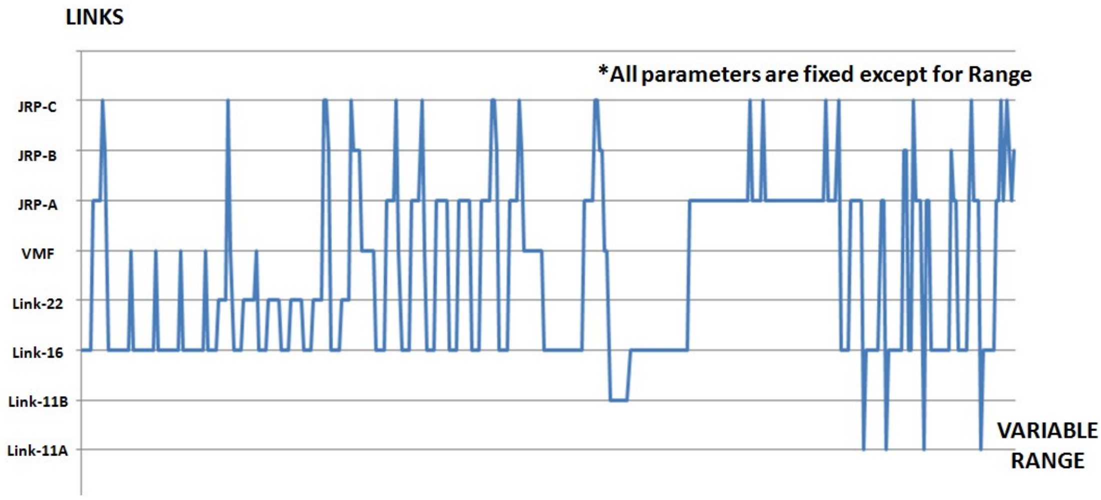


Figure 4.7 Optimization State in Variable Range in the Presence of All Platforms

According to Figure 4.5, Link-22 selection is a surprising result because it is a modern link. Link-22 is strong in long distance. In Figure 4.8, all parameters are fixed except for range. The range is left as a variable. After the optimization codes are executed, Figure 4.8 results are shown. The superiority of Link-16 and JREAP-A has begun to cross Link-22.

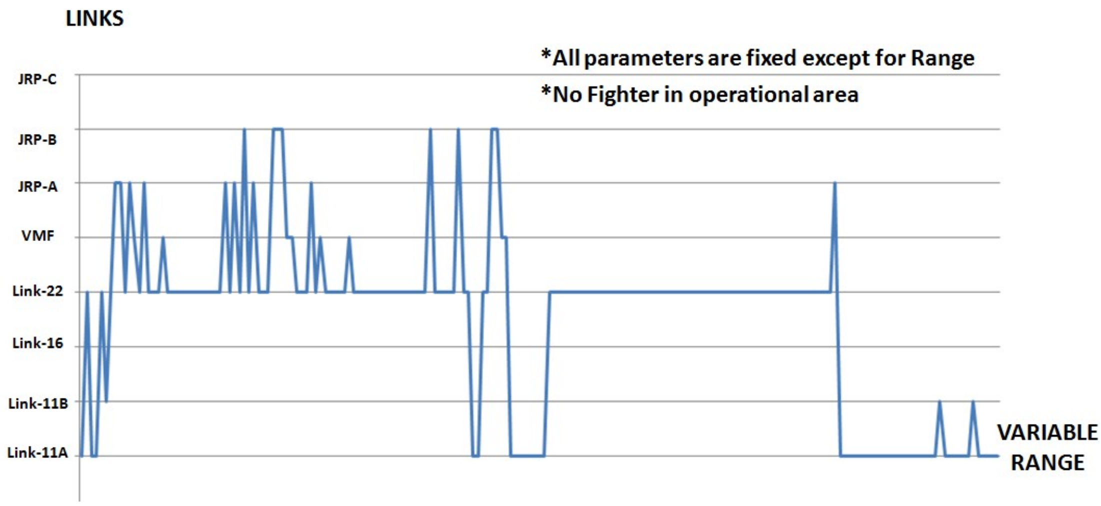


Figure 4.8 Optimization State in Variable Range in the Presence of All Platforms Except for Fighters

When codes are executed in the presence of all platforms except for fighters, Figure 4.9 results are shown. The superiority of Link-16 and JREAP-A has fully shifted to cross Link-22. We are able to understand that Link-22 is better in the environment where the range is variable and there are no fighters. Therefore, the use of Link-22 in platforms except for fighters should be widespread.

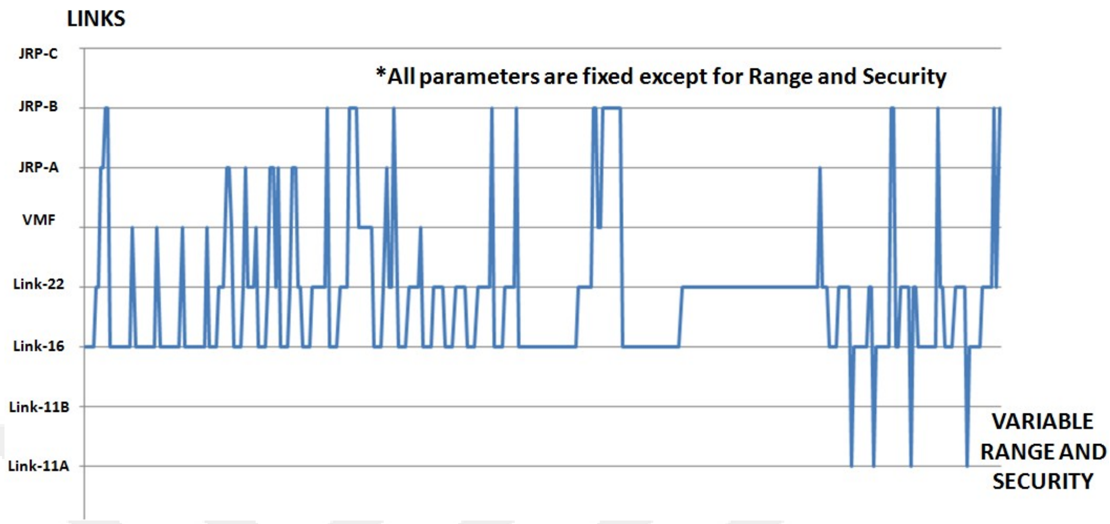


Figure 4.9 Optimization State in Variable Range and Security in the Presence of All Platforms

When range and security are considered together as a variable in the presence of all platforms, Link-22 is more likely to be selected in Figure 4.10.

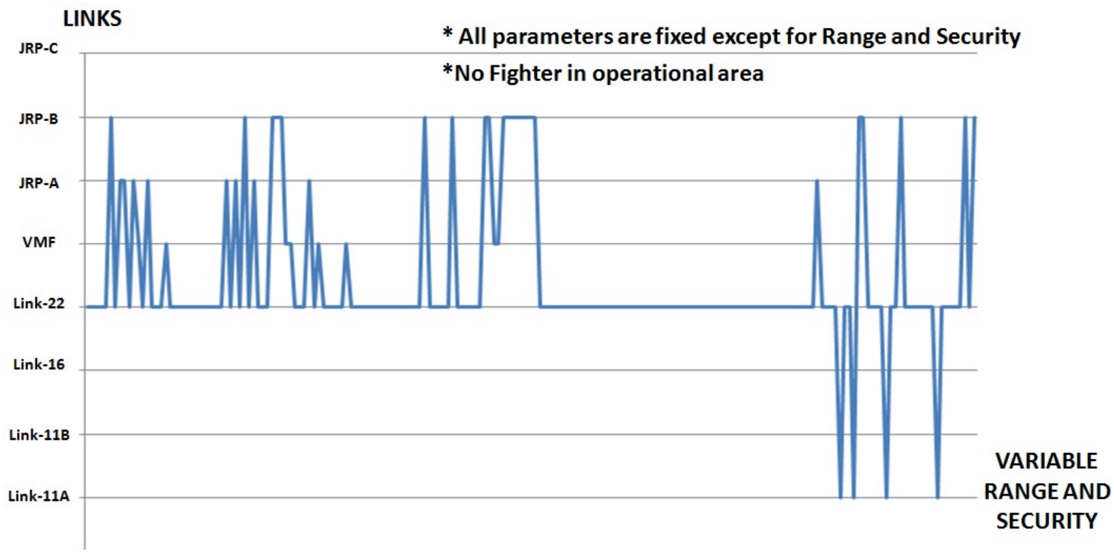


Figure 4.10 Optimization State in Variable Range and Security in the Presence of All Platforms Except for Fighters

As for Figure 4.11, Link-22 is better than the other links because of strong security. In this option only range and security are variable, other parameters are fixed.

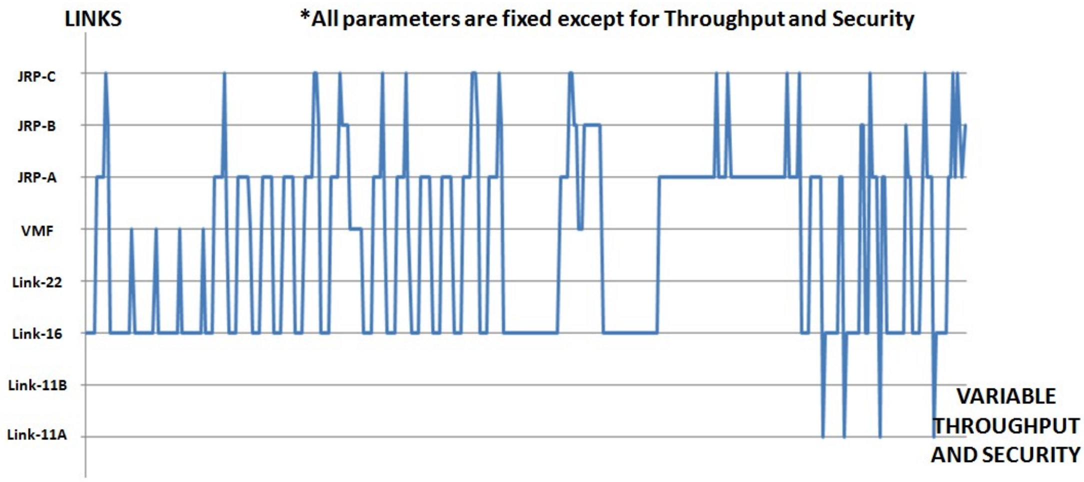


Figure 4.11 Optimization State in Variable Throughput and Security in the Presence of All Platforms

When variable parameters change, for example, throughput and security, results have completely changed. JREAP-A and Link-16 have been the best link in the operational area in Figure 4.12.

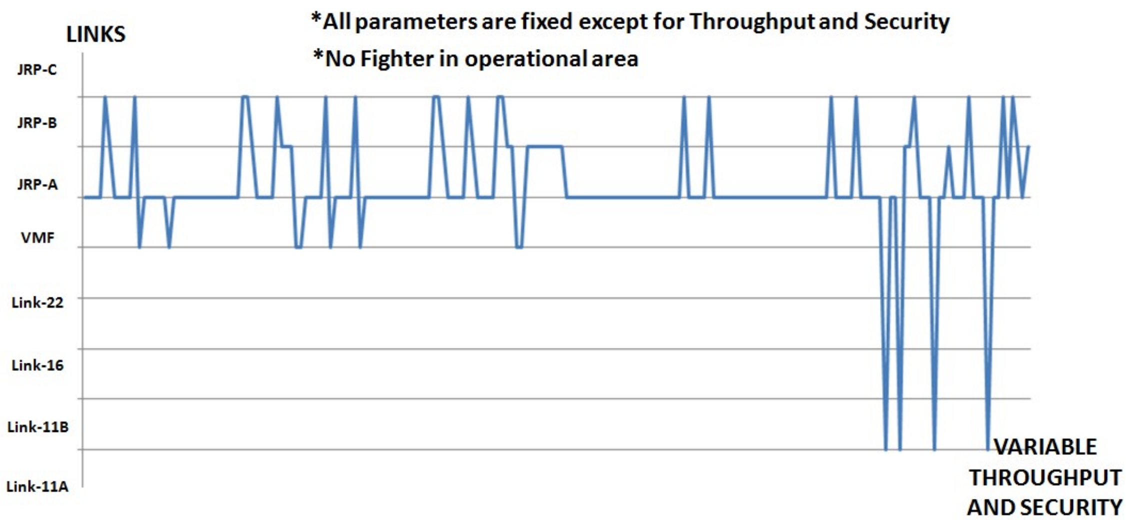


Figure 4.12 Optimization State in Variable Throughput and Security in the Presence of All Platforms Except for Fighters

According to Figure 4.13, in the Presence of all platforms except for fighters Link-16 has been replaced to JREAP-A. The reason of this, fighters use Link-16 as the main link.

4.4 Conclusion and Evaluations

In today’s TDL environment, battlefield area’s communications consist of legacy equipment. Production years of TDLs vary and they show different characteristics. These are Link-11A, Link-11B, Link-16, Link-22, Variable Message Format, JREAP-A, JREAP-B and JREAP-C. These have different capabilities. Some TDLs show superiority in sending some data while other TDLs dominance in transmission other information. In addition, every TDL has constraints and advantages in terms of data set diversity, the amount of maximum/minimum data rate, the amount of the highest security level and degree of significance level. With respect to platform TDL capabilities of specific platforms, they are all unsimilar. For instance, while F-16 Fighter has only Link-16 and VMF, Airborne Early Warning aircraft may have capable of Link-11A, Link-16, Link-22, VMF and JREAP-A. Moreover, platforms are able to join lots of TDLs at the same time. This position will be much more complex in developing operational environment. As a result of these inputs, the necessity of an optimization is indispensable.

Until now, there are some TDL optimization studies in the academic literature. The studies cover; real-time tactical mobile network optimization, modeling the wired and wireless links in near real time by using simulators, optimizing system performance via configuration control, composing mixed tactical network consists of different links which have line-of-sight or beyond line-of-sight, monitoring varied links in order to use as input for optimization. Despite many studies, there are only few TDL optimization software kits in the market. Hence, TDL users will need to choose a specific link or have to lose information with developing technology in future when they send their data to other users.

As technology progresses and the amount of TDLs are increases, inasmuch as the operational stage is more complex than before, the load on the man and manual errors will increase unless optimization is given the necessary attention.

In this thesis, TDLs are explained in detailed. It is mentioned that TDL responsibility is to ensure the mechanism for the automated real-time and near real-time information exchange among the platforms participated TDL network.

The components of TDL were mentioned and clarified briefly. These components are data source which can normally be a sensor system, HMI (Human Machine Interface) system which is used to control parameters of TDL operations, cryptographic system which provides encryption of transferred data and increases resistance against hostile ECM, communication system (modem, radio transceiver and antenna), and message set which allows exchange of information.

Each common TDL is described and unfolded in-depth. These are Link-11, Link-16, Link-22, VMF and JREAP-A/B/C. Link-11 is composed of two types. They are Link-11A and Link-11B. Link-11A is an automated, one- or two-way, HF data link to distribute information within the Tactical Data System. Link-11B is ground Link-11. Link-11B uses the same message catalog as Link-11A, but the transmission environment is ground. Link 16 is a TDMA-based secure, jam-resistant, high-speed digital data link which operates in its specific l-band radio frequency. Link 22 is NATO Improved Link Eleven (NILE) network which is a secure digital radio link that uses both HF and UHF band. VMF is a communication protocol which has flexible architecture. JREAP-A/B/C is a Joint Range Extension Application Protocol used satellite, serial line and Ethernet infrastructure.

Optimization Theory was reviewed. Optimization can be defined as the process of finding the best solution or design of a problem. It was mentioned that the mathematical definition of a general optimization problem consisted of three parts. They were Decision Variable, Objective function and Constrains. Moreover, it was mentioned that single variable optimization and multi-variable optimization.

Finally, an optimization has been made among TDLs. All parameters are grouped, sorted and clarified. Optimization sets are produced. Parameters are located to the tables and parameter levels are converted to numerical values for the computer to understand. TDL capabilities maximum levels are pointed out and added the tables. Link capabilities of TDL participants are fixed and their communication maps are revealed. Lastly, optimization equations are generated carefully. It was mentioned that Utility Matrix was a substantial parameter for optimization model, it contributed the optimization in final part and utility table was produced by three different methods. They were Method of Spider Web Diagram Area Calculation, Method of Expected Value and Method of Analytical Hierarchical Processing (AHP).

Although Utility Matrices have small differences, results of the three methods were the same for the selected demand data. It is resulted that minor changes in Utility Matrices are not effective factors for the selected demand data.

According to an example of data flow (Annex A), results were revealed. The optimization model was performed with developed algorithms using IBM ILOC CPLEX tool.

Recently, TDL Optimization issues have been started to work on the operational area. Therefore this is a very new field in the academic community. Because optimization is the selection of the best TDL (with regard to some criterion) from some set of available alternatives, it is very remarkable for developers. The modern operational area has lots of multilink devices on a specific platform. In future, TDL issues will become more complicated. Accordingly, what information should be sent by which Tactical Data Link is the crucial issue. In this regard, TDL Optimization will fill an important gap in tactical communication. If the studies increase in TDL optimization issues, information exchange can realize automatically without data loss.

The optimization model presented in this thesis is so flexible in terms of adding additional capabilities or further links. In future, this model can be transformed more comprehensive with little changes.

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- Tactical Data Links
- Command and Control Systems
- Air Defense Systems
- Military Communication Systems

ANNEX A

DEMAND DATA

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
1	NM	G1	F1	1	2	1	1
2	NM	G1	F2	1	2	1	1
3	NM	G1	F3	1	2	1	1
4	NM	G1	F4	1	2	1	1
5	NM	G1	A1	1	2	1	1
6	NM	G1	A2	1	2	1	1
7	NM	G1	N1	1	2	1	1
8	NM	G1	N2	1	2	1	1
9	NM	G1	G2	1	2	1	1
10	NM	G1	S1	1	2	1	1
11	PLIS	F1	F2	3	3	3	2
12	PLIS	F1	F3	3	3	3	2
13	PLIS	F1	F4	3	3	3	2
14	PLIS	F1	A1	3	3	3	2
15	PLIS	F1	A2	3	3	3	2
16	PLIS	F1	N1	3	3	3	2
17	PLIS	F1	N2	3	3	3	2
18	PLIS	F1	G1	3	3	3	2
19	PLIS	F1	G2	3	3	3	2
20	PLIS	F1	H1	2	3	3	2
21	PLIS	F2	F1	3	3	3	2
22	PLIS	F2	F3	3	3	3	2
23	PLIS	F2	F4	3	3	3	2
24	PLIS	F2	A1	3	3	3	2
25	PLIS	F2	A2	3	3	3	2
26	PLIS	F2	N1	3	3	3	2
27	PLIS	F2	N2	3	3	3	2
28	PLIS	F2	G1	3	3	3	2
29	PLIS	F2	G2	3	3	3	2
30	PLIS	F2	H1	2	3	3	2
31	PLIS	F3	F1	3	3	3	2
32	PLIS	F3	F2	3	3	3	2
33	PLIS	F3	F4	3	3	3	2
34	PLIS	F3	A1	3	3	3	2
35	PLIS	F3	A2	3	3	3	2
36	PLIS	F3	N1	3	3	3	2
37	PLIS	F3	N2	3	3	3	2
38	PLIS	F3	G1	3	3	3	2
39	PLIS	F3	G2	3	3	3	2
40	PLIS	F3	H1	2	3	3	2
41	PLIS	F4	F1	3	3	3	2
42	PLIS	F4	F2	3	3	3	2
43	PLIS	F4	F3	3	3	3	2
44	PLIS	F4	A1	3	3	3	2
45	PLIS	F4	A2	3	3	3	2
46	PLIS	F4	N1	3	3	3	2
47	PLIS	F4	N2	3	3	3	2
48	PLIS	F4	G1	3	3	3	2
49	PLIS	F4	G2	3	3	3	2
50	PLIS	F4	H1	2	3	3	2

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
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52	PLIS	A1	F2	3	3	3	2
53	PLIS	A1	F3	3	3	3	2
54	PLIS	A1	F4	3	3	3	2
55	PLIS	A1	A2	3	3	3	2
56	PLIS	A1	N1	3	3	3	2
57	PLIS	A1	N2	3	3	3	2
58	PLIS	A1	G1	3	3	3	2
59	PLIS	A1	G2	3	3	3	2
60	PLIS	A1	H1	2	3	3	2
61	PLIS	A2	F1	3	3	3	2
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63	PLIS	A2	F3	3	3	3	2
64	PLIS	A2	F4	3	3	3	2
65	PLIS	A2	A1	3	3	3	2
66	PLIS	A2	N1	3	3	3	2
67	PLIS	A2	N2	3	3	3	2
68	PLIS	A2	G1	3	3	3	2
69	PLIS	A2	G2	3	3	3	2
70	PLIS	A2	H1	2	3	3	2
71	PLIS	N1	F1	3	3	3	2
72	PLIS	N1	F2	3	3	3	2
73	PLIS	N1	F3	3	3	3	2
74	PLIS	N1	F4	3	3	3	2
75	PLIS	N1	A1	3	3	3	2
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79	PLIS	N1	G2	3	3	3	2
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81	PLIS	N2	F2	3	3	3	2
82	PLIS	N2	F3	3	3	3	2
83	PLIS	N2	F4	3	3	3	2
84	PLIS	N2	A1	3	3	3	2
85	PLIS	N2	A2	3	3	3	2
86	PLIS	N2	N1	3	3	3	2
87	PLIS	N2	G1	3	3	3	2
88	PLIS	N2	G2	3	3	3	2
89	PLIS	G1	F1	3	3	3	2
90	PLIS	G1	F2	3	3	3	2
91	PLIS	G1	F3	3	3	3	2
92	PLIS	G1	F4	3	3	3	2
93	PLIS	G1	A1	3	3	3	2
94	PLIS	G1	A2	3	3	3	2
95	PLIS	G1	N1	3	3	3	2
96	PLIS	G1	N2	3	3	3	2
97	PLIS	G1	G1	3	3	3	2
98	PLIS	G1	G2	3	3	3	2
99	PLIS	G1	S1	3	3	3	2
100	PLIS	G2	F1	3	3	3	2
101	PLIS	G2	F2	3	3	3	2
102	PLIS	G2	F3	3	3	3	2
103	PLIS	G2	F4	3	3	3	2
104	PLIS	G2	A1	3	3	3	2

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
105	PLIS	G2	A2	3	3	3	2
106	PLIS	G2	N1	3	3	3	2
107	PLIS	G2	N2	3	3	3	2
108	PLIS	G2	G1	3	3	3	2
109	PLIS	G2	S1	3	3	3	2
110	PLIS	S1	G1	3	3	3	2
111	PLIS	S1	G2	3	3	3	2
112	PLIS	H1	F1	2	3	3	2
113	PLIS	H1	F2	2	3	3	2
114	PLIS	H1	F3	2	3	3	2
115	PLIS	H1	F4	2	3	3	2
116	PLIS	H1	A1	2	3	3	2
117	PLIS	H1	A2	2	3	3	2
118	SUR	A1	F1	3	3	3	2
119	SUR	A1	F2	3	3	3	2
120	SUR	A1	F3	3	3	3	2
121	SUR	A1	F4	3	3	3	2
122	SUR	A1	A2	3	3	3	2
123	SUR	A1	N1	3	3	3	2
124	SUR	A1	N2	3	3	3	2
125	SUR	A1	G1	3	3	3	2
126	SUR	A1	G2	3	3	3	2
127	SUR	A1	H1	2	3	3	2
128	SUR	A2	F1	3	3	3	2
129	SUR	A2	F2	3	3	3	2
130	SUR	A2	F3	3	3	3	2
131	SUR	A2	F4	3	3	3	2
132	SUR	A2	A1	3	3	3	2
133	SUR	A2	N1	3	3	3	2
134	SUR	A2	N2	3	3	3	2
135	SUR	A2	G1	3	3	3	2
136	SUR	A2	G2	3	3	3	2
137	SUR	A2	H1	2	3	3	2
138	SUR	N1	F1	3	3	3	2
139	SUR	N1	F2	3	3	3	2
140	SUR	N1	F3	3	3	3	2
141	SUR	N1	F4	3	3	3	2
142	SUR	N1	A1	3	3	3	2
143	SUR	N1	A2	3	3	3	2
144	SUR	N1	N2	3	3	3	2
145	SUR	N1	G1	3	3	3	2
146	SUR	N1	G2	3	3	3	2
147	SUR	N2	F1	3	3	3	2
148	SUR	N2	F2	3	3	3	2
149	SUR	N2	F3	3	3	3	2
150	SUR	N2	F4	3	3	3	2
151	SUR	N2	A1	3	3	3	2
152	SUR	N2	A2	3	3	3	2
153	SUR	N2	N1	3	3	3	2
154	SUR	N2	G1	3	3	3	2
155	SUR	N2	G2	3	3	3	2
156	SUR	G1	F1	3	3	3	2
157	SUR	G1	F2	3	3	3	2
158	SUR	G1	F3	3	3	3	2

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
159	SUR	G1	F4	3	3	3	2
160	SUR	G1	A1	3	3	3	2
161	SUR	G1	A2	3	3	3	2
162	SUR	G1	N1	3	3	3	2
163	SUR	G1	N2	3	3	3	2
164	SUR	G1	G1	3	3	3	2
165	SUR	G1	G2	3	3	3	2
166	SUR	G1	S1	3	3	3	2
167	SUR	G2	F1	3	3	3	2
168	SUR	G2	F2	3	3	3	2
169	SUR	G2	F3	3	3	3	2
170	SUR	G2	F4	3	3	3	2
171	SUR	G2	A1	3	3	3	2
172	SUR	G2	A2	3	3	3	2
173	SUR	G2	N1	3	3	3	2
174	SUR	G2	N2	3	3	3	2
175	SUR	G2	G1	3	3	3	2
176	SUR	G2	S1	3	3	3	2
177	INT	A1	F1	1	2	2	3
178	INT	A1	F2	1	2	2	3
179	INT	A1	F3	1	2	2	3
180	INT	A1	F4	1	2	2	3
181	INT	A2	F1	1	2	2	3
182	INT	A2	F2	1	2	2	3
183	INT	A2	F3	1	2	2	3
184	INT	A2	F4	1	2	2	3
185	INT	N1	F1	1	2	2	3
186	INT	N1	F2	1	2	2	3
187	INT	N1	F3	1	2	2	3
188	INT	N1	F4	1	2	2	3
189	INT	N2	F1	1	2	2	3
190	INT	N2	F2	1	2	2	3
191	INT	N2	F3	1	2	2	3
192	INT	N2	F4	1	2	2	3
193	INT	G1	F1	1	2	2	3
194	INT	G1	F2	1	2	2	3
195	INT	G1	F3	1	2	2	3
196	INT	G1	F4	1	2	2	3
197	INT	G2	F1	1	2	2	3
198	INT	G2	F2	1	2	2	3
199	INT	G2	F3	1	2	2	3
200	INT	G2	F4	1	2	2	3
201	INT	A1	A2	3	4	2	2
202	INT	A2	A1	3	4	2	2
203	INT	N1	N2	1	3	1	1
204	INT	N2	N1	1	3	1	1
205	INT	G1	G2	1	4	3	3
206	INT	G2	G1	1	4	3	3
207	INT	G1	S1	1	2	3	3
208	INT	G2	S1	1	2	3	3
209	INT	A1	H1	1	3	2	2
210	INT	A2	H1	1	3	2	2
211	WC	G1	S1	2	3	1	1
212	WC	G2	S1	2	3	2	1

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
213	WC	G1	S1	2	2	1	1
214	WC	G2	S1	2	2	2	1
215	WC	G1	S1	1	3	1	1
216	WC	G2	S1	1	3	2	1
217	WC	G1	S1	1	2	1	1
218	WC	G2	S1	1	2	2	1
219	FCNT	A1	F1	2	4	3	3
220	FCNT	A2	F1	2	4	3	3
221	FCNT	N1	F1	2	4	3	3
222	FCNT	N2	F1	2	4	3	3
223	FCNT	G1	F1	2	4	3	3
224	FCNT	G2	F1	2	4	3	3
225	FCNT	A1	F2	2	4	3	3
226	FCNT	A2	F2	2	4	3	3
227	FCNT	N1	F2	2	4	3	3
228	FCNT	N2	F2	2	4	3	3
229	FCNT	G1	F2	2	4	3	3
230	FCNT	G2	F2	2	4	3	3
231	FCNT	A1	F3	2	4	3	3
232	FCNT	A2	F3	2	4	3	3
233	FCNT	N1	F3	2	4	3	3
234	FCNT	N2	F3	2	4	3	3
235	FCNT	G1	F3	2	4	3	3
236	FCNT	G2	F3	2	4	3	3
237	FCNT	A1	F4	2	4	3	3
238	FCNT	A2	F4	2	4	3	3
239	FCNT	N1	F4	2	4	3	3
240	FCNT	N2	F4	2	4	3	3
241	FCNT	G1	F4	2	4	3	3
242	FCNT	G2	F4	2	4	3	3
243	EW	A1	A2	3	3	2	2
244	EW	A1	N1	3	3	2	2
245	EW	A1	N2	3	3	2	2
246	EW	A1	G1	3	3	2	2
247	EW	A1	G2	3	3	2	2
248	EW	A2	A1	3	3	2	2
249	EW	A2	N1	3	3	2	2
250	EW	A2	N2	3	3	2	2
251	EW	A2	G1	3	3	2	2
252	EW	A2	G2	3	3	2	2
253	EW	N1	A1	3	3	2	2
254	EW	N1	A2	3	3	2	2
255	EW	N1	N2	3	3	2	2
256	EW	N1	G1	3	3	2	2
257	EW	N1	G2	3	3	2	2
258	EW	N2	A1	3	3	2	2
259	EW	N2	A2	3	3	2	2
260	EW	N2	N1	3	3	2	2
261	EW	N2	G1	3	3	2	2
262	EW	N2	G2	3	3	2	2
263	EW	G1	A1	3	3	2	2
264	EW	G1	A2	3	3	2	2
265	EW	G1	N1	3	3	2	2
266	EW	G1	N2	3	3	2	2

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
267	EW	G1	G2	3	3	2	2
268	EW	G2	A1	3	3	2	2
269	EW	G2	A2	3	3	2	2
270	EW	G2	N1	3	3	2	2
271	EW	G2	N2	3	3	2	2
272	EW	G2	G1	3	3	2	2
273	EW	A1	A2	2	2	1	3
274	EW	A1	N1	2	2	1	3
275	EW	A1	N2	2	2	1	3
276	EW	A1	G1	2	2	1	3
277	EW	A1	G2	2	2	1	3
278	EW	A2	A1	2	2	1	3
279	EW	A2	N1	2	2	1	3
280	EW	A2	N2	2	2	1	3
281	EW	A2	G1	2	2	1	3
282	EW	A2	G2	2	2	1	3
283	EW	N1	A1	2	2	1	3
284	EW	N1	A2	2	2	1	3
285	EW	N1	N2	2	2	1	3
286	EW	N1	G1	2	2	1	3
287	EW	N1	G2	2	2	1	3
288	EW	N2	A1	2	2	1	3
289	EW	N2	A2	2	2	1	3
290	EW	N2	N1	2	2	1	3
291	EW	N2	G1	2	2	1	3
292	EW	N2	G2	2	2	1	3
293	EW	G1	A1	2	2	1	3
294	EW	G1	A2	2	2	1	3
295	EW	G1	N1	2	2	1	3
296	EW	G1	N2	2	2	1	3
297	EW	G1	G2	2	2	1	3
298	EW	G2	A1	2	2	1	3
299	EW	G2	A2	2	2	1	3
300	EW	G2	N1	2	2	1	3
301	EW	G2	N2	2	2	1	3
302	EW	G2	G1	2	2	1	3
303	FT	A1	F1	2	1	1	1
304	FT	A1	F2	2	1	1	1
305	FT	A1	F3	2	1	1	1
306	FT	A1	F4	2	1	1	1
307	FT	A1	A2	2	1	1	1
308	FT	A1	N1	2	1	1	1
309	FT	A1	N2	2	1	1	1
310	FT	A1	G1	2	1	1	1
311	FT	A1	G2	2	1	1	1
312	FT	A1	S1	2	1	1	1
313	FT	A2	F1	3	1	1	1
314	FT	A2	F2	3	1	1	1
315	FT	A2	F3	3	1	1	1
316	FT	A2	F4	3	1	1	1
317	FT	N1	F3	3	1	1	1
318	FT	N1	F4	3	1	1	1
319	FT	N2	G1	3	1	1	1
320	FT	N2	G2	3	1	1	1

Index	DataType	Orig	Dest	DataS	SecL	SignL	DataR
321	FT	N2	S1	3	1	1	1
322	FT	G1	F1	3	1	1	1
323	FT	G1	F2	3	1	1	1
324	FT	G1	F3	3	1	1	1
325	FT	G1	F4	3	1	1	1
326	FT	G2	F1	3	1	1	1
327	FT	G2	F2	3	1	1	1
328	FT	S1	G1	3	1	1	1
329	FT	S1	G2	3	1	1	1
330	FT	A1	F1	3	1	1	1
331	FT	A1	F2	3	1	1	1
332	FT	A1	N1	3	1	1	1
333	FT	A1	N2	3	1	1	1
334	FT	A1	G1	3	1	1	1
335	FT	A1	G2	3	1	1	1
336	FT	A1	S1	3	1	1	1
337	FT	A2	G1	3	1	1	1
338	FT	A2	G2	3	1	1	1
339	FT	N1	F1	3	1	1	1
340	FT	N1	F2	3	1	1	1
341	FT	N2	F1	3	1	1	1
342	FT	N2	F2	3	1	1	1
343	FT	N2	F3	3	1	1	1
344	FT	N2	F4	3	1	1	1
345	FT	G1	F3	3	1	1	1
346	FT	G2	F3	3	1	1	1
347	FT	S1	G2	1	1	1	1
348	FT	A1	N1	1	1	1	1
349	FT	A2	N2	1	1	1	1
350	FT	N1	F1	2	1	1	1
351	FT	N1	F2	2	1	1	1
352	FT	N1	F3	2	1	1	1
353	FT	N1	F4	2	1	1	1
354	FT	N1	A1	2	1	1	1
355	FT	N1	A2	2	1	1	1
356	FT	N1	N2	2	1	1	1
357	FT	N1	G1	2	1	1	1
358	FT	N1	G2	2	1	1	1
359	FT	N1	S1	2	1	1	1
360	FT	N2	F4	1	1	1	1
361	FT	G1	F1	2	1	1	1
362	FT	G1	F2	2	1	1	1
363	FT	G1	F3	2	1	1	1
364	FT	G1	F4	2	1	1	1
365	FT	G1	A1	2	1	1	1
366	FT	G1	A2	2	1	1	1
367	FT	G1	N1	2	1	1	1
368	FT	G1	N2	2	1	1	1
369	FT	G1	G2	2	1	1	1
370	FT	G1	S1	2	1	1	1
371	FT	G2	N2	1	1	1	1
372	FT	S1	G1	1	1	1	1

ANNEX B

IBM ILOC CPLEX CODES OF MODEL

```
/*********************************************
 * OPL 12.6.1.0 Model
 * Author:
 * Creation Date: Mar 26, 2016 at 8:49:08 PM
 *********************************************/
 /****************************
*SETS, TUPLES AND PARAMETERS
****************************/
{string}        DataType=...;
{string}        CapSet=...;
{string}        NodeSet=...;
{int}       DataR=...;
{int}       SecL=...;
{int}       SignL=...;
{int}       DataS=...;

tuple       Demand {
                int         Index;
                string              DataType;
                string      Orig;
                string      Dest;
                int         DataS;
                int         SecL;
                int         SignL;
                int         DataR;
                };
{Demand}  D=...;
int     DataS_max[CapSet]=...;
int     DataR_max[CapSet]=...;
int     SecL_max[CapSet]=...;
int     SignL_max[CapSet]=...;
int     Utility[D][CapSet]=...;
int     CapTest[NodeSet][CapSet]=...;

/********************
*DECISION VARIABLES
********************/
dvar boolean      link[D][CapSet];
```

```
/*******************

*MATHEMATICAL MODEL
********************/
//Objective Function
maximize   sum(d in D,k in CapSet)  Utility[d,k]*link[d,k];
subject to   {
        forall(d in D,i in NodeSet:d.Orig==i,j in NodeSet:d.Dest==j,k in CapSet)
          CapabilityFeasible:
                 link[d][k]<=CapTest[i][k]*CapTest[j][k];

        forall(d in D)
          SatisfyAllDemands:
                 sum(k in CapSet)link[d][k]==1;

        forall(d in D)
          DataSizeConstraint:
                d.DataS <=sum(k in CapSet) DataS_max[k]*link[d][k];

        forall(d in D)
          SecLConstraint:
                d.SecL <=sum(k in CapSet) SecL_max[k]*link[d][k];

        forall(d in D)
          DataRConstraint:
                d.DataR <=sum(k in CapSet) DataR_max[k]*link[d][k];

        forall(d in D)
          SignLConstraint:
                d.SignL <=sum(k in CapSet) SignL_max[k]*link[d][k];

};
```

ANNEX C

IBM ILOC CPLEX CODES OF DATA

```
/*********************************************
 * OPL 12.6.1.0 Data
 * Author:
 * Creation Date: Mar 26, 2016 at 8:49:08 PM
 *********************************************/
SheetConnection sheet("Ersin0710.xlsx");
DataType        from SheetRead(sheet,"DataType");
NodeSet         from SheetRead(sheet,"NodeSet");
CapSet          from SheetRead(sheet,"CapSet");
DataR           from SheetRead(sheet,"DataR");
SecL            from SheetRead(sheet,"SecL");
SignL           from SheetRead(sheet,"SignL");
DataS           from SheetRead(sheet,"DataS");
D               from SheetRead(sheet,"D");
DataS_max       from SheetRead(sheet,"DataS_max");
DataR_max       from SheetRead(sheet,"DataR_max");
SecL_max        from SheetRead(sheet,"SecL_max");
SignL_max       from SheetRead(sheet,"SignL_max");
Utility         from SheetRead(sheet,"Utility");
CapTest         from SheetRead(sheet,"CapTest");
```

ANNEX D

THE OUTPUT OF IBM ILOC CPLEX FOR THREE METHOD

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
1	0	0	1	0	0	0	0	0
2	0	0	1	0	0	0	0	0
3	0	0	1	0	0	0	0	0
4	0	0	1	0	0	0	0	0
5	0	0	0	0	0	1	0	0
6	0	0	0	0	0	1	0	0
7	0	0	0	0	0	1	0	0
8	0	0	0	0	0	1	0	0
9	0	0	0	0	0	0	0	1
10	0	0	0	0	0	0	1	0
11	0	0	1	0	0	0	0	0
12	0	0	1	0	0	0	0	0
13	0	0	1	0	0	0	0	0
14	0	0	1	0	0	0	0	0
15	0	0	1	0	0	0	0	0
16	0	0	1	0	0	0	0	0
17	0	0	1	0	0	0	0	0
18	0	0	1	0	0	0	0	0
19	0	0	1	0	0	0	0	0
20	0	0	0	0	1	0	0	0
21	0	0	1	0	0	0	0	0
22	0	0	1	0	0	0	0	0
23	0	0	1	0	0	0	0	0
24	0	0	1	0	0	0	0	0
25	0	0	1	0	0	0	0	0
26	0	0	1	0	0	0	0	0
27	0	0	1	0	0	0	0	0
28	0	0	1	0	0	0	0	0
29	0	0	1	0	0	0	0	0
30	0	0	0	0	1	0	0	0
31	0	0	1	0	0	0	0	0
32	0	0	1	0	0	0	0	0
33	0	0	1	0	0	0	0	0
34	0	0	1	0	0	0	0	0
35	0	0	1	0	0	0	0	0
36	0	0	1	0	0	0	0	0
37	0	0	1	0	0	0	0	0
38	0	0	1	0	0	0	0	0
39	0	0	1	0	0	0	0	0
40	0	0	0	0	1	0	0	0
41	0	0	1	0	0	0	0	0
42	0	0	1	0	0	0	0	0
43	0	0	1	0	0	0	0	0
44	0	0	1	0	0	0	0	0
45	0	0	1	0	0	0	0	0
46	0	0	1	0	0	0	0	0
47	0	0	1	0	0	0	0	0
48	0	0	1	0	0	0	0	0
49	0	0	1	0	0	0	0	0

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
50	0	0	0	0	1	0	0	0
51	0	0	1	0	0	0	0	0
52	0	0	1	0	0	0	0	0
53	0	0	1	0	0	0	0	0
54	0	0	1	0	0	0	0	0
55	0	0	0	0	0	1	0	0
56	0	0	0	0	0	1	0	0
57	0	0	0	0	0	1	0	0
58	0	0	0	0	0	1	0	0
59	0	0	0	0	0	0	0	1
60	0	0	0	0	1	0	0	0
61	0	0	1	0	0	0	0	0
62	0	0	1	0	0	0	0	0
63	0	0	1	0	0	0	0	0
64	0	0	1	0	0	0	0	0
65	0	0	0	0	0	1	0	0
66	0	0	0	0	0	1	0	0
67	0	0	0	0	0	1	0	0
68	0	0	0	0	0	1	0	0
69	0	0	0	0	0	1	0	0
70	0	0	0	0	1	0	0	0
71	0	0	1	0	0	0	0	0
72	0	0	1	0	0	0	0	0
73	0	0	1	0	0	0	0	0
74	0	0	1	0	0	0	0	0
75	0	0	0	0	0	1	0	0
76	0	0	0	0	0	1	0	0
77	0	0	0	0	0	1	0	0
78	0	0	0	0	0	1	0	0
79	0	0	0	0	0	1	0	0
80	0	0	1	0	0	0	0	0
81	0	0	1	0	0	0	0	0
82	0	0	1	0	0	0	0	0
83	0	0	1	0	0	0	0	0
84	0	0	0	0	0	1	0	0
85	0	0	0	0	0	1	0	0
86	0	0	0	0	0	1	0	0
87	0	0	0	0	0	1	0	0
88	0	0	0	0	0	1	0	0
89	0	0	1	0	0	0	0	0
90	0	0	1	0	0	0	0	0
91	0	0	1	0	0	0	0	0
92	0	0	1	0	0	0	0	0
93	0	0	0	0	0	1	0	0
94	0	0	0	0	0	1	0	0
95	0	0	0	0	0	1	0	0
96	0	0	0	0	0	1	0	0
97	0	0	0	0	0	0	0	1
98	0	0	0	0	0	0	0	1
99	0	0	0	0	0	0	1	0
100	0	0	1	0	0	0	0	0
101	0	0	1	0	0	0	0	0
102	0	0	1	0	0	0	0	0
103	0	0	1	0	0	0	0	0

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
104	0	0	0	0	0	1	0	0
105	0	0	0	0	0	1	0	0
106	0	0	0	0	0	1	0	0
107	0	0	0	0	0	1	0	0
108	0	0	0	0	0	0	0	1
109	0	0	0	0	0	0	1	0
110	0	0	0	0	0	0	1	0
111	0	0	0	0	0	0	1	0
112	0	0	0	0	1	0	0	0
113	0	0	0	0	1	0	0	0
114	0	0	0	0	1	0	0	0
115	0	0	0	0	1	0	0	0
116	0	0	0	0	1	0	0	0
117	0	0	0	0	1	0	0	0
118	0	0	1	0	0	0	0	0
119	0	0	1	0	0	0	0	0
120	0	0	1	0	0	0	0	0
121	0	0	1	0	0	0	0	0
122	0	0	0	0	0	1	0	0
123	0	0	0	0	0	1	0	0
124	0	0	0	0	0	1	0	0
125	0	0	0	0	0	1	0	0
126	0	0	0	0	0	0	0	1
127	0	0	0	0	1	0	0	0
128	0	0	1	0	0	0	0	0
129	0	0	1	0	0	0	0	0
130	0	0	1	0	0	0	0	0
131	0	0	1	0	0	0	0	0
132	0	0	0	0	0	1	0	0
133	0	0	0	0	0	1	0	0
134	0	0	0	0	0	1	0	0
135	0	0	0	0	0	1	0	0
136	0	0	0	0	0	0	0	1
137	0	0	0	0	1	0	0	0
138	0	0	1	0	0	0	0	0
139	0	0	1	0	0	0	0	0
140	0	0	1	0	0	0	0	0
141	0	0	1	0	0	0	0	0
142	0	0	0	0	0	1	0	0
143	0	0	0	0	0	1	0	0
144	0	0	0	0	0	1	0	0
145	0	0	0	0	0	1	0	0
146	0	0	0	0	0	1	0	0
147	0	0	1	0	0	0	0	0
148	0	0	1	0	0	0	0	0
149	0	0	1	0	0	0	0	0
150	0	0	1	0	0	0	0	0
151	0	0	0	0	0	1	0	0
152	0	0	0	0	0	1	0	0
153	0	0	0	0	0	1	0	0
154	0	0	0	0	0	1	0	0
155	0	0	0	0	0	1	0	0
156	0	0	1	0	0	0	0	0
157	0	0	1	0	0	0	0	0

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
158	0	0	1	0	0	0	0	0
159	0	0	1	0	0	0	0	0
160	0	0	0	0	0	1	0	0
161	0	0	0	0	0	1	0	0
162	0	0	0	0	0	1	0	0
163	0	0	0	0	0	1	0	0
164	0	0	0	0	0	0	0	1
165	0	0	0	0	0	0	0	1
166	0	0	0	0	0	0	1	0
167	0	0	1	0	0	0	0	0
168	0	0	1	0	0	0	0	0
169	0	0	1	0	0	0	0	0
170	0	0	1	0	0	0	0	0
171	0	0	0	0	0	1	0	0
172	0	0	0	0	0	1	0	0
173	0	0	0	0	0	1	0	0
174	0	0	0	0	0	1	0	0
175	0	0	0	0	0	0	0	1
176	0	0	0	0	0	0	1	0
177	0	0	1	0	0	0	0	0
178	0	0	1	0	0	0	0	0
179	0	0	1	0	0	0	0	0
180	0	0	1	0	0	0	0	0
181	0	0	1	0	0	0	0	0
182	0	0	1	0	0	0	0	0
183	0	0	1	0	0	0	0	0
184	0	0	1	0	0	0	0	0
185	0	0	1	0	0	0	0	0
186	0	0	1	0	0	0	0	0
187	0	0	1	0	0	0	0	0
188	0	0	1	0	0	0	0	0
189	0	0	1	0	0	0	0	0
190	0	0	1	0	0	0	0	0
191	0	0	1	0	0	0	0	0
192	0	0	1	0	0	0	0	0
193	0	0	1	0	0	0	0	0
194	0	0	1	0	0	0	0	0
195	0	0	1	0	0	0	0	0
196	0	0	1	0	0	0	0	0
197	0	0	1	0	0	0	0	0
198	0	0	1	0	0	0	0	0
199	0	0	1	0	0	0	0	0
200	0	0	1	0	0	0	0	0
201	0	0	0	0	0	1	0	0
202	0	0	0	0	0	1	0	0
203	0	0	0	0	0	1	0	0
204	0	0	0	0	0	1	0	0
205	0	0	0	0	0	0	0	1
206	0	0	0	0	0	0	0	1
207	0	0	0	0	0	0	1	0
208	0	0	0	0	0	0	1	0
209	0	0	0	0	1	0	0	0
210	0	0	0	0	1	0	0	0
211	0	0	0	0	0	0	1	0

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
212	0	0	0	0	0	0	1	0
213	0	0	0	0	0	0	1	0
214	0	0	0	0	0	0	1	0
215	0	0	0	0	0	0	1	0
216	0	0	0	0	0	0	1	0
217	0	0	0	0	0	0	1	0
218	0	0	0	0	0	0	1	0
219	0	0	1	0	0	0	0	0
220	0	0	1	0	0	0	0	0
221	0	0	1	0	0	0	0	0
222	0	0	1	0	0	0	0	0
223	0	0	1	0	0	0	0	0
224	0	0	1	0	0	0	0	0
225	0	0	1	0	0	0	0	0
226	0	0	1	0	0	0	0	0
227	0	0	1	0	0	0	0	0
228	0	0	1	0	0	0	0	0
229	0	0	1	0	0	0	0	0
230	0	0	1	0	0	0	0	0
231	0	0	1	0	0	0	0	0
232	0	0	1	0	0	0	0	0
233	0	0	1	0	0	0	0	0
234	0	0	1	0	0	0	0	0
235	0	0	1	0	0	0	0	0
236	0	0	1	0	0	0	0	0
237	0	0	1	0	0	0	0	0
238	0	0	1	0	0	0	0	0
239	0	0	1	0	0	0	0	0
240	0	0	1	0	0	0	0	0
241	0	0	1	0	0	0	0	0
242	0	0	1	0	0	0	0	0
243	0	0	0	0	0	1	0	0
244	0	0	0	0	0	1	0	0
245	0	0	0	0	0	1	0	0
246	0	0	0	0	0	1	0	0
247	0	0	0	0	0	1	0	0
248	0	0	0	0	0	1	0	0
249	0	0	0	0	0	1	0	0
250	0	0	0	0	0	1	0	0
251	0	0	0	0	0	1	0	0
252	0	0	0	0	0	1	0	0
253	0	0	0	0	0	1	0	0
254	0	0	0	0	0	1	0	0
255	0	0	0	0	0	1	0	0
256	0	0	0	0	0	1	0	0
257	0	0	0	0	0	1	0	0
258	0	0	0	0	0	1	0	0
259	0	0	0	0	0	1	0	0
260	0	0	0	0	0	1	0	0
261	0	0	0	0	0	1	0	0
262	0	0	0	0	0	1	0	0
263	0	0	0	0	0	1	0	0
264	0	0	0	0	0	1	0	0
265	0	0	0	0	0	1	0	0

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
266	0	0	0	0	0	1	0	0
267	0	0	0	0	0	0	0	1
268	0	0	0	0	0	1	0	0
269	0	0	0	0	0	1	0	0
270	0	0	0	0	0	1	0	0
271	0	0	0	0	0	1	0	0
272	0	0	0	0	0	0	0	1
273	0	0	0	0	0	1	0	0
274	0	0	0	0	0	1	0	0
275	0	0	0	0	0	1	0	0
276	0	0	0	0	0	1	0	0
277	0	0	0	0	0	1	0	0
278	0	0	0	0	0	1	0	0
279	0	0	0	0	0	1	0	0
280	0	0	0	0	0	1	0	0
281	0	0	0	0	0	1	0	0
282	0	0	0	0	0	1	0	0
283	0	0	0	0	0	1	0	0
284	0	0	0	0	0	1	0	0
285	0	0	0	0	0	1	0	0
286	0	0	0	0	0	1	0	0
287	0	0	0	0	0	1	0	0
288	0	0	0	0	0	1	0	0
289	0	0	0	0	0	1	0	0
290	0	0	0	0	0	1	0	0
291	0	0	0	0	0	1	0	0
292	0	0	0	0	0	1	0	0
293	0	0	0	0	0	1	0	0
294	0	0	0	0	0	1	0	0
295	0	0	0	0	0	1	0	0
296	0	0	0	0	0	1	0	0
297	0	0	0	0	0	0	0	1
298	0	0	0	0	0	1	0	0
299	0	0	0	0	0	1	0	0
300	0	0	0	0	0	1	0	0
301	0	0	0	0	0	1	0	0
302	0	0	0	0	0	0	0	1
303	0	0	1	0	0	0	0	0
304	0	0	1	0	0	0	0	0
305	0	0	1	0	0	0	0	0
306	0	0	1	0	0	0	0	0
307	0	0	0	0	0	1	0	0
308	0	0	0	0	0	1	0	0
309	0	0	0	0	0	1	0	0
310	0	0	0	0	0	1	0	0
311	0	0	0	0	0	1	0	0
312	1	0	0	0	0	0	0	0
313	0	0	1	0	0	0	0	0
314	0	0	1	0	0	0	0	0
315	0	0	1	0	0	0	0	0
316	0	0	1	0	0	0	0	0
317	0	0	1	0	0	0	0	0
318	0	0	1	0	0	0	0	0
319	0	0	0	0	0	1	0	0

Demand Index	L11A	L11B	L16	L22	VMF	JRP-A	JRP-B	JRP-C
320	0	0	0	0	0	1	0	0
321	1	0	0	0	0	0	0	0
322	0	0	1	0	0	0	0	0
323	0	0	1	0	0	0	0	0
324	0	0	1	0	0	0	0	0
325	0	0	1	0	0	0	0	0
326	0	0	1	0	0	0	0	0
327	0	0	1	0	0	0	0	0
328	0	0	0	0	0	0	1	0
329	0	0	0	0	0	0	1	0
330	0	0	1	0	0	0	0	0
331	0	0	1	0	0	0	0	0
332	0	0	0	0	0	0	0	1
333	0	0	0	0	0	1	0	0
334	0	0	0	0	0	1	0	0
335	0	0	0	0	0	1	0	0
336	1	0	0	0	0	0	0	0
337	0	0	0	0	0	1	0	0
338	0	0	0	0	0	1	0	0
339	0	0	1	0	0	0	0	0
340	0	0	1	0	0	0	0	0
341	0	0	1	0	0	0	0	0
342	0	0	1	0	0	0	0	0
343	0	0	1	0	0	0	0	0
344	0	0	1	0	0	0	0	0
345	0	0	1	0	0	0	0	0
346	0	0	1	0	0	0	0	0
347	0	0	0	0	0	0	1	0
348	0	0	0	0	0	1	0	0
349	0	0	0	0	0	1	0	0
350	0	0	1	0	0	0	0	0
351	0	0	1	0	0	0	0	0
352	0	0	1	0	0	0	0	0
353	0	0	1	0	0	0	0	0
354	0	0	0	0	0	1	0	0
355	0	0	0	0	0	0	0	1
356	0	0	0	0	0	1	0	0
357	0	0	0	0	0	1	0	0
358	0	0	0	0	0	1	0	0
359	1	0	0	0	0	0	0	0
360	0	0	1	0	0	0	0	0
361	0	0	1	0	0	0	0	0
362	0	0	1	0	0	0	0	0
363	0	0	1	0	0	0	0	0
364	0	0	1	0	0	0	0	0
365	0	0	0	0	0	1	0	0
366	0	0	0	0	0	1	0	0
367	0	0	0	0	0	0	0	1
368	0	0	0	0	0	1	0	0
369	0	0	0	0	0	0	0	1
370	0	0	0	0	0	0	1	0
371	0	0	0	0	0	1	0	0
372	0	0	0	0	0	0	1	0